ASSESSMENT OF EFFECTS CAUSED BY TENNIS EQUIPMENT CHANGE, UNDER EXTENDED REAL PLAY USE

by

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ABSTRACT

There is an increasing awareness of the necessity to evaluate the effects of tennis equipment in combination with players and the corresponding need for new methods of testing to be developed. This research has investigated the effectiveness of a range of objective measurements of player performance and their ability to quantify the effects of equipment modification and player fatigue.

The hypothesis of this research was that if different designs of tennis equipment affect a player differently in terms of either accelerated/reduced fatigue or increased/reduced likelihood of injury, then there must be some changes in either the impact dynamics in terms of shock loading and vibration transmission, or through kinematic changes in terms of swing motion and biomechanics. Furthermore, it was hypothesised that using state-of-the-art instrumentation technologies in conjunction with a controlled experimental protocol, it may be possible to measure some of these changes.

Three experimental studies were undertaken in support of this research, the first two being sponsored by the ITF to investigate the effects of playing with a larger Type 3 tennis ball. Based on the findings of the ITF studies, it was recommended that a test device be developed that was capable of more sensitively detecting changes in racket-hand interaction, especially grip performance during play.

The research questions can be summarised as follows:

1. Could an instrumented test racket be designed to provide dynamic measurements of tennis shots with sufficient sensitivity and repeatability to enable the characterisation of different levels of player fatigue and discriminate between shots made with different designs of tennis equipment?
2. Does playing tennis with a bigger ball have a positive/detrimental effect on the style or quality of tennis played?
3. Does playing tennis with a bigger ball have a positive/detrimental effect on the players in terms of increased muscle fatigue/soreness?

An instrumented tennis racket was designed, developed and assembled to measure in-play grip pressure, shock loading and racket vibration. In support of this, a controlled test protocol was also developed to induce accelerated fatigue in the functionally relevant muscles symptomatically involved in tennis elbow. Fatigue status was selected for manipulation because of the potential end use of this type of measurement device, i.e. to determine relative effects of equipment in terms of fatigue and injury. The test protocol was designed to investigate 'in-play'

effects and was therefore designed to provide a tennis-realistic test environment whilst maintaining adequate control for the purposes of results comparison and repeatability.

The novelty of the approach used in this third study was the simultaneous measurement of in-play grip vibration, shock loading and grip pressure in tennis whilst in addition incorporating the component of fatigue. Previous studies that have investigated components of vibration and grip pressure have neglected the fatigue component of player performance. It is suggested that this is important in respect of determining the relative effects of equipment on fatigue and in the future may enable identification of a causal link with the incidence of overuse injuries.

Use of the instrumented racket as an in-play measurement device was found to exhibit improved capabilities for measuring hand-grip fatigue status, as compared to a static hand-grip device. Several parameters of grip pressure that relate to fatigue status were successfully identified.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Tennis is played and watched by many people; it is estimated that the game is played by up to 60 million players in 200 countries worldwide and that the tennis industry results in an annual turnover figure of several billion U.S. dollars worldwide (Coe, 2000). The U.S. Tennis Open in 2002 had $16m total prize money available. All major sports equipment companies showcase their premium equipment in the hands, or on the feet, of leading players. In the modern era of professional tennis, the increasing financial rewards on offer to winners is driving the requirement to invest more heavily in the process of winning. Winning and being seen to win at the highest level is the ultimate endorsement of a sports equipment product. In this environment, increased investment in the research and development of sports equipment is easily justified.

Every year for the five years between 1976 and 1980, Bjorn Borg won the Wimbledon tennis tournament with a wooden racket. Since then, racket development has been dramatic, utilising exotic materials and aerospace derived technologies. Future developments are likely to produce diminishing performance gains, but research and development money will still be invested. Professional players are nowadays required to perform at the highest level more frequently. Club and recreational level tennis players are also seeking improved performance, greater consistency and lower incidence of injury. Many of these players are prepared to pay considerable sums for equipment that provides such benefits. However, customers are becoming aware that many so-called technical developments are simply gimmicks or marketing hype. At a time when the importance of winning and investment in winning are high and when the rapid advancement in new racket technologies is slowing, it is becoming increasingly necessary to support new developments with improved scientific testing and evaluation.

The motivations for developing improved methods of testing and evaluation are many and varied and extend across different stakeholders throughout tennis. Manufacturers could quantify the effects of new equipment designs. Players could select equipment more suited to their physical attributes and playing style. Coaches could assess the relative merits of different playing techniques. Medical professionals could assess the causes of injury or even pre-screen for high stress conditions and risk factors. Governing bodies could make informed decisions about the likely impact of rule changes on the game, particularly with regards to promoting a rewarding spectator experience. Overall, performance and enjoyment could be improved.

Elite and recreational players typically use different rackets due to their different requirements in terms of, for example, performance and comfort and also due to their different levels of ability (skill) and conditioning. For elite players, performance enhancement and an acceptable level of injury risk are the key factors in equipment choice. Elite athletes, because of their skill and conditioning, can play with equipment that would be uncomfortable and induce a higher probability of injury in the hands of a recreational player. Professional players tend to prefer an increased level of 'feel', considering this to give them improved ball control and also better feedback about the likely shot outcome. The speed of the game is such that an elite player has to make decisions about their next movement without seeing the outcome of a shot. Positioning themselves ready for the next shot is partly based on the anticipated outcome of their present shot and 'feel' contributes to this.

For recreational players, equipment choice is more influenced by comfort, skill enhancement, minimal injury risk and status enhancement. Racket and ball technology developments have resulted in significant changes in performance and skill enhancement. However, researchers have continued to experience difficulty in quantifying comfort, fatigue rates and injury risk either absolutely or relatively. With likely diminishing returns from technological advancements to boost performance, injury prevention and comfort features become more important as product differentiators.

Dabnichki (1998) identifies the main aims of sports equipment design as performance enhancement and injury prevention. Historically, performance enhancement, hitting faster, further or for longer, has been the primary goal of design changes. However, performance improvement almost inevitably leads to increases in loading on certain parts of the body. Increasingly, attention is being given to the question of how improvements in equipment design can alleviate the symptoms of or even reduce the likelihood of developing injuries.

According to Dabnichki "biomechanical aspects should be given thorough consideration in sport equipment design. However, such a task demands that purpose-built instrumentation and specifically designed, controlled tests be used. The design of sports equipment ought to be based on analysis of the external forces and related stress distribution in the human limbs, in order to assess the potential hazards to the athletes. To accomplish this, one needs to study the dynamic response of the equipment and related body response. Kinematic data are insufficient to provide an accurate estimate of the dynamic loading acting on the athletes body and should be carefully assessed if utilized."

The main design goal for new tennis rackets is that they sell well. This requires making rackets that players believe in, or at least can be convinced they want. In support of this requirement, manufacturers and users are interested in proving the worth of design features. An essential part of any evaluation process is the collection of objective performance data. Although essentially sports equipment is a 'product', its performance is affected by its interaction with the human using it. To fully evaluate the performance of sports equipment, tests need to be introduced in the context of this interaction. In practice, a large part of equipment testing is laboratory based, using robots, machines and computer simulation programs that test the equipment in isolation from the player. The majority of human interaction testing tends to be limited to non-controlled, subjective evaluation by a sample of players to gain insight into the 'feel' of the equipment. Objective in-play testing is currently the weak link between objective laboratory tests and subjective player testing.

As awareness of the necessity to evaluate the effects of equipment in combination with the player has increased, so too has the need for methods of testing to be developed. Moritz (2002) states that "final users should be integrated into the design process as early as possible". Furthermore, he stresses the importance of not limiting this feedback to that of elite players because generally their requirements are different to those of beginners or intermediates.

This research has investigated the effectiveness of a range of objective measurements of player performance and their ability to quantify the effects of equipment modification. The measurements are objective in that they are quantitative rather than qualitative and reproducible given adequate controls. Player performance has been investigated as opposed to equipment performance. In this respect, measures to assess the performance of player and equipment in combination have been assessed, rather than measures of either in isolation. The objective measurements of interest do not therefore encompass machine-based testing of equipment or physiological testing of players remote from the sports equipment. The stated intention of investigating the effects of equipment modification provided a means of exercising candidate objective measurements. By applying systematic input changes such as ball type and player fatigue status, it was possible to investigate the effectiveness of the objective measurements.

The potential for making objective measurements across a wide range of player performance characteristics has been investigated. Player performance characteristics are here defined as any outcome or effect which is elicited in response to equipment change (in the case of this research) or indeed, more generally, in response to any other variable change, such as, conditioning regime, technique modification, dietary intake intervention, playing conditions or healthy versus injured. For the purposes of this research study, the player performance characteristics have been classified under the three main headings of 'performance outcome characteristics', 'physical condition characteristics' and 'player perception characteristics'. Of these three main categories, this research has mainly concentrated on investigating the potential for obtaining objective measurements of physical condition characteristics, although the other two have also been considered. The following sub-sections introduce the three categories of player performance characteristics.

1.1.1 Performance outcome characteristics

Performance outcome characteristics encompass all of the measures used to describe the result of an activity and therefore the success of a player's tennis performance. Of the three categories of player performance characteristics, performance outcome characteristics are the most straightforward to assess objectively. Examples include 'number of points won', 'number of first serves in', 'number of aces', 'serve velocity.' Perhaps less obviously, performance outcome characteristics may also be used in the assessment of various aspects of 'style of play', and 'quality of the viewing spectacle', which is of particular relevance to commercial backers of tennis. Performance outcome characteristics are independent of a player's perception of them. As such, performance outcome characteristics provide objective data, which translates to feedback about the success or failure of a performance.

Match analysis statistics have recently been used to support the need for intervention to address the high speed issue and as evidence of the effectiveness of the introduction of the larger ball as a solution to this issue.

Hughes and Clarke (1993) compared patterns of play from the 1992 Wimbledon Championships and the Australian Open. Data were limited to male singles play. On the synthetic surface of the Australian Open, the average number of shots in a rally was found to be 52% greater than on the grass courts of Wimbledon. However, the average time of each rally was 93% greater. Hughes and Clarke went on to say this indicates that not only was the number of shots on grass less but that the shots occurred in more rapid succession to each other. Fast surfaces such as grass certainly lend themselves to a more attacking serve and volley game, with more points being settled by winning shots rather than errors. The probability of holding serve is also known to be greater on a fast surface and the percentage of tiebreak games is correspondingly higher (Coe, 2000) and so favours strong servers.

Although the study by Hughes and Clarke generated an overview of differences in-play on the two surfaces, data were limited to a selection of players and matches. O'Donoghue (2001) developed a computerized data management system and data analysis software and entered details of points played in 252 tennis matches from both men's and women's singles events of all four grand slams from 1997 to 1999. These data paint the most comprehensive picture of patterns of play and strategy to date. Rallies were calculated to be significantly longer on the slower clay courts of the French Open and significantly shorter on the faster grass surface at Wimbledon, than at any other tournament. Play on clay resulted in a greater proportion of baseline rallies and on grass a greater proportion of serve and volley points were played.

Gender was found to be a factor affecting style of play with average rally length being greater for women; women playing a significantly greater proportion of baseline rallies when compared to men.

Klaassen (2000) studied points from the 1992 to 1995 Wimbledon Championships to investigate serve dominance, which is considered to have a negative effect on the attractiveness of the game to spectators. This issue is discussed in more detail in Chapter 2.

1.1.2 Player perception characteristics

Player perception characteristics are about the player's interpretation of outcomes and interaction with his/her environment and as such are difficult to quantify objectively. In the literature these characteristics are often referred to as 'feel' characteristics. Reporting on research done in the field of golf, Hocknell *et al.* (1996) and Roberts *et al.* (2001) found that feel was a complex term incorporating visual information, sound and direct feedback to the hands via the grip of the club. It has already been stated that, performance outcome characteristics "are as they are" and remain independent of a player's perception of them. However, it must also be recognised that a player's perception of the performance outcome characteristics will influence future outcomes, which forms the basis for skill development and also gives rise to positive or negative thinking.

1.1.3 Physical condition characteristics

Physical condition characteristics relate to the condition of the player, the equipment and these in combination. Examples include 'muscle soreness' and 'fatigue'. Physical condition characteristics have a direct influence on the performance outcome characteristics. Increasingly products are being advertised on the basis of their ability to reduce the symptoms and risk of injury. Mitt for example state on their website that the Rocker System Racket "is the only tennis racket guaranteed to improve your game and eliminate tennis elbow" (MittUSA, 2002). However, the causative mechanism of tennis elbow is as yet unknown and an objective test to substantiate these claims does not currently exist. There is a complex interaction of factors contributing to the onset of injury and as a result the implications of intervention with respect to injury are difficult to ascertain.

Tennis is a physically demanding game and the margin between winning and losing can be very small. The total time of an uninterrupted tennis match is usually between 30 to 120 minutes, while some rare matches can last as long as six hours (Richers, 1995). In such a physically demanding game it is not surprising that injuries occur. Tennis elbow is the most common tennis injury and it is estimated that up to 50% of all recreational tennis players have symptoms of tennis elbow at some time (Coonrad and Hooper, 1973; Giangarra *et al.*, 1993; Nirschl, 1973; Plancher *et al.*, 1996; Roetert *et al.*, 1995). In modern times, increasing interest is being shown in how the design of equipment impacts upon a player in terms of injury likelihood. To determine with absolute confidence the effect of equipment in terms of injury is difficult as the likely cause is a complex interaction of factors likely to be different depending on the individual.

If equipment is to affect a player's likelihood of injury, then there must be some change in either the impact dynamics in terms of shock loading and vibration transmission, or through kinematic changes in terms of swing motion and biomechanics. Motion analysis equipment and techniques are well developed and capable of investigating the in-play effect of equipment in terms of technique changes. In terms of detecting changes to impact dynamics in terms of shock loading and vibration transmission, it is logical to assume that some physical change will occur at the hand-racket interface during impact, which will manifest itself as a physical characteristic. It is also logical to assume that less vibration and less shock loading will be positive with respect to injury. These parameters are often measured on the racket in isolation, but the argument put forward in this thesis is that isolated measurements are inadequate to measure the physical effects occurring during real play. Any equipment modification designed to reduce injury can only be effective if it results in a change that reaches the player. As stated, the main objective of the research reported in this thesis has been to evaluate the application of current technology for use in the measurement of candidate physical characteristics.

1.1.4 Introduction to experimental variables

A whole series of variables can be identified that affect the three categories of player performance characteristics. New methods of objective measurement would provide a means of evaluating the effects of these variables. For the purposes of this research study, variables have been classified under the three main headings of 'equipment variables', 'player variables' and 'environmental variables'. Equipment variables cover factors such as string tension, ball type, racket material, and racket head size. Player variables include such factors as ability level, age, gender, reasons for participation, level of conditioning, technique, style of play. These variables combine to define the player population being investigated. Environmental variables include court surface, weather conditions, indoors or outdoors. This research has investigated the potential for obtaining objective measurements of player performance characteristics to assess the effects of applying controlled interventions to equipment variables and player variables. More specifically, the variables of ball type, ability level and fatigue status have been investigated. Feedback provided by this approach can be used for the performance development of equipment and players.

A further important factor considered in this research is the dimension of time. The effect that variables will have on player performance characteristics will continually change over time. In other words, each performance outcome characteristic, physical condition characteristic, or player perception characteristic may or may not also have an associated time-effect. Thus, for example a player's performance outcome characteristic of service shot velocity may at first increase as a player warms up and then gradually decrease as fatigue sets in. Conversely, the player's perception of this service shot velocity may be that it gradually increases throughout the game. In this example therefore, different time-effect trends would exist for the performance outcome characteristic and for the player's perception characteristic of the same measure. Time-effects become most evident in the context of the physical condition characteristics, in the form of fatigue and injury. Time effects may occur gradually (e.g. fatigue or chronic injury) or more suddenly (e.g. acute injury), and be more predictable (e.g. fatigue) or less predictable (e.g. acute injury).

1.1.5 Research approach

In conducting this research, it was necessary to identify and review current methods for the measurement and evaluation of tennis equipment performance and player performance. There are several very different approaches, with a main differentiator being the involvement or not of a human subject. Human testing may be further subdivided into either static or dynamic. Static player testing involves firing tennis balls from a ball cannon at a racket held statically by a subject. This approach offers the advantage of improved consistency of results because the ball can be accurately and repeatedly directed at a particular position on the racket. Dynamic player testing involves player subjects swinging a racket and actively striking a ball. This approach offers the advantage of added realism; whilst making a shot a player's muscles are actively contracting and therefore behaving differently from in the static testing case. Non-human based methods most importantly include simulation modelling. Simulation modelling covers a broad range of techniques, which can be classified according to whether they utilise a physical or non-physical model. Physical simulation models for tennis are typically based on a mechanical arm designed to simulate a human arm. Non-physical models are mathematical models. The development of sophisticated mathematical simulation models benefits from the availability of powerful computer facilities and will continue to develop as computer technology evolves.

Following an evaluation of the existing methods of player performance measurement, it became evident that there is currently no objective means of determining the effect of equipment modifications on the likelihood of causing injury. This is partly due to the difficulty of determining the causal mechanisms of injury and partly due to the difficulty of controlling all of the variables. Indeed, some researchers claim that it is ineffective to involve players in the performance evaluation of equipment by objective measurement because of the variability which players introduce (Hatze, 1992b). However, in consideration of the relative merits of the various methods, it is important to recognise that no single method can provide the panacea of a 'complete solution'. At best, each method can offer an insight into certain aspects of the overall situation and can provide a complementary contribution. To date, very few researchers have investigated methods of dynamic human testing. Those most relevant to this research are Kawazoe (Kawazoe *et al.*, 2002; Kawazoe and Yoshinari, 2000, Knudson and Blackwell, 2000; Knudson, 1991a; Knudson, 1991b and Stretch *et al*, 1995), researching in the fields of tennis, tennis and cricket respectively. However, the studies in the area of dynamic human testing often involve testing of just one subject and recommend the need for future testing to incorporate a testing protocol that enables variation in the results to be accounted for; variations being inevitable in human testing of this nature. Furthermore, with the exception of physiological studies investigating the effects of dietary intervention on tennis performance and fatigue, researchers have not considered the effects of equipment over time and during fatigue. This is important because the effects in question might not show up in a fresh subject and chronic injuries, such as tennis elbow, are dependent on exposure levels.

The first main experimental study reported in this thesis was commissioned by the International Tennis Federation (ITF) to investigate the effects of playing with an oversize Type 3 tennis ball, as compared with a standard sized Type 2 ball. The ITF is the worldwide governing body of tennis. This work formed a part of the ITF's evaluation process for adoption of the Type 3 ball. Comparison was made across a broad range of factors, including investigation of whether the Type 3 ball might increase player fatigue, or whether use of the Type 3 ball materially affects the nature of the game (e.g. rally length), or the outcome of the game (by providing bias advantage to certain styles of play), and how players perceive the Type 3 ball compared to the Type 2. Testing was performed on different demographic groups, to investigate the extent to which results were dependent on player ability level. Testing included a range of measures to assess player fatigue status. A hand-grip strength test involving use of a static hand-grip dynamometer was performed to assess how fatigue status affected grip strength. A possible weakness of this approach was identified as the potential for rapid post-exercise recovery of any grip strength reduction. It was established that a dedicated, commercially available, in-play, non-invasive method of directly measuring grip pressure did not exist. Use of ad hoc instrumentation by researchers had neglected the time/fatigue component of player performance. It was proposed that the existence of such a method may provide insight into the effects of equipment modifications on fatigue. Furthermore it was proposed that the in-play measurement of grip pressure should be combined with measurement of shock loading and vibration; these factors all being identified as possible causes of injury (Fairley, 1985; Hennig *et al.*, 1992; Knudson, 1988; Stone *et al.*, 1999).

Instrumentation technologies and devices were sought and methods of human performance testing in other disciplines, sporting and non-sporting, were investigated. The concept of developing a non-invasive instrumented tennis racket was established and a requirements specification drawn up. An instrumented racket was assembled which was capable of making in-play, non-invasive measurements of the dynamic effects of playing tennis. Experiments were designed and conducted to investigate the influence of fatigue on player performance, including shot accuracy. During the experiments, objective measurements of player performance were gathered. Evaluation of the sensitivity, repeatability, robustness and usability of the objective measurements also enabled assessment of the worthiness of the measurement techniques themselves.

1.2 HYPOTHESIS & RESEARCH OBJECTIVES

The hypothesis of this research was that if different designs of tennis equipment affect a player differently in terms of either accelerated/reduced fatigue or increased/reduced likelihood of injury, then there must be some changes in either the impact dynamics in terms of shock loading and vibration transmission, or through kinematic changes in terms of swing motion and biomechanics. Furthermore, it was hypothesised that by using state-of-the-art instrumentation technologies and in conjunction with a controlled experimental protocol, it may be possible to measure some of these changes.

The first general objective of this research study has been to investigate the potential for obtaining objective measurements of player performance characteristics to assess the effects of applying controlled interventions to equipment variables and player variables. The motivation for this activity has been to contribute new knowledge to the science of sport specific performance measurement, and to add to the pool of tennis specific data available. In support of this has been the development of new sport specific tests to assess the effects of of various aspects of player performance.

An objective has been to investigate the influence of particular variables on player performance. Specifically, the variables of ball type, ability level and fatigue status have been investigated to assist with an ITF decision on whether to introduce an oversize, Type 3 tennis ball for use in major tournaments on fast surfaces. Systematic differences between the Type 3 ball and the standard sized Type 2 ball were investigated in terms of point play outcome, player perception and muscle soreness and fatigue. Investigations have been based on studies of in-play testing, which were designed to simulate normal playing conditions.

Having identified deficiencies in off-court player performance assessment instruments and protocols, the most recent objective has been to design, develop and assemble an instrumented tennis racket which is capable of measuring in-play grip pressure, shock loading and racket vibration (physical phenomena). An additional requirement has been the development of a controlled test protocol to exercise the instrumented racket to test its effectiveness, the aim being to identify physical phenomena that change in response to differences in equipment and fatigue status. The developed instrumentation has enabled initial investigation of the grip pressure profile through shot impact. It has also enabled investigation of the relationships between grip pressure, shot accuracy and measured and perceived fatigue. A further objective has been to identify the current limitations of performance measurement capabilities and make recommendations for future developments.

The research questions can be summarised as follows:

1. Could an instrumented test racket be designed to provide dynamic measurements of tennis shots with sufficient sensitivity and repeatability to enable the characterisation of different levels of player fatigue and discriminate between shots made with different designs of tennis equipment?
2. Does playing tennis with a bigger ball have a positive/detrimental effect on the style or quality of tennis played?
3. Does playing tennis with a bigger ball have a positive/detrimental effect on the players in terms of increased muscle fatigue/soreness?

1.3 THESIS OUTLINE

The chapter outline of the thesis is as follows:

Chapter 2 provides a discussion of current knowledge based on a review of the literature relevant to the research aims. The scope and limitations of previously reported research is identified leading to the utilisation of current instrumentation technologies and protocols in new combinations within the research reported herein.

Chapters 3 and 4 summarises the preliminary experimental work undertaken to investigate the effects of playing tennis with the Type 3 larger tennis ball. It describes two studies conducted on behalf of the ITF.

Following a review of the findings of the above studies, it was decided to focus on investigating and developing new methods of objectively measuring player performance. Chapter 5 describes the development of these new methods, the trial use of which is then reported in Chapter 6.

Chapter 7 provides a general discussion and presents conclusions about the research outcomes with reference to the original aims and objectives. The new knowledge generated by the research studies is highlighted. Chapter 8 provides recommendations for further work.

CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter presents a review of current knowledge based on the published literature. It begins with a short history of the game and an overview of the main developments, particularly with respect to equipment changes and their affect on player performance. This leads into a general review of performance measurement and evaluation, which plays a vital part in equipment design and development. Next, the issue of injury is considered, in terms of likely cause and possible prevention. Tennis elbow affects a significant proportion of players, but its cause is not well understood. Indeed, the combination of mechanical stresses and strains that leads to inflammation or tears of the tendon presently remains unknown. Factors suspected of exacerbating tennis elbow are reviewed, particularly in relation to equipment effects. The final parts of this chapter review current capabilities with respect to the measurement of hand forces, grip pressure, and impact shock loading and vibration. Gaining a better understanding of these aspects is considered important in the design of equipment for performance improvement and vital in order to establish the causal mechanism(s) of tennis elbow. Weaknesses and gaps in current capabilities are identified and the basis for the work reported in this thesis is established.

2.2 DEVELOPMENT OF THE GAME OF TENNIS

Since the 'tennis boom' of the 1970's, tennis has become a multi-billion dollar per year industry. Television pays enormous sums of money for the rights of coverage, sponsors pay to promote their products, tournament organisers offer ever increasing appearance fees and prize money to entice the big name players who in turn ensure mass media coverage of the event. Playing tennis is relatively accessible to the general public, evidenced by interest in the leading players in the 1970's transferring to mass participation at a recreational level. Advances in technology and the application of science have significantly improved the design of tennis equipment over the last thirty years (Brody *et al.*, 2002; Cochran, 2002; Coe, 2000). Increasingly sophisticated manufacturing techniques have been developed, for example, CAD/CAM, agile manufacturing, blow-moulding and thermosetting. Materials such as carbon fibre reinforced composites have been introduced from other industries, for example, aerospace. Relatively cheap glass fibres may be used, or in some instances, the fibres may be braided or include more exotic filaments (e.g. titanium, Kevlar, high modulus carbon). It is unlikely that such a large advancement as the move to composites from wood will ever happen again; as time goes on any advances made based on this technology will consequently be smaller. However in the sports industry a small improvement is thought to potentially make the difference between winning and losing and the incentives for doing so are large and increasing. The following section describes the development and changing nature of the game of tennis from its roots in the late nineteenth century to modern day.

2.2.1 History of tennis

Tennis is believed to have originated in France in the twelfth century from the game of 'Jeu de paumme' which translates to 'game of the hand' (Heathcote *et al.*, 1987). The game spread to England in the sixteenth century by way of its popularity as a pastime amongst royalty. During the seventeenth and eighteenth centuries the ancient game continued to develop particularly in England. In 1873 Major Walton Clopton Wingfield registered a patent for a game he called 'Sphairistike'. Although the name was soon changed to 'tennis' the game he patented took off and developed into the game played today. In 1877, the first organised tennis tournament took place at Wimbledon and Spencer Gore became the first ever singles champion winning 12 guineas and a silver cup (Dunkley, 1998). The game continued to grow and to be played worldwide. A major change came in 1968 when the game turned professional, television paid for coverage and sponsors used the media coverage to promote their products. The game became extremely popular, with more people taking up the game for enjoyment. The period is now referred to as the 'tennis boom'.

2.2.2 Rules

The first formal set of tennis rules were included in Major Wingfield's patent in 1873. In 1875, the Marylebone Cricket Club (M.C.C.) published a standardised set of rules of the game and the hourglass playing court that Wingfield introduced became the rectangular court we use today (ThinkQuest, 2003). The All England Croquet Club adopted the game of tennis in 1875 and the game became so popular that by the following year the club had changed their name to the All England Croquet and Lawn Tennis Club. The club committee effectively took over the development of the game. They introduced several modifications to the game, for example, lowering the net, allowing the over arm serve and introducing the 'let' rule (BBC, 2003). The rules in use today remain fundamentally the same as those used during the first Wimbledon Championships in 1877. Other changes that have taken place between 1880 and the present day are the foot-fault rule and the introduction of the tiebreak rule in 1979 to limit the length of matches (Furlong, 1993). The foot-fault rule now allows the server to leave the ground before the ball is struck, which enables them to get to the net quicker (Brody and Cross, 2000). The players now change ends after every odd game instead of after every set (Smyth, 1953) and they are permitted to sit down and rest for a maximum of one minute and thirty seconds when changing ends.

2.2.3 Equipment

2.2.3.1 Rackets

Rackets saw only minor changes between 1874 and the end of the wooden racket era more than 100 years later. Wooden rackets did get better during this time due to improvements in laminating technology (i.e. using thin layers of wood glued together), which allowed the stiffness and strength of the rackets to be increased. Lamination also improves dimensional stability to reduce warping and makes racket properties more uniform. The best of the wooden rackets were heavy in comparison to contemporary rackets and had a relatively small head size (around 420 cm^2).

The structural limitations of wood dictated the early design of rackets. The frame could not be made very thick or else it would be too heavy to swing comfortably; this resulted in flexibility particularly near the tip (Brody, 2001). Maximum swing weight restrictions also limited racket head size and wooden rackets had to be smaller than can be achieved now in composites. Moisture absorption, resulting in warping, was still a problem.

Non-wooden tennis rackets first appeared in the form of the Wilson T2000 in 1967 and this marked the start of a new era for racket development. The T2000 was a long-throated, small-headed, aluminium racket that was used by Jimmy Connors during the 1970's. The aluminium was stronger and lighter than wood.

In 1976, Prince introduced the first oversized racket to gain widespread popularity, the Prince Classic. Weed USA had unsuccessfully introduced their oversized racket on the market earlier in 1975. The Prince Classic and the more expensive Prince Pro had aluminium frames and a string area more than 50 percent larger than the standard 420 cm^2 wooden racket. The light weight, huge sweet spot, and greatly increased power of these first oversized rackets made tennis much easier for non-advanced players, but for powerful, advanced players the mixture of flexibility and power in the frames resulted in too much unpredictability in where the ball would land. Hard, off-centre shots would momentarily distort the aluminium frame, changing the direction in which the string plane was facing, and the lively string bed would then send the ball speeding off in a somewhat unintended direction.

Table 1 presents a comparison of the typical characteristics of tennis rackets manufactured in 1973 and 1998.

Advanced players needed a stiffer frame material, and the best material proved to be a mixture of carbon fibres and a plastic resin to bind them together. This new material acquired the name 'graphite', even though it isn't true graphite such as you would find in a pencil or lock lubricant. The hallmark of a good racket quickly became graphite construction. By 1980, rackets could pretty much be divided into two classes: inexpensive rackets made of aluminium and expensive ones made of a carbon fibre composite.

Table 1: A comparison of tennis racket characteristics between 1973 and 1998 (Coe 2000)

Property / Specification	1973	1998
Material	Laminated wood	Carbon fibre composite
Weight (unstrung)	368 to 425 g (13 to 15 oz)	213 to 283 g (7.5 to 10 oz)
Balance from butt end	31.8 to 33.0 cm (12.5 to 13 in)	36.8 to 38.1 cm (14.5 to 15 in)
Head size	420 to 452 cm^2 (65 to 70 in^2)	581 cm^2 to 871 cm^2 (90 to 135 in^2)
Length	66.0 to 68.6 cm (26 to 27 in)	68.6 to 73.7 cm (27 to 29 in)
Swing weight	370 kg cm^2	290 to 310 kg.cm^2
Vibration frequency	Approx. 90 Hz	Approx. 150 to 220 Hz

It might be considered that wood no longer offered anything that another material could not provide better, except for antique and collectible value. However, wood offers enviable vibration damping characteristics, to the extent that a recent modern 'graphite' racket included a wood hoop in the head for this reason. Wood is also environmentally friendly. Due to its low strength to weight ratio, it imposes a natural restriction on racket power that many in the game believe it lost to the detriment of player and spectator enjoyment.

The key properties for a racket material are high specific strength and stiffness to achieve a low racket mass. Graphite remains the most common choice for stiff rackets, and the technology for adding stiffness without adding weight continues to improve. Probably the most famous of the early graphite rackets was the Dunlop Max 200G, used by both John McEnroe and Steffi Graf. Its weight in 1980 was 354 g (12.5 oz). Over the 20 years since, average racket weights have decreased to around 283 g (10 oz), with some rackets as light as 198 g (7 oz). Other material fibres such as glass, boron, titanium and kevlar have been tried, almost always in a mix with graphite. (Easterling, 1993; Kuebler, 2001).

In 1987, Wilson came up with an idea for increasing racket stiffness without finding a stiffer material. Wilson's Profile racket was the first 'wide body'. In retrospect, it seems strange that no one thought of the idea sooner to increase the thickness of the frame along the direction in which it must resist the impact of the ball. The Profile was a radically wider racket, with a frame 39 cm wide at the middle of its tapered head, more than twice the width of the classic wooden frame. By the mid 1990's, such extreme widths had fallen out of favour, but the wide body innovation carries forward. Most frames sold today are wider than the pre-1987 body standard.

The problem with these wide frames was that when trying to apply extreme levels of spin to the ball the risk of clipping the frame was much higher. Elite players play with rackets that are no wider than the original composite 200G, since adequate stiffness is easily achieved with modern materials. Recreational players generally need lighter rackets and the wider body makes this possible while achieving adequate stiffness.

The racket makers have, to some extent, suffered from their own success. Unlike wood rackets, which warped, cracked, and dried out with age, graphite rackets can last for many years without a noticeable loss of performance. A 10 year old graphite racket can be so good and so durable that its owner has little motivation to replace it. The racket companies have met this problem with a stream of innovations, some of which, like the oversized head, wider frame, and lighter weight are evident in almost every racket made today. Other innovations have been less universal, such as extreme head-heavy balance as seen in the Wilson Hammer rackets, and extra length, first introduced by Dunlop.

More recently, Head has developed a racket that uses piezoelectric technology. Piezoelectric materials convert strain caused by vibration or motion to and from electrical energy. Head's new racket takes the vibration resulting from impact with the ball and converts it to electrical energy. A circuit board in the racket's handle then amplifies that electrical energy and sends it back to the piezoelectric ceramic composites in the frame, causing those materials to contract, which serves to oppose and dampen the original vibration. A limited clinical study is reported by Kotze *et al.* (2003) indicating that this technology may benefit recreational players that suffer with tennis elbow.

Mitt markets rackets with the patented Mitt Rocker Stringing System, which it claims reduces the symptoms of tennis elbow. The strings pass over small metal rockers in the outer edges of the head so that increased tension in one string is passed on to the next. Mitt claims this dissipates the vibration more evenly and so shocks the arm less.

The current regulations on tennis rackets as specified by the ITF (ITF, 2003) are divided into four sections. The racket should be characterised by the following: (Kotze et al., 2000)

- A flat hitting surface consisting of a uniform pattern of crossed strings. Strings must be free from attached objects
- Dimensions not exceeding:
  - 73.7 cm for the length and 32.8 cm in width for the frame
  - 39.4 cm in length and 29.2 cm in width for the string surface
- The frame should be free of any objects not reducing wear and tear and vibration

- The frame should be free of any device that will allow it to change the physical property of the racket during the playing of a point

The improvement in racket manufacture is often presumed to be solely responsible for many of the major changes the game has experienced in the past thirty years, in the main the increase in speed. The Apparent Coefficient of Restitution (ACOR) has been used as a means to compare the 'power' of different rackets. The maximum ACOR of a wooden racket was 35%, whereas the maximum ACOR of an oversized graphite racket is about 45%. This provides an approximate increase in power on a groundstroke of about 28%. On the serve, the graphite lightweight racket provides an increase in power of about 18%, helping to achieve a ball speed of over 62.6 $m.s^{-1}$ (140 mph) (Coe, 2000). The potential difference in power and therefore ball speed that the graphite racket is capable of generating has contributed to the increased speed evident in today's game.

2.2.3.2 Balls

The first Wimbledon of 1877 saw balls hand stitched into covers made of white cloth (Smyth, 1953). Ball regulations were not yet in place and so each ball was capable of bouncing in a different manner and had a different hardness. By the 1880 Wimbledon Championships, the hand stitched ball had been replaced by the Ayres manufactured ball (Smyth, 1953) and by 1901, Slazenger, as today, took on the role of ball provider for the Championships. These balls were made with a pressurised rubber core and cemented covers and sold for about sixty-five pence (Coe, 2000).

During the final sixty years of the twentieth century, balls remained similar to these with a forward deformation of between 0.673 cm and 0.737 cm. Deformation is a static measure of ball stiffness and an acceptable range of values for tennis balls is specified within the ITF rules. Interestingly, although dynamic stiffness typically varies with strain rate, the ITF has no separate specification for this measure.

In performance terms, deformation affects the interaction between the ball and the court surface, including the angle of rebound. A lower forward deformation will result in a lower angle of rebound and therefore a reduced reaction time for the player. It was not until the 1960's, with the advent of the pressurised ball that the ball became harder and therefore faster. Amendments were made to the forward deformation specification to allow harder balls of between 0.559 cm and 0.737 cm. It was not long before manufacturers used this extended deformation range to produce harder balls that maintained their 'hardness', therefore increasing their shelf life.

Current tournament balls are made of hollow inflated rubber covered with a fabric made from a mixture of natural and artificial fibres. Regulations state they must be between 6.35 cm and

6.67 cm in diameter with a weight between 56.7 g and 58.5 g. When dropped from a height of 2.5 metres on to a concrete surface, the height of the bounce must be between 135 cm and 147 cm (ITF, 2003 p.2-3). Many different tennis balls are available with a slightly different 'felt' or 'nap'. They are marketed for different court surfaces and different styles of play. For example, balls designed for grass courts have a different felt to those intended for clay.

In July 1999, the ITF Annual General Meeting approved a two-year experiment in which two new types of tennis ball were permitted for use in tournaments for the purpose of evaluation and development. In September 2001, following a review of the data collected during the trial period, the ITF Annual General Meeting voted to include the two new ball types into the rules of tennis.

The two new types of ball were designed to have specifications that will result in different performance characteristics derived from their differing dynamic and aerodynamic properties. A system was developed in conjunction with the balls (known as the ITF Surface Pace Rating) to enable alternative court surfaces to be classified into one of three types: slow pace, medium pace or fast pace. It was intended that the two new ball types in addition to the existing ball type be introduced and developed to improve the enjoyment and appeal of tennis played on each type of surface. The three types of tennis ball are to be known as Type 1, Type 2 and Type 3. The specifications of the three balls are as follows: (ITF, 2003 p.2-3 Appendix 1)

- Type 1 balls have been developed for use on slow pace courts such as clay. The ball is to be produced with a harder specification and forward deformation readings in the range of 0.495 cm to 0.597 cm. The diameter should be 6.541 cm to 6.858 cm. The purpose of the Type 1 ball is to produce a lower angle of bounce off the court surface. A clay court offers high frictional characteristics due to the loose material on the surface. A "normal" ball bounces at a relatively steep angle off the court surface giving the player more time to play the shot. This is the main reason why rallies are longer on a clay surface than grass. The felt covering on a Type 1 ball will be finer so as not to fluff up excessively.
- Type 2 balls are for use on medium paced courts and are the standard ball already in use. The diameter should be 6.541 cm to 6.858 cm. The forward deformation of the ball should be 0.559 cm to 0.737 cm. Forward deformation is measured under a static load of 8.16 kgf (18 lbf).
- Type 3 balls are proposed for use on fast surfaces such as grass and are larger in diameter than the standard ball. The diameter of the Type 3 ball should be 6.985 cm to 7.303 cm. Such a ball will be 6 to 8% larger in diameter than the conventional ball. The difference in size results in different aerodynamic drag characteristics, so that the ball slows down more in the air giving the receiver more time to react. The rebound angle of

the ball following the bounce is also steeper than a standard ball due to a steeper incoming trajectory and the different compression of the ball on the court surfaces. This will give the receiver marginally more time (~10%) to react and return the ball. (Note: aerodynamic drag is a measure of air resistance and can be modelled by the equation, $D = C_d.\frac{1}{2}(\rho.v^2.A)$, where, D is the drag force, C_d is the drag coefficient, ρ is the air density, v is the velocity and A is forward cross-sectional area. The drag coefficient, C_d, is a number used to model all of the complex dependencies of drag on projectile shape, surface friction properties and some flow conditions. Since A for a tennis ball is proportional to the square of its diameter, relatively small increases in size have a more significant effect on ball speed.)

All tennis balls are made of a rubber shell with a felt covering, but the type of rubber shell used depends on whether the ball is pressurised or not. A pressurised ball loses its bounce gradually as air seeps out. A pressureless ball has greater longevity in terms of retaining its bounce. Pressurised tennis balls are by far the most common type. They typically perform better than a pressureless ball when brand new, but lose their bounce fairly quickly. Many players use them for just one match and then throw them away. A study by Wilson indicates that a typical pressurised ball becomes unplayable after a little more than two weeks. Several companies produce pressurised balls designed to last longer. Wilson's Double Core ball has an extra inner coating designed to keep air from escaping. Gamma produces a ball filled with nitrogen, which is supposed to leak more slowly.

Pressureless balls get their bounce from the structure of their rubber shell, which retains its elasticity without the assistance of artificially pressurised gas pushing at it from inside. When brand new, they are typically stiffer and less bouncy than a pressurised ball, although Tretorn makes a ball which is fairly bouncy. As they age, pressureless balls get bouncier, because their felt wears down, making them lighter. They should be discarded when they become so bald that they become too bouncy and lose their normal aerodynamics.

In the same way that Mitt and Head are marketing rackets to reduce the occurrence of tennis elbow, Dunlop produces the 'Abzorber' ball which they claim helps prevent tennis elbow by reducing the amount of shock transmitted to a player's arm by up to 15%.

2.2.3.3 Court surface

In the late nineteenth century, tennis was played on lawns previously used for croquet. Alternative court surfaces were sought when the game spread to America chiefly because the climate makes maintenance of grass surface impractical (Coe, 2000). One of the first court surfaces developed as an alternative to the lawn was a form of crushed brick. Clay courts developed from this, followed by cement, wood and other granular surfaces. Later in the twentieth century as material technology developed so did the range of court surfaces; courts with a cushioned coating, textiles, artificial grass and hard courts with polymer coatings (Coe, 2000). From a game played only on the lawns of the leisured classes with no public courts in existence, (Smyth, 1953) an estimated three quarters of a million tennis courts are now present throughout the world (Coe, 2000).

The characteristics of the different court surfaces affect the manner in which the ball bounces which consequently affects the style of play. The four Grand Slam tournaments are played on different surfaces. Both the Australian Open and the U.S. Open since 1978 are played on hard court surfaces, Rebound Ace and Decoturf respectively. The bounce and the speed of the ball on this type of surface is highly consistent when compared to grass and clay. There has been some controversy recently over the Rebound Ace courts used in the Australian Open with players voicing concerns over the 'stickiness' of the surface particularly when temperatures are high. Mark Philippoussis and Andy Roddick are just two of a number of players who have blamed the surface for injuries sustained during the tournament (BBC, 2003). The counter argument is that the tournament is played early on in the season and following an off-season competitive break. The French Open is played on clay at the Roland Garros arena. The loose surface slows the ball down and causes it to bounce relatively high resulting in games consisting of longer than usual rallies because it is hard to hit a winning shot. Wimbledon is the only major tennis tournament in the world to be played on grass. The bounce is low, sometimes unpredictable and the pace fast. Big servers and players who can back up their serve by attacking at the net to volley weak returns are at an advantage on grass.

2.2.4 Players

The physical attributes of top players are quite different to those of the past. Coe (2000) discusses the physical development of leading players over the years. Data available from the leading players of the 1920's and 1930's was compared with that of the top players in 1998. The body weight of top male players in 1998 was found to be between 2% and 22% greater than in the 1920's and 1930's. The height of the 1998 male players was on average greater than that of the early players. Coe (2000) also compares average weight and height data of the top 20 female players from 1975 with the top 10 female players in 1998. Over 23 years the average weight of leading female players has increased by 6.9% and the average height increased by 4.5%.

As well as being taller and heavier players of today are better conditioned and benefit from improved coaching and sports nutrition. The game is professional with big financial rewards for success at tournaments. All this combined with advances in equipment technology, particularly rackets, produces a faster, more powerful game than in the past with players more capable of sustaining a higher energy expenditure for longer. There is a year on year increase in recorded maximum serve velocity for both men and women. In 1990 when serve velocities first began to be recorded in the professional game, the number of male players who registered serves over 55.6 m s^{-1} (124.3 mph) was just 5. By 1995 this number had risen to 38. It is likely that the majority of players in the ATP Tour top 200 are now capable of serving at 55.6 m.s^{-1} (Coe, 2000). Greg Rusedski claimed the world record in 1998 with a serve velocity of 66.6 m.s^{-1} (149 mph) during the ATP Cup at Indian Wells, which is at high altitude. Andy Roddick equalled this record at sea level in June 2003 at the Stella Artois Championships, although interestingly Andre Agassi still managed to successfully return the serve (Roddick did eventually win the point). The fastest serve ever recorded for women is 56.9 m.s^{-1} (127.4 mph) by Venus Williams during the European Indoor Championships in Zurich in 1998.

2.2.5 Speed of the game

It is recognised and generally accepted that the modern game of professional tennis is too fast. The serve dominates most points on fast surfaces with some players winning 40% of their first serves as aces (Brody and Cross, 2000). Coe (2000) believes that the speed of serve in the men's professional game is approaching the limit of human reaction time for those at the receiving end (Haake, 1999). This means that if service speeds consistently go beyond 62.6 m.s^{1} (140 mph) then the elite game will merely consist of serves and short rallies that are difficult to track with the human eye.

There has been considerable discussion about the present game and what aspect of the game could be changed to make it more appealing on fast surfaces such as grass. The statistics from a match during Wimbledon 1997 between Greg Rusedski and Mark Philippoussis demonstrate the dominance of the serve. One hundred and eight points out of a total of two hundred and eighteen points in the match consisted of a single shot (i.e. an ace or a service winner) and not one rally exceeded five shots. During the two-hour contest active play occurred for less than four minutes per hour compared to an average of eight minutes per hour on hard surfaces and thirteen minutes per hour on clay (Henderson, 1997).

The power debate in the men's professional game has been a major issue for over a decade. In 1999, the ITF conducted a survey asking 3500 tennis playing households whether they thought the men's game had become too powerful. The results concluded that only a third of respondents believed the present game was acceptable as it is; almost half believed that the game was too powerful (ITF, 1999). It is estimated around 60 million people participate in tennis in more than 200 countries (Coe, 2000). However, since the boom of tennis in the 1970's, it is estimated that up to 20 million people in the US have given up playing tennis (Gray, 2000).

Given that a small proportion of tournaments and recreational games take place on the fast surfaces, such as grass, the ITF and others have perhaps overemphasised the link between high speed serves and reduced participation. Other trends associated with a preference for a sedentary, non-participative lifestyle or competition with other activities, for example, the increasing popularity of computer gaming, are likely to also play a part in this statistic. Nonetheless, whilst the ITF acknowledge this to be the case, by proposing changes to racket technology, with associated research to determine the consequences, the ITF is ensuring that those aspects of the game over which they have control are appropriately regulated to as far as possible combat the trend towards reduced participation.

Tennis is a multi-billion pound business and the opinions of those playing, and in particular, spectating the sport cannot be ignored. Although it seems many would like to see the game slowed to resemble a game more similar to that played several decades ago, few would wish to see a fundamental change affecting how the game is played. What is needed is a means of slowing the game to decrease the dominance of the serve and increase the number of rallies, which might improve the aesthetic quality of the game for those spectating. What is crucial is that any change is accepted by those playing the game at both the professional and recreational level. The main concern should be for tennis to remain the exciting, challenging game it is today for both those playing and spectating.

Several ideas have been suggested to slow the game down. Suggestions put forward include eliminating the second serve, reducing the size of the service box and returning to wooden rackets (Gray, 2000). Other suggestions that are currently being piloted to increase the attraction of tennis are to introduce 'no-ad' scoring and reduce the number of games in a set (Bumgardner, 2000). However, the idea that the ITF found most appealing to slow down the game was to alter the size of the ball. As previously discussed, in 2001 the ITF introduced two new specifications of ball. The Type 3 ball is 6% larger in diameter and has been designed and tested to slow the game down on faster surfaces.

2.3 TENNIS ELBOW

2.3.1 Overview

A comprehensive review of literature concerned with injuries in tennis is beyond the scope of this research. However, since the aim of this research has been to develop new measurement methods to potentially enable the causes of injuries to be investigated, it is important to consider the subject of tennis elbow and gain an appreciation of the current knowledge about how equipment changes and other variables affect injuries. The key question of relevance to this research is whether the incidence of injuries can be influenced by intervention, specifically in this case by the design of equipment.

Tennis elbow is the injury most associated with tennis. It is estimated that up to 50% of all recreational tennis players have symptoms of tennis elbow at some time (Coonrad and Hooper, 1973; Giangarra *et al*, 1993; Nirschl, 1973; Plancher *et al.* 1996; Roetert *et al.*, 1995). Tennis elbow known also as lateral epicondylitis is an overuse injury characterised by pain on the lateral epicondyle of the elbow, which usually improves on resting. Although synonymous with tennis, tennis elbow is also widespread in physical occupations such as carpentry, plumbing and meat cutting (Ciccotti and Charlton, 2001; Galloway *et al.*, 1992). McLaughlin (1980) lists many non-sporting activities that can cause tennis elbow including baggage handling, long-hand writing and shaking hands. Note that some of these occupations involve no impact or vibration. Peters and Baker (2001) describe the term 'tennis elbow' as a misnomer given that only about 5% to 10% of patients evaluated for lateral epicondylitis are actually tennis players. However, it is likely that many tennis players who develop symptoms self treat or see private physiotherapists due to information on the condition being readily available. Medial epicondylitis known as golfers elbow can occur in tennis but is more common in golf. Leach (1987) estimated that lateral epicondylitis occurs 7 to 10 times more frequently than medial epicondylitis.

2.3.2 Anatomy

A description of the anatomy of the upper extremity can be found in various levels of detail in textbooks, research papers and on the world wide web. The upper limb comprises the shoulder, elbow and wrist joints and associated muscle groups. The shoulder joint is the articulation between the head of the humerus and the glenoid fossa of the shoulder blade. It is a synovial joint of the ball and socket variety, in which freedom of movement is available but at the expense of stability. The shoulder joint is almost completely surrounded by muscles passing between the pectoral girdle and the humerus. The movements, of which the shoulder is capable, are flexion and extension, abduction and adduction and medial and lateral rotation. The elbow is responsible for shortening and lengthening the upper limb. The elbow is a synovial joint of the hinge variety and is the articulation between the distal end of the humerus and the head of the ulna. The movements possible at the elbow are flexion and extension. The wrist joint is not a single joint but comprised of the articulations between the carpal bones and the articulation with the forearm. The wrist complex is capable of movement in two directions, however, when combined with pronation and supination the hand appears to be connected to the forearm by a ball and socket joint, thereby permitting movement in three axes.

Tennis elbow affects the muscles of the forearm that control hand and wrist movements. They are attached via tendons to two small areas of bone just above the elbow, one on the outer lateral side and the other on the inner medial side. Muscles connected to the outer side of the elbow are responsible for straightening the fingers, rolling the forearm to bring the hand into a palms-up position, bending the wrist upwards. Muscles connected to the inner side of the elbow are responsible for bending the fingers, bending the wrist downwards and rolling the forearm to bring the hand into a palms-down position.

The muscles that arise from the region of the lateral epicondyle of the elbow include the extensor carpi radialis longus, the extensor carpi radialis brevis, the extensor digitorum communis and the extensor carpi ulnaris. The extensor carpi radialis longus arises from the lateral margin of the lateral supraconylar ridge. The extensor carpi radialis brevis lies deep next to the extensor carpi radialis longus and is just superficial to the lateral joint capsule. The extensor carpi radialis brevis has a complex origin with contributions from the common extensor origin, lateral collateral ligament, annular ligament, investing fascia and the intermuscular septum.

The tendons that connect the forearm muscle to the elbow can be overloaded when the hand and forearm are used in strong, jerky movements such as gripping, lifting, or throwing. Tendons are rope-like structures made of smooth inelastic fibres that do not stretch readily when pulled. Strong forces or sudden impacts can eventually tear the fibres apart in much the same way a rope becomes frayed. This type of injury is called a strain, and usually results in formation of scar tissue. With sustained exposure to overloading stimuli, strained tendons become thickened and without time to heal can become permanently weakened. Damaged tendons can occur on either side of the elbow; when damage occurs on the outside of the elbow, which is most common, the condition is called tennis elbow. Pain from tennis elbow is likely to result from the side effects of tendon damage, including localised inflammation impinging on the nerves that pass near the elbow region.

Cyriax (1936) was the first to recognize that the origin of the extensor carpi radialis brevis was the primary site of injury during tennis elbow cited in (Ciccotti and Charlton, 2001). Pathologic changes have been documented consistently in this area (Coonrad and Hooper, 1973). Nirschl (1979) found the extensor carpi radialis brevis tendon to be involved in 91% of patients, with 64% of patients having isolated involvement of this tendon. The anterior margin of the extensor digitorum communis has been found to be involved in 35% of patients who have surgical intervention (Regan *et al.*, 1992).

2.3.3 Etiology

Runge first described the condition of lateral epicondylitis or tennis elbow in 1873 (Runge, 1873). Most of the literature on epicondylitis suggests that the primary etiology is repetitive stress or overuse (Grouchow and Pelletier, 1979; Leach and Miller, 1987; Nirschl and Pettrone, 1979). Lateral epicondylitis is accepted to be caused by activities that require forceful and repetitive wrist extension. Medial epicondylitis is caused by activities requiring repetitive wrist flexion or forearm pronation.

There is general agreement in the literature that lateral epicondylitis involves repetitive microtearing of the lateral tendon origin where the extensor muscles attach. This can result in failure of the tendon's healing response and eventual tendon degeneration (Ciccotti and Charlton, 2001; Peters and Baker, 2001). It is important to rest at the onset of symptoms in order to avoid long term damage to the tendon area. Engel (1995) points out the agreement in the literature that the repetitive need to stabilize the wrist whilst playing tennis, especially the backhand stroke, is the main pathogenic factor (Bernhang *et al*, 1974; Knudson, 1991b; Leach and Miller, 1987; McLaughlin and Miller, 1980; Nirschl, 1975; Priest *et al*, 1980a). During tennis the repetitive impacts on the ball are transmitted by the tennis racket to the wrist extensor muscles, mainly the extensor carpi radialis brevis, resulting in micro-tears at the lateral epicondyle (Hennig *et al.*, 1992). The extensor muscles are used to pull the hand 'backwards', for example during a backhand tennis stroke, as well as to open or twist the hand. Peters and Baker (2001) note that the extensor carpi radialis brevis is accepted to be the main muscle affected during tennis elbow with occasional involvement of the extensor digitorum communis tendon. It is not understood which of the impact constituents transmitted to the player's hand is the one causing tennis elbow. Possible candidates include peak force, torque or particular vibration frequencies.

Diagnosis of tennis elbow is fairly straightforward usually involving little more than an examination of the painful area. The athlete with tennis elbow complains of lateral elbow pain and forearm pain exacerbated by activities requiring wrist extension. The 'coffee cup test' is a frequently mentioned means of diagnosis and involves the patient grasping or pinching with the wrist extended. This usually reproduces pain at the point of tenderness in cases of tennis elbow. Another test is grip force measured with a dynamometer. Patients with tennis elbow are reported to have a significant reduction in grip force (De Smet and Fabry, 1997). Symptoms generally improve with rest, but in persistent cases cortisone injections are reported to be very beneficial (Roussopoulos and Cooke, 2000) and in extreme cases surgery is an option. During surgery the damaged part of the tendon is removed and then the tendon is reattached to the bone.

Being able to determine the potential effect of equipment changes on tennis elbow is one of the motivations for this research.

2.3.4 Epidemiology

Tennis elbow can be a serious and debilitating condition that can keep a player sidelined for many months (Pluim, 2000). According to Nirschl and Pettrone (1979) lateral epicondylitis typically occurs between the ages of 30 and 50 years, although it has been identified in patients ranging in age from 12 to 80 years (Nirschl, 1985).

A study of 2633 average tennis players showed that 31% of all players either had current pain or a history of pain (Priest *et al*, 1980b). Carroll, (1981b) and Grouchow, (1979) found slightly higher frequencies of 35% and 41% respectively in intermediate level players (cited in Plum, 2000). In a study of 260 long term players by Kamien, (1988) 57% had experienced tennis elbow symptoms.

Hang (1984) found the male and female prevalence rates to be equal as did Allman (1975). However, Grouchow and Pelletier (1979) and Priest *et al.* (1980b) found that women were affected more often than men. Grouchow and Pelletier (1979) also noted an association between playing time and the incidence of tennis elbow in club players. The risk of developing symptoms of tennis elbow was 2.0 to 3.5 times greater in players with over two hours of racket time per week than in those who played tennis less than two hours per week. Compared with younger players, male and female players over age 40 had a fourfold and twofold greater incidence of tennis elbow, respectively.

Several risk factors have been identified for epicondylitis in relation to tennis. Proposed causes include bad technique, mishits and the 'jerk' that accompanies the ball being hit. According to Cooke and Roussopoulos (2000) this jerk comprises the actual impulse of the ball's impact and any twisting as a result of the hit being off centre and accompanying vibrations. Inadequate strength, primarily of the forearm muscles, is considered to play a role in causing tennis elbow (Kulund *et al.*, 1979).

Many studies cite improper technique as a cause of tennis elbow. Technical errors, for example leading on the groundstroke with a flexed elbow and hitting the ball off centre on the racket, have been reported to increase the occurrence of tennis elbow in several studies by (Bernhang *et al.*, 1974; Kelley *et al.*, 1994; Nirschl and Pettrone, 1979). Blackwell and Cole (1994) found that wrist kinematics differ in expert and novice tennis players when performing backhand strokes and that this has implications for the development of tennis elbow. The authors suggest that skilled players maintain a constant wrist position, whereas novice players tend to use more wrist motion to produce the stroke and this requires greater forces from the wrist extensor muscles. This finding is in agreement with studies by Bernhang (1974) and Pecore (1978) cited in Blackwell and Cole (1994).

Ilfield (1992) reported significant improvements in tennis elbow symptoms simply by modifying stroke technique. Ilfeld analysed the strokes of 57 patients with elbow pain and claims to have identified the errors in forehand, backhand or serve that led to the injuries. Of the 57 subjects, the majority (48) reported pain on the lateral side and 9 on the medial side. 24

subjects had most pain during the forehand, 12 on the backhand, 11 during the serve and 10 had pain on all strokes. All the subjects who had pain during the backhand had it on the lateral side. The incorrect stroke in the 20 subjects who had lateral elbow pain when using the forehand stroke was reported to stem from pronation of the forearm and racket head in the follow through. Ilfeld explains that in an attempt to obtain top spin, the player pronated or rolled over the forearm and racket head. This motion apparently crowds or cramps the lateral compartment of the elbow joint, straining the lateral muscles and ligaments of the elbow. To correct the forehand stroke the patient was instructed to turn sideways and hit the ball in the racket's sweet spot with the vertical racket face moving forward on a low to high flight pattern. In the 7 subjects who suffered lateral elbow pain when serving, the error was attributable to forearm pronation or twisting of the racket head. The stroke often ended with the racket head on the wrong side of the body. In the 12 who experienced lateral elbow pain on backhand strokes, the observed error was failure to turn sideways and hitting the ball with the elbow ahead of the racket. The correct stroke according to Ilfeld requires turning the body and shoulders sideways and throwing the racket head in advance of the elbow with the wrist dorsiflexed and pronated. The length of follow up for this study was on average 3 years during which the original intervention remained successful.

Tennis elbow has been shown to be more common in less experienced recreational tennis players than in elite players (Grouchow and Pelletier, 1979; Peters and Baker, 2001). Recreational players are more likely to have flaws in their technique and are less well conditioned. Epidemiological studies such as Grouchow and Pelletier (1979), have shown that tennis elbow occurs 7 to 10 times more frequently in less experienced players compared with high level players. Much research exists to suggest that the one handed backhand contributes greatest to the stresses on the extensor muscles associated with tennis elbow (Blackwell and Cole, 1994; Giangarra *et al.*, 1993; Groppel and Nirschl, 1986; Hennig *et al.*, 1992; Plancher *et al.*, 1996; Roetert *et al.*, 1995).

2.3.5 Muscle soreness

In the present research, raised levels of muscle soreness are reported used as an indicator of an increased likelihood of injury. The following brief description provides an introduction to the symptoms and causes of muscle soreness.

Muscle damage due to overload is often accompanied by muscle soreness, whereby the level of soreness provides an indirect indication of the extent to which a muscle has been stressed. The intensity of soreness increases during the first 24 hours, peaks at 24 to 48 hours (delayed onset muscle soreness – DOMS), and subsides within 5 to 7 days post-exercise (Armstrong, 1984, MacIntyre *et al*, 1995). Muscle soreness can accompany all forms of muscular work but is particularly pronounced after a bout of eccentric exercise, where the muscle is forced to *lengthen* under tension as opposed to the more typical concentric exercise modality whereby the muscle *shortens* under tension. The muscles of the forearm perform both eccentric and concentric types of contraction during tennis.

The sensation of pain and stiffness associated with muscle soreness can adversely affect muscular performance, both from voluntary reduction in effort and from inherent loss of capacity of the muscles to produce force (Armstrong, 1984). This reduction in performance is temporary under normal circumstances. The aetiology and cellular mechanisms of DOMS are complex and are likely to be due to a combination of both mechanical and biochemical factors (Hilbert *et al*, 2003). A number of clinical correlates are associated with DOMS including elevations in plasma enzymes and abnormal muscle histology (Smith, 1991). In physiological studies, the presence of increased levels of creatine kinase and aspartate aminotransferase are used as indications of muscle damage.

2.4 EQUIPMENT EFFECTS ON FATIGUE & INJURY

2.4.1 Introduction

The use of poorly sized or inappropriate equipment can also be a risk factor (Ciccotti and Charlton, 2001). Tennis equipment factors such as grip size, racket mass and material, racket flexibility, racket balance, string type, string tension, mass and type of ball and playing surface all have a potential to cause or aggravate tennis elbow.

2.4.2 Grip size

The grips of most rackets range from between 10.5 cm and 12.4 cm in circumference. The sizes are usually labelled from 1 to 7. According to Plum (2000) players in the past used thicker grips and grip sizes 6 and 7, which used to be very common, are very hard to find today. A common method of determining correct grip size is by measuring the distance from the long crease in the palm (the second one down from the fingers) to the tip of the ring finger.

Kulund (1982) proposed that a proper grip size helps to reduce torque. Larger grip size increases a player's mechanical advantage, as long as the grip is not so large as to reduce the player's grip force. Brody (1989) noted that if a grip is too large or too small the player may have to grip the racket too tightly to prevent it from twisting, and high grip force may increase the risk of elbow injury. Increased grip tension at the moment of impact dampens the vibration of the racket. However, due to the increased mechanical coupling between the racket and the hand, the player experiences increased arm vibration (Hennig *et al.*, 1992; Knudson, 1991a). Murley (1987) explains that the larger the grip size, the greater the dorsal flexion of the wrist and the lower the tension on the origin of the forearm extensor muscles. Norris (1994) states that 'pain usually increases when small objects are gripped as this hand position places additional stretch on the forearm extensors'. Pluim (2000) cites a study by Adelsberg (1986) which, by using electromyography, showed that racket torque is best controlled by using the largest comfortable grip size. Pluim, (2000) in summary advises use of a good high friction non-slip grip cover, squeezing the handle firmly and using the largest grip that is comfortable.

2.4.3 Racket materials

Composite rackets were introduced in the 1980's. These generally consist of a combination of graphite and fibreglass, to which other materials such as Kevlar, boron or ceramic are added. The addition of these materials results in a racket with certain flexibility, strength, weight and other properties that no single material possesses. Kevlar, which is used in bulletproof vests, has good vibration damping properties and is also light and hard wearing. Boron adds rigidity and is light and resilient. Graphite has good vibration damping qualities and is light but can be fragile. Short carbon fibres are more effective in damping vibrations because long fibres offer a continuous path for the transmission of vibrations (Kamien, 1988). Pluim, (2000) notes that by increasing the ratio of the matrix to fibres, less vibration occurs on ball impact. A nylon matrix also dampens vibrations more effectively than the commonly used epoxy resin. The Dunlop 200G used a nylon matrix with short chopped fibres and achieved damping properties similar to wood. In contrast, long, high modulus carbon fibres in an epoxy matrix enables stronger, stiffer, lighter, larger rackets.

2.4.4 Racket size

There are two main reasons for increasing the size of the racket head. The first is that in general the larger the racket head, the larger the sweet spot area. This lowers the chance of hitting the ball off centre. An off centre impact results in loss of ball control and velocity and an increased load on the arm. There are three sweet spots on the face of a racket, areas where the rebound velocity of the ball are greatest and impact shock and vibration are minimal. Brody in the Physics of Tennis explains this concept in detail (Brody, 1981). Elliot *et al.* (1980) demonstrate the lower vibration levels and higher rebound velocities in oversized rackets.

The second reason for using an oversize racket head is that it increases what is commonly referred to by manufacturers as the polar moment of inertia. A racket's 'polar' moment of inertia is measured about its axis of symmetry along the grip/shaft. It is generally the smallest of its three principal moments of inertia and is a measure of the racket's resistance to moments that tend to rotate the racket about this axis. When a ball hits a racket off its axis of symmetry it causes the racket to twist. Twisting involves rotational acceleration; the resistance of an object to undergo rotational acceleration is dependent upon its moment of inertia about the axis of rotation. A higher moment of inertia results in a lower rotational acceleration for a given rotational force. An object has a higher moment of inertia when its mass is distributed further from its axis of rotation. For a racket with a wider head, the mass of the racket frame is further from the centre of rotation and it is therefore more stable and less prone to twisting than a narrow headed racket.

2.4.5 Racket mass

Rackets vary in weight between 275 and 360 grams. Both racket weight and the speed of the racket head are factors that determine the velocity of the ball (Brody, 1988). According to Pluim, (2000) the extra racket head speed that can be achieved with a lighter racket head may more than compensate for its lighter weight and lead to higher ball velocity.

Conflicting evidence exists on whether a light or heavy racket is preferable in the context of tennis elbow. It has been suggested that altering the weight of the racket can be a preventative measure against tennis elbow (Lachmann, 1988). Research by Kulund, (1982) suggested that heavy rackets can cause injury at the elbow when compared to lighter ones. A heavier racket produces more momentum and will place greater strain on the muscles of the forearm. However, the consensus in the literature is that a heavier racket is preferable. Although more effort is required to generate racket speed the shock transmitted to the hand and arm is less. This is because the greater the mass of the racket, the greater its ability to absorb shock. A heavier racket is also known to reduce twisting of the racket.

2.4.6 Racket stiffness

Pluim (2000) explains the relationship between racket stiffness and power, as follows: When the ball hits a flexible racket the racket head deforms considerably. The time taken for the racket to deform and return to its original shape is approximately 15 ms. This is longer than the dwell time for the ball on the strings, about 4 to 6 ms (Groppel *et al.*, 1987). Therefore, the ball has already left the strings before the frame has straightened again and the energy fed into the racket deformation is lost to the ball. Consequently, there is a loss of kinetic energy.

To achieve maximum power, a very stiff racket is required and the design requirement is to achieve all the deformation in the strings, as these are the most efficient in returning the kinetic energy to the ball. Some compromise in string tension is necessary for adequate accuracy.

That said, the more flexible the racket the more the shock is absorbed. Data from a study by Stone *et al.* (1999) suggests that since the introduction of stiffer composite rackets incidence of tennis elbow has gone up. A possible solution to the problem is to use a racket with a stiff head but flexible shaft. This is achieved in rackets with a so-called tapered profile, which are thin and flexible in the shaft and wide and stiff in the head.

2.4.7 Racket balance

A racket that has its centre of mass at its geometrical centre is considered balanced. A head heavy racket has its balance point on the head side of the racket centre and a head light racket has its balance point closer to the grip than to its head (Brody, 1988). Tennis players who play a basic baseline game in most instances prefer a racket that has increased mass in the head and players with a serve and volley game usually prefer a racket that has less mass in the head (Lehman, 1988). The moment of a racket is calculated by multiplying the weight of the racket by the distance from the balance point to the location of the hand. In a head light racket it will be lower than in a head heavy racket. This is why a head light racket will feel lighter to a player than a head heavy racket even though they may be the same mass. A low moment racket will typically be easier to manoeuvre and therefore a head light racket may be more suitable to players will elbow problems.

2.4.8 Strings

Strings can be either gut or synthetic. Despite being less durable and more expensive most top players prefer gut strings. This is because gut strings give slightly higher post-impact ball velocities, improved control, better damping qualities and therefore better racket 'feel' (Ellis *et al.*, 1978; Groppel *et al.*, 1987). A variety of synthetic strings are on the market and there is a range of different qualities. Mono-filamented strings that are made of nylon are the cheapest but have the poorest playing qualities. The playing qualities of multi-filamented strings resemble those of gut more closely but are cheaper and more durable than gut.

The thickness of a tennis string is measured in gauges. A lower gauge indicates a thicker string. Strings are usually 16 to 18 gauge. Thicker strings are more durable than thinner strings. However, a thinner string is more elastic and so absorbs more shock. It is advised therefore for players with a history of tennis elbow to use thinner strings.

For maximum power rackets should be strung loosely although more control is associated with higher string tension. Strings return 90 to 95% of ball impact energy (Plum, 2000). If the ball is dropped on a string bed it will bounce more highly than it will on a hard floor because less energy is dissipated. Lower string tensions mean the strings 'give' more and the ball will deform less. The strings in this situation return more energy to the ball, the ball loses less energy and power is optimised. Because less swing is required to achieve power, loading on the arm is decreased.

Another advantage of low string tension is that it increases the time the ball is in contact with the string bed. This spreads the shock of the ball impact over a longer time resulting in the magnitude of the force at any given time being reduced. Elliot (1982) warns that if string tension is lower than 18 kgf, energy is lost because of excessive string movement.

The density of a string pattern measured in strings per square meter is another factor. The effect of a high density pattern according to Pluim, (2000) is similar to that of a racket that is tightly strung.

2.4.9 Vibration dampers

Vibration dampers are widely available on the market and are used by many players. Research questions their effectiveness. In a study by Tomosue *et al.* (1992) it was shown that the damping material was effective in reducing impact shock. The researchers concluded that a damper appreciably reduced the amplitude of string vibrations, which has an apparent effect on frame vibrations. In a study by Wilson and Davis (1995) the effectiveness of damping devices on frame vibration was found to be negligible. Pluim, (2000) offers an explanation of the different conclusions in these studies. He suggests that when the ball is hit exactly at the vibrational sweet spot of the racket, the vibration stopper works quite well at damping down the high frequency vibrations. However, when the ball is hit off centre the vibration stopper makes no appreciable difference to the vibrations transmitted to the hand.

Roetert *et al.* (1995) explains that the mass of the strings is about 15 grams compared with the frame mass of about 300 grams. The energy involved in string vibrations is very small. If a damping device weighing 1 to 2 grams can absorb all the energy from the vibration of the strings, it seems unlikely that those vibrations can be the cause of any injury to the arm. Kuessner (1991) cited in Roetert *et al.* (1995) stated that vibrations which cause injury are transmitted through the racket head. No anti-vibration device in the strings, regardless of shape, size or material is going to stop those vibrations.

The following points summarise some additional information about vibration dampers:

- Head has put dynamic vibration absorbers in the racket handle.
- Head intellifibre technology previously mentioned is a high tech vibration damper.
- Dunlop and others have introduced damping material between the grip and head/throat/shaft in varying configurations to reduce vibration transmission.
- In-play data quantifying benefits of the above interventions is unavailable.
- Players generally feel vibrations are reduced but power and feel are deadened.

2.4.10 Ball type

Studies indicate that non-pressurised balls generally have a lower coefficient of restitution than pressurised balls (Caffi and Casolo, 1995). This means that to achieve the same speed of shot with a non-pressurised ball, a player has to hit the ball harder. For this reason players with elbow problems are advised in general to play with pressurised balls. Caffi and Casolo (1995) also found the same effect of playing with worn balls, players need to hit them harder to achieve a given speed. Similarly, some media and player comments have suggested that the larger Type 3 ball will increase the incidence of injury.

The contact time of the larger Type 3 ball on the strings is slightly longer than for a standard ball due to deformation (Haake, 1999). Therefore at a given inbound velocity the impact force for the larger ball will be very slightly smaller than for the standard ball (assuming equal ball mass and equal impulse). The vibration effects have not yet been compared and it is possible that the frequency of vibrations for the larger ball are different to the standard ball as the deformation properties of the balls are different. One view is that the effect of slowing the ball down by increasing the drag may result in the player trying to compensate by hitting the ball harder. This may lead to greater fatigue in the forearm muscles, which may in turn cause more injuries.

2.4.11 Playing surfaces

Faster court surfaces generate higher ball speeds. This may place greater stress on the wrist flexors and extensors. In a review by Carroll (1981a) some players cited irregularities in the court surface as possible factors in the development of their tennis elbow. These irregularities caused the ball to bounce unexpectedly and consequently the stroke was incorrectly timed and resulted in strain due to faulty technique. A slow court will decrease the ball velocity thereby minimising the impact and torsional forces during impact. In addition a slow court gives a player more time to prepare for a shot and this generally will result in better technical stroke execution. It is understandable therefore, that the use of slow courts is suggested for players with tennis elbow problems.

2.5 MEASUREMENT OF GRIP FORCES

2.5.1 Tennis grip technique

Tennis can be played with a range of grip techniques. Depending on the angle at which the hand is placed relative to the floor the grip can be classified from Continental to Western, the mid point being Eastern. According to coaches, in the last thirty years the average position of professional forehand grips has evolved from slightly 'east' of Continental to fully Semi-Western. This can be attributed to the trend toward increasing power and top spin. Generally, as the grip moves from Continental toward Western, the player finds it easier to generate topspin and return high balls, but harder to generate slice and handle low balls. In the 1960's, when grass tournaments were much more prevalent, it was fairly typical to return the ball at or below waist height with slice to accentuate that low bounce. This was typically achieved using a Continental grip. Modern players who have been successful on the grass of Wimbledon such as Martina Navratilova and Jana Novotna used an Eastern grip, which is more Continental than the Western grip. Today shots are often played with heavy topspin on courts that produce higher bounce, as a result the ball is often returned from shoulder height and a Western grip makes this easier.

2.5.2 Measurement of static grip forces

Hand-grip strength measurement has many applications. A reduction in maximal grip strength is well documented in individuals diagnosed with tennis elbow (Bohannon, 1990; De Smet and Fabry, 1997; Kramer and Knudson, 1992; Richards and Palmiter-Thomas, 1996; Stratford *et al.*, 1989; Strizak *et al.*, 1983). Grip strength is an objective assessment of hand strength that is easy, non-invasive and quick to perform. Devices that are portable are available and results are immediate. Because a weak grip is often indicative of other clinical states that are more difficult to measure (e.g., postoperative complications, progress from rehabilitation, functional status in the presence of arthritis), the assessment of grip strength can be a useful clinical tool. Clinicians often measure grip strength to evaluate a patient's strength relative to some normative level. This can then be used as an assessment of whether a patient is able to return to work following injury, illness or surgery. In a review Richards and Palmiter-Thomas (1996) noted that grip strength reduction has been found to be one of the most highly sensitive indicators of postoperative complications. Several studies are cited that give evidence for this. One study by Griffith *et al.* (1989) found that the grip strength reductions in individuals who developed complications post surgery were measurable before these complications became clinically apparent.

Most assessments conducted are a test of maximum voluntary contraction of the transverse volar grasp, sometimes referred to as the 'power grip'. The transient maximal grip is the most common clinical measure, probably because it is the simplest and requires inexpensive equipment. Although devices are primarily used for testing hand-grip strength, some have attachments which allow individual finger or pinch strength to be tested in more specialised situations.

Grip strength has now been adopted as a tool in studies of sports. Studies typically use devices and test procedures that have been researched and accepted for clinical use. They therefore measure isometric grip strength and report the parameter of peak force. Grip is an important factor in many sports such as tennis, cricket, golf and rock climbing. Isometric grip strength can be correlated with upper extremity and even overall body strength (Richards and Palmiter-Thomas, 1996) Grip strength reduction is indicative of muscle fatigue and muscle fatigue can be related to overload on the muscle. It is assumed then that the greater the overload on the muscle the greater the reduction in grip strength. As impact loading may be related to injury incidence, hand-grip strength assessment has been suggested as a useful indication of potentially harmful overload.

2.5.2.1 Current devices

Devices for measuring grip strength use a variety of force detecting systems, including hydraulics, springs and load cells or strain gauges. Each system is associated with different advantages and disadvantages.

Because hydraulic and spring systems are non-electrical they have the advantage of not requiring a power source or having batteries to replace or recharge. The force display of spring and hydraulic based devices in generally that of a dial, whereas load cell based devices generally have digital display. The latter is more accurate to read as with a dial display measurements can fall between divisions on the face. Some devices can be connected to a computer for accurate recording of measurements but this reduces the portability and so is less useful in certain applications. A disadvantage of spring-based devices is that the springs can fatigue over time reducing reliability. Bohannon (1989) demonstrated such inaccuracy in spring-based devices after only two years of use. They reported that strain gauge devices remained accurate over this time.

The most commonly used device clinically is the Jamar dynamometer and others based on it. It measures transverse volar grip strength via a hydraulic system. These devices are readily available and easy to use. Dynamometers using strain gauge principles are available but tend to be used in research rather than clinically. An example is the NK Biomedical digital hand-grip dynamometer, which connects to a computer. In this device a series of force transducers located between two parallel rods allow grip force to be measured continuously throughout the contraction.

The most recent addition to grip strength measurement devices are the work simulators, such as the Baltimore Therapeutic Equipment Work Simulator (BTE), which have attachments and performance modes designed to measure isometric grip strength. Richards and Palmiter-Thomas (1996) explain that this device consists of a protruding shaft interfaced with a computer and variable assembly kit. A number of attachments are available that fit onto the adjustable length shaft to allow for various types of work simulation. The BTE 'attachment #162', which resembles a large pair of pliers, is the attachment designed to measure grip strength. The resistance produced by work simulators is adjustable and is set by the tester prior to testing. Strength testing can be accomplished either isometrically or dynamically. With the BTE, isometric grip strength is tested in the static/isometric mode, with the amount of torque generated providing an indication of grip strength force. This is an example of a device that allows testing to be tailored to the activity by the choice of protocol and choice of hand interface.

2.5.2.2 Test protocol

It is important to be consistent about both the testing method and equipment in order to maintain the validity and reliability of grip strength assessment. Many variables have been identified that potentially affect grip strength data such as upper extremity and body position, choice of instrument and calibration, number and duration of trials, impairment of the individual to be tested and individual motivation and sincerity of effort. It is therefore important to follow a protocol that considers each of these variables.

Protocols for measuring grip strength vary. The American Society of Hand Therapists (ASHT) recommends the following position. The subject should be seated in a straight back chair with the feet flat on the floor, the shoulder adducted and in a neutral rotation and flexion. The subject's elbow should also be flexed to 90 degrees with the forearm and wrist in neutral. Using the Caldwell Regimen test procedure the subject builds up force over a two second interval and then maintains the maximal force for at least three seconds. Mathiowetz (1990) recommended that the mean of three trials be used as the recorded measure.

Variations from the above standard position result in changes in measured grip strength. It is therefore most important that a standard protocol is adhered to when changes in grip strength are being assessed. It is likely that changes in grip strength with different body positions is attributable to the line of pull of the muscle being changed (Richards and Palmiter-Thomas, 1996). All muscles have an optimal length at which they produce maximal contraction. Any external shortening or lengthening of a muscle changes the length tension relationship of its fibres and impairs the ability of the muscle to contract maximally (Norkin and Levangie, 1992).

Richards and Palmiter-Thomas (1996) review in detail studies that examine the effect of altering body position on grip strength. The authors discuss a study by Teraoka *et al.* (1979) that reported grip strength was significantly stronger in the standing rather than sitting position and significantly stronger whilst sitting than when supine. Balogun *et al.* (1991) compared grip strength in sitting and standing while the elbow was either flexed to 90° or fully extended. They found stronger grips when subjects were standing but only when the elbow was extended. Mathiowetz *et al.* (1985) demonstrated that grip strength was significantly stronger when the elbow was flexed at 90° versus fully extended. A number of studies have documented that varying forearm and wrist position does affect grip strength. Richards *et al.* (1996) measured grip strengths while the forearm was in supination, pronation or neutral positions. They found that grips in supination were the strongest, followed by grips in neutral. Holding the forearm in pronation resulted in the weakest grips being produced. Kraft and Detels (1972) found no significant difference in grip strength when the wrist was in neutral, 15 or 30 degrees of extension. However, significantly lower scores were reported when the wrist was flexed 15 degrees. Pryce (1980) confirmed that the 15 degrees flexed position, as well as the 30 degrees ulnar deviation position resulted in significantly lower grip strength. These studies provide clear evidence that body position needs to be standardised during grip strength measurement.

Mathiowetz *et al.*(1984) demonstrated that the retest reliability based on the mean score of three tests was greater than the mean score of two tests or a single test. Typically no more than three grip trials at a time are measured clinically. If multiple grip tests are to be taken within a session Stratford *et al.* (1989) found that a 4 to 6 minute rest period should be adequate for preventing fatigue effects. Mathiowetz also investigated the diurnal effects on grip strength. Grip tests performed in the morning were weaker than grip tests performed later in the day and therefore repeat tests must be at the same time of the day to be accurate.

Several studies have investigated the effect of handle spacing on grip strength. There is no doubt that the handle spacing affects grip strength and so it is important to be consistent with repeat tests on the same subject. Sincerity of effort is another important factor. Because of the clinical use of grip tests, research has been conducted into determining if a patient is faking reduction in grip strength. Stokes (1983) contended that subjects with true weakness of grip would have a slightly skewed bell shaped curve for both the injured and uninjured hand. Subjects presenting false weakness of grip would have a straight line for the fained weak hand and a bell shaped curve for the uninjured hand. Results presented by Stokes supported this theory. To produce a maximal voluntary contraction the subject has to be motivated and it is important that the tester offers verbal encouragement to ensure this.

In summary, it is important to follow certain rules during testing to maximise the reliability and validity of the assessment. Dynamometers must be calibrated periodically and devices should not be used interchangeably. The same device should be used in pre and post testing of subjects. Standard positioning of subjects must be ensured as well as protocol of number, duration and rest interval of trials. The average of three tests is recommended and where possible repeat tests should be conducted at the same time of day. Subjects should be encouraged to give a sincere full effort during tests.

2.5.2.3 Measurement parameters

The primary clinical measurement in assessing grip strength has been peak force, which is the maximal force produced during a transient grip of up to 5 seconds (Richards and Palmiter-Thomas, 1996). The strength of the grip is measured either in units of force or pressure. Kirkpatrick (1956) cited in Richards and Palmiter-Thomas (1996) recommends measuring grip strength in force units rather than pressure units. The reason being that pressure equals force divided by area and so pressure measurements are highly influenced by the area of contact between the hand and the instrument used to assess grip strength. Individuals producing the same amount of grip force will have very different grip pressures depending upon their hand sizes.

With the introduction of digital grip dynamometers which connect to a computer additional measures of grip strength based on a force time curve can be calculated. Measures that have been reported include the acceleration time (time to reach peak force), average force over a percentage of each trial, fatigue rate, percentage of fatigue, reaction time and rate of release. However, peak force remains the most often quoted parameter of grip strength and only a small amount of literature is available on sustained grip strength parameters. It seems likely that because peak force is the measure that has traditionally been reported in the medical literature, other disciplines continue to adopt the same measure. It is proposed that an activity specific test approach in this case tennis specific, is likely to provide a more sensitive measure.

Although typically no more than three grip trials at a time are measured clinically, many daily activities and sports require repeated grips. A few studies have investigated the fatigue effects over more than three trials. Montazer and Thomas (1991) found that grip strength decreased to 75% of maximal strength after 20 trials and 70% after 30 trials. In an additional study subjects performed 200 repetitive grip trials. Although subjects reported forearm stiffness and palm and finger pain, grip strength remained at 60% of maximal after 100 trials and 48.5% after 200 trials (Montazer and Thomas, 1992).

Most studies examining the effect of multiple trials on grip strength have requested a maximum effort on each trial. Marion and Niebuhr (1992) compared subjects who performed 6 sub-maximal (50% of maximal) grips prior to performing 6 maximal grips with those who had performed grips in the reverse order. Those who had first performed the sub-maximal grips, produced the strongest maximal grips. Longer bouts of sub-maximal grips are likely to be detrimental to the production of maximum grips. Mundale (1970) had subjects perform sub-maximal grips (at varying percentages of maximal grip strength) for 10 minutes and then measured maximal grip strengths. Fatigue effects following sub-maximal efforts were reported even when the preceding bout of sub-maximal grips were at a low percentage of maximal grip strength (albeit as low as a 5% reduction in pre-exercise maximal effort). In respect of the study reported in Chapters 5 of this thesis, Mundale's study suggests that it is reasonable to expect grip force to reduce due to fatigue resulting from non maximal tennis performance.

Bystrom and Fransson-Hall (1994) claims that the use of one indicator is not adequate for determining when fatigue is present in the muscles. He investigated the effect of various contraction intensities, contraction/relaxation schedules, and exercise durations on multiple physiological measures of muscular fatigue and found that intermittent grips produced fatigue in at least one of the recorded measures if they were greater than or equal to 17% of maximal.

Continuous grips produced fatigue effects if they were only 10% of maximal. These findings suggest that a few sub-maximal warm up trials of less than 17% maximal intensity prior to assessing maximal grip strength are beneficial.

Fatigue effects from repeated grips may be lessened or reduced by training. Kramer and Knudson (1992) failed to find fatigue effects in a group of trained tennis players after they performed 30 maximal grips. The authors suggest that training in tasks requiring strong grips leads to an ability to resist fatigue resulting from multiple maximum grips. Similar effects of training have been found for other muscle groups (Hamill and Knutzen, 1995). Rest periods between trials may minimise fatigue effects. Although Richards and Palmiter-Thomas (1996) report that there is no standard inter-trial rest period in common usage, many researchers have subjects alternate hands between grips and perform only three trials on each hand.

The nature of hand-grip fatigue as opposed to hand-grip strength has not been fully explored. Richards and Palmiter-Thomas (1996) summarise two studies where the grip strength has been found to be inversely proportional to grip endurance. Nwuga (1975) had subjects attempt to hold a maximal grip as long as they could and measured the time it took the grip strength to drop to 50% of maximal. He found that individuals with stronger grips could maintain those grips for shorter amounts of time than individuals who had weaker grips. This was especially true for females, who had better grip endurance than males. Mundale (1970) had subjects produce sub-maximal grips for 10 minutes. Like Nwuga he found that stronger individuals were able to maintain a smaller proportion of their maximal grip strength than were weaker individuals. Mundale also found that women had higher grip endurance scores than men but had weaker grips.

Watts *et al.* (1996) investigated the time course of recovery from hand-grip fatigue in the context of rock climbers. Eleven expert rock climbers tackled an indoor competition standard climbing wall route repeatedly with no rest until a fall occurred. Finger tip blood samples were obtained 10 minutes pre-climb, at post-climb, and at 5-, 10-, and 20-minutes recovery and analysed for lactate. Maximum hand-grip strength was measured at the same intervals. A measure of hand-grip endurance, defined by the authors as the time that the dominant hand-grip force could be sustained above 70% of hand-grip strength was determined pre-climb, post-climb and at 20-minutes recovery. This was a deviation from the norm as typically studies only measure peak hand-grip strength regardless of the application. This may be because hand-grip strength measurement has traditionally been used in medical applications where it is adequate to measure maximum grip strength and compare it to normative levels or an existing baseline measurement taken from the same patient. In the context of sports, it may be argued that other parameters such as reaction time, fatigue rate, hand-grip endurance, hand-grip utilising a repeat 'pulsing' protocol, etc. may be more appropriate and informative. Watts *et al.* (1993) reported that blood lactate remained significantly elevated at 20 minutes after ending the climb. Hand-grip strength and hand-grip endurance were decreased by 22 percent and 57 percent respectively post-climb with both remaining depressed after 20 minutes recovery. However, hand-grip strength was found to recover at a faster rate than hand-grip endurance.

Evidence points to the need for more specific methods of testing for sporting applications. Donnelly *et al.* (1991) found no difference in grip strength between elite climbers and non-climbers but did find a significant difference for climbing specific strength (i.e. using the index and middle fingers in a climbing specific manner). This was supported by Watts (1993) who reported that high grip strength may not be a necessary attribute of elite climbers. Grant *et al.* (2001) attempted to identify the characteristics that distinguish elite climbers from recreational and non-climbers. No difference was found in a test of pincer strength which is similar to hand-grip strength but involves squeezing with just the thumb and forefinger without contact with the palm of the hand. Differences were found in finger strength.

2.5.3 Measurement of hand forces & grip pressure during tennis impacts

Research investigating shock and vibration in tennis is divided into two approaches; simulation modelling and human testing. Simulation modelling has been achieved by either physical simulation, for example, a mechanical arm or robot; or by mathematical modelling. Human testing can be subdivided into static or dynamic testing. Each approach has its own advantages and disadvantages and it is suggested that all four can make a complementary contribution to building up a complete picture.

There have been two main reasons for investigating the forces transmitted to the hand during tennis strokes reported in the literature. The first is to investigate the relationship between grip firmness and rebound velocity and control of the ball. Early studies concentrate on the relationship between rebound ball velocity and grip firmness. Watanabe suggests this is because of the importance in modern day tennis of generating high ball velocity in certain shots (Watanabe *et al*, 1979). The second issue is the relationship between grip firmness and the transmission of impact forces to the hand. The impact force loads experienced in tennis have been hypothesised to contribute to lateral epicondylitis or tennis elbow (Nirschl, 1973). The physical stimuli possibly causing injury can be identified as:

- a single exposure to excessive stroke production loads pre-impact
- a single exposure to excessive shock load due to impact
- a single exposure to excessive post-impact residual vibrations
- repeated exposure to adverse stroke production loads pre-impact
- repeated exposure to adverse shock loads from multiple impacts
- repeated exposure to adverse post-impact residual vibrations

Published research has been unable to establish whether any or all of these stimuli are responsible. Researchers are in disagreement on this issue and where one proposes one reason another contradicts this and proposes another. The likelihood is that a combination of the above is responsible, the contribution of each being case dependent.

Some studies such as Plagenhoef (1970) and Hatze (1976) found that the firmer the grip the greater the impulse imparted to the ball. This is in agreement with the advice traditionally given by coaches. Recent studies have found the coefficient of restitution to be independent of grip firmness (Baker and Putnam, 1979; Daish, 1972; Grabiner *et al*, 1983; Knudson, 1991a; Miyashita *et al*, 1980; Watanabe *et al.*, 1979). A long running debate exists on whether tennis rackets should be modelled as having clamped or free handles. The consensus is for the latter.

According to Plagenhoef (1970) in the book 'Fundamentals of Tennis', "the firmness of grip at impact is the single most important factor in hitting a tennis ball". He explained that the hand must control movement of the racket head so that it is properly placed at impact and also so that it transfers maximum force. This is in agreement with Bunn (1955) who states that "the wrist must be rigid and the grip firm at impact to avoid recoil". Similarly Broer (1973) suggests that "squeezing the racket at impact aids in resisting the force of the ball against the racket because it tightens the wrist muscles". Tilden (1970) advises that "the time to hold the racket firmly is at the moment of impact" as does Tilmanis (1975). Historically a good firm grip at impact was the advice given to players. However, research on the effects of grip firmness on the player is inconclusive.

The first study attempting to determine the most desirable grip tightness during tennis strokes was by Hatze (1976). Impacts were compared whilst rackets were either clamped, held by a player or swung by a player. Only one subject was tested. Strain gauges, sensitive to bending in two planes were attached to the racket at a point just above the handle. The impulse and vibration at this point were then generated experimentally and calculated mathematically. The experimental results were in accordance with the predictions of the proposed mathematical model, which allowed for the deflection of the strings and bending of the racket. Ball rebound velocity was found to be greatest in the clamped conditions, though only central impacts were considered. The author made reference to the trade off between injury and performance and cautioned that more vibration is likely to be transmitted to the hand during a tight grip. He suggested coaches should encourage unskilled players who are more likely to hit off centre shots to use a loose grip and skilled players to use a tight grip.

Hatze concluded that the linear and angular impulse at the racket handle which he refers to as recoil, were of a magnitude that could not be significantly counteracted by the player. This result suggests that the study of the arm reaction can be decoupled from the racket reaction, as the arm does not affect the racket significantly. Therefore Hatze recommended that the racket may be modelled as free standing. The ball impact resulted in a 'jerk' or physical displacement of about 1mm at the grip. He states that whilst the forces transmitted to any given muscle in the forearm may depend on how tightly the handle is gripped, the strength of the grip will have a minimal influence on the distance the handle jerks or moves. Interestingly the author reports that the time the ball is in contact with the racket strings is typically 4ms, but that the vibration of the racket continues for approximately a further 40ms.

Subsequent studies by Watanabe *et al.* (1979), and Baker and Putnam (1979) found ball rebound velocity to be independent of grip firmness, although grip firmness is important for racket control. Both these studies involved testing racket responses under free standing and clamped conditions. In addition, Watanabe included measurements taken from a racket held by one subject. Grabiner *et al.* (1983) found no difference in ball rebound velocity between free and clamped conditions for centre or off centre impacts. It was noted that during play, a firm grip would be required in off centre impacts to prevent twisting of the racket face due to torque and so grip firmness is an important factor in racket control. It is likely that the value in coaches advice to players to have a firm grip is in the control aspect rather than the power.

Optimum grip pressure will be an issue for any sport where an implement is used to strike a ball and tennis, cricket, golf and baseball are all obvious examples of this. These are all sports that are highly professional and the stakes at the highest level are large. Eggeman and Noble (1982, 1985) has conducted considerable research investigating hand grip forces in the sport of baseball by instrumenting bats with transducers. Similarly Stretch *et al.* (1995) attempted to identify the variability of grip forces in a typical attacking stroke in cricket batting. They state that the timing, positioning and firmness of the grip in cricket are the factors that determine the success of the resulting shot.

This is also true in golf where excessive grip pressure can reduce the smoothness of the swing and negatively affect the resulting shot. Grip pressure profiles for amateur golfers were demonstrated to differ from those of professional players in a study by Budney and Bellow (1979). A steel shafted driver was instrumented to measure grip pressure at three locations under the hands and a strain gauge was positioned just next to the club head in order to detect the moment of impact. He suggested that a graphic record providing feedback made available immediately after each swing would serve as a basis for correction of possible swing faults. The author, explaining why the measurement of grip pressure is important in golf, states that "it is difficult to convey the feel of correct grip pressure; what may be moderate grip pressure to the instructor could feel light to the golfer". According to Budney (1990) some professional golfers and golf teachers consider grip pressure important, whereas others do not. Toski and Flick (1978) noted that "when the grip pressure is minimal, the muscles are at ease enhancing the feel for striking the ball". Yet others such as Barber (1978) claim a firm grip is essential and the key to club head control.

Skills can be categorised on a continuous scale from 'open' at one end to 'closed' at the other end. Golf can be categorised as more of a 'closed' skill. Closed skills take place under fixed conditions, are predictable and have clearly defined beginning and ending points. They are usually 'self-paced' in the sense that the performer begins movement when he is ready. The game of tennis is an 'open' skill performed in a constantly changing environment where decisions have to be made constantly and rapidly, according to the current game situation. An 'open' skill by its nature is more difficult to investigate because it is not just the movement, but the movement in the context of the situation that is important. Whilst tennis match play is an 'open' skill individual elements, for example, the service can be regarded as 'closed' skills. Closed skills naturally lend themselves to laboratory based testing, whereas the intrinsic variability of 'open' skills makes them more difficult to investigate objectively. As a result of the practical difficulties of investigating real play there is a general lack of research data in this area.

Returning to tennis, McLaughlin (1980) made the first attempt at in-play dynamic measurement of gripping forces in order to investigate technique differences amongst players with a view to correlating aspects of technique with susceptibility to injury. The study was limited due to unsuccessful instrumentation of the racket and results were predominantly based upon high speed three dimensional cinematography. The authors recommended that future efforts be concentrated on analysis of the backhand as this is the stroke likely to be most prevalent in causing tennis elbow.

Elliott (1982) used a pneumatically driven mechanical arm to swing a racket toward the ball impact whilst varying the firmness of the connection of the arm to the racket handle. Central and off centre impacts were considered. Gröppel (1975) cited in Groppel (1986) found that the "majority of impacts of highly skilled competitors occur off centre, deviating from the long axis of the racket". Elliot found that for off centre impacts, greater grip firmness resulted in higher ball rebound velocity, though for central impacts ball velocity was independent of grip firmness. The author does caution that a tighter grip would in practice increase the amount of vibration transmitted to the hand, which may in turn contribute to the risk of injury.

Attempts have been made to determine the loads on the individual structures of the forearm by mathematical modelling techniques (Casolo and Ruggieri, 1991; Freund, 2001; Hatze, 1976; Kawazoe and Yoshinari, 2000; Lemay and Crago, 1996; McLaughlin and Miller, 1980). Freund (2001) reports, "one of the practical problems of modelling is the lack of reliable data on geometrical and physical parameters". The human musculoskeletal system is highly complex and a model is inevitably a simplified version. McLaughlin (1980) notes "the musculature in the lower arm is redundant in an engineering sense, so that it is not possible to deduce the forces in any given muscle from the forces applied to the arm unless some further assumptions are made".

Knudson is at the forefront of human dynamic testing of hand forces during tennis strokes and has published research on the subject from 1988 to today. Knudson and White (1989b) explain "to understand the mechanical interaction of the soft tissue of the hand with the racket and to establish a relationship between loading and potential injury, the measurement of forces on the hand is critical". In this paper he noted that "the measurement of forces acting on the body has been limited until recently by the way force transducers were developed, which is for use on rigid and regular surfaces". To measure hand forces during tennis strokes, Knudson used two force-sensing resistors mounted on a tennis racket handle. The top sensor was positioned to record impact forces at the base of the index finger, while the bottom sensor was placed to record the primary gripping force created by the last three fingers of the hand (hypothenar eminence). A triaxial accelerometer was positioned at the centre of gravity of the racket in order to measure racket vibration. Balls were fed to the players by a ball machine at a speed appropriate to the stroke and skill level of player under investigation.

Knudson (1989a) used this technique, together with three dimensional video analysis, to determine the effect of grip firmness on coefficient of restitution. Two university players were the subjects and forehand strokes were analysed. The coefficient of restitution was not found to be significantly affected by gripping forces nor was the increase in momentum of the ball/racket system affected by increasing pre-impact forces. Knudson attributed the minimal support from the results for the influence of grip firmness to the elastic nature of the stringing used, and the large hand force normally used by the subjects. Knudson cites supporting previous research demonstrating that the elastic nature of the strings is the dominant factor affecting ball rebound velocity in central impacts (Baker and Putnam, 1979; Brody, 1979; Watanabe *et al.* 1979; Elliot, 1982; Grabiner *et al.* 1983). This was one of the first experimental examinations of the effect of grip forces on impact mechanics in actual stroking conditions. Knudson states that more research is needed in realistic stroking conditions to establish the biomechanical significance of hand forces on tennis impacts.

Knudson (1989b) then recorded the forces during a series of standardised forehand strokes of seven highly skilled tennis players. The general pattern of the force curves from the two hand positions for the forehand were described. The gripping force measured at the hypothenar sensor increased in preparation for impact, decreased due to the moment created by the force of impact, and later increased, probably due to the subject attempting to regain control of the racket head. The force at the top sensor decreased in preparation for impact, which may be attributed to a combination of increased hypothenar force evident as large gripping forces measured by the lower sensor and the small accelerations of the racket near impact. The force of impact displaced the racket backwards relative to the forearm, creating a sharp increase in the force recorded by the sensor at the top of the hand, which quickly decreased. The forces observed at the top of the hand were consistent with the shape and magnitude of the force data presented by Plagenhoef (1979).

Although this study produced valuable data, its usefulness was, by the author's own admission, limited by the large variability of the post-impact forces. Plagenhoef (1979) reported that the large variability of peak forces after impact was related to impact location: "When a ball hits in the centre of percussion of the racket face, the net force to the hand, following impact, will be negligible". However, when a ball hits off centre on the racket face, the racket tends to twist along its long axis. This twisting effect could have severe effects on the shot and cause serious strain to the forearm muscles which are contracting to control excessive racket movement (Brody, 1979). Knudson comments that the large variability in post-impact forces cannot be wholly attributed to vibrational forces. He suggests ball/racket impact velocity, impact location, gripping conditions and racket vibration all interact to determine the forces transmitted to the hand. Knudson concludes with the suggestion that "future research should document the range and variability of forces on the hand for the variety of strokes and stroking conditions encountered in tennis play in order to shed light on the force loading in tennis." Furthermore "until inter- and intra-subject variability is accounted for, the potential for optimising equipment design to reduce adverse force loading in tennis is limited."

Knudson (1991a) then used the same instrumentation to attempt to account for the variability of the hand forces found in his previous studies. He calculated pre-impact grip tightness and impact location to account for 66% of the variability of post-impact peak force loading in the tennis forehand drive. Based on these results and previous research, he recommended that players with tennis elbow symptoms or history should use a light grip particularly at the base of the index finger. They should also "minimise the effect of off centre impacts by: stringing at a lower tension, using an oversized racket to increase the racket's polar moment of inertia and selecting a racket with moderate longitudinal stiffness characteristics".

Knudson then went on to study the forces on the hand during a one handed backhand (Knudson, 1991b). He cites several epidemiological studies that link the one handed backhand to incidence of tennis elbow (Gerberich and Priest, 1985; Grouchow and Pelletier, 1979; Priest *et al.*, 1980a). Knudson (1991) notes that previously Bernhang *et al.* (1974) and McLaughlin and Miller (1980) had studied the forces involved in the one handed backhand. He notes that the former was limited because the total grip pressures were not quantified and the location of the hand compressive forces could not be determined. The latter used extensive modelling and assumptions to estimate forces in selected forearm muscles and only considered the swing phase of the stroke and not the actual impact, which may be most related to the etiology of tennis elbow.

Knudson instrumented the racket, similarly to his previous studies, with two miniature load cells to measure force applied by the hand to the racket at two hand locations. The position of the load cells corresponded to the base of the thenar eminence and the lower portion of the hypothenar eminence when the subjects held the racket with a one handed backhand grip. Six advanced and six intermediate male tennis players were the subjects. Post-impact peak forces on the thenar eminence were reported to range from 5.7 N to 123.6 N. The magnitude and variability of these post-impact peak forces were smaller than those observed in previous studies of forehand drives (4 N to 309 N: Knudson and White, 1989; 125 N to 259 N: Plagenhoef, 1979). In the forehand drive, the hand is directly behind the handle of the racket and the force of impact is more directly in line with the axis of the arm, and therefore the hand experiences large peak forces (Knudson and White, 1989; Plagenhoef, 1979). However, in the one handed backhand grip, the hand is placed on top of the racket handle where the force of impact is more eccentric to the arm and wrist axis. Unresisted impact forces are likely to produce a rapid stretch of the wrist extensors. This mechanism of injury was hypothesized by Kamien (1990) in an extensive review of the literature on tennis elbow.

Knudson proposed a possible explanation for the greater incidence of tennis elbow in less skilled players compared to skilled players. The results showed that the advanced subjects rapidly increased thenar forces in preparation for impact as compared to the less skilled players. The smaller thenar forces at impact may create less resistance to the acceleration caused by ball impact and as explained above this may lead to a rapid stretch of the wrist extensors which may result in tendon damage.

Sakamoto *et al.*, (1992) used seven pressure sensitive conductive rubber sensors attached to the subject's hand to measure grip pressure during ground strokes. The grip pressure of three subjects of varying ability was recorded for a series of forehand strokes. It was found that the most experienced player gripped the handle softly and gave extra pressure only at the impact. The least experienced player's grip pressure increased well before impact and was greater after impact. The author suggests that the over gripping occurring in the unskilled player may lead to premature muscular fatigue, reduced control and possible injury. Less skilled players should therefore be encouraged to grip more lightly whereas skilled players can afford to grip more tightly (which is the opposite advice to that given in the studies discussed previously). These results are in agreement with golf research conducted by Budney (1979, 1990) where the grip of novice and professional players is compared. Novice players were found to over grip and exhibit more inconsistent grip patterns.

Measuring hand forces on the racket during play is not straightforward. The racket handle needs to be instrumented in an unobtrusive way so that no alteration is made to how the racket and grip feels or performs. This means that the sensors used to measure the force must be small, light and robust. There is then the issue of the wires necessary to connect the sensors to a data recorder or computer. To do this telemetrically is expensive and requires battery power which may be heavy. The forces recorded need to be related to the area on the hand and the difficulty is that the grip position changes depending on the shot type. This is why studies tend to concentrate on a chosen shot. To get meaningful data the results from a number of trials should ideally be combined. Much variation exists in the data so far available and it may be very difficult to establish a direct relationship because of the complex nature of the inter-relating factors. It remains unclear as to which aspect of the impact, if indeed any, causes injury. What does seem clear is that the tighter the player grips the racket, the greater is the transmission of forces to the arm. It would be useful to determine what aspects of these forces is harmful so that positive interventions can be made and it can be ensured that any equipment modifications will tend to improve rather than exacerbate the problems.

Table 2 provides a summary of the advantages and disadvantages. Modelling relies on assumptions and simplification of the complex musculoskeletal system, but does offer the best way of evaluating the effect of controlling and manipulating variables. Human static testing is conducted in a more controlled environment that bears little resemblance to real life play conditions. Human dynamic testing is based on real play and players. However, due to the interaction of many factors that are difficult to control, results presented to date in this area have shown large variability.

Table 2: Advantages and disadvantages of simulation modelling and human testing

		Advantages	Disadvantages
Simulation modelling	Mechanical arm	Control, good for isolated equipment testing	Lacks complexity of human body
	Mathematical	Ability to change variables	Assumptions, simplification
Human testing	Static	Control of impact factors	Unrepresentative of tennis
	Dynamic	Realistic, full context	Lack of control, variability of results

Human dynamic testing is necessary to gain insight into the interaction between the player and the equipment. Real life data is required to validate and develop models. This research is concerned with furthering knowledge in the area of human dynamic testing. This approach is the least well developed.

2.6 MEASUREMENT OF VIBRATION DURING TENNIS IMPACTS

It seems unlikely that vibration alone causes injury at the elbow. If the levels of vibration resulting from repeated tennis impacts were that damaging then the resulting condition is likely to take the form of Vibration White Finger, a condition accepted to occur as a result of repeated exposure to vibration. Occupational research indicates that individuals exposed to damaging levels of vibration suffer from localised (in the tips of the fingers and hands) blood vessel restriction causing various degrees of numbness eventually leading to vascular and neurological damage (Griffin, 1990). Most of the vibration associated with impact has been demonstrated to be damped before even reaching the elbow. There is a possibility that the vibration from mishits may be sufficient to aggravate symptoms, but on the whole it seems unlikely that vibration contributes significantly to tennis elbow. Despite this, the advertisements of many tennis racket manufacturers claim that the excellent damping qualities of their rackets prevent tennis elbow. What is possible, however, is that injury could result from a combination of what in isolation would be undamaging levels of vibration with adverse biomechanical movement (i.e. in cases of bad technique, when fatigued, as a result of mishits).

Much research has been conducted to study levels of vibration in the hands of those who work with power tools. Renstrom (1993) cites three studies where it has been found that for high frequencies (defined as above 100 Hz), vibration entering the hand will remain in the hand and fingers whereas lower frequencies (defined as less than 70 to 80 Hz for finger grip and 20 to 50 Hz for palm grip) tend to transmit vibration up the arm (Cundiff, 1974; Reynolds *et al.*, 1982; Suggs *et al.*, 1977). In each of these studies the transmissibility was obtained by mounting accelerometers onto the tool and onto the hands and arms of the operator, whereby a transfer function was measured. Reynolds *et al.* (1982) found that annoyance owing to vibration applied to the hand decreases as frequencies exceed 180 Hz. This suggests that discomfort during tennis racket impacts is caused by frame vibration rather than by the higher frequency, lower intensity string vibration. This explains why studies have questioned the effectiveness of string dampeners despite many players reporting their effectiveness.

Stroede *et al* (1999) agrees that string dampers eliminate high frequency vibration but not frame vibration and this has the effect of reducing the 'ping' on impact. He suggests that it is possible that by reducing the audible 'ping', players experience sensory confusion and associate the sound reduction with a reduction in hand and arm discomfort. This theory was tested out and players were asked to indicate their discomfort immediately after impact with various rackets either with or without string dampers. The players were prevented from seeing or hearing the impact. No significant differences were found in discomfort ratings between damped and undamped impacts or between racket types, but central impacts were found to be more comfortable than impacts 100 mm distant from the centre. This is in agreement with a study by Tomosue *et al.* (1991). Vibration traces from an accelerometer mounted on the racket handle revealed that the string dampers absorbed the high frequency string vibration without affecting the lower frequency frame vibration.

When a tennis racket hits a ball, most of the energy involved goes into deformation of the ball, strings and racket frame. Some of this energy is fed back into the ball in the form of kinetic energy. Some of the energy which is stored in the frame and strings becomes energy of vibration. Roetart *et al* (1995) explains that the point of impact on the racket head that minimises the resulting vibration of the frame is called the node of the fundamental bending mode of vibration. On most rackets the node is located near the centre of the racket head or slightly above it and the frequency of this mode in a typical composite racket is between 125 and 200 Hz. The further away from this node that the ball impacts, the larger the amplitude of vibrations. Also, the greater the ball-racket velocity, the larger the amplitude of oscillation. Nallakatla *et al.* (1995) cite a study by racket designer Marvin Sassler (reported in Yeapie, 1987) who found that average players hit 90% of their strokes off centre. Consideration of the vibrations occurring in a racket during and after impact are complex and involve the vibration parameters of mode, amplitude, amplitude decay (damping) and frequency.

The position of impact is an important factor in both the resulting impulse and frame vibration. Brody (1981) describes a study by Hedrick *et al.* (1979) who investigated the effect of ball impact location on a freely suspended racket using an accelerometer mounted on the handle. The results showed that when the ball hits the centre of percussion there is no impulse and when the ball hits the node of the fundamental free mode of oscillation there is no vibration. The latter point is known as the sweet spot.

Vibration measurements in rackets have been carried out in several studies mostly in an attempt to determine the relative difference between types of rackets on the market. Some racket manufacturers claim that their racket damps out vibrations more than other rackets and they use this as a selling point. Carroll (1981a) compared a variety of rackets and found that the level of vibration parameters is dependant on the size, weight and material of the racket, how it is gripped and on the position of ball impact on the string bed He took the racket with the most rapid amplitude decay and had 42 club players with a history of tennis elbow play with this racket instead of their own for two seasons. Interestingly most of the players in the study reported considerable improvement in symptoms suggesting that the racket is an important contributory factor in the development of tennis elbow. The sample size in this study was 42 and although an impressive majority of the subjects reported improvements in symptoms, factors other than the racket may have contributed. A 'blind' study design with a control group in this type of investigation, as commonly used in clinical trials, may have helped to overcome the potential for a placebo effect where subjects under the 'attention' of a study 'expect' to improve.

Brody (1989) compares the damping time, defined as the time for the amplitude of the oscillation to fall to half its value, of rackets hand held and freely suspended. A Kynar vibration sensor that is small and light was fixed to the throat of the rackets. Balls were then fired at the strings near the tip and the output of the sensor observed through an oscilloscope. The traces were measured to determine damping time. Hand held rackets showed vibrational modes similar to freely suspended rackets but both were different to clamped rackets. He stated that "a free racket's lowest frequency of oscillation is from 100 Hz to 175 Hz which is similar to the higher frequency of the clamped racket". When compared, the damping times of the hand held rackets were an order of magnitude less than those of the free rackets. Results also showed that the damping time depended on how tightly the racket was gripped and where the grip force was applied. Brody (2002) claims that the vibrations of a tennis racket that are most 'annoying' are caused by the first harmonic mode of oscillation. He explains that this mode has a node near the centre of the head, a node near the top of the grip and antinodes at the tip, butt end and near the throat. The frequency of this mode of oscillation runs from between 120 Hz and 200 Hz depending largely on the stiffness of the racket frame.

Tomosue *et al.* (1994) investigated the effectiveness of damping materials in reducing impact shock and vibration transfer. Unfortunately only one subject was tested under static conditions (no swing) with five shots using each of seven different rackets. Accelerometers were positioned both on the player's wrist and 12 cm from the end of the racket handle. No significant differences were found between the rackets in vibration responses either at the wrist or on the handle. When comparing position of impact differences were found. For central impacts, the amplitude of the vibration in the wrist was one tenth of that in the racket handle and so considered negligible. Furthermore, high frequency vibrations were only evident on the racket handle. Off centre impacts gave 1.9 to 3.1 and 1.3 to 1 6 times greater vibrations in the wrist and racket handle respectively. Elliot *et al.* (1980) performed a similar study investigating vibration transfer in conventional and oversized rackets. Although it was concluded that the oversize racket design reduced vibrations transferred to the arm, only one subject was tested and only under static (no swing) conditions.

Dynamic human measurement of effects of tennis rackets on vibration transmission was investigated in a study by Fairley (1985). Although in this study the player swung the racket, again only one subject was tested. Impact location and grip firmness were identified as significant variables in respect to vibration transmission.

A study by Hatze (1992a) investigated the effectiveness of grip bands in reducing racket vibration and slipping. An artificial arm fitted with pressure and acceleration sensors was used with a standard tennis racket. Balls were fired at 20 $m.s^{-1}$, while the impact location was described to be 32.5 mm distant from the sweet spot at the nodal point of the fundamental transverse vibration mode on the racket long axis. Although cushion grip bands were found to reduce impact shock and vibration transfer it was suggested that a much more efficient way of reducing post-impact vibration transfer is to reduce the grip tightness to a level just sufficient for effective play. In a previous study by Hatze (1976) skilled players were shown to reduce racket acceleration to zero just before impact which apparently also induces a loosening of grip pressure, at least at the base of the index finger. The results of a study by Knudson and White (1989) are in agreement with this. Grip bands were found to reduce slipping considerably which would have the effect of reducing the torque from off centre impacts.

The consensus of opinion is that most of the vibration from impacts stays at hand level. Hennig *et al.* (1992) investigated the transfer of tennis racket vibrations to the forearm. Accelerometers were placed at the wrist and elbow of 24 subjects who performed simulated backhands with 23 different tennis rackets. In contrast to Tomosue *et al.* (1991) they found differences between the rackets. Two rackets with particularly high resonance frequencies (about 185 Hz) gave noticeably lower vibrations compared with the rest of the rackets which all gave similar vibration levels and had resonance frequencies in the range 105 to 145 Hz. In total, there was a significant correlation between high resonance frequencies and lower transferred vibration levels. They reported greater vibrations by a factor of three during off centre impacts which is in agreement with Tomosue *et al.* Vibration levels at the elbow were found to be approximately a third of those at the wrist.

Carroll (1981) and Elliot (1988) have demonstrated the increase in both amplitude and frequency of vibration due to torque resulting from off centre impacts. Studies using EMG have shown there is an increase in muscle activity associated with off centre impacts (Adelsberg, 1986; Bernhang *et al*, 1974; Giangarra *et al.*, 1993; Morris *et al.*, 1989).

In summary, it seems that the vibration from the racket stays at the level of the hand. It seems that mishits, which produce racket torsion and result in increased lower arm muscle activity, are most likely to be the main contributor to tennis elbow. Vibration does not appear to be implicated in causing tennis elbow, but may aggravate the condition once a player has the injury.

2.7 SUMMARY

Section 2.2 of this chapter has discussed the developments that have and are occurring across all aspects of the game of tennis. Taken together with Chapter 1, this establishes the context for and relevance of the research. Manufacturers are constantly striving to make performance improvements to their equipment and the application of science and technology now plays a vital role in the modern game of professional tennis. As the technology behind recent advancements matures, particularly the materials and construction technologies, it was argued that further modifications and interventions will yield diminishing improvements without radically different racket construction technologies. Improved techniques are required to gather better test data to validate designs and support their implementation.

Section 2.3 of this chapter focused on tennis injuries, in terms of cause and prevention, particularly in relation to equipment design. Exactly what causes tennis elbow in terms of the combination of mechanical stresses and strains leading to inflammation or tears of the tendon presently remains unknown. This uncertainty has been identified by prominent researchers in the field and has led to speculation and interest about possible causes. Hatze (1976) says "it would be of interest to investigate whether large frequency vibrations could have an effect on the development of tennis elbow". Roetert *et al.*, (1995) stated that "it is evident that a need exists for a specific study of the muscular response during impact... particularly for the one handed backhand groundstroke". Brody, in a newspaper article is quoted as saying "no one has done any real experiments to determine a racket's influence on injury" (Beer, 1998). Speed (2000), cited in Roussopoulos and Cooke (2000), noted "there is a distinct lack of adequate research on the issues of specific mechanisms in the etiology i.e. the cause of any upper limb injuries in tennis". In summary, Roussopoulos and Cooke (2000), have suggested that "the injury may be the result of any or a combination of the following: a single sharp impulsive stress and strain to the muscles as from a badly hit ball, an accumulation of 'normal' or slightly high stresses from prolonged playing, a sharp vibration in the loaded muscle, an accumulation of many vibrations, each one not in itself dangerous". Roussopoulos and Cooke highlighted the need in their review, to address the question of whether it is the impulse or the vibration that cause injury, or whether both are important.

The issue of fluctuations in muscle soreness was raised as a potential indicator of increased likelihood of injury and because of the allowances needed for delayed onset muscle soreness (DOMS) when conducting experimental evaluation of equipment affects with prolonged exposure.

It is proposed that the lack of agreement over the definitive cause(s) of tennis elbow is due at least in part to a lack of published research identifying changes in upper limb distress caused by specific equipment interventions objectively measured under prolonged exposure or fatigue conditions. Testing the proposed research hypothesis makes a direct contribution in this respect.

Sections 2.5 and 2 6 reviewed previous research with respect to the measurement of hand forces, grip pressure, and impact shock loading and vibration, since these are considered the primary external stimuli to the upper limb. Fluctuations in the levels of these phenomena arguably indicate both changes in upper arm function and the duress to which it is subjected. Behm (1988) states: "Both the strength of grip imparted on the racket and the endurance of the gripping muscles are of great importance in tennis players in order to stabilise the racket at impact point and prevent injury." Several researchers have identified the need for further consideration of these issues. For example, Kramer and Knudson (1992) state: "Although there is a common understanding of the importance of gripping the racket in tennis, little research has been conducted to document the effects of fatigue on grip strength in relation to playing tennis." Knudson later emphasised the relevance of research in these areas to better understand injury when he stated: "Since hand and forearm strength may be related to performance and the development of tennis elbow, further studies documenting grip strength and fatigue in tennis players are needed" (Knudson and Blackwell, 2000).

It has been shown that previously employed methods offered only limited capabilities and this demonstrates the requirement for more sophisticated techniques. Several authors have identified that work in this area is technically challenging. For example, McLaughlin and Miller (1980) indicate the complexity of interacting phenomena in their statement: "It is commonly believed that tennis elbow is caused by ball/racket impact forces. However not all activities that have been reported to cause tennis elbow involve impact. It seems possible that tennis elbow may not be caused by impact but by other loadings on the forearm during the tennis swing." As does Griffin (1990) in his comment "Exposures to hand transmitted vibration are complex and cannot be quantified simply. The vibration received by a person will depend on his technique and vary according to the dynamic response of their fingers, hands and arm." This establishes the main focus of this research, which has been to develop instrumentation and a controlled protocol for the purposes of objectively measuring the loading on a tennis player during a single handed backhand and investigating the potential for detecting differences resulting from equipment design interventions. It is proposed that advances in technology, particularly instrumentation technology, offer the potential for new information to be collected about the equipment-player interaction. Research in biomedical engineering and robotics has begun to develop force transducing applications of conductive elastomers that are inexpensive and useful for measuring forces on soft tissue.

The following two chapters present two studies that were carried out for the International Tennis Federation (ITF) to characterise the positive and negative effects of using a 6% larger ball (Type 3). Although funding restrictions constrained the population size studied and the period during which they were exposed to the larger ball, a broad assessment of the comparative effects on play including grip strength, muscle soreness, point play and player perception was achieved.

From these initial studies, a number of useful and timely insights into the effect of the larger ball and its potential benefits were identified. The research reported was the first of its kind in this area.

Weaknesses in the commercially available instruments for monitoring grip performance in this type of study were identified and inspired the development of improved tennis specific instruments and testing protocols. This work is reported in Chapter 5. A detailed experimental study to evaluate the effectiveness of the device and protocol to measure the effect of fatigue and equipment design changes is reported in Chapter 6.

CHAPTER 3

STUDY A: THE COMPARATIVE EFFECTS OF PLAYING TENNIS WITH THE LARGER TYPE 3 BALL & STANDARD TYPE 2 BALL AMONGST ADVANCED PLAYERS

3.1 INTRODUCTION

In July 1999, the ITF Annual General Meeting approved a two year experiment in which a 6% larger ball (Type 3) was permitted for use in tournaments for the purposes of evaluation and development. In April 2000, the Sports Technology Research Group (STRG) at Loughborough University undertook an ITF funded pilot study to identify the effects of playing with the Type 3 larger ball on a closed group of high standard players (Mitchell and Caine, 2000). The study indicated some interesting trends and differences when playing with Type 3 as compared to Type 2 standard sized balls.

One of the main recommendations of the April 2000 study, was for two further research studies to be undertaken. This recommendation was endorsed by the ITF, which subsequently commissioned the STRG to carry them out. One of the additional studies, interchangeably referred to as either Study A or April 2001 Study, is reported in this chapter and was also separately reported to the ITF (Mitchell *et al.*, 2001). The other additional study, study B, is reported in Chapter 4.

The findings of the two additional studies were also presented at an ITF Technical Commission meeting and at a meeting of ball manufacturers, both in June 2001. In September 2001, following a review of the data collected during the trial period, the ITF Annual General Meeting voted to include the Type 3 ball into the Rules of Tennis.

3.2 BACKGROUND

The larger Type 3 ball was introduced by the ITF primarily to slow the game down on fast court surfaces, such as grass. The larger ball is nominally 7.09cm in diameter compared to 6.68 cm for the Type 2 ball, a diameter increase of 6%. The larger ball weighs exactly the same as the standard ball, which is achieved by manufacturing it with a thinner shell from a lower density rubber compound. The ITF's 'Tennis Towards 2000' survey reported a marked reduction in tennis activity worldwide. Though the many and varied reasons for this are beyond the scope of this research, two particular issues stand out. Firstly, at a recreational level, tennis is a difficult game to play. Secondly, the general perception of the viewing public is that the professional game is now too fast and not as exciting to watch as two decades ago.

An ITF study of tiebreak data from men's grand slam events from 1968 to 1998 supports the view that on the faster surfaces the first serve dominates the game. On grass, the probability of men holding serve and a set going to a tiebreak is far greater than on slower surfaces (Haake *et al*, 2000a). Match play statistics show that top male players play for an average of only four minutes per hour on grass with very few points exceeding rally lengths of three shots, including the serve. In contrast, the speed is lower in the women's game and interestingly many people comment that a better game of tennis is played.

Research indicates that the fastest serves may actually exceed the receiver's response threshold, making it theoretically beyond human capabilities to return these serves. However, at the elite level it is speculated that receivers can anticipate serve direction based on subtle differences in the service action of the serving player (Fery and Crognier, 2001; Hernandez and Sicilia, 1998; Klaassen and Magnus, 2000). Furthermore, it has proved difficult for scientists to explain the extremely quick response times made in sports such as Formula One. Following lab tests, Haake (Haake *et al.*, 2000b) found that the bigger ball gives the receiver about 10 milliseconds more reaction time when facing a first serve and up to 16 milliseconds more for a second serve. This is primarily due to increased drag. The larger ball was also found to bounce more steeply giving the player more time on the ball.

The ITF's objectives for introducing the larger ball were to improve the appeal of tennis for spectators and make the game easier and more enjoyable for recreational players to play. However, the introduction has been met with resistance from a section of players. Pete Sampras openly voiced his concerns that the larger ball unfairly narrows the gap between players of different abilities. The other main concern is that players may suffer arm and ligament injuries as they swing the racket more aggressively to coax extra speed out of the ball. During player testing reported in this chapter, the author encountered several subjects who had negative preconceptions about using the larger ball, although the majority had never previously played with it. Typically the better players had more concerns, possibly because they had read more tennis magazine articles about the Type 3 ball and its perceived shortcomings.

3.3 AIMS & OBJECTIVES

The primary aims of the April 2000 study were "to determine objectively, as far as possible within the scope of a pilot study, whether playing with the bigger ball has a detrimental effect on the style and quality of tennis played and whether the likelihood of injury is increased" (Mitchell and Caine, 2000). The requirements of the validation study (Study A: April 2001) summarised in this chapter were the same as those of the April 2000 study and can be summarised as follows:

- To provide a comparative assessment of the larger ball effects with respect to the standard ball
- To assess style of play
- To assess muscle fatigue and muscle soreness
- To base the study on playing conditions commonly experienced by tennis players
- To control, and ideally keep constant, all other factors (e.g. playing conditions, activity type, exertion levels and duration) to achieve credible comparison between standard and larger sized balls

The purpose of Study A was to repeat the April 2000 study using the same experimental protocol and with player subjects of similar ability level, to validate the previous findings.

3.4 METHODS & TEST MEASURES

3.4.1 General

Four indoor acrylic courts situated in Loughborough University's Dan Maskell tennis centre were chosen as the location for the testing to provide a uniform playing surface and controlled playing conditions for all sessions. Dunlop Slazenger supplied both the Type 2 standard balls (Slazenger Wimbledon) and the Type 3 larger balls (Dunlop Slazenger Precision).

Eight University Scholars/First Team players, four men and four women, were chosen as subjects for the study (age 21.3 yrs ± 1.6 SD). They reported playing competitive tennis for on average 11.3 yrs ± 2.8 SD and had a mean LTA rating of 2.1 ± 0.7 SD.

To expose the players to a level of tennis activity that was physically demanding and yet representative of the physical requirements made of tennis players, the format of a four-day training camp was chosen. This not only provided an opportunity to study play and players over an extended period but also enabled testing using different balls on alternate days. Standard balls were used on days 1 and 3 and larger balls were used on days 2 and 4. Although it was acknowledged that the different levels of fatigue would affect comparisons between ball types over the four days, this order was chosen to bias the study in favour of finding increased fatigue levels with the bigger ball instead of concealing them. New balls were used for each training drill session and tennis match, thus minimising any variations in ball performance due to wear.

On each day, play was separated into two sessions, one in the morning and one in the afternoon. The morning sessions, lasting for two hours, were dedicated to functionally relevant training drills, representative of actual training and match play scenarios. This activity was chosen to achieve a more intense activity level than normal match play, in an attempt to maximise muscle fatigue. The use of training drills, also permitted control over the activity content so that measures obtained with the different balls could be compared under more closely matched conditions.

The afternoon sessions were dedicated to match play. On Days 1 and 2, the 4 male subjects each played 3 matches of 30 minutes duration in a round robin format, (i.e. 6 matches per day in total). Similarly the 4 females played a round robin of matches. The number of games played was not limited to one set, instead the players were required to play for the full 30 minutes. On Days 3 and 4, the subjects played single set matches in a knockout format (2 matches per day for each subject, i.e. semi-final followed by winners' final or losers' final). The seedings were different on Day 4 from those on Day 3. Although the round robin match play format utilised on Days 1 and 2 was more suited to achieving consistent ball comparisons, the change in format for Days 3 and 4 was adopted to promote more competitive match play and maintain player motivation.

3.4.2 Grip strength

One of the main aims of the study was to investigate whether the larger ball resulted in a greater incidence of injury. The principal tennis injury is tennis elbow, which is a tendon injury associated with overuse. Without clinical assessment it is difficult to quantify the severity of tendon damage. Furthermore, the symptoms are typically only observed after prolonged exposure to a repetitive stimulus. Thus, it is impossible to quantify the magnitude of damage caused by a single bout of tennis. In the context of the study reported here, which investigated the effects of playing tennis with two different balls, examination was limited to making indirect measures of muscle stress that may indicate the likelihood of injury if experienced on a regular, frequent basis. In this respect, hand-grip strength was considered a useful measure given that reductions in strength are indicative of fatigue, whereby the greater the overload on a muscle the greater the extent of fatigue.

A digital hand-grip dynamometer (NK Biomedical) was used to assess hand-grip strength. As identified in section 2.5.2 the grip strength test provides a non-invasive test to assess muscle fatigue status. It benefits from being an easy test to perform, which is non-stressful to the subject. The grip test is often employed in a clinical environment as an indicator of medical conditions, post operative complications, industrial injuries etc. As an indicator of muscle status it is used to assess the effectiveness and progress of rehabilitation routines. It is also used for patient assessment in compensation claims. The grip strength test uses the forearm muscles, which are known to be affected in tennis players suffering from tennis elbow.

The grip strength test protocol employed required subjects to perform a maximal effort, isometric grip contraction of duration 3 seconds by exerting a gripping force on two parallel rods (Figure 1). A series of force transducers located between the rods permitted grip force to be measured continuously throughout the contraction. Subjects initiated and terminated the contraction in response to a series of audio cues. For each trial session, three contraction measures were obtained with each hand, with subjects alternating hands between measures. Subjects were given verbal encouragement throughout the contraction period and although they were permitted to observe the force profile generated, they were not provided with specific feedback on individual trials. All trials were recorded using a data acquisition device and dedicated software, thus permitting detailed analysis of the force traces at a later stage.

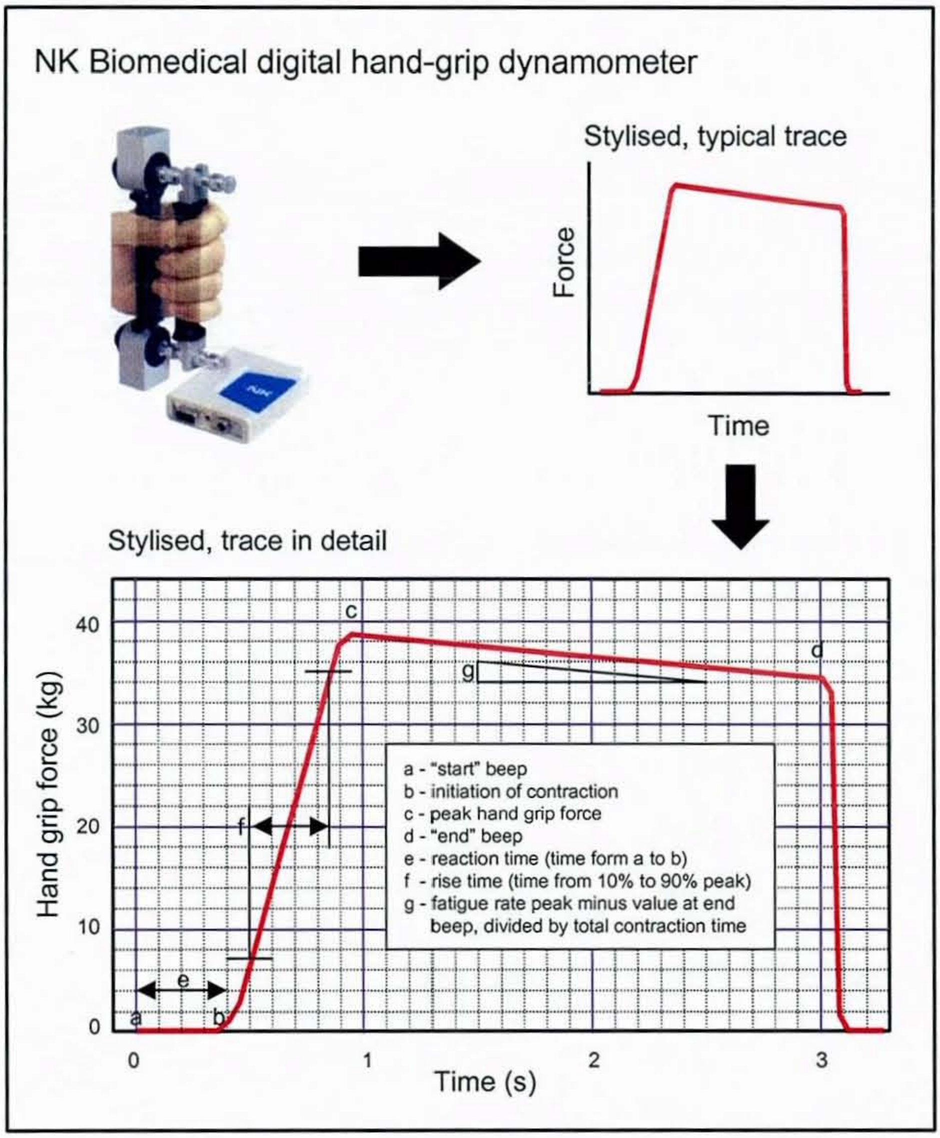


Figure 1: Image of the digital hand-grip dynamometer with stylised force time trace

The grip strength test was applied before and after each morning and afternoon session, in order to monitor muscle fatigue throughout the training camp.

A number of parameters were derived from the raw data (Figure 1). Reaction time denotes the time taken for a subject to initiate a contraction following an audio cue. This is a global measure of the time taken to respond to a cue, which includes both the perception time and also the neuromuscular response time. Rise time is the time taken for the force to increase from 10% peak force to 90% peak force, and therefore indicates the rate of force generation i e. the velocity of muscle shortening. Peak force denotes the highest force achieved during a continuous increase in force production and is taken as a measure of maximum isometric strength (kgf). However, because of the manner in which it is calculated, greater forces are sometimes observed in the later stages of the contraction following an initial decline in force generation. Fatigue rate is the peak force minus the force achieved upon termination of the contraction, divided by the total contraction duration, thereby indicating the rate of decay in force production.

3.4.3 Perceived muscle soreness

A series of visual analogue scales in a questionnaire format originally constructed by Dr Mike Caine, was used to record perceptions of muscle soreness (Appendix 1). An anatomical diagram depicting the muscles of the upper limb was utilised to identify a series of individual muscles in both anterior and posterior perspectives. Subjects were asked to make a mark on a 10 cm horizontal line to depict the level of their current muscle soreness. Two descriptors were used as anchor points for the scale, these being "no soreness at all" and "maximal soreness". To help subjects contextualise the concept of "maximal soreness" the term was described as the highest level of upper limb soreness previously experienced as a result of physical activity. Muscle soreness ratings were obtained for both right and left upper limbs.

Six muscles were highlighted in the anterior perspective, these were the:

- Coracobrachialis
- Triceps brachii, long head
- Biceps brachii
- Brachioradialis
- Flexor carpi radialis
- Palmaris longus

Likewise the following muscles were highlighted in the posterior perspective:

- Deltoid
- Triceps brachii, lateral head
- Brachioradialis
- Extensor carpi radialis longus
- Extensor digitorum
- Extensor carpi ulnaris

Subjects were asked to complete a muscle soreness questionnaire before and after each day of testing.

3.4.4 Point play outcome

Match play was monitored using a combination of video cameras and point recording sheets originally devised by Dr Sean Mitchell (Appendix 3). The point recording sheets include provisions for recording the outcome of each point played in terms of:

- Winner (server/receiver)
- Service outcome (1st serve ace, 2nd serve ace, double fault, missed return, rally)
- Rally outcome (winner, out net, mishit, number of shots)
- Winning/losing rally shot description (forehand/backhand, shot type, court position)

Microsoft Excel was used for statistical analysis of a variety of factors such as rally length, number of aces, percentage of volleys and unforced errors, in order to evaluate and compare the style and quality of play with the alternative ball types.

3.4.5 Perception

Each player's perception of how the larger ball differed from the standard ball was elicited using a Player Perception Questionnaire also devised by Dr Sean Mitchell (Appendix 2). Most of the subjects had not previously played with the larger size of ball. To provide maximum time to overcome the initial 'novelty' of the larger ball, subjects were not asked to complete the perception questionnaire until the end of their fourth (final) day of testing.

The player perception questionnaire was designed to avoid ambiguity. The main features of the questionnaire were as follows:

- The 24 questions were grouped into three sections: racket/ball interaction, ball surface interaction and general properties
- The questions were stated explicitly as a clearly understood sentence, where possible using appropriate tennis specific terminology
- Each question involved assessing the larger ball's performance by comparison to the standard ball, this approach being designed to promote clarity and emphasise the differences between the two ball types
- The response to each question was recorded using a bipolar five point scale with a clearly understood worded indication of the difference between each point on the scale
- Provision was made for the players to indicate whether they felt unsure about their ability to answer any given question, although they were encouraged to still record a response
- The players were also given the opportunity to comment on the positive and negative aspects of the larger ball

Players were encouraged, verbally and in writing, to express their own opinions, not those of their teammates. They were also encouraged to not discuss their responses with each other until after completing the questionnaire. Each player was given as much time as they required to complete the questionnaire. The questions were also discussed in an open session, once the questionnaires were completed, to ensure they had been clearly understood.

Only in a few instances did players indicate they were unsure of their ability to answer, and these related to their assessment of secondary ball characteristics such as impact sound and wear. All players indicated that they were used to playing with an equivalent Dunlop Slazenger brand ball to the standard ball used in the tests.

3.5 RESULTS

3.5.1 Data analysis

The data were entered into a series of Microsoft Excel spreadsheets for analysis. The results are shown in a series of bar graphs in the following section. The results were analysed for statistical significance both collectively and by gender using two-tailed t-tests with a P value less than 0.05 indicating significance and between 0.05 and 0.1 suggesting a trend towards significance Comparisons for day 2 versus day 1, day 4 versus day 3 and days 2+4 versus days 1+3 were made using a paired data t-test to identify differences between the two ball types. Comparisons for day 3 versus day 1 and day 4 versus day 2 were made using a two-sample equal variance test to identify differences using the same ball on different days and with different play formats. Unless in the following sections a comparison is identified as indicating a significant difference, or showing a trend towards significance, it can be assumed to have yielded a P value greater than 0.1.

3.5.2 Grip strength

The following charts illustrate pre- and post-session values for a range of hand-grip related measures. All measures are of group mean values obtained for the dominant hand. These permit comparisons to be made between drill and match play tennis and between standard and larger balls.

With reference to Figure 2 to Figure 5 inclusive, it can be seen that reaction times varied little (no significant differences) across the testing sessions. Ball size appeared to have little bearing on reaction time. There was some evidence of a learning effect as reaction times became marginally faster over the four day test period. Inter-subject variability was quite large, with coefficients of variability being around 20% and reaction times ranging from approximately 0.25 s to approximately 0.35 s.

With reference to Figure 6 to Figure 9 inclusive, it can be seen that rise times generally increased as the camp progressed, from around 0.25 s on day 1 to approximately 0.30 s to 0.35 s on day 4. This trend was evident for both drill and match play sessions. All post-session measures were lower than equivalent pre-session measures (some being lower with a statistical significance of >95%), which may suggest that rise time is most effected by cumulative activity rather than the immediate preceding period of exercise. In other words, the slower rise times observed towards the end of the camp may well be a consequence of chronic exposure to forearm exercise. In addition, the fact that post-session measures were typically faster may indicate a warm-up effect, whereby a period of exercise actually promotes quicker rise times. Ball size did not appear to be the key factor in determining rise time changes across the four days.

Peak force remained reasonably consistent, fluctuating around 45 kg throughout the second camp and around 42 kg when the two test sessions are combined (see Figure 10 to Figure 13 inclusive). There was a suggestion that post-session measures were marginally greater than pre-session equivalents. This observation would indicate that any warm-up effect elicited by the drill and match play sessions outweighs any fatiguing effects. There were no discernible differences between large and standard size balls.

Fatigue rates varied over the four days, this variation being most pronounced in post-session tests (see Figure 14 to Figure 17 inclusive). In all cases the rate of fatigue was less than 4.0 $kg \cdot s^{-1}$ (approximately 9% peak force over the course of the contraction). Fatigue rates comprise two components. Positive fatigue is observed where the subject achieves a peak force quickly and then subsequently fatigues as demonstrated by decay of the force profile. Negative fatigue equates to an increase in force over the contraction, such that the force observed at the end of the contraction is greater than the initial "peak". This phenomenon occurs when a subject reaches an artificial peak followed by a subsequent rise in force. This pattern of muscle contraction indicates an inability to generate a maximal force quickly and is consistent with fatigue of fast twitch muscle fibres. The fact that this phenomenon only occurred on days 3 and 4 only suggests that fatigue rates and muscle activation patterns were largely independent of ball type, being more heavily influenced by longer-term exposure to tennis per se. It is evident that contraction patterns varied considerably amongst players, some always exhibiting positive fatigue, whilst others switched from positive to negative fatigue over the course of the camp.

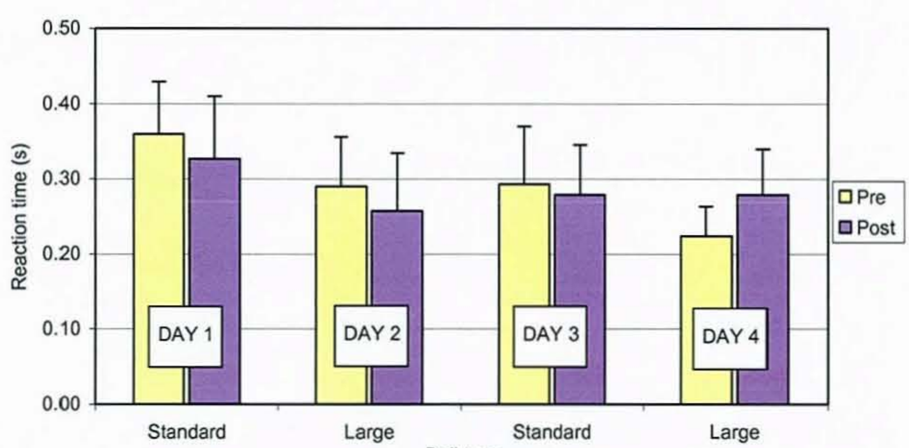


Figure 2: Reaction times observed before and after drills (Study A)

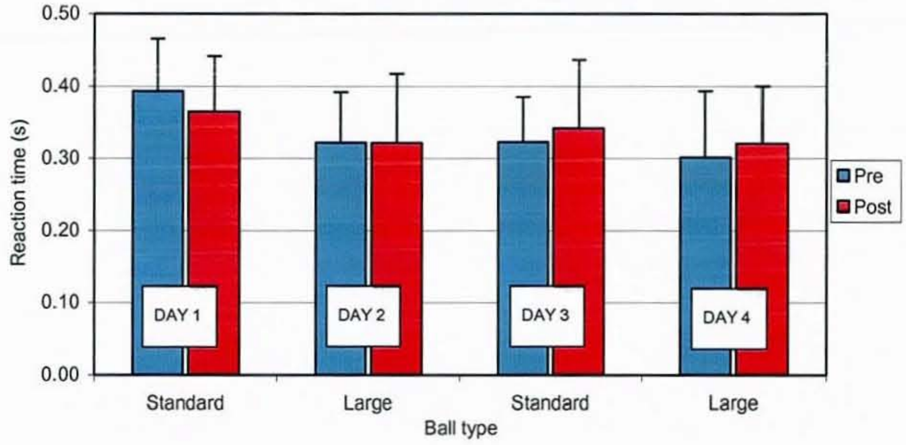


Figure 3: Reaction times before and after drills (April 2000 & Study A)

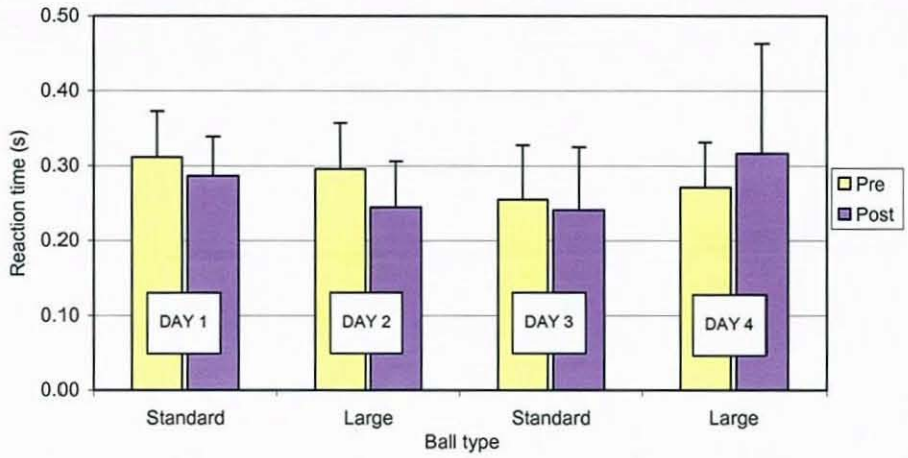


Figure 4: Reaction times observed before and after match play (Study A)

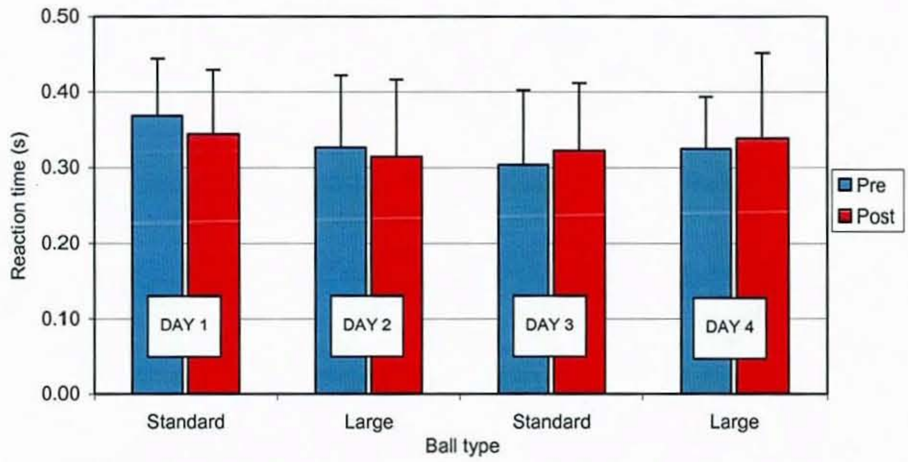


Figure 5: Reaction times observed before and after match play (April 2000 & Study A)

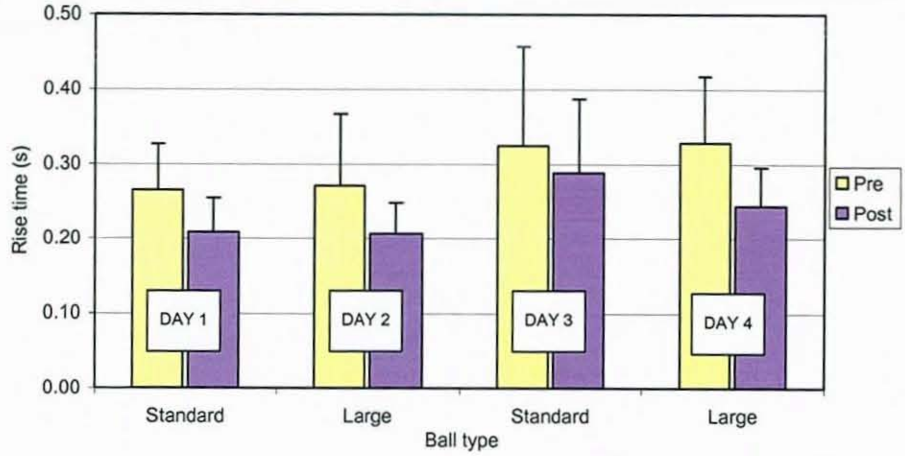


Figure 6: Rise times observed before and after drills (Study A)

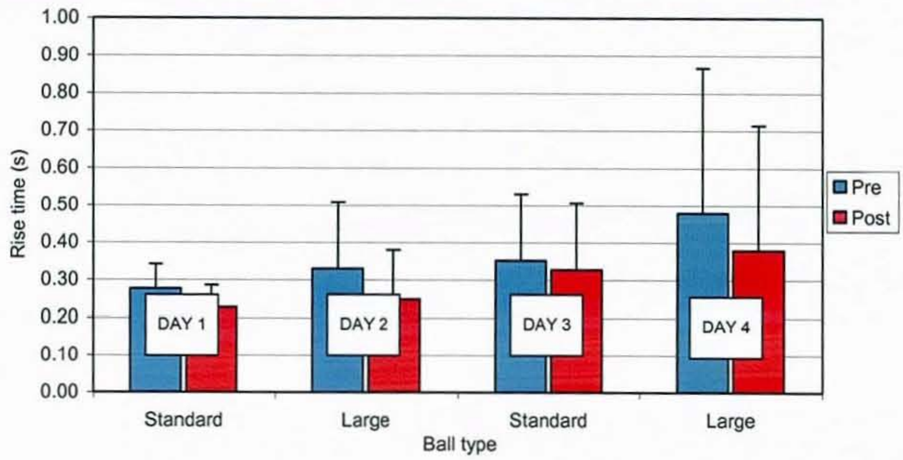


Figure 7: Rise times observed before and after drills (April 2000 & Study A)

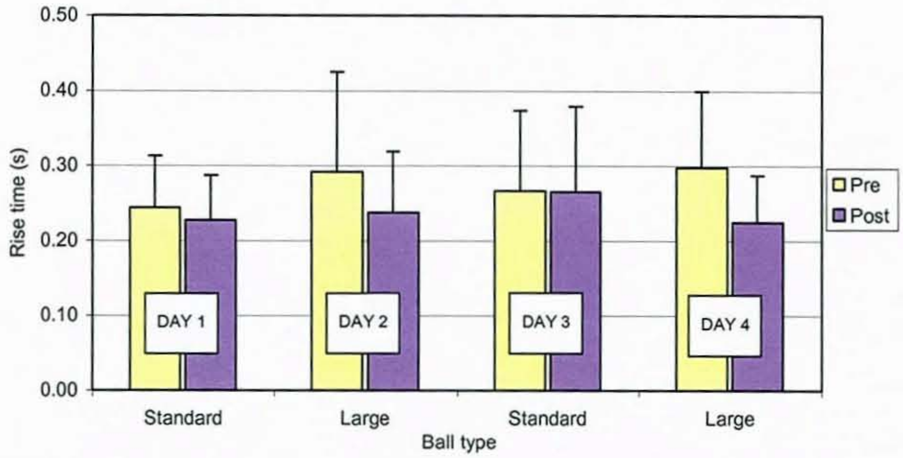


Figure 8: Rise times observed before and after match play (Study A)

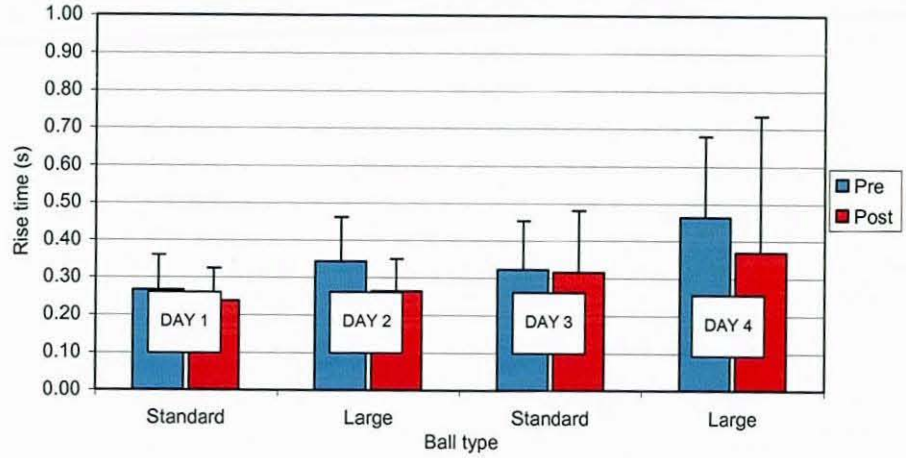


Figure 9: Rise times observed before and after match play (April 2000 & Study A)

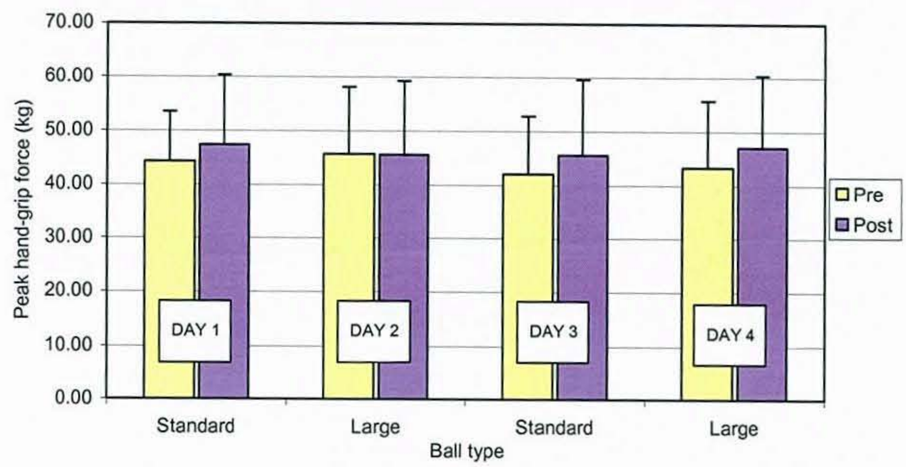


Figure 10: Peak forces observed pre and post tennis drills (Study A)

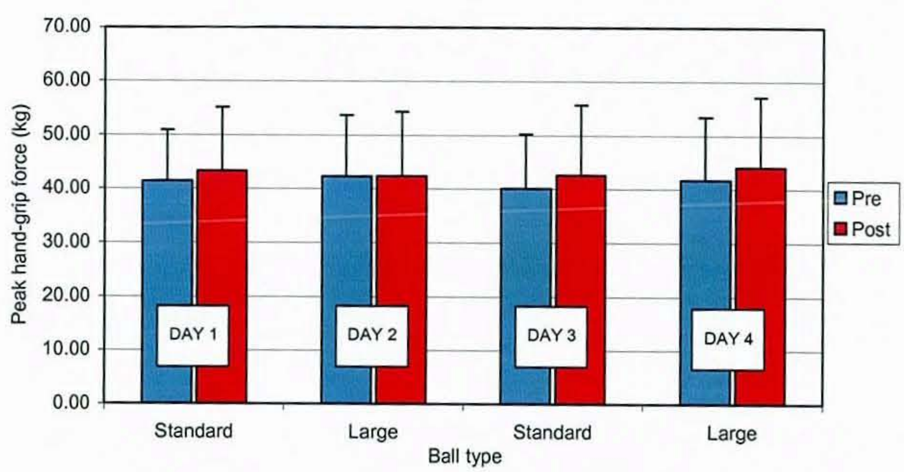


Figure 11: Peak forces observed pre and post tennis drills (April 2000 & Study A)

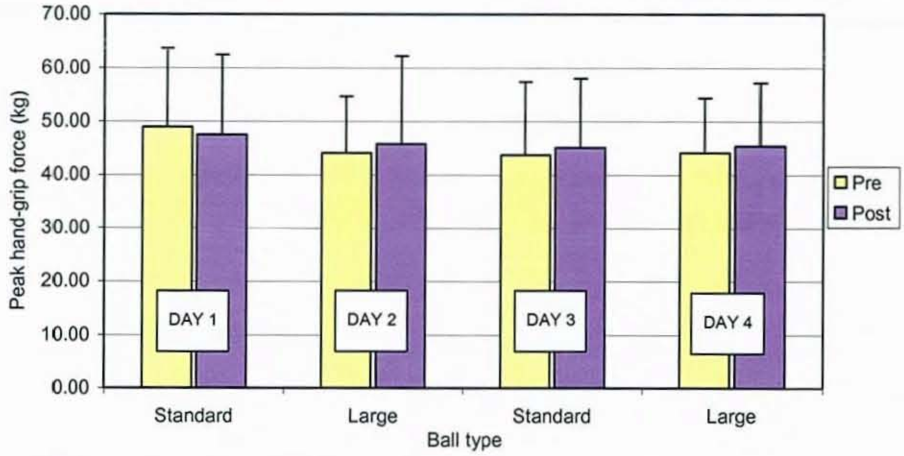


Figure 12: Peak forces observed pre and post tennis match play (Study A)

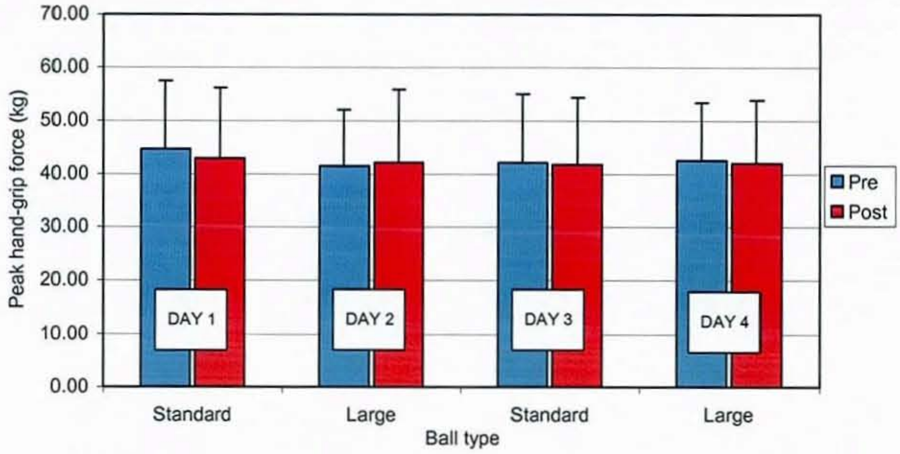


Figure 13: Peak forces pre and post tennis match play (April 2000 & Study A)

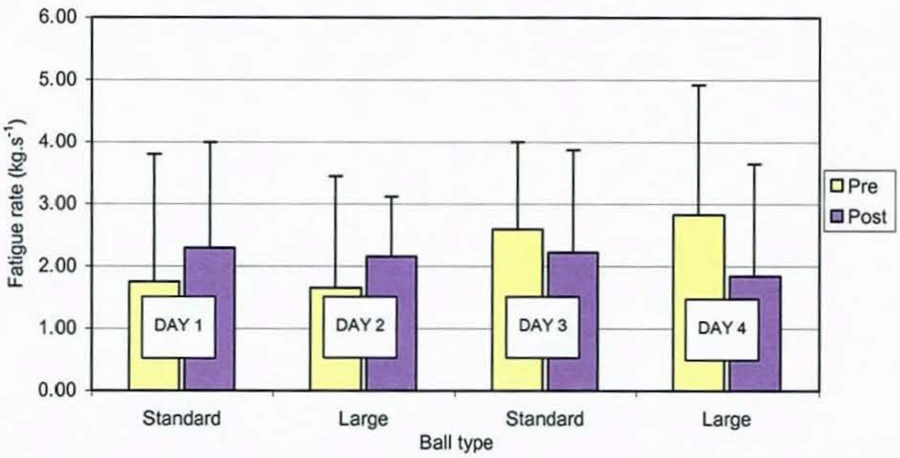


Figure 14: Fatigue rates observed pre and post tennis drills (Study A)

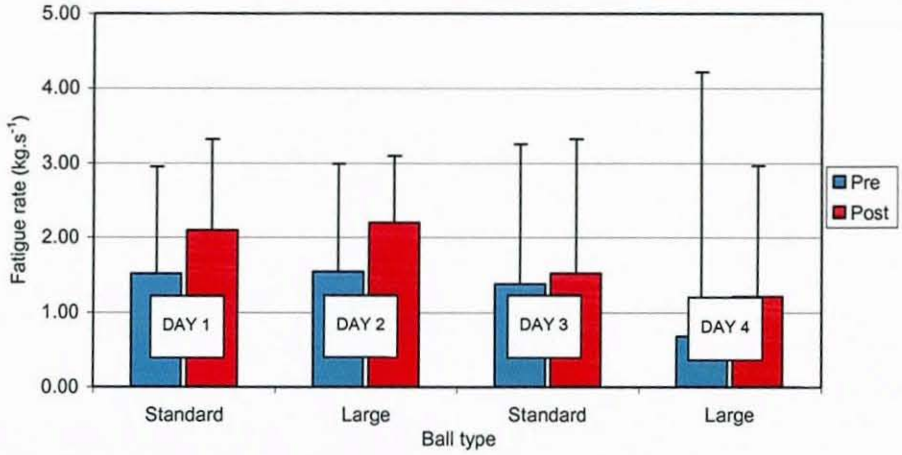


Figure 15: Fatigue rates observed pre and post tennis drills (April 2000 & Study A)

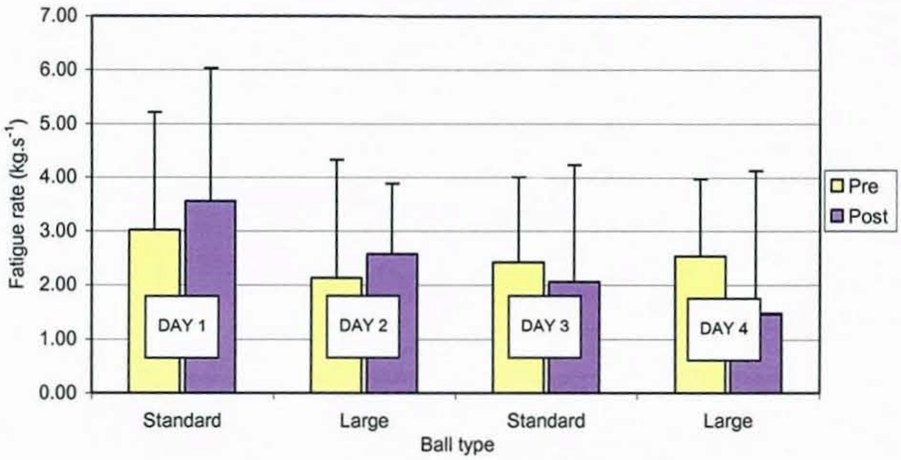


Figure 16: Fatigue rates observed pre and post tennis match play (Study A)

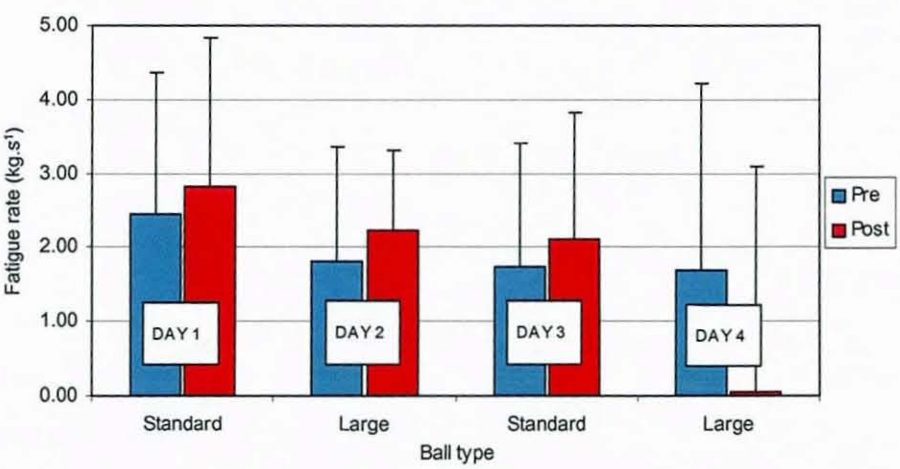


Figure 17: Fatigue rates pre and post tennis match play (April 2000 & Study A)

Figure 18 combines dominant hand-grip data obtained from the Study A training camp to illustrate the key differences between conditions.

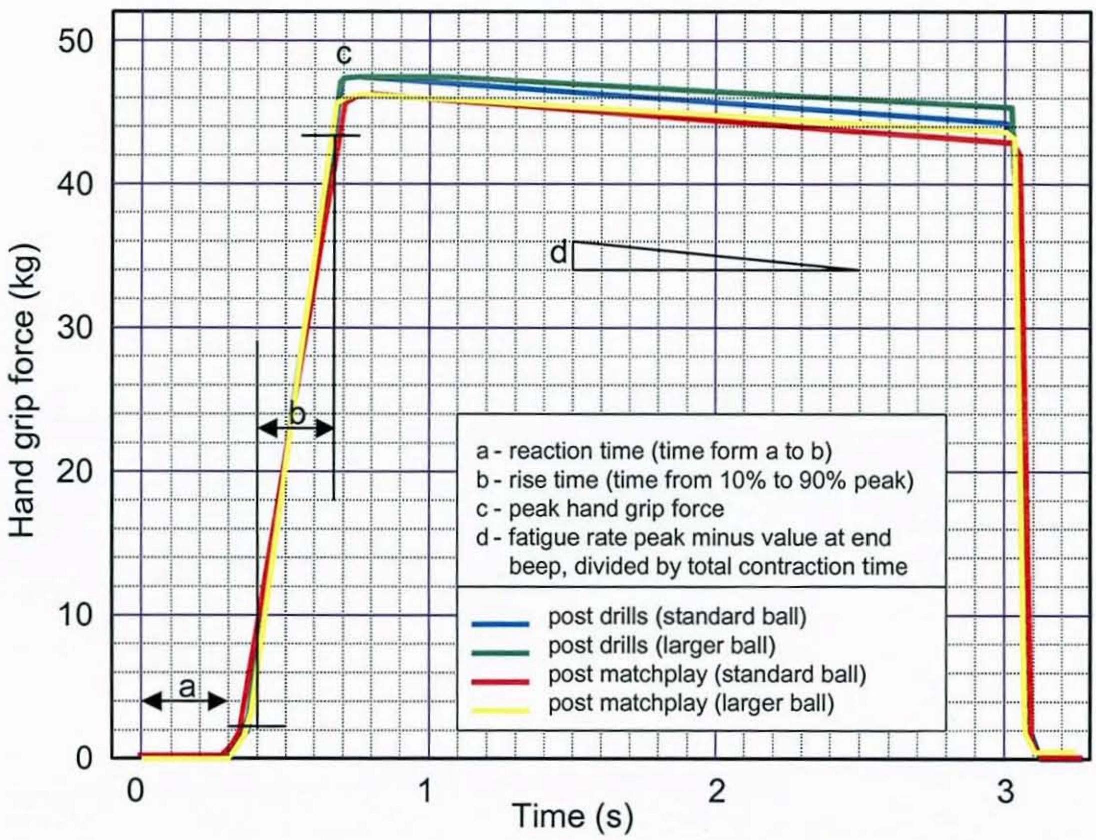


Figure 18: Aggregate hand-grip force profiles generated post drill and match play

It can be seen from Figure 18 that all traces are similar, with only minor differences being observed. Reaction times were all very similar ranging from 0.37 s to 0.40 s. Rise times were more disparate. The quickest, 0.31 s for both standard and larger balls, followed the drill sessions. The slowest, 0.43 s, was observed after larger ball match play. Peak forces were all similar 38.4 kgf to 39.9 kgf. Fatigue rates varied considerably from 0.55 $kgf{\cdot}s^{-1}$ following large ball match play to 2.13 $kgf{\cdot}s^{-1}$ following standard ball match play. This schematic serves only to illustrate the aggregate differences observed over the course of the camp and as such is unable to distinguish between the effects caused by ball size and the effects attributable to the order of match play and drill sessions. With reference to the data obtained from the April 2000 tennis camp, it was evident that the data obtain from the Study A camp were very similar.

3.5.3 Perceived muscle soreness

A series of muscle soreness contour maps follow (Figure 19 to Figure 26). These provide a visual representation of group mean ratings of muscle soreness for the dominant hand obtained from the second tennis camp. These illustrations permit comparisons to be made between drill and match play tennis and between standard and larger balls. No condition resulted in a mean muscle soreness rating in excess of 35% maximal muscle soreness. For illustrative purposes the magnitude of soreness for each muscle is depicted by colour. A series of eight soreness groupings are used, with each corresponding to a discrete colour on a blue-red continuum.

Only modest levels of muscle soreness were reported both before and after drills on day 1 using standard size balls (Figure 19). The differences observed between pre and post-conditions were not significant except for the anterior brachialis. However, it is interesting to note that some muscle soreness (typically around 5 to 10% maximal soreness) was rated prior to any tennis being played. This is likely to be a consequence of tennis played prior to the camp commencing.

Modest levels of muscle soreness were reported before drills on day 2 using larger size balls This soreness was greater than the levels observed pre-drills on day 1, suggesting the presence of some overnight soreness (Figure 20). In addition, an increase in soreness was observed post-drills; these increases were generally not significant, however, as with day 1 the increase in soreness of anterior brachialis was significant. In addition, it should be noted that the greatest magnitude of soreness was rated for upper arm and shoulder muscles.

Only modest levels of muscle soreness were reported both before and after drills on day 3 using standard size balls (Figure 21). The differences observed between pre and post-conditions were not significant. However, pre-session soreness was slightly greater than that observed for days 1 and 2 again suggesting the presence of residual soreness.

Muscle soreness ratings typically exceeded 10% maximal soreness pre-drills and were as high as 21% for the deltoid on day 4 using larger size balls (Figure 22). Greater ratings of soreness were observed post-drills although these differences only reached significance for the extensor carpi ulnaris (an increase in soreness from 8.9% to 13.4% maximal) and the coracobrachialis (an increase in soreness from 13.4% to 23.6%). It should be noted that the greatest magnitude of soreness was rated for upper arm and shoulder muscles, as was seen on day 2 under the same conditions.

The differences in muscle soreness observed before and after match play on day 1 using the standard ball were not significant (Figure 23). In common with the "drills data" the greatest ratings of muscle soreness were reported for upper arm (<20%) as opposed to forearm muscles (<10%).

Pre-match play muscle soreness on day 2 using the larger ball was considerable, typically being in the range of 15 to 25 % maximal soreness. With the exception of the brachioradialis, the small increase in muscle soreness observed after match play was not significant (Figure 24).

The differences in muscle soreness observed before and after match play on day 3 using the standard ball was not significant (Figure 25). Furthermore, the pattern of muscle soreness was similar to that observed on day 1 under the same conditions.

The differences in muscle soreness observed before and after match play on day 4 using the larger ball were, with the exception of the brachioradialis, not significant (Figure 26). However, an increase in muscle soreness was discernible particularly in the upper arm and shoulder muscles.

A series of muscle soreness charts are shown in Figure 27 to Figure 30 inclusive. These provide a visual representation of group mean ratings of muscle soreness for the dominant hand obtained by combining data obtained from both tennis camps. These data also merge measures obtained on days 1 and 3 and days 2 and 4, thus the standard ball data and larger ball data have been independently pooled. This manipulation permits comparisons to be made between drill and match play tennis and between standard and larger balls without the distraction of temporal changes.

With reference to Figure 27, it can be seen that muscle soreness prior to testing was present albeit at a modest level (<10% max muscle soreness). Post drills with the standard ball muscle soreness increased in all muscles (some significantly). However, the magnitude of increases was small; typically than 5% max muscle soreness.

Figure 28 shows that muscle soreness remained unchanged following drills with the larger ball. Whilst muscle soreness was present it was not exacerbated by the preceding period of tennis play.

Figure 29 and Figure 30 demonstrate that muscle soreness was greatest in the shoulder and upper arm following match play. Once corrections for pre-session soreness levels were made, soreness levels were comparable between both standard and larger balls. It would appear that muscle soreness was slightly greater following match play than following drills. However, in both cases the patterns of soreness were broadly similar. Furthermore, whilst there was considerable inter subject variability, the overall levels of soreness observed were low.

The April 2000 study results are were confirmed by Study A (April 2001) for grip force and muscle soreness.

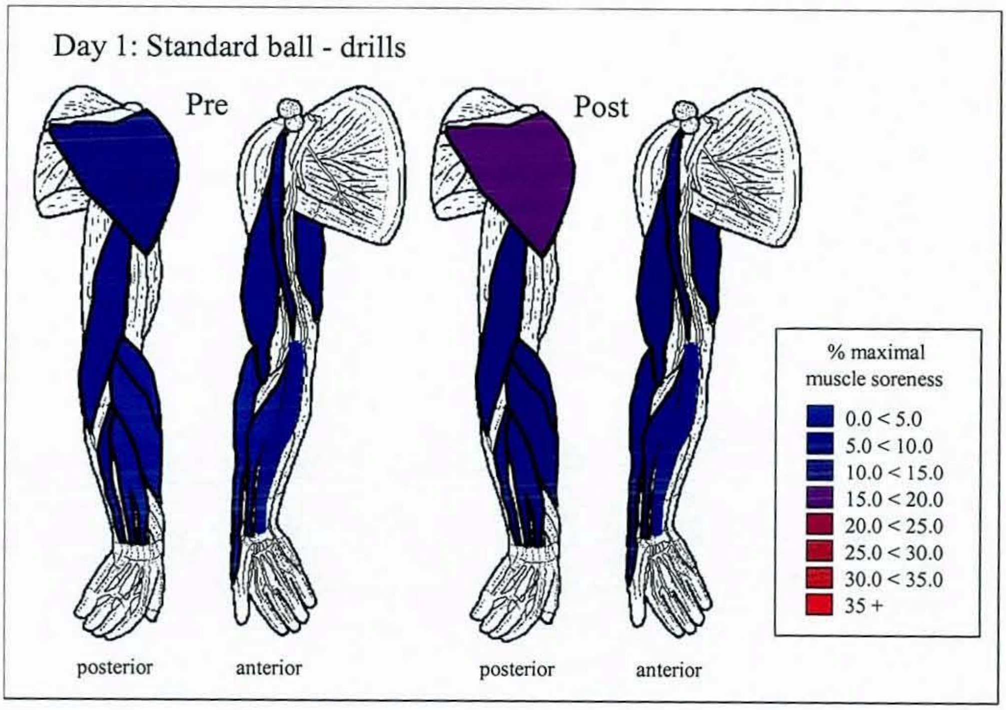


Figure 19: Muscle soreness ratings before and after drills (Day 1: standard ball)

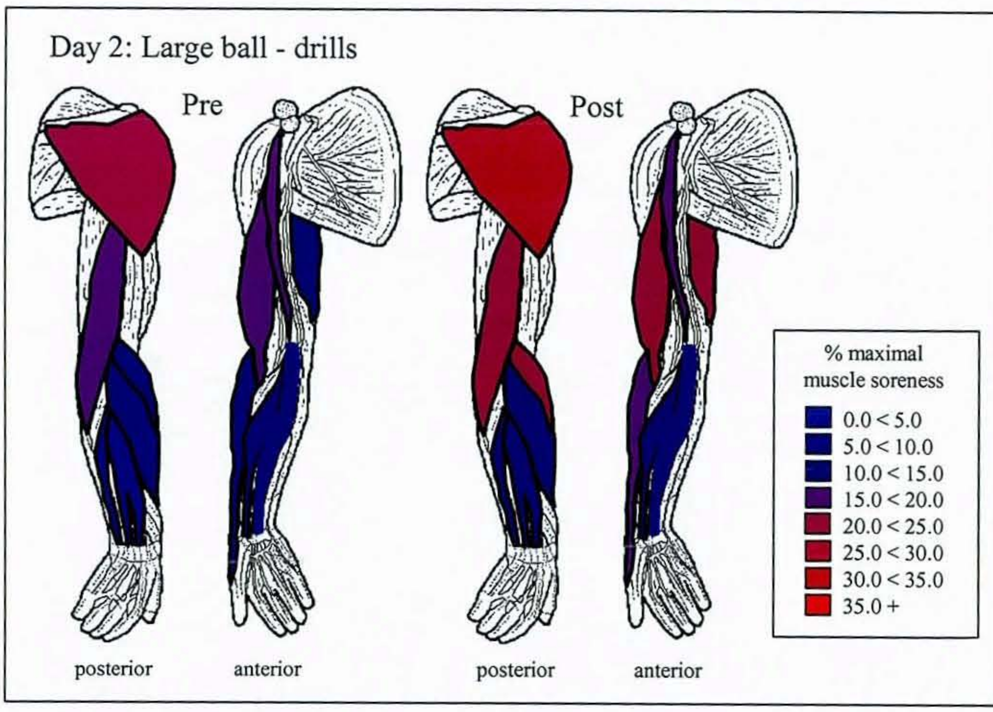


Figure 20: Muscle soreness ratings before and after drills (Day 2: bigger ball)

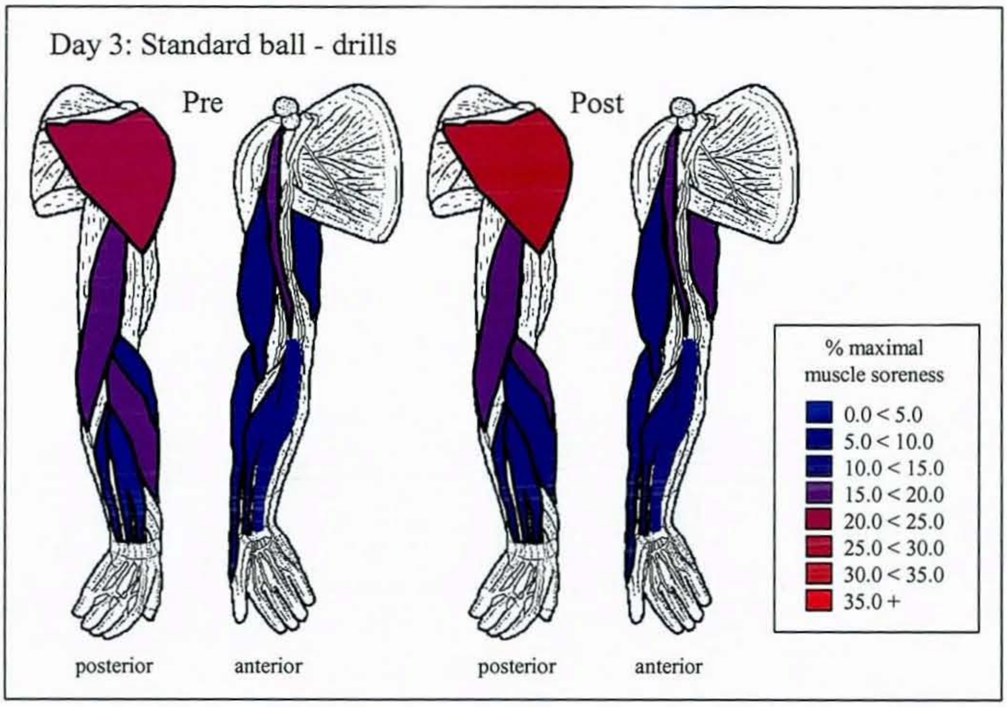


Figure 21: Muscle soreness ratings before and after drills (Day 3: standard ball)

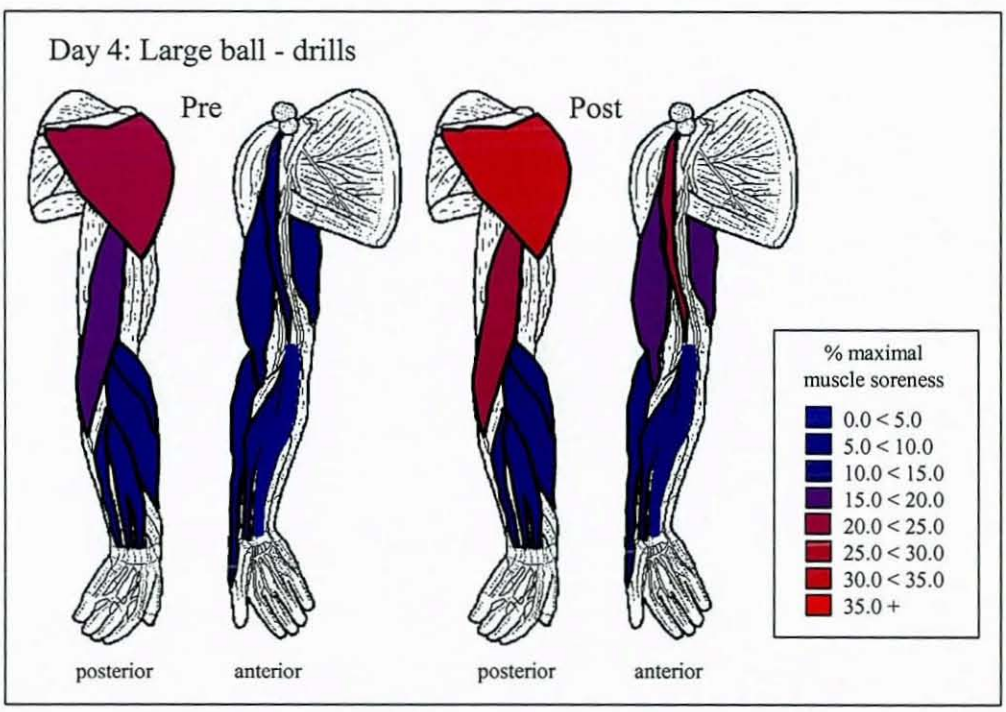


Figure 22: Muscle soreness ratings before and after drills (Day 4: bigger ball)

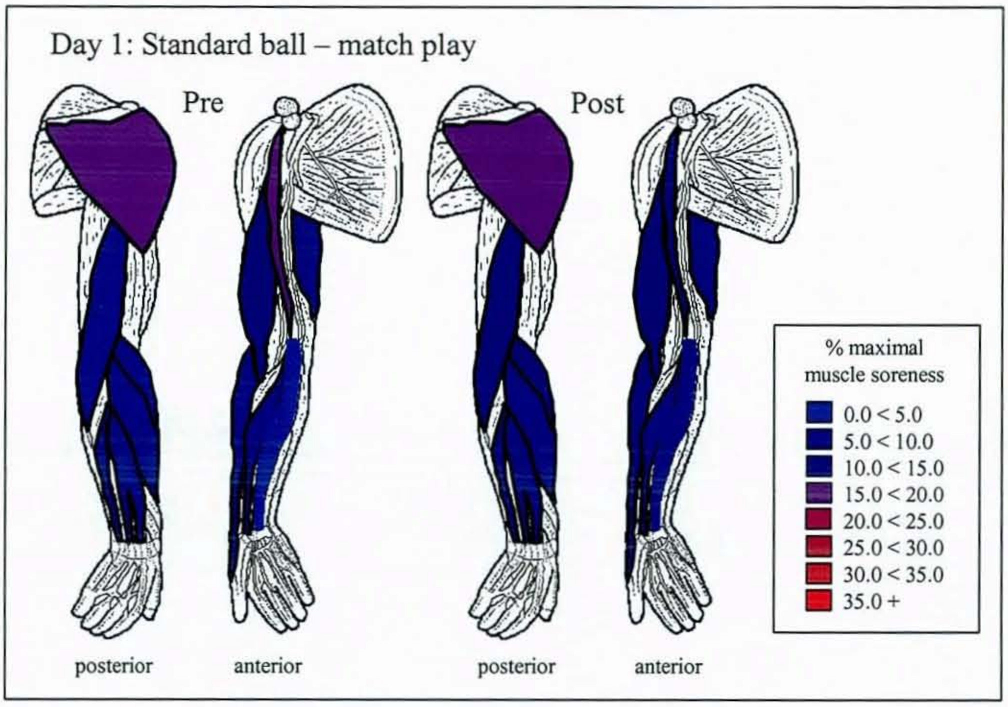


Figure 23: Muscle soreness ratings before and after match play (day 1: standard ball)

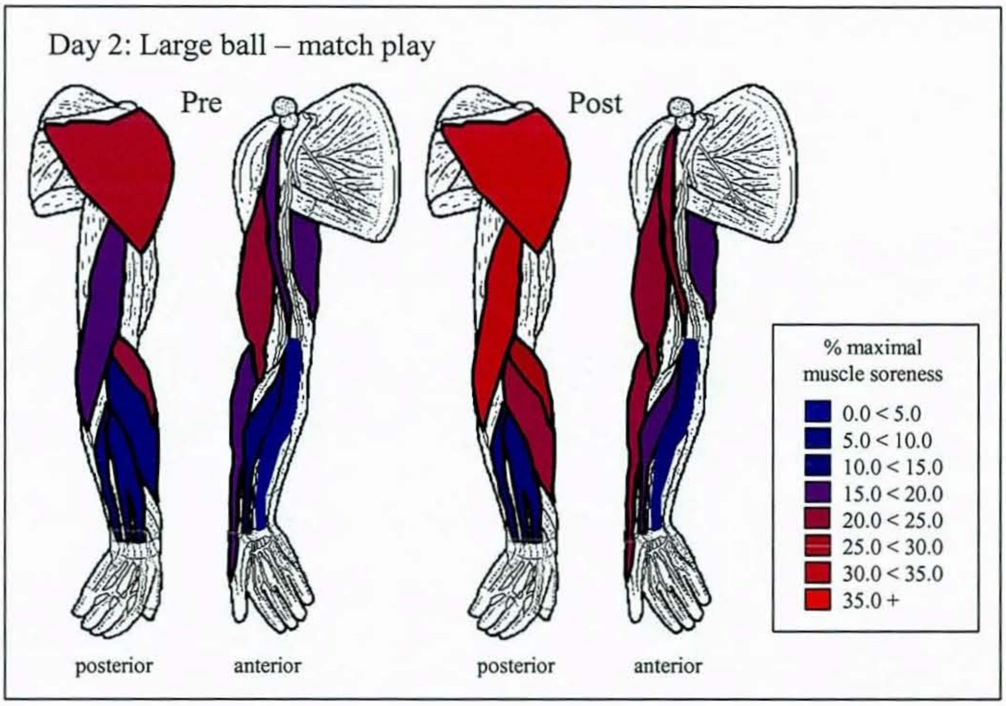


Figure 24: Muscle soreness ratings before and after match play (day 2: bigger ball)

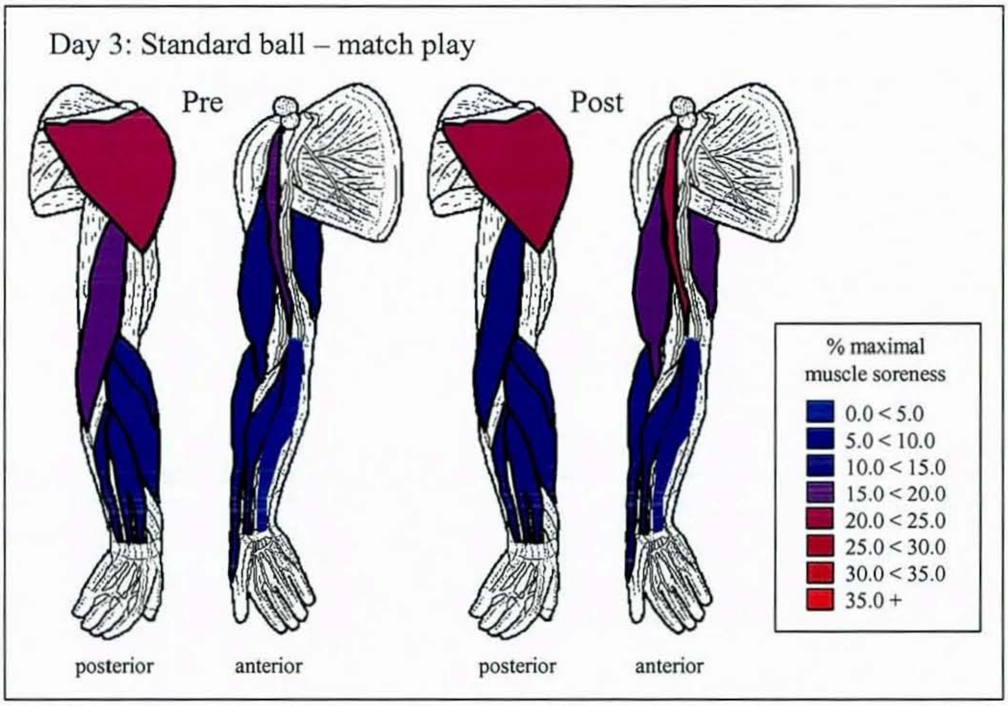


Figure 25: Muscle soreness ratings before and after match play (day 3: standard ball)

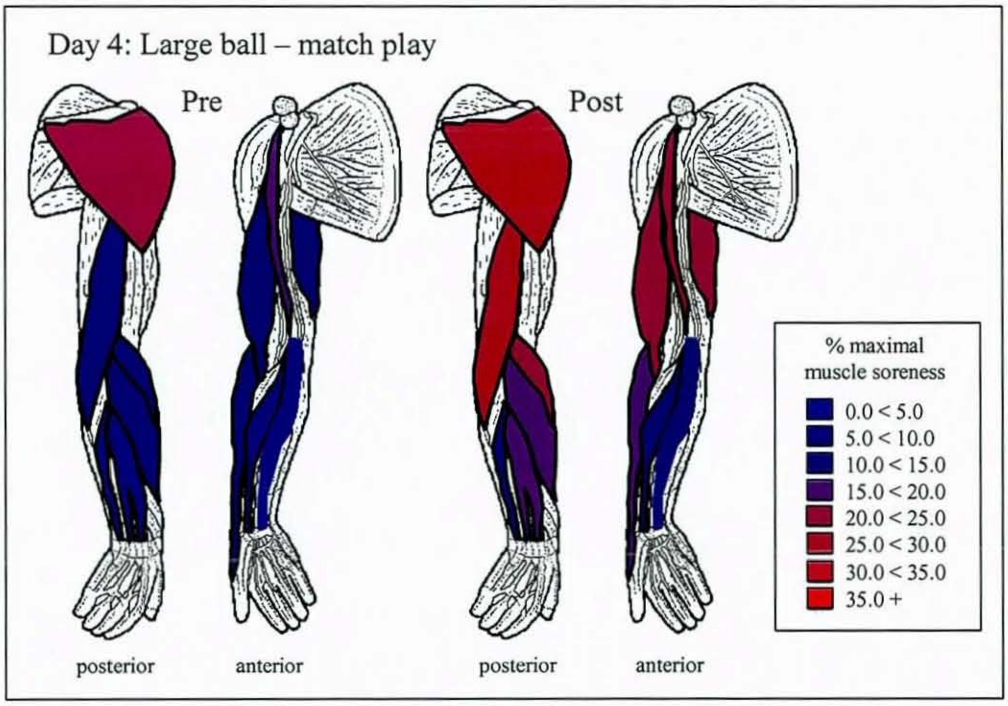


Figure 26: Muscle soreness ratings before and after match play (day 4: bigger ball)

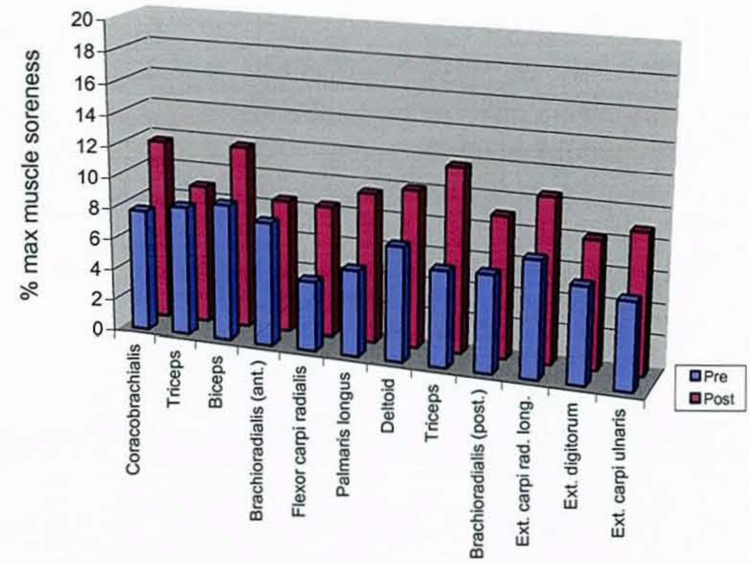


Figure 27: Pre and post drills muscle soreness data obtained using the standard ball

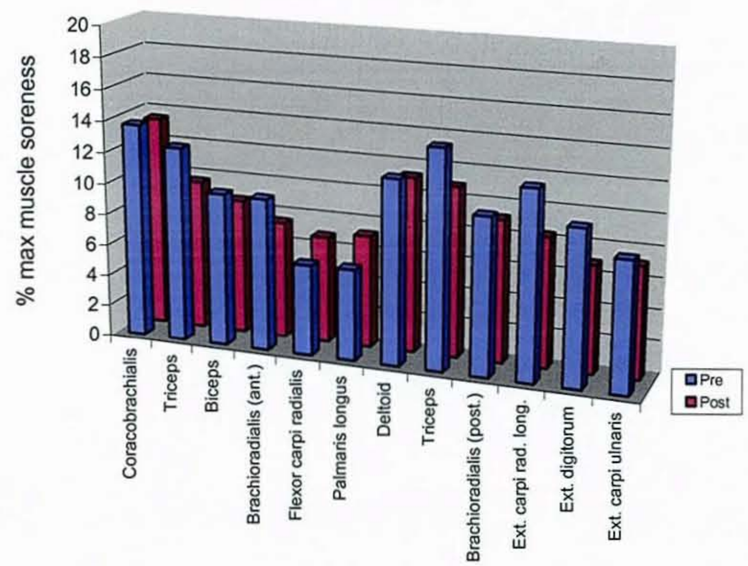


Figure 28: Pre and post drills muscle soreness data obtained using the larger ball

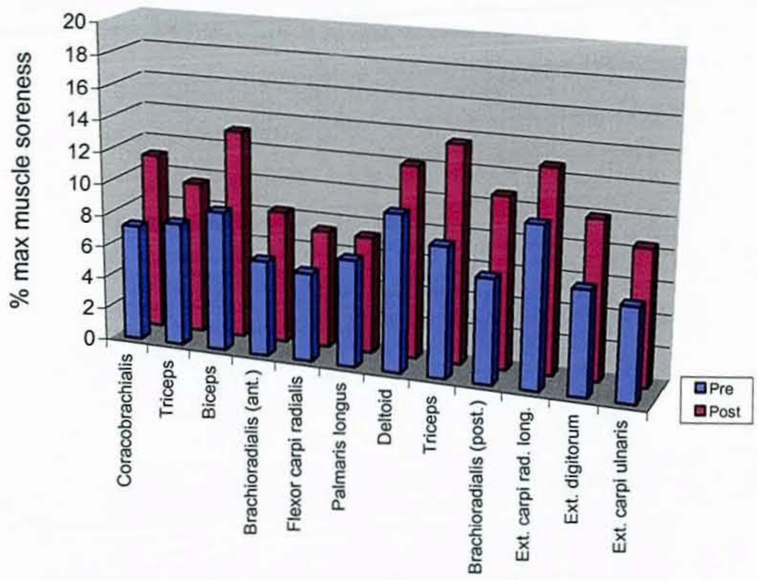


Figure 29: Pre and post match play muscle soreness data obtained using the standard ball

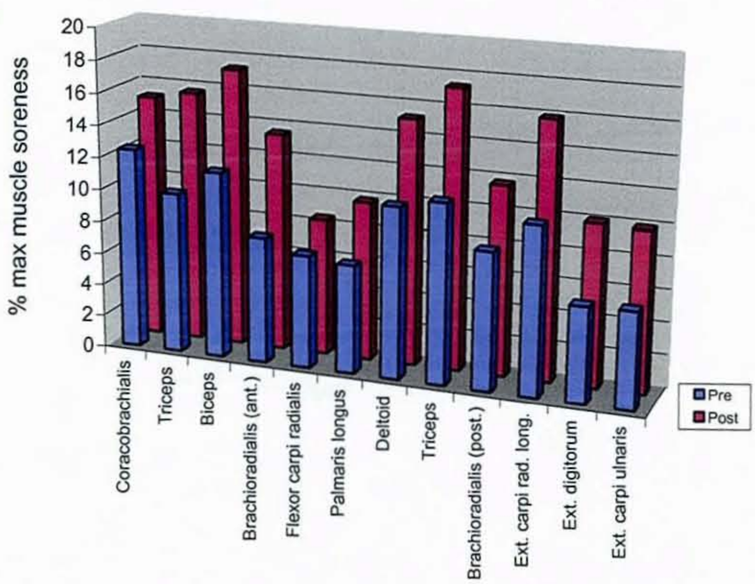


Figure 30: Pre and post match play muscle soreness data obtained using the larger ball

3.5.4 Point play outcome

The total number of matches, games, points and shots played in each study, and for both studies combined are given in Table 3.

Table 3: Matches, games, points and shot totals

	April 2000	April 2001	Apr 2000 + April 2001
No. matches	40	40	80
No. games	345	341	386
No. points	2329	2193	4522
No. shots	11062	9105	20167

The ability to record all the point play outcome data on the recording sheet whilst the match was in progress varied between observers, although all successfully recorded the point outcome in terms of winning player and service outcome. The missing data were collected after the match play sessions by observing video recordings of each match.

None of the players exhibited particularly dominant serves in either study with the normal ball. Perhaps as a consequence of this only one tiebreak occurred in the 40 matches played. This makes it impossible from this study to conclude anything about the performance of the larger ball from a reduction in tiebreak incidence. Instead, the results are discussed with reference to three possible propositions for the effect of the larger ball (two undesirable, one desirable), as follows:

a) The relative ability of all players becomes less distinct

- The dominance of any one player's serve is reduced but so too is their ability to hit winning shots. The stronger players are affected to a relatively greater extent than the weaker ones so that they become more evenly matched.
- The nett effect is a greater number of games, points and shots required to decide a match. A greater tiebreak incidence would also be expected. The match outcome is more dependent on chance

b) The relative ability of all players becomes more distinct

- The serve and rally shot performance of the weaker players is reduced relative to that of stronger players so that the later become more dominant.
- The nett effect is that fewer games, points and shots are required to decide a match. Fewer tiebreaks are apparent, but match outcomes become more predictable.

c) The quality of tennis improves

- The effort required to produce a winning shot increases but the effect is no greater for any one type or class of player.
- The service outcome becomes less dominant. The number of games and points required to decide a match remains substantially unchanged as does the likely outcome, but the number of shots required to decide a point increases.

Match Overview

The match summary data for all four days are given in Table 4 and Table 5. The data are shown graphically in Figure 31 to Figure 39. The results for men, women and men and women combined are coloured blue, red and yellow respectively in each of the graphs. Although there were no unexpected match outcomes, based on the players' LTA ratings, using either the standard or larger balls during the April 2000 study the highest seeded male player in the April 2001 study did perform below the level expected.

Table 6 lists the statistically significant differences between ball types indicated by each study and the data from both studies combined.

Table 4: April 2000 match summary data

	day 1			day 2			day 3			day 4		
	M	F	M+F	M	F	M+F	M	F	M+F	M	F	M+F
Total No Games	46	53	99	50	53	103	31	38	69	38	36	74
Mean Games per Match	7.7	8 8	8 3	8 3	8 8	8 6	7 8	9 5	8 6	9 5	9 0	9 3
Total No. Points	357	354	711	364	327	691	196	231	427	264	236	500
Mean Points per Match	59 5	59 0	59 3	60 7	54 5	57 6	49 0	57 8	53 4	66 0	59 0	62 5
Mean Points per Game	9 2	6 7	8 0	7 6	6 3	6 9	6 3	6 0	6.1	7 0	6.6	6 8
Total No Shots	1566	1514	3080	1744	1428	3172	920	1097	2017	1588	1205	2793
Mean Shots per Match	261 0	252 3	256 7	290 7	238 0	264 3	230 0	274 3	252 1	397 0	301 3	349 1
Mean Shots per Game	39 7	28 7	34 2	36 2	27 6	31 9	29 3	27 4	28 4	42 3	34.1	38 2
Mean Shots per Point	4 4	4 3	4 3	4 8	4.4	4 6	4 6	4 5	4 6	6 1	5 2	5.6

Table 5: April 2001 match summary data

	day 1			day 2			day 3			day 4		
	M	F	M+F	M	F	M+F	M	F	M+F	M	F	M+F
Total No. Games	57	48	105	60	45	105	36	30	66	29	36	65
Mean Games per Match	9 5	8 0	8 8	10 0	7 5	8 8	9 0	7 5	8 3	7 3	9 0	8 1
Total No. Points	375	292	667	374	290	664	222	200	422	196	244	440
Mean Points per Match	62 5	48 7	55 6	62 33	48 33	55 33	55 5	50 0	52 8	49 0	61.0	55 0
Mean Points per Game	6 6	6.1	6 4	6 4	6 5	6 4	6 0	6 7	6 4	6 8	6 8	6 8
Total No Shots	1384	1181	2565	1419	1301	2720	1015	816	1831	875	1114	1989
Mean Shots per Match	230.7	196 8	213 8	236 5	216 8	226 7	253 8	204 0	228 9	218 8	278 5	248 6
Mean Shots per Game	24 5	25 0	24 7	25 0	29 1	27 0	27.2	27 2	27 2	29 8	30 7	30.3
Mean Shots per Point	3.7	4 1	3 9	3 8	4 5	4 2	4 6	4 1	4 3	4 4	4.5	4 5

Table 6: Statistically significant differences from game, point and shot comparisons of the larger to the standard ball[1]

		Men			Women			Men & Women		
		2000	2001	Both	2000	2001	Both	2000	2001	Both
Day 2 vs. 1	games per match									
	points per match									
	points per game									
	shots per match					+10%				
	shots per game									
	shots per point									
Day 3 vs. 1	games per match									
	points per match	-18%								
	points per game									
	shots per match									
	shots per game									
	shots per point									
Day 4 vs. 2	games per match		-28%			+20%				
	points per match		-21%			+26%	+17%			
	points per game									
	shots per match	+37%			+27%	+28%	+27%	+32%		+22%
	shots per game						+14%			+16%
	shots per point	+27%		+22	+18%			+23%		+15%
Day 4 vs. 3	games per match					+20%				
	points per match	+35%								
	points per game			+12%				+11%		+9%
	shots per match	+73%						+38%		+24%
	shots per game	+45%		+28%				+35%		+23%
	shots per point	+32%						+23%		+13%
Day 2+4 vs. 1+3	games per match									
	points per match									
	points per game									
	shots per match	+34%				+21%		+17%		+12%
	shots per game					+15%	+11%			
	shots per point	+18%				+11%	+9%	+13%		+9%

Number of Games

Figure 31 shows the total number of games were played on each day. It shows that more games were played by both men (blue) and women (red) on days 1 & 2 than on days 3 & 4. This was because each group played a total of six 30-minute sessions on days 1 & 2 and only four sets on days 3 & 4.

The mean numbers of games per match for all sessions/matches were actually very similar in April 2000. The same was generally true in April 2001, except when comparing the number of

[1] A highlighted percentage denotes a significant difference as opposed to a trend towards significance.

games per match played with the bigger balls on days 2 and 4. The men played significantly fewer games and the women significantly more on day 4.

Figure 32 shows the average number of games per match for each day for the men (blue), women (red) and men and women combined (yellow).

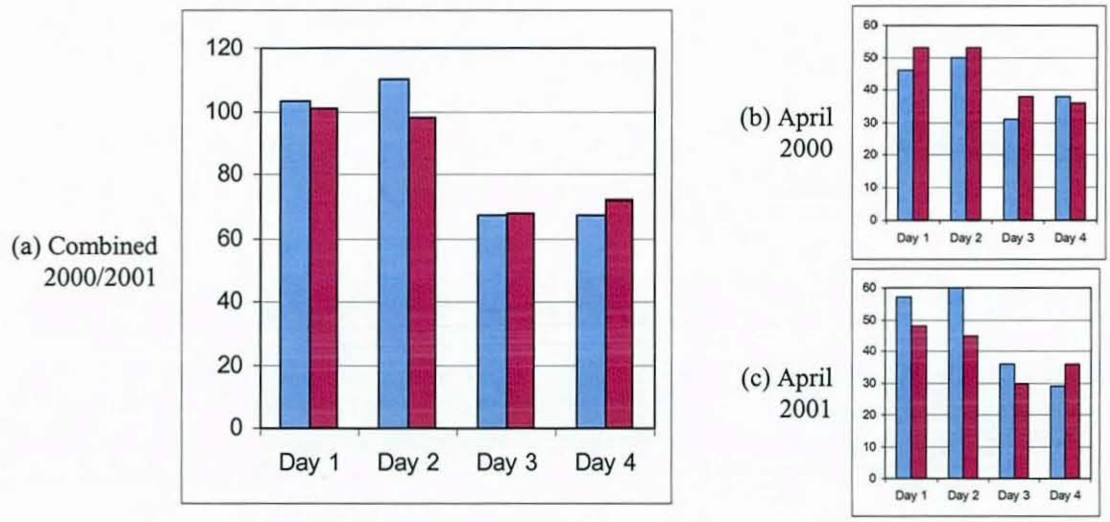


Figure 31: Total number of games

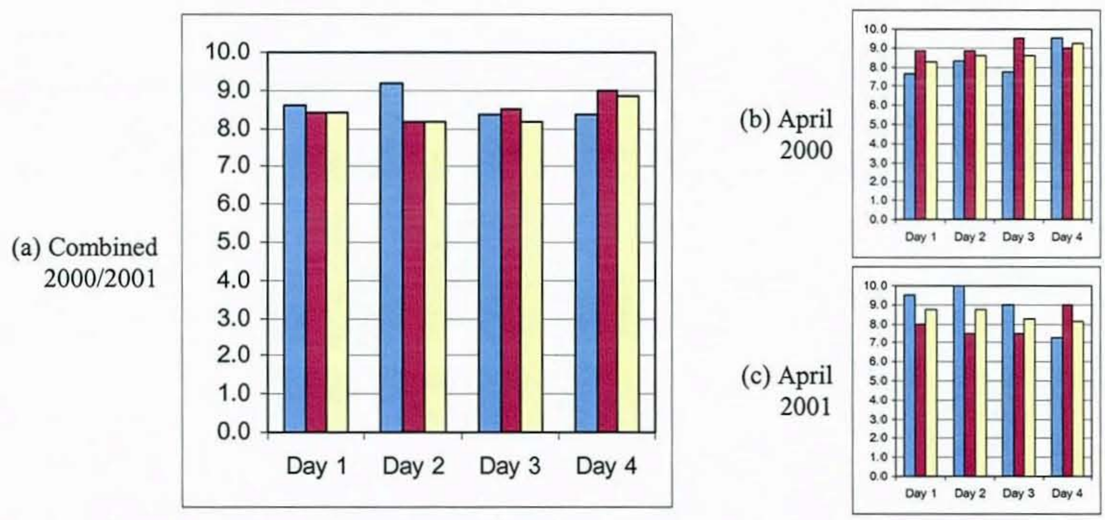


Figure 32: Mean number of games per match

The difference detected between the points per match comparing days 2 and 4 suggests a change in motivation or strategy for both the men and women. Since both groups were playing with the larger balls on both days and the difference recorded is opposite for the two groups the results seem unlikely to be attributable to different ball properties. The statistically significant decrease for the men suggests either their relative abilities had become more distinct, perhaps through fatigue or adaptation to the bigger ball, or that the weaker player was less motivated or the stronger player more so. The statistically significant increase in the number of points per match for the women suggests either their relative abilities had become less distinct, again perhaps through fatigue or adaptation to the bigger ball, or that the weaker players were more motivated or the stronger players less so.

No significant difference was detected between the numbers of games per match for the combined male/female populations in both studies. Considered as a whole, the combined results from both studies indicate no significant difference for the men, women or men and women combined when using the larger ball. A similar number of games per match superficially suggests a similar level of effort in each match, but more importantly that the relative ability of the players has not changed substantially with the bigger ball.

The lack of a significant difference from the day 1 versus day 2 comparison indicates little immediate change from using the bigger ball. This was the players' first exposure to the larger ball under match play conditions and so may be due to lack of familiarity, although it should be remembered that the players had completed an intense 2 hour training session with the larger ball in the morning of day 2. Increased familiarity might also explain the bigger change for the day 2 vs. day 4 comparison. However, the change in format for days 1 & 2 versus days 3 & 4 and the lack of statistical significance means that the only conclusion that can be drawn is that the study did not find a significant difference between the larger ball and standard ball.

Number of Points

Figure 33 shows more points were played in total on days 1 & 2 than on days 3 & 4 by both the men and women, essentially for the same reason that more games were played on the first two days due to the match format. Figure 34 shows the mean number of points per match played on each day.

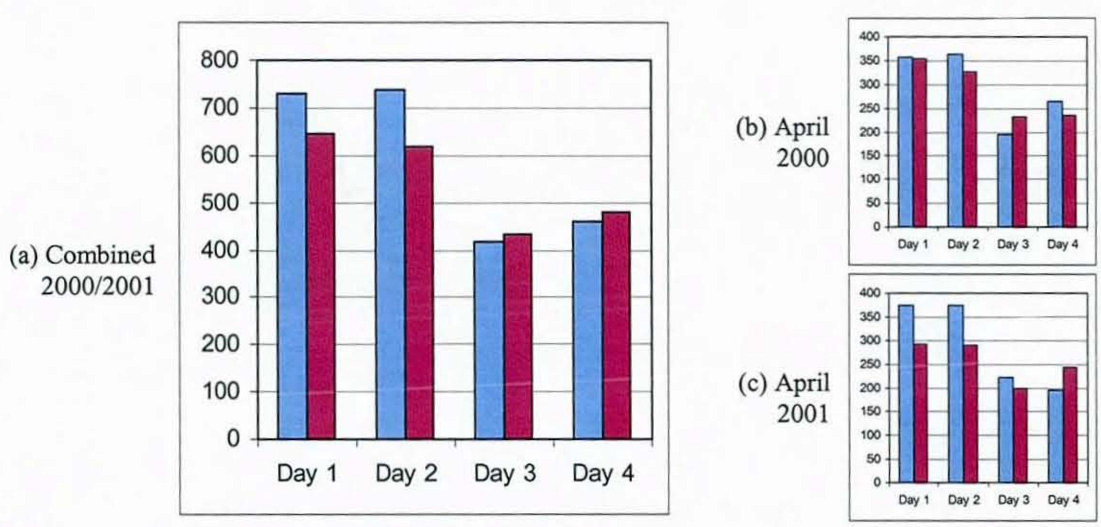
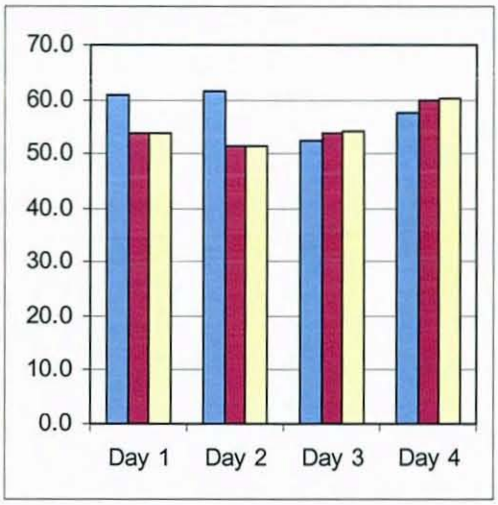
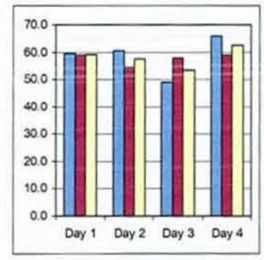


Figure 33: Total number of points

(a) Combined 2000/2001



(b) April 2000



(c) April 2001

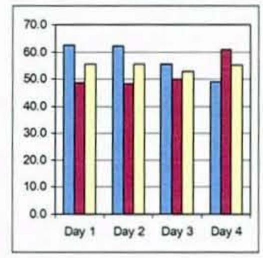
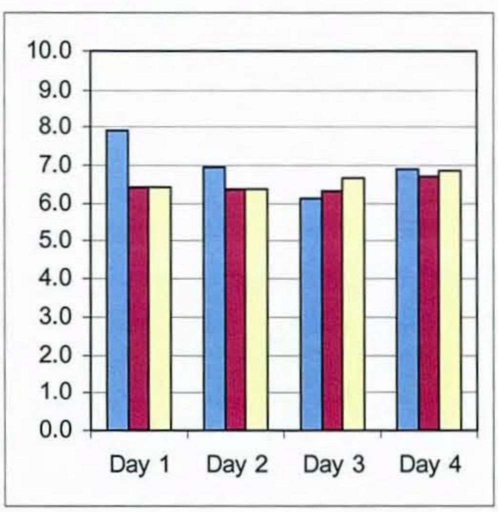


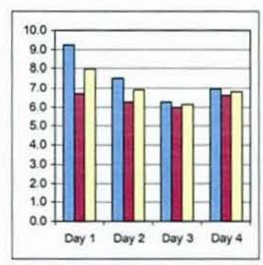
Figure 34: Mean number of points per match

There was no statistically significant difference in the number of points per match for either the men or women, except when comparing the two days spent playing with the larger ball. The men played significantly fewer and the women significantly more points per match on day 4 compared with day 2. Given that there was no significant difference between the points per game played on either day (Figure 35) the number of points per match fluctuations correspond to the games per match fluctuations discussed above.

(a) Combined 2000/2001



(b) April 2000



(c) April 2001

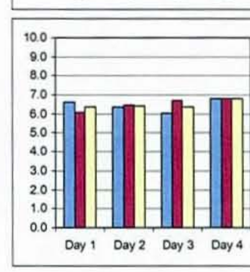


Figure 35: Mean number of points per game

Considered as a whole, the results indicate no significant difference for the men, women or men and women combined when using the larger rather than the standard ball, even though the combined data for the women indicates a significant increase in the number of points per match the second time the larger ball was used.

The day 1 versus 2 comparisons indicate little immediate change from using the bigger ball. Again, a lack of familiarity with the balls on day 2 and increased familiarity on day 4 may explain this finding.

Figure 35 shows the mean number of points per game. No significant differences were identified between the different ball types for either the men or women, although there was a suggested trend towards a ~10% increase amongst the men and the combined male/female group on day 4 versus day 3. This suggests that play with the larger ball may be only slightly more evenly matched, if at all, when compared to the standard ball. This tends to support the proposition that play is improved rather than differences in ability emphasised or suppressed.

Number of Shots

Figure 36 and Figure 37 show the total number of shots and the mean number of shots per match executed during each of the four match play sessions. Figure 38 and Figure 39 similarly show the mean number of shots per game and the mean number of shots per point respectively.

More shots were played by both the men and women on both days 1 and 2 than on days 3 and 4 primarily for the same reason that more games and points were played (i.e. fewer matches were played on days 3 and 4). No statistically significant difference was detected between the ball types for the men in terms of the number of shots played. However, results for the women showed a significant increase in shots per match, when playing with the larger ball as opposed to the standard ball.

There was no statistically significant difference between the number of shots per match, game or point played on days 1, 2 or 3 by men, women or the combined population for either study. The significant differences that were apparent derive from comparing days 2 or 3 with day 4.

The number of shots per point executed by the women was consistent across all 4 days indicating no significant difference between the ball types. The increase in shots per match played on day 4 versus day 2 was instead attributable to the increased number of games and so points per match as discussed above.

Finally, the effect of playing with the bigger ball can be compared with that of the standard ball by comparing match play on both days exposed to the larger ball to both days playing with the standard ball for both men and women. This approach had the benefit of maximising the sample population and revealed no statistically significant difference in the number of games per match, or points per game. However, it did indicate a statistically significant 9% increase in the number of shots per point when playing with the larger ball.

This last finding, i.e. the increase in the number of shots per point when playing with the larger ball, supports the proposal that the quality of tennis is improved by playing with the larger ball.

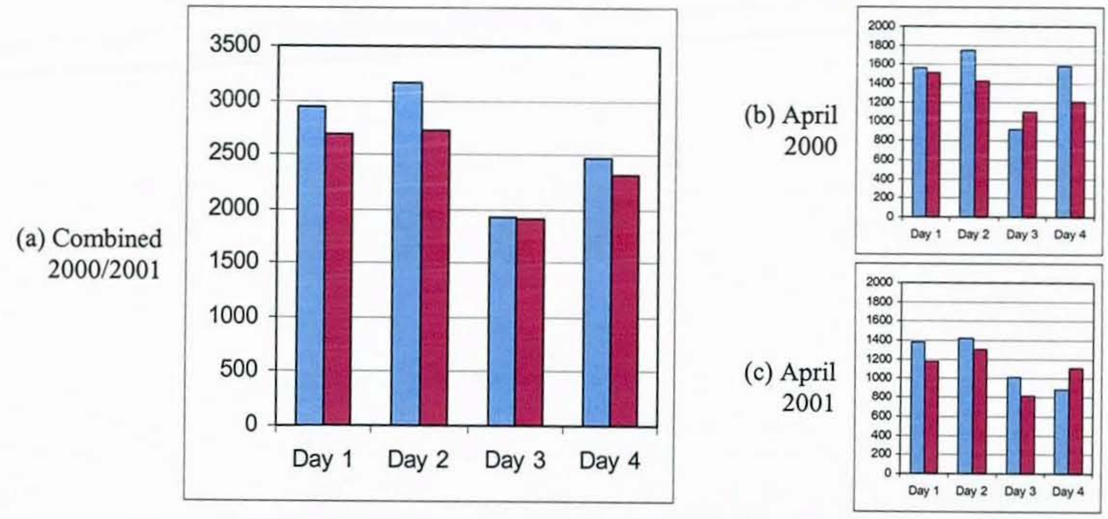


Figure 36: Total number of shots

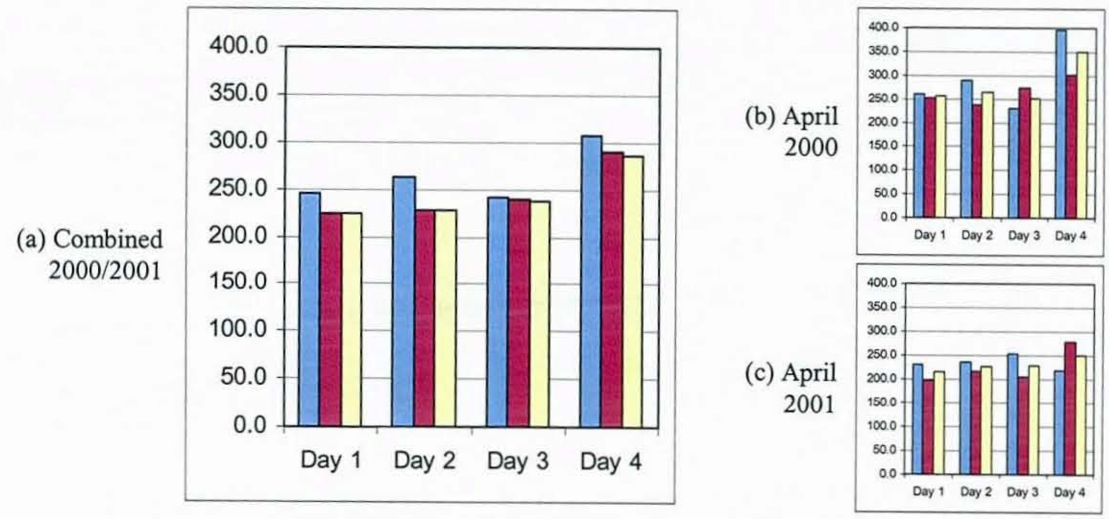


Figure 37: Mean number of shots per match

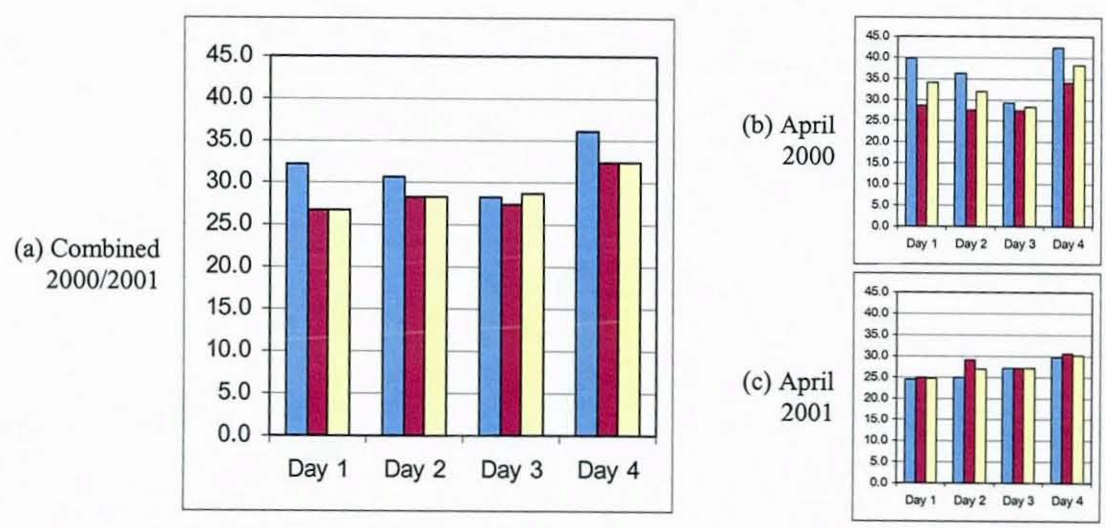


Figure 38: Mean number of shots per game

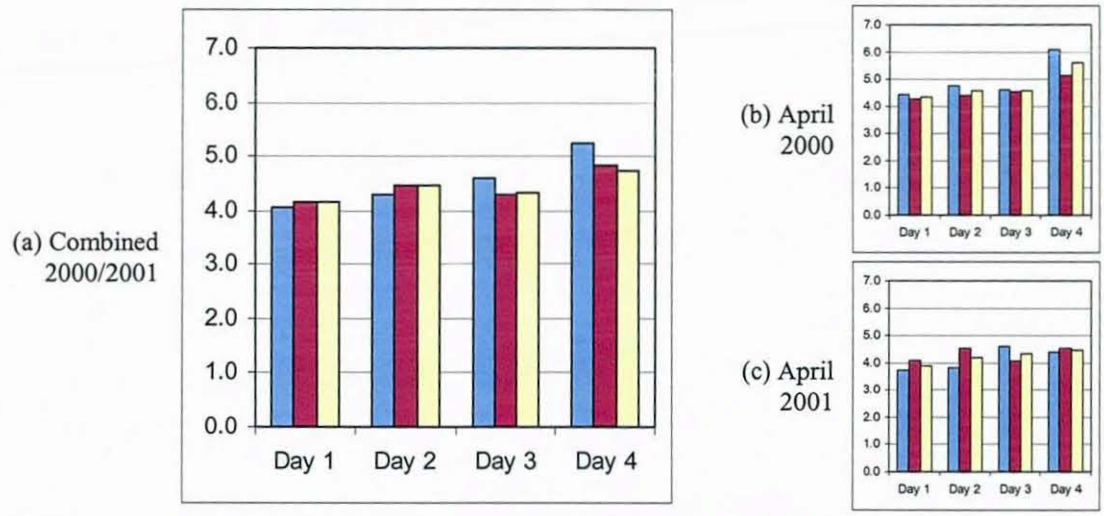


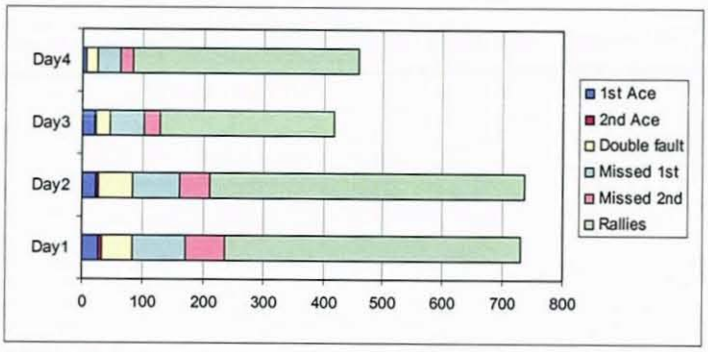
Figure 39: Mean number of shots per point

<u>Service Overview</u>

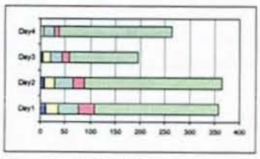
Figure 40 to Figure 43 show the service outcome results averaged for all matches during each of the four match play sessions for both men and women. Figure 40 and Figure 41 show the results for men and women in terms of total number of points and clearly show the difference in the number of points played on each day. Figure 42 and Figure 43 show the results as a percentage per point. The findings for both men and women indicate a reduction in the dominance of service play (1st and 2nd serves, double faults, 1st and 2nd service return errors) and an increase in the importance of rally play when using the larger ball, although the difference for men was more pronounced than for women.

Comparing play with the standard balls on different days (1 and 3) there was no significant difference in the service outcomes per point for either the men, women or the two groups combined. The results were similar when comparing days 2 and 4 for the bigger balls except the men's results showed a significant reduction in the number of aces (particularly the first serve), a significant reduction in the number of double faults and a corresponding significant increase in the number of rallies. The results for men and women combined indicated a significant increase in the number of rallies too. The difference between days 2 and 4 can be attributed to increased familiarity with the larger ball.

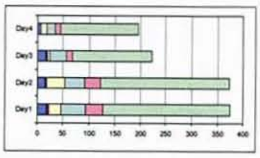
Table 7 lists the significant differences identified from the results. Comparing days 2 versus 1, 4 versus 3, and 2 + 4 versus 1 + 3 combined showed little difference in the number of aces, but since the number of aces was only a very small proportion of standard ball play this was perhaps not surprising. However, there were significant decreases in the number of missed service returns and corresponding increases in the number of rallies, particularly amongst the men and for the male and female groups combined.



(a) Combined 2000/2001

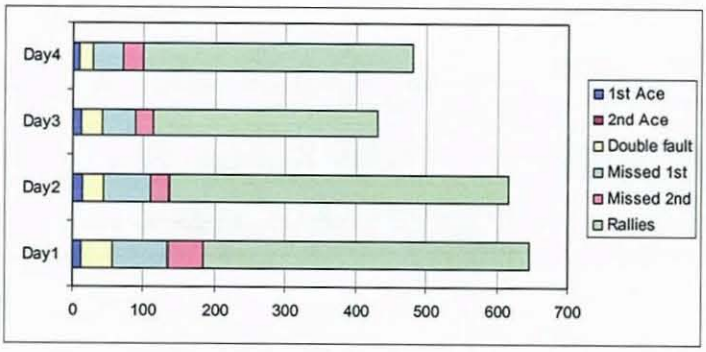


(b) April 2000

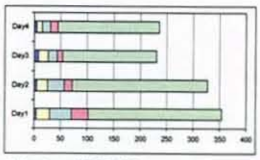


(c) April 2001

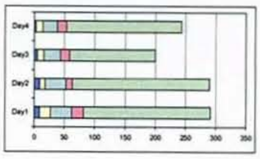
Figure 40: Men's service outcome (totals)



(a) Combined 2000/2001

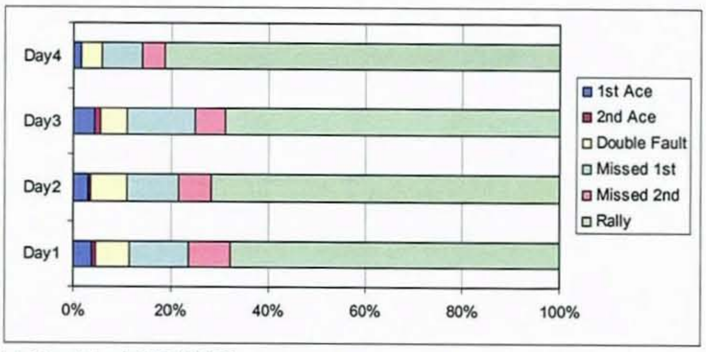


(b) April 2000

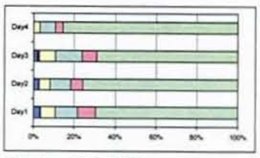


(c) April 2001

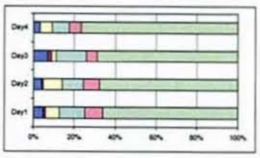
Figure 41: Men's service outcome (per point)



(a) Combined 2000/2001

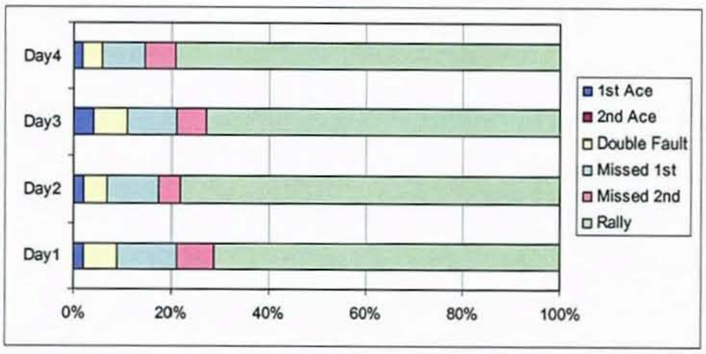


(b) April 2000

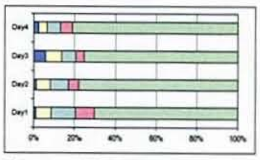


(c) April 2001

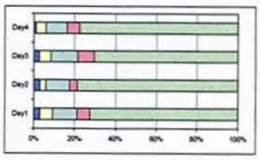
Figure 42: Women's service outcome (totals)



(a) Combined 2000/2001



(b) April 2000



(c) April 2001

Figure 43: Women's service outcome (per point)

Table 7: Statistically significant differences from service outcome comparisons of the larger to the standard ball[2]

			Men			Women			Men & Women		
			2000	2001	Both	2000	2001	Both	2000	2001	Both
Day 2 vs. 1	Aces	1st serve									
		2nd serve									
		Combined									
	Double faults										
	Missed returns	1st serve									
		2nd serve									-32%
		Combined						-25%	-26%		-21%
	Rallies	1st serve	+23%				+18%	+20%	+22%		+15%
		2nd serve									
		Combined	+9%				+8%	+10%	+10%		+8%
	No. Lets			-59%							
Day 4 vs. 3	Aces	1st serve	-100%								
		2nd serve									
		Combined	-100%								
	Double faults		-65%						-59%		
	Missed returns	1st serve		-42%	-41%					-32%	-30%
		2nd serve									
		Combined			-37%		-22%			-26%	-24%
	Rallies	1st serve									
		2nd serve				+49%			+38%		+23%
		Combined	+24%		+18%				+15%		+13%
	No. Lets										
Day 2+4 vs. 1+3	Aces	1st serve									
		2nd serve			-67%						-67%
		Combined	-50%								-39%
	Double faults		-42%					-33%	-36%		
	Missed returns	1st serve			-25%				-20%		-20%
		2nd serve									-26%
		Combined	-29%	-21%	-25%			-19%	-25%	-20%	-22%
	Rallies	1st serve	+22%		+13%			+11%	+14%		+12%
		2nd serve								+4%	
		Combined	+15%		+11%	+9%	+9%	+9%	+12%		+10%
	No. Lets										

The nett result was that the service outcome results from the combined data sets supported the hypothesis that the quality of tennis was improved by using the bigger ball.

Rally Outcome

Figure 44 to Figure 47 show the rally outcome results averaged for all matches during each of the four match play sessions for both men and women. Figure 44 and Figure 46 show the results for men and women in terms of the total number of rallies culminating in each shot type and

[2] A highlighted percentage denotes a significant difference as opposed to a trend towards significance.

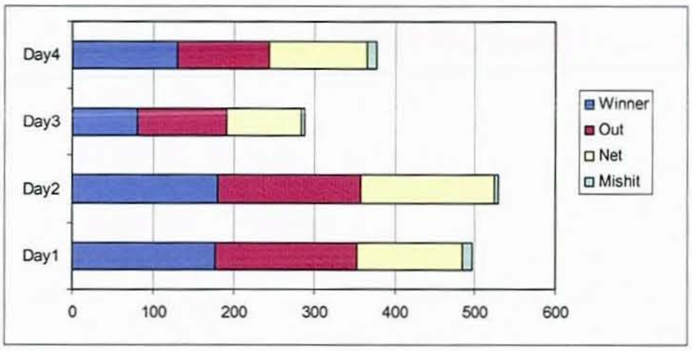
clearly reflect the difference in the number of rallies played on each day. Both figures generally show an increase in the number of rallies with the bigger ball.

Figure 45 and Figure 47 show the mean rally outcomes as a percentage per rally. The first impression conveyed from these figures is that the proportion of rallies ending in either a winner, the ball going out or hitting the net was roughly one third for each. In all instances the number of mishits was almost negligible. The second impression conveyed is that these proportions varied very little over the four days.

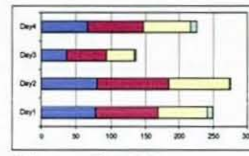
Table 8 lists the significant differences indicated from playing with the larger ball. Comparing the results for different balls on subsequent days reveals very few significant differences for the men. The women's results indicate more significant differences; a reduction in the number of balls hit out (day 2 versus 1 and days 2+4 versus 1+3) and an increase in the number of shots into the net (day 4 versus 3), with the bigger ball.

Comparing results for all players and combining results from both days using the larger ball there was a significant reduction in the number of balls out and a suggested trend towards an increase in the number of balls hit into the net. Given the naturally shorter trajectory of the larger ball this observation was perhaps not surprising. The results also suggested a trend towards an increase in the number of winners, due to a nett decrease in the number of errors. Perversely, the long-term effect of introducing a ball with which it is harder to hit a winning shot (using pace) may be that more points are actually won by an outright winner (using placement).

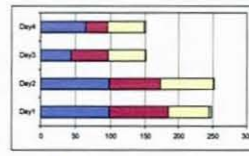
Since the results revealed very little by way of a statistically significant difference in rally outcome from playing with the larger ball, particularly for the men, it still seems safe to conclude that only the length and not the nature of the rally outcome is affected by the bigger ball.



(a) Combined 2000/2001

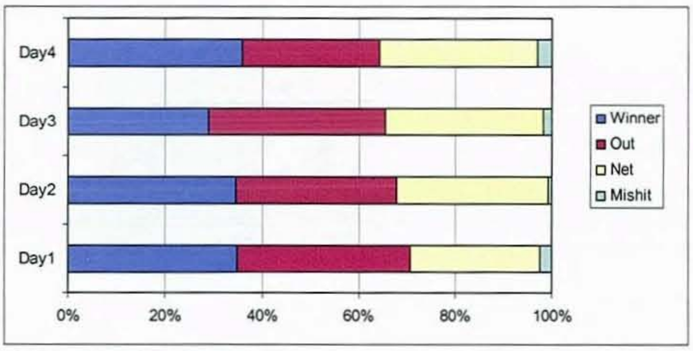


(b) April 2000

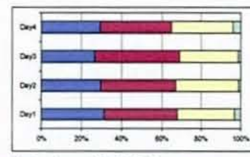


(c) April 2001

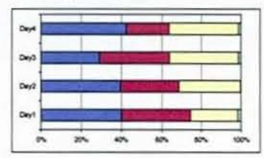
Figure 44: Rally point outcome totals (men)



(a) Combined 2000/2001

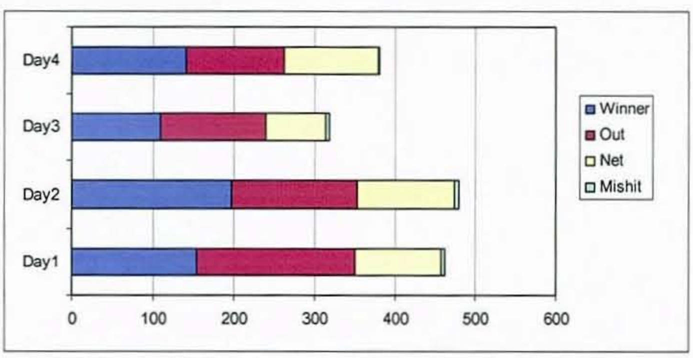


(b) April 2000

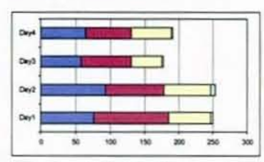


(c) April 2001

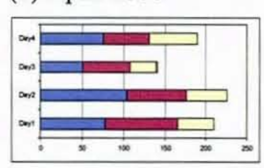
Figure 45: Rally point outcome per point (men)



(a) Combined 2000/2001

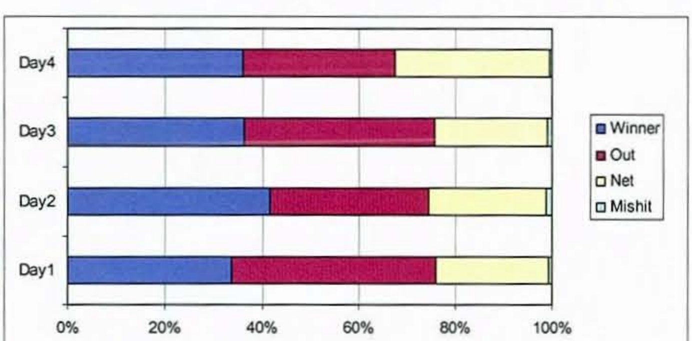


(b) April 2000

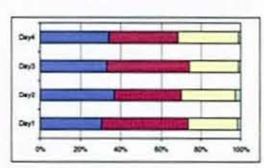


(c) April 2001

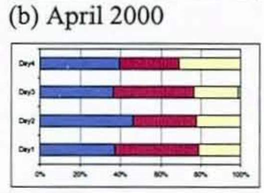
Figure 46: Rally point outcome totals (women)



(a) Combined 2000/2001



(b) April 2000



(c) April 2001

Figure 47: Rally point outcome per point (women)

Table 8: Statistically significant differences from rally outcome comparisons of the larger to the standard ball[3]

			Men			Women			Men & Women		
			2000	2001	Both	2000	2001	Both	2000	2001	Both
Day 2 vs. 1	Winner						+23%	+24%			
	Errors	Out				-22%	-24%	-23%		-21%	-16%
		Net									
		Mishit	-65%		-69%	+66%		+66%			
		Combined					-14%	-12%			
Day 4 vs. 3	Winner			+43%							
	Errors	Out				-15%		-20%			-21%
		Net						+38%			+15%
		Mishit	+138%								
		Combined		-18%							
Day 2+4 vs. 1+3	Winner										+11%
	Errors	Out		-24%	-13%	-15%	-18%	-22%	-23%	-24%	-18%
		Net									+13%
		Mishit									
		Combined									-5%

3.5.5 Perception

The results from the questionnaire are shown as composite bar graphs in the following section. The responses from the men and women are indicated using blue and red shading respectively. The results were analysed for statistical significance both collectively and by gender using two-tailed t-tests with a P value less than 0.05 indicating significance and between 0.05 and 0.1 suggesting a trend towards significance. To do this the five points on the scale were assigned integer values of -2, -1, 0, 1 and 2 from pole to pole respectively. A summary of the statistical analysis findings is presented in Table 9. Where the calculated P value was less than 0.05 this is indicated with a bold font and grey shading. Where the calculated P value was between 0.05 and 0.1 a plain font is used.

Racket/ball interaction - Impact severity

When asked to compare the bigger ball with the standard ball in terms of impact severity the responses indicated that the bigger ball/racket impact was harsher (Figure 48). Analysis indicates this was a statistically significant difference for the male, female and combined male/female study populations.

[3] A highlighted percentage denotes a significant difference as opposed to a trend towards significance.

Racket/ball interaction - Impact vibration

The results for male players suggested a trend towards the response that more vibration occurred when using the bigger ball (Figure 49). Although the women's responses did not indicate a significant difference, results for the combined male/female population indicated a statistically significant difference.

Racket/ball interaction - Pace generation, control & shot length

Since the larger ball experiences more drag during flight it is not surprising that the players almost unanimously indicated that it is harder to generate pace with the larger ball (Figure 50). Although the individual responses were more disparate, statistical analysis of the answers to the question about ease of pace control indicated no significant difference was found (Figure 51). When considering the ease with which they could generate shot length all the players, except for one female, indicated that it was more difficult with the larger ball. This result was statistically significant for the male and female populations individually as well as combined (Figure 52).

Racket/ball interaction - Spin generation and control

The four questions about spin generation and control for topspin and slice from both studies were broadly similar. The combined male/female results showed no significant differences (Figure 53 to Figure 56).

Racket/ball interaction - Shot direction & hitting shots in

When asked about their ability to control shot direction with the bigger ball versus the standard ball, no significant difference was indicated (Figure 57). In contrast, when asked about their ability to hit shots in the combined male/female results indicated a significant difference in this respect (Figure 58). Unfortunately the players were not asked whether it was as easy to clear the net with the bigger ball as with the standard ball.

Racket/ball interaction - Hit sound

A statistically significant difference was identified between the ball/racket impact sound for the two ball sizes, it sounding 'duller' with the bigger ball, particularly to the female players (Figure 59). However, there was no preference between the different sounds of the two ball types (Figure 60).

Ball/surface interaction - Rebound speed and angle

The players unanimously answered that the larger ball surface rebound speed was slower than the standard ball (Figure 61). Opinion differed on the rebound angle between the male and female subject groups. The women indicated a trend response that they believed the rebound angle was less steep. However, the men perceived no significant difference between the larger and standard balls, and the women's results only suggest a trend towards the response that the rebound angle is less steep (Figure 62).

Ball/surface interaction - Bounce sound

The results showed trends towards the response that the larger ball bounce sound was duller than the standard ball amongst the male and female groups with a statistically significant difference in this respect for the combined male/female population (Figure 63). Results indicated that overall the players had no preference for either a duller or sharper ball bounce sound (Figure 64).

General properties - Ball size

Opinion was divided as to whether the bigger ball was excessively large in comparison to the standard ball. Overall, there was a trend towards agreeing that it was excessively large (Figure 65).

General properties - Ball mass

The majority of men considered the larger ball to feel 'heavier' than the standard ball, and this finding was statistically significant. No significant difference was detected for the women, but analysis of the results for men and women combined indicated a significant difference was detected (Figure 66).

This finding was perhaps surprising given that most players would have been aware that the large and standard balls have the same mass. This prompts the conclusion that the players were restating their impression of the ball/racket interaction and their perceived difficulty in generating pace and length. The results of the men indicated a significant increase in perceived ball mass.

General properties - Ball wear

Players as a whole thought the larger ball was more durable, this being a trend result (Figure 67).

General properties - Ball visibility

The majority of men in both studies considered the larger ball easier to see, but the majority of women considered it to be no different (Figure 68). Both findings were statistically significant, the difference likely to be attributable to the greater shot speed of the men.

General properties - Change over time

The subjects did not identify any change in their performance with the bigger ball over time (Figure 69). Note that 'over time' is defined by the length of the session.

General properties - Playing confidence & ball preference

Although the majority view of the players was that they either felt more confident or as confident with the larger ball, tests failed to indicate the difference detected was significant (Figure 70). Similarly, there was no particular preference for either ball size (Figure 71).

Player Comments

Table 10 lists the additional positive and negative comments made by the players about the larger ball. The players made the following additional points during the final discussion session after the questionnaires were completed:

- "When playing with the big ball on these (acrylic) courts it simulates clay court speed and style of play." (Male 3, a strong server)
- The male players were in agreement that if you slow the game down on a fast court then it becomes like a clay court and the beauty of the different surfaces is that different styles of play are more effective. They also made the point that if you slowed down play the clay court specialists who win on clay would just come and win Wimbledon.
- Male 2 likened the 'heaviness' on the racket he felt when playing with the bigger ball to the Tretorn pressureless ball. A few players agreed that they felt the pressureless balls they had tried previously were similar on the racket to the bigger ball.
- Some players said that they would probably restring their racket to a lower tension (down 1 or 2 lbs.) to play with the bigger ball.
- They did not feel that they mistimed the bigger ball more often but when they did they felt it much more. The consensus was that it feels fine when hit directly on the sweet spot but feels heavy on the racket if slightly off.
- The players said that they became frustrated at not being able to hit winners and that they tried to overcome this by hitting the ball harder.
- Playing with the bigger ball they were more tempted to come into the net and most agreed it would be a suitable ball to play on grass with.
- With the bigger ball short angles and drop shots were more effective.
- Overall the players could see the limitations the bigger ball put on their game but these were counterbalanced by the advantages they gained with it.

The general impression from the research staff was that the female subjects were more open minded and not as rigid in their style of play as the men. They appeared more willing and able to adjust to the larger ball and did so with less negative comment.

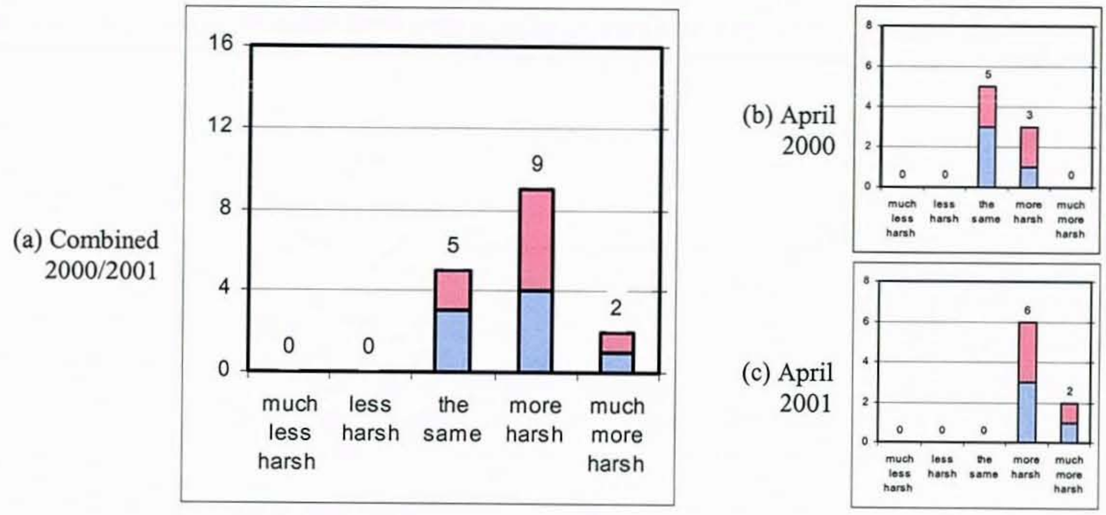


Figure 48: Impact severity

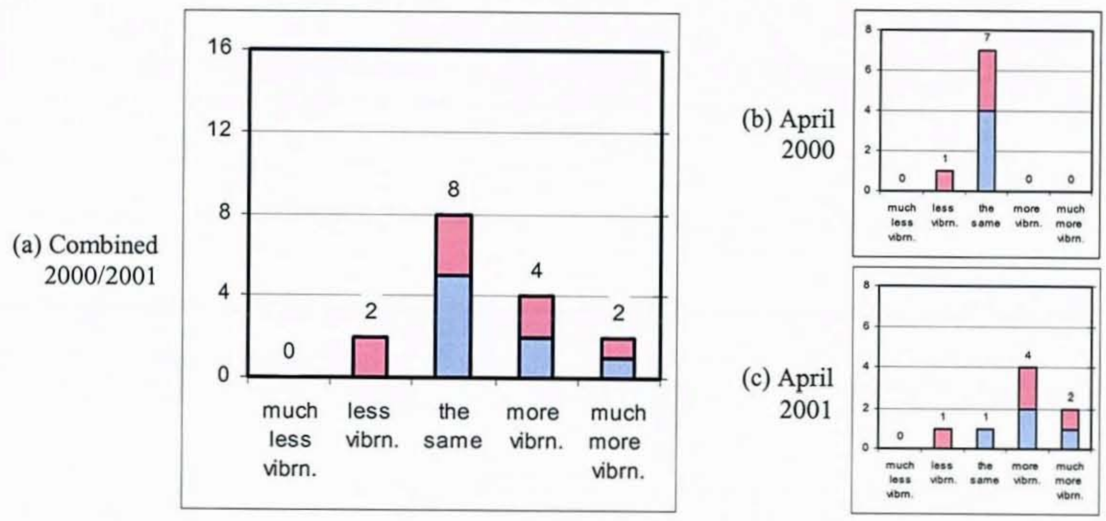


Figure 49: Impact vibration

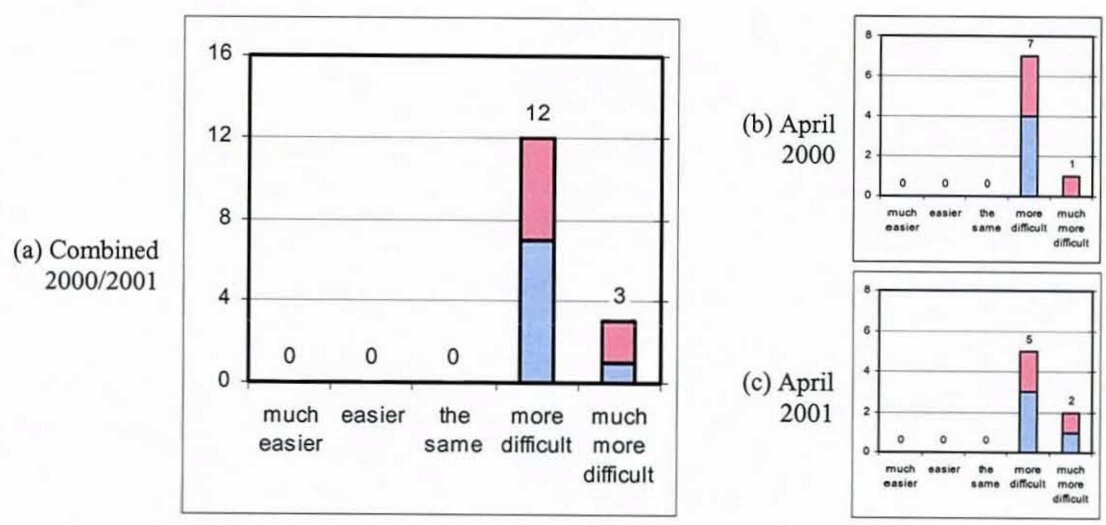


Figure 50: Pace generation

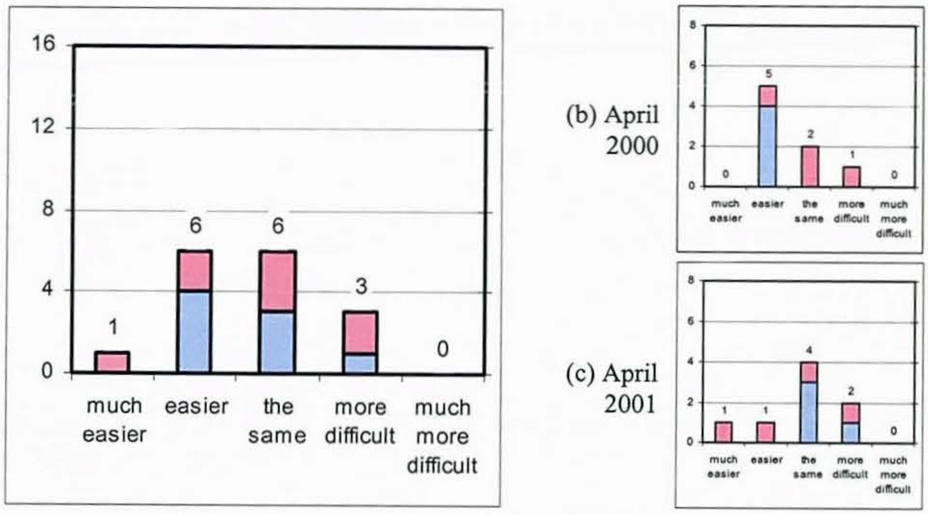


Figure 51: Pace control

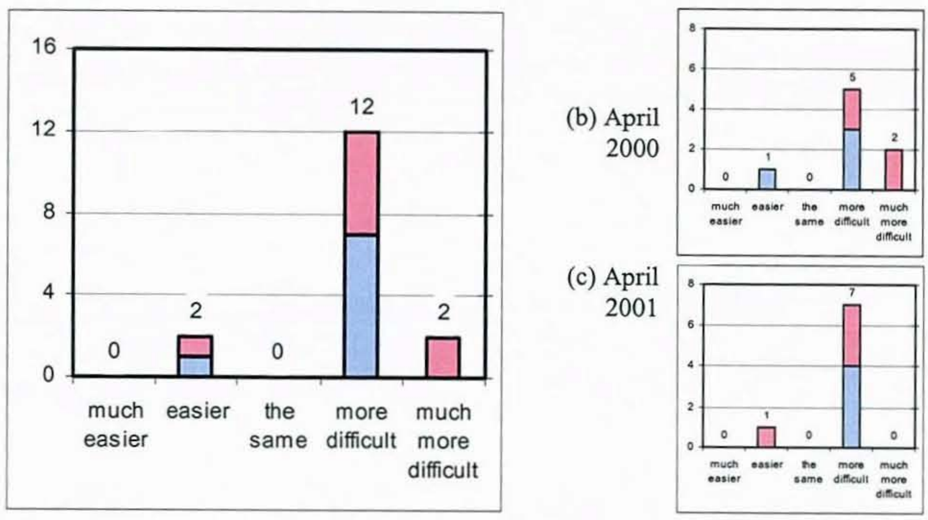


Figure 52: Shot length

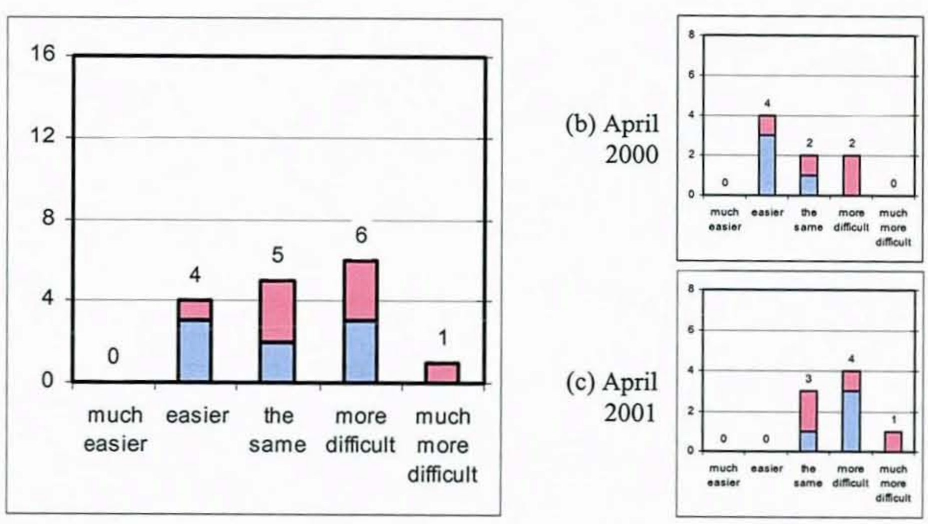


Figure 53: Topspin generation

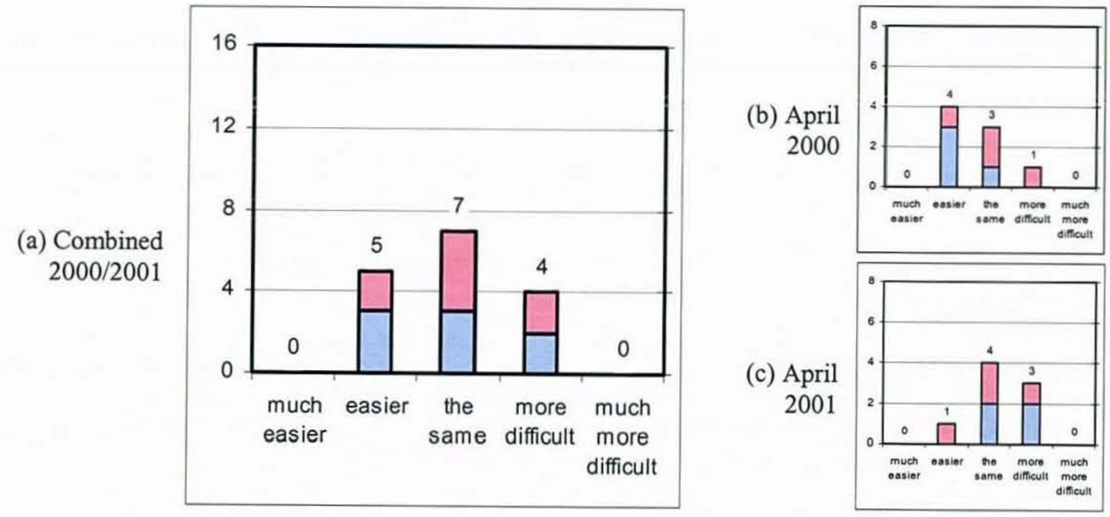


Figure 54: Topspin control

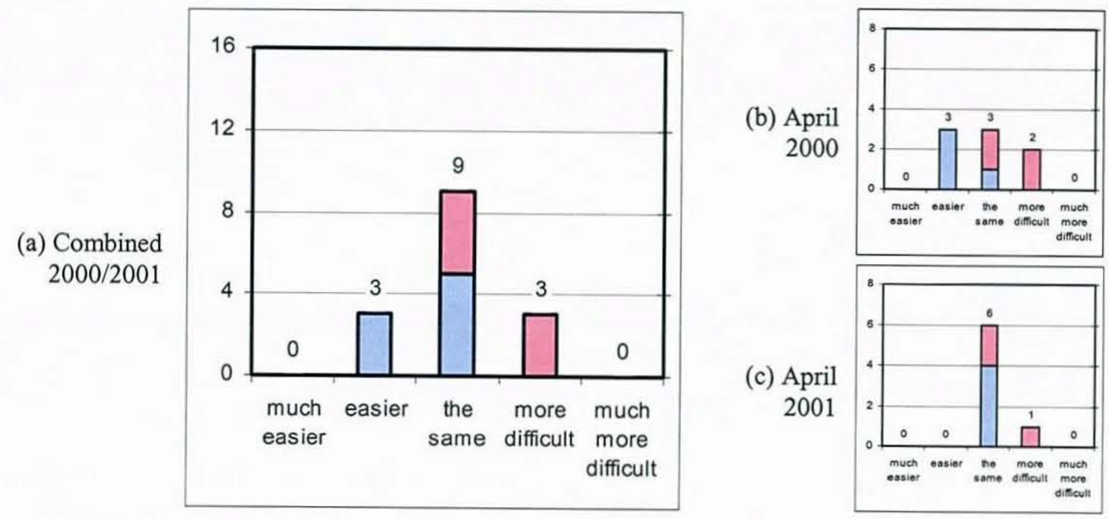


Figure 55: Slice generation

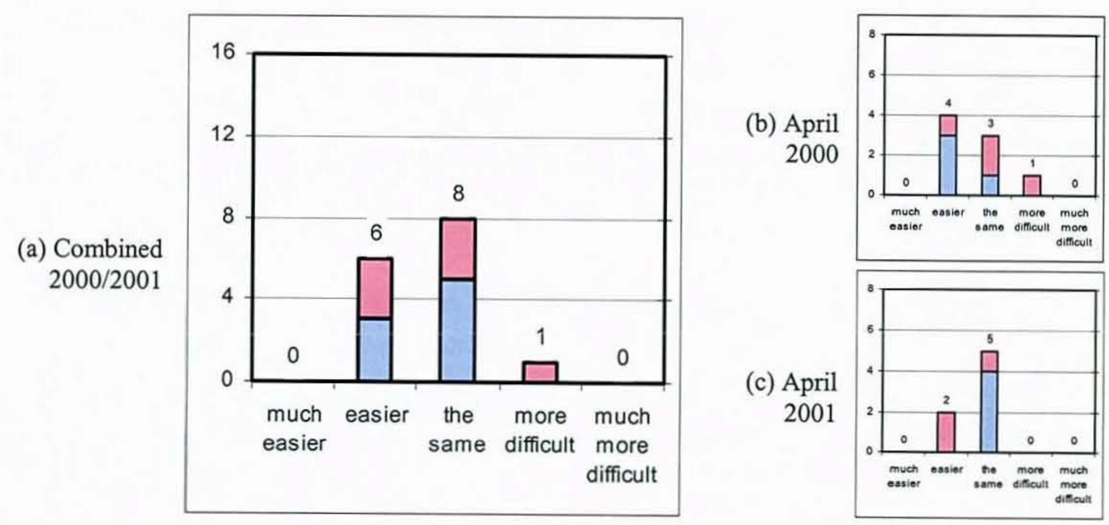


Figure 56: Slice control

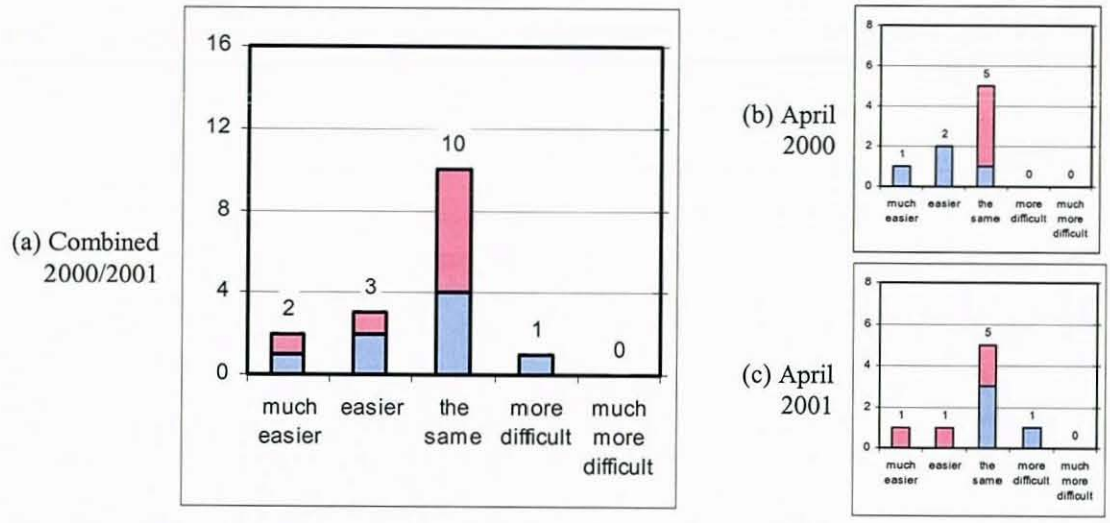


Figure 57: Shot direction

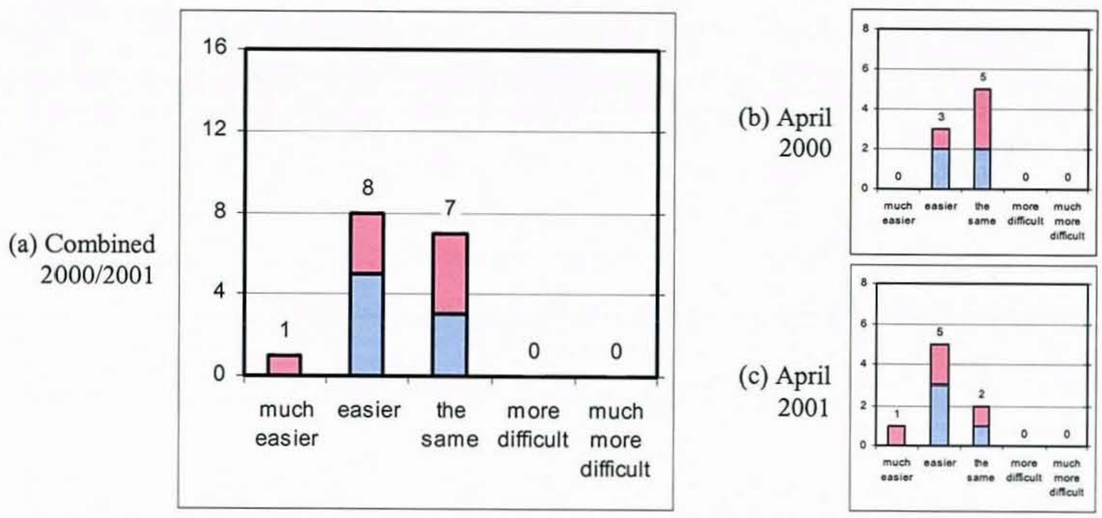


Figure 58: Hitting shots in

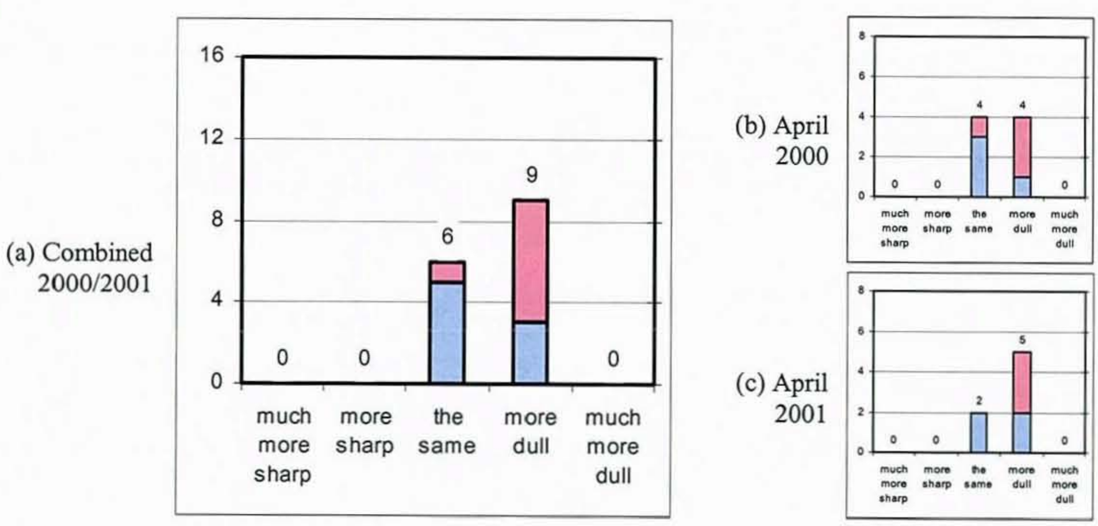


Figure 59: Hit sound

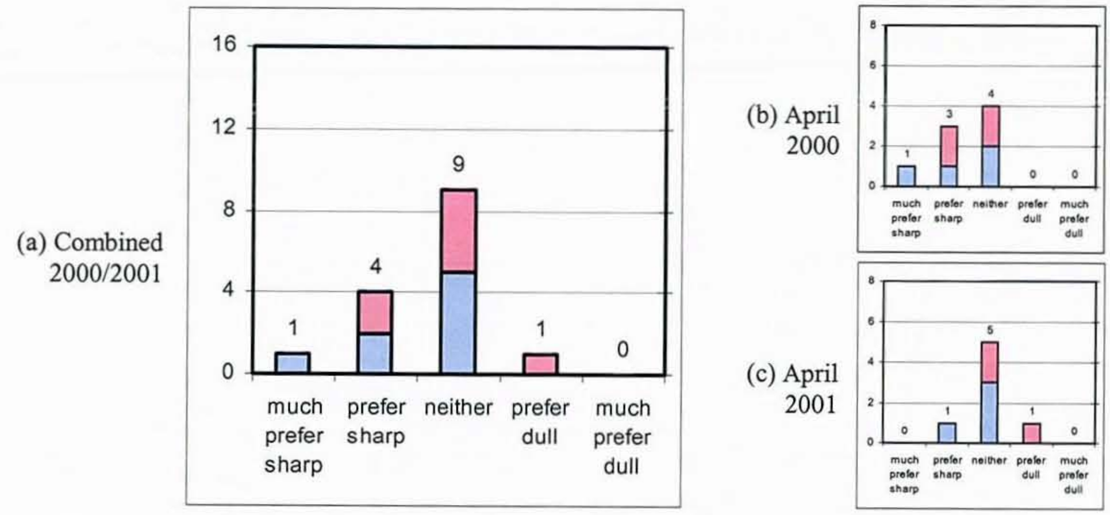


Figure 60: Hit sound preference

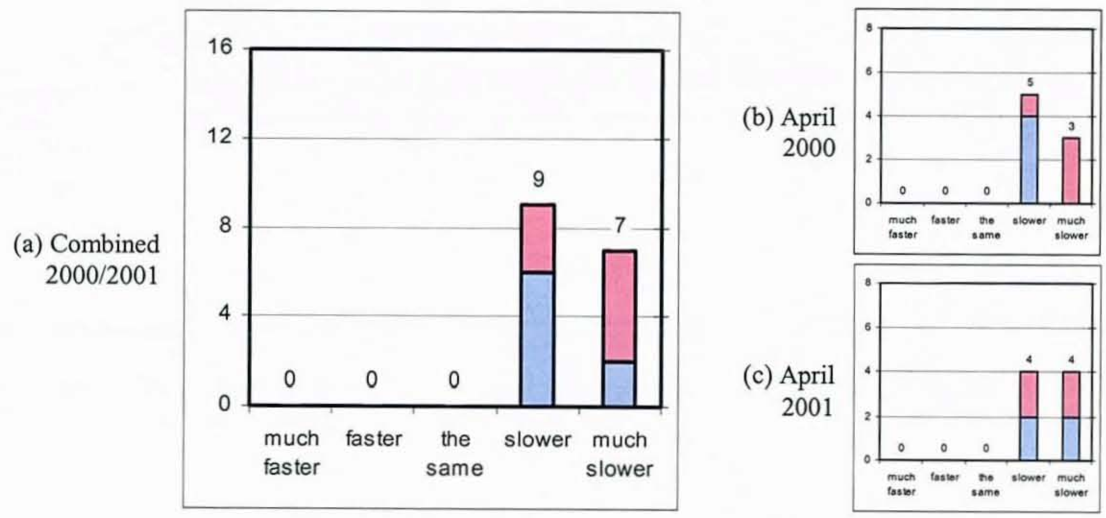


Figure 61: Rebound speed

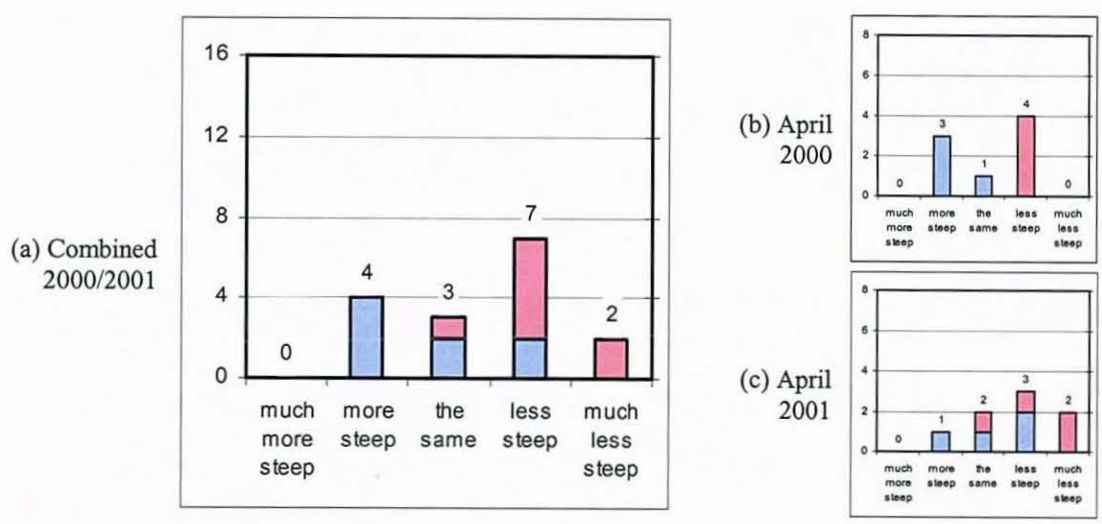


Figure 62: Rebound angle

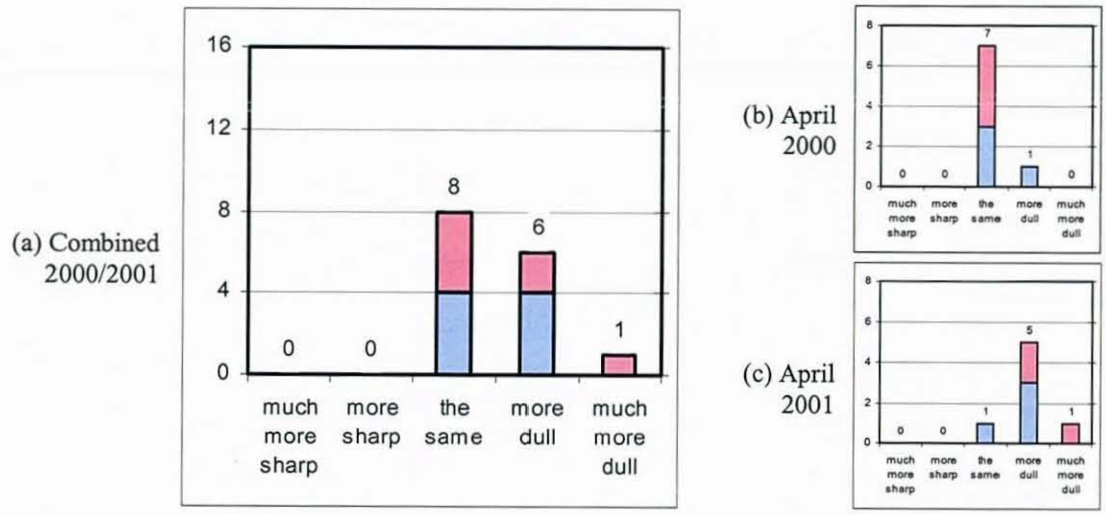


Figure 63: Bounce sound

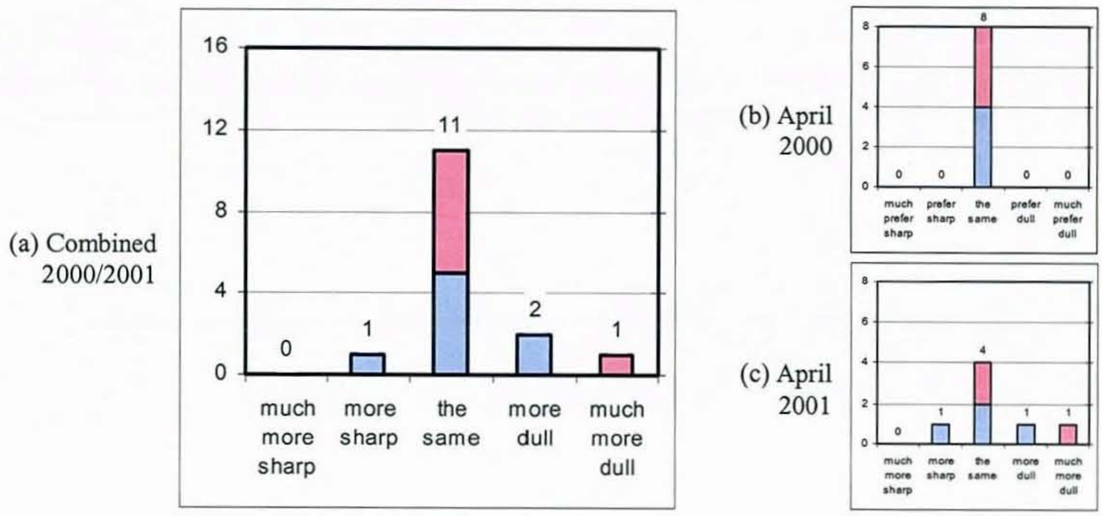


Figure 64: Bounce sound preference

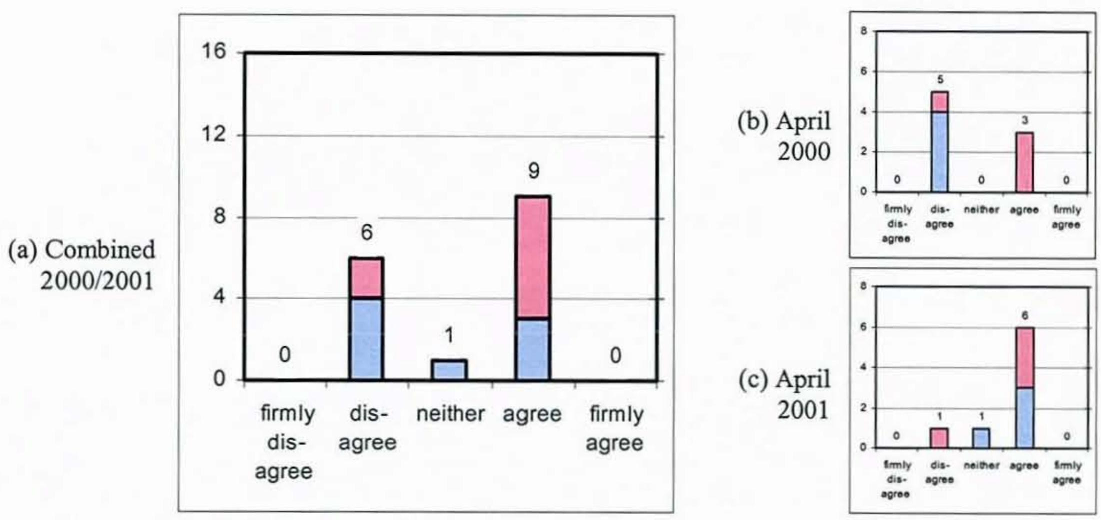


Figure 65: Ball size

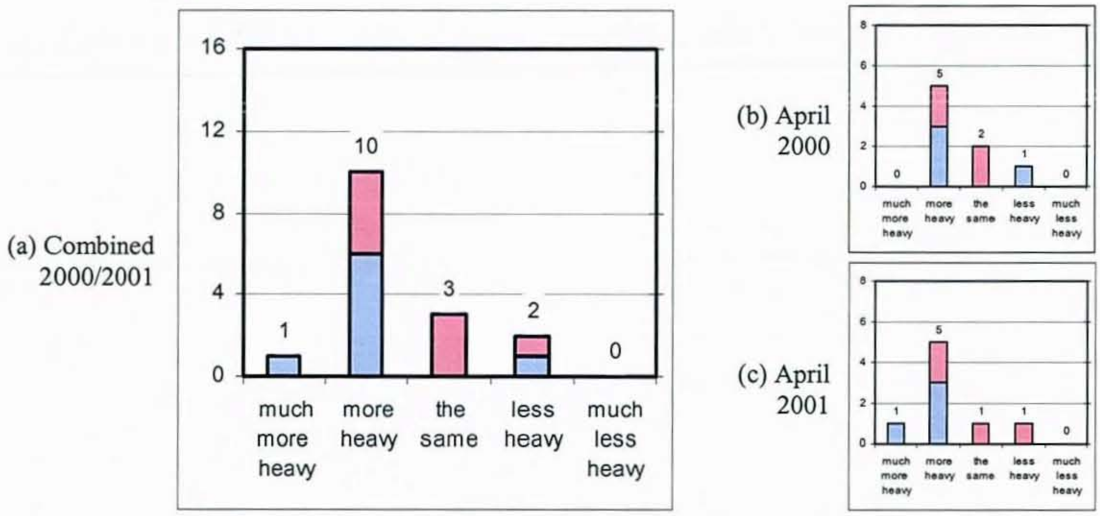


Figure 66: Ball mass

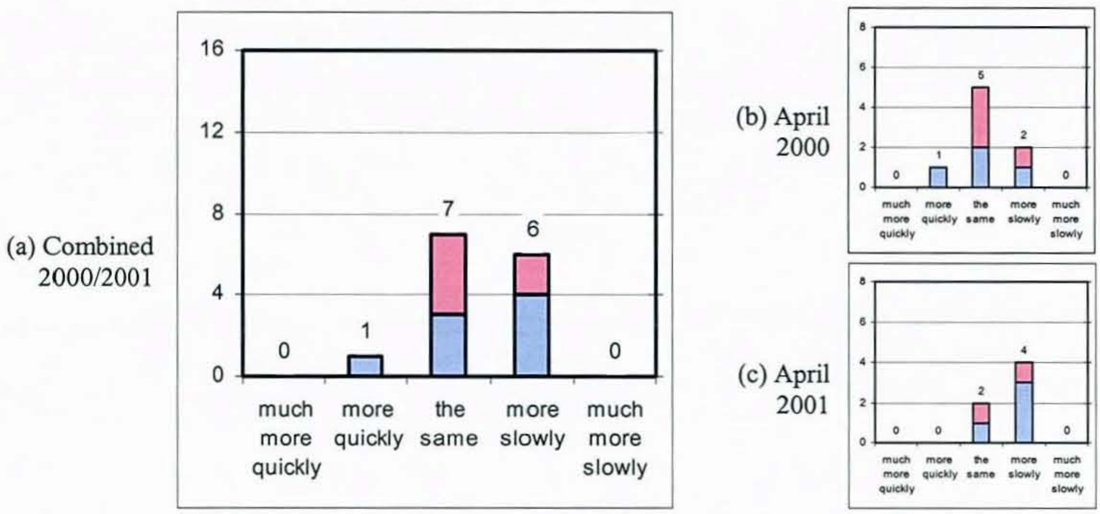


Figure 67: Ball wear

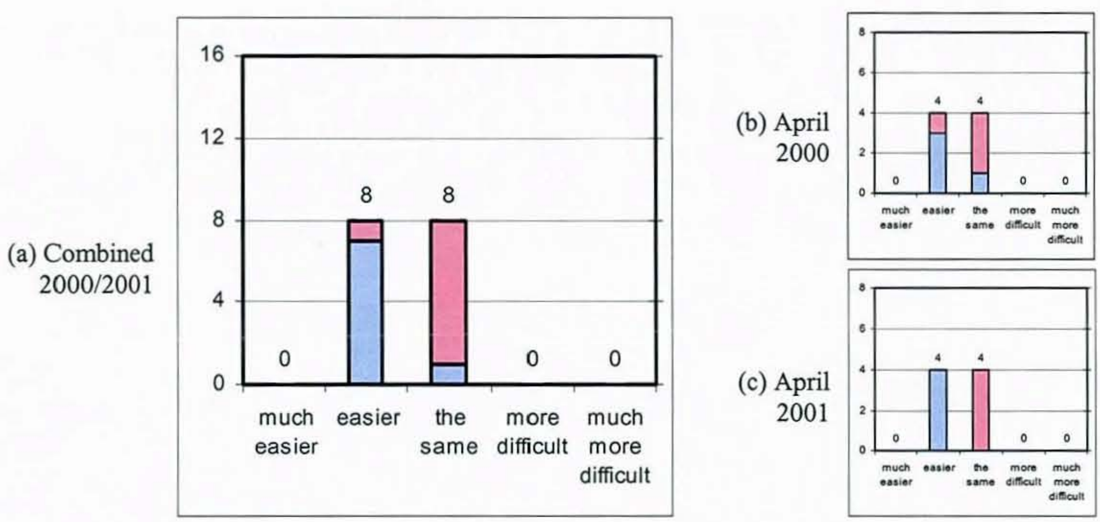


Figure 68: Ball visibility

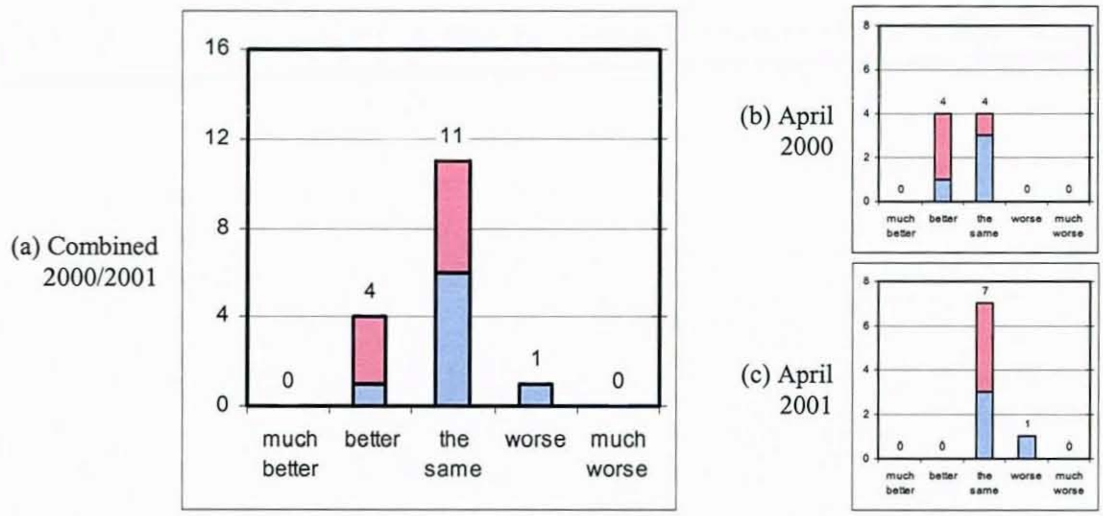


Figure 69: Change over time

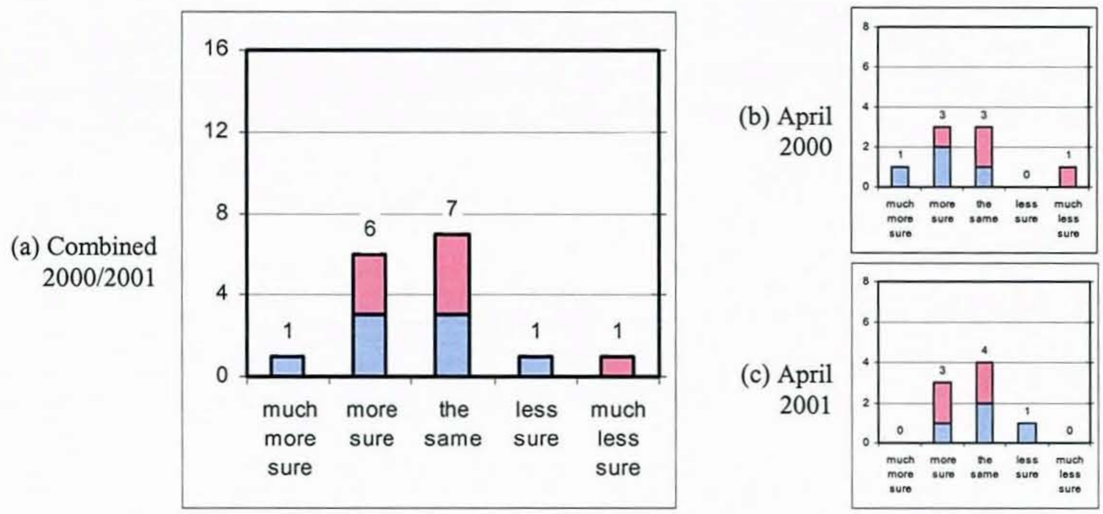


Figure 70: Playing confidence

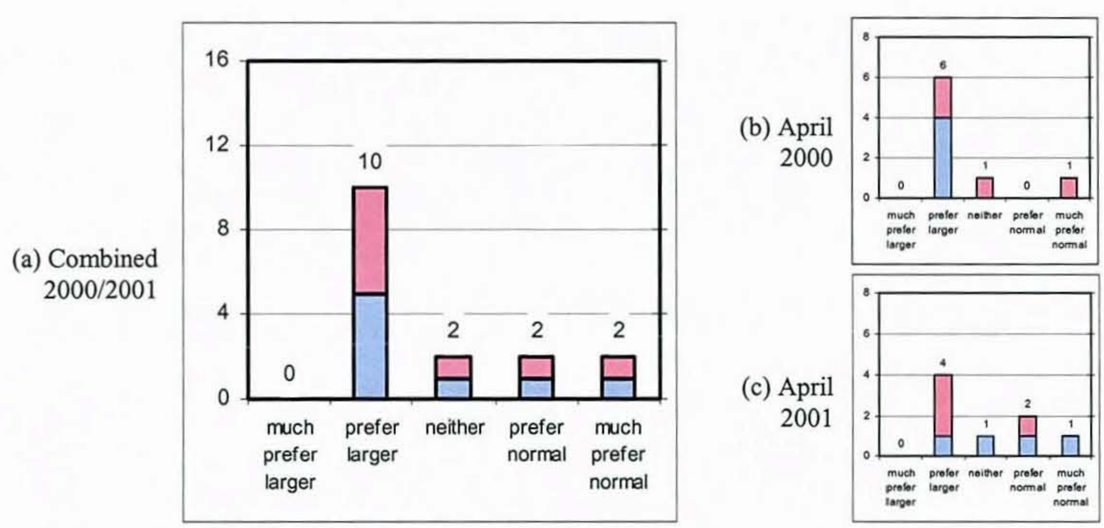


Figure 71: Ball preference

Table 9: Significant differences in perception of the larger ball vs. the standard ball[4]

		April 2000			April 2001			April 2000 + 2001 combined		
		Men	Women	Both	Men	Women	Both	Men	Women	Both
Racket/ball interaction	Impact severity			more harsh	**more harsh**	**more harsh**	**more harsh**	**more harsh**	**more harsh**	**more harsh**
	Impact vibration				more vibrn.		**more vibrn.**			
	Pace generation	**harder**	**harder**	**harder**	**harder**	harder	**harder**	**harder**	**harder**	**harder**
	Characteristics	**April 2000**	**April 2001**	**Combined**						
	Shot length generation		**harder**	**harder**	**harder**		**harder**	**harder**	**harder**	**harder**
	Topspin generation	easier			harder		**harder**			
	Topspin control	easier								
	Slice generation	easier						easier	harder	
	Slice control	easier								easier
	Shot direction	easier								easier
	Shots in			easier	easier	easier	**easier**	**easier**	**easier**	**easier**
	Hit sound		more dull	more dull		more dull	**more dull**	more dull	**more dull**	**more dull**
	Hit sound preference			**sharp**						sharp
Bounce	Rebound speed	**slower**	**slower**	**slower**	**slower**	**slower**	**slower**	**slower**	**slower**	**slower**
	Rebound angle	**steeper**	**less steep**			less steep	less steep		**less steep**	less steep
	Bounce sound				more dull	more dull	**more dull**	**more dull**	more dull	**more dull**
	Bounce sound preference									
General impressions	Ball size	**not too big**			too big		**too big**			
	Ball mass				**heavier**		**heavier**	**heavier**		**heavier**
	Ball wear				more slowly		**more slowly**			more slowly
	Ball visibility	easier		**easier**	**easier**		**easier**	**easier**		**easier**
	Change with time		better	**better**					better	
	Playing confidence	more sure								
	Ball preference	**larger ball**								

[4] A highlighted percentage denotes a significant difference as opposed to a trend towards significance

Table 10: Player Comments

	Positive	*Negative*
Male 1	"Being slower it allowed the rally to last longer and therefore the practice quality was possibly higher"	"Not east to hit winners and this sometimes caused frustration"
Male 2	"I could return harder servers serves with more success" "I had more time after the bounce to play my groundstrokes" "I could see the ball easier"	"It may have caused a little soreness in my upper arm" "It was difficult to generate as much pace"
Male 3	"Useful to slow game down in preparation to clay court tournaments"	"Arm sore because try to force your shots and generally not nice to play with"
Male 4	"Slower and easier to rally with" "Easier to return serve"	"Hard to hit ball deep" "Kids may struggle to hit ball over the net" "Could lead to arm/shoulder injuries when serving with it"
Female 1	"Slower pace so more time to react and reach shots"	"Difficult to create pace on shots and did not bounce very high"
Female 2	"You could reach more balls when pushed wide" "Drop shots easier return"	"Returning slices were more difficult as the ball didn't bounce as much"
Female 3	"Had more control and easier to return serve" "Drop shots easier to do as ball does not bounce as high" "Doesn't rebound from strings as quick"	"Game slower with longer rallies" "Get less pace on your serves" "Difficult to produce a lot of topspin"
Female 4	"I made fewer mistakes with the alternative ball when under pressure, especially off return of serve" "Able to reach more balls"	"Serves are less effective" "Sometimes felt jarring in my arm and shoulder"

3.6 DISCUSSION & CONCLUSIONS

The main findings from Study A were as follows:

- Ball size appeared to have little effect on either hand-grip performance measures or upper limb muscle soreness, following completion of either intensive drills or match play tennis.
- The number of shots required to determine the outcome of a point (i.e. rally length) was significantly greater with the larger ball.
- The importance of the service game in determining match outcome was diminished when playing with the larger ball.
- Rally composition was independent of ball size: the proportion of shots being won by winners and the proportion of errors were both unaffected by ball type.
- The outcome of a match did not appear to be affected by ball size in players with moderate service speeds playing on acrylic.
- Playing with the larger ball neither emphasised nor suppressed the distinction between players.
- Players found it more difficult to generate pace with the larger ball.
- Players found the larger ball easier to return, which may have been due to the perceived increase in time to prepare their shot and improved ability to hit the ball in.
- In general, players were more positive than negative about the playing characteristics of the larger ball.
- A key finding was that the players repeatedly reported the bigger ball as feeling heavier to hit, although in reality it was the same mass as the standard ball.

3.6.1 Grip strength

Reaction times varied little across the testing sessions and ball size appeared to have little bearing on this measure of player fatigue. Rise times became consistently longer as the camp progressed. Although this trend applied to both drill and match play sessions, it was not observed in all subjects. The data suggested that rise time was most affected by cumulative activity rather than by the immediately preceding bout of exercise. No statistically significant difference was found between changes in rise time and use of alternative ball sizes in the immediately preceding bout of exercise.

Peak force remained consistent throughout both Study A and Study B, with no discernible difference being detected between large and standard size balls. Fatigue rates varied over the four days, this variation being most pronounced post-session. In all cases, the rate of fatigue was less than 4.0 $kgf.s^{-1}$ (approximately 9% peak force over the course of the contraction). In the later testing sessions there was a trend towards more gradual force development, with subjects reaching a peak towards the end of the contraction. Paradoxically, this change in force profile resulted in reduced fatigue rates.

Overall, it was concluded that whilst both drill and match play tennis did result in detectable changes in hand-grip performance measures, these differences were small. Furthermore, the changes observed following standard ball sessions were similar to larger ball sessions.

3.6.2 Perceived muscle soreness

Upon initial arrival at the tennis camp, subjects reported modest levels of muscle soreness (typically less than 20% maximal muscle soreness), which remained throughout the four day period. It was therefore difficult to determine the extent to which muscle soreness was induced by the immediately preceding exercise versus that induced by prolonged exposure to tennis. Post drill muscle soreness appeared to be marginally greater than post match play soreness. Ball type did not appear to affect this relationship. In addition, the greatest level of soreness was rated for upper arm and shoulder muscles as opposed to forearm muscles. It is likely that the drill sessions isolated discrete muscle groups due to their repetitive nature, whereas the more varied match play resulted in less specific muscle overload. It was reassuring that low levels of muscle soreness were reported, particularly as forearm muscle soreness rarely exceeded little more than baseline levels.

3.6.3 Point play outcome

Comparing the number of games, points and shots played in the match play sessions confirmed that the larger ball did not alter the tennis played in terms of games per match or points per game. This supports the theory that the relative ability of players is not affected.

A review of the service outcome statistics confirmed that playing with the larger balls significantly reduced the importance of the service game in determining match outcome and that the importance of rally play was correspondingly increased.

When playing with the bigger balls, there was no change in the proportion of points lost by errors. There was a decrease in the number of shots hit out and a corresponding increase in the number of shots into the net. This was undoubtedly caused by players' failure to adjust to the larger ball's different flight characteristics: the aerodynamic properties of the larger and standard balls being different. There was also a suggested trend of more rallies being won by outright winners. Thus, the implication from both service and rally outcome analyses was that the bigger ball improved the quality of play, but the nature of the outcome remained unaffected.

3.6.4 Perception

The male subjects in particular indicated that compared to the standard ball, the larger ball seemed to be heavier and generated more vibration at impact. The players found it harder to generate pace with the bigger ball, but generally found it easier to return, particularly in terms of their ability to hit shots in.

On balance, the players' opinions reflected the view that the benefits of playing with the bigger ball outweighed its drawbacks.

CHAPTER 4

STUDY B: THE COMPARATIVE EFFECTS OF PLAYING TENNIS WITH THE LARGER TYPE 3 BALL & STANDARD TYPE 2 BALL AMONGST RECREATIONAL PLAYERS

4.1 INTRODUCTION

In this chapter the second study arising from initial work in April 2000 (Mitchell and Caine, 2000), Study B is reported. The April 2000 work indicated some interesting trends and differences when playing with Type 3 as compared to Type 2 standard sized balls, and these were substantially confirmed by Study A (Chapter 3). Study B was intended to explore, using similar techniques, the effect of playing with the bigger ball for recreational players. The findings were reported to the ITF in 2001 (Bowyer *et al.*, 2001).

4.2 AIMS & OBJECTIVES

The primary aims of Study B were the same as those of both the April 2000 study and its validation study: Study A (Chapter 3). The only difference between Study B and the two earlier studies was the ability level of the tennis players involved in the testing. Whilst the April 2000 study and Study A had both tested subjects classified as being of a high playing standard, Study B differed by testing players classified as being of a recreational standard only.

4.3 METHODS & TEST MEASURES

4.3.1 General

As for the previous two studies, four indoor acrylic courts situated in Loughborough University's Dan Maskell tennis centre were chosen as the location for the testing. Dunlop Slazenger supplied both the Type 2 standard balls (Slazenger Wimbledon) and the Type 3 larger balls (Dunlop Slazenger Precision).

30 recreational standard players were chosen as subjects, 20 men and 10 women (age 20 yrs ± 2 SD). They reported playing tennis on average 1.5 ± 0.5 SD times per week. The 30 subjects were split up into 6 cohorts of 5 players, according to ability. The testing was conducted over 3 consecutive weekends with each group playing on both days of 2 of the weekends, i.e. for a total of 4 of the 6 days. On one weekend, each group played with the standard ball on Saturday and the larger ball on the Sunday. On their other weekend, the ball order was reversed. Each group therefore played with the standard ball in 2 sessions and the larger ball in 2 sessions. Whether they used the standard or larger ball on the Saturday of their first weekend was varied between groups. During each of their 4 sessions, each subject played a round robin of matches

against the other 4 members of their respective group. Each subject therefore played a total of 16 matches. Over the course of the testing, a total of 240 matches were played; 60 different pairings each repeating twice with the standard ball and twice with the larger ball, thus enabling comparisons to be made.

Each match was a timed 25 minutes of continuous play, breaking only to change ends. New balls were used every 25 minutes thus minimising variations in performance due to ball wear. As a control, the players were all asked not to exercise on the day before testing (Friday). There was a 5 minute break between matches. The duration of 25 minutes per match was chosen following consultation with a Lawn Tennis Association (LTA) accredited coach. Since the subjects were not conditioned to playing for long periods, the chosen workload of 100 minutes playing time per day, on two consecutive days, was judged to be sufficient to fatigue the players without causing undue levels of stress.

The results and findings presented for Study B are based on analysis of data from play on the Saturdays only. This avoids any possible distortion due to play on consecutive days, players potentially becoming more fatigued, depending on individual levels of conditioning.

4.3.2 Test measures

The test measures used were the same as those reported in Chapter 3. The only slight difference between the two studies was the method by which the grip strength test was deployed. In Study A, muscle fatigue was monitored throughout the training camp before and after each morning and afternoon session by measuring grip strength but for Study B muscle fatigue was monitored immediately before and after each whole day of play by measuring grip strength. This was because of the difference in play protocol. The advanced players in Study A played two sessions per day where as the recreational players who were not conditioned to this amount of play only played in one session per day.

4.4 RESULTS

4.4.1 Data analysis

The data were entered into a series of Microsoft Excel spreadsheets for analysis. The results are shown in a series of bar graphs in the following section. The results were analysed for statistical significance both collectively and by gender using two-tailed t-tests with a P value less than 0.05 indicating significance and between 0.05 and 0.1 suggesting a trend towards significance. Unless in the following sections a comparison is identified as indicating a significant difference, or showing a trend towards significance, it can be assumed to have yielded a P value greater than 0.1.

4.4.2 Grip strength

A series of charts follow (Figure 72 to Figure 75) to illustrate pre- and post-session values for the four previously described hand-grip related measures. All measures are group mean values obtained for the dominant hand. These permit comparisons to be made on the effects of playing with the standard and larger balls. The blue column refers to pre-test values and the pink column refers to post-test values.

With reference to Figure 72 it can be seen that reaction times varied little (no significant differences) pre- and post-session and also across testing days. Inter-subject variability was quite large, with coefficients of variability being around 25% and reaction times ranging from approximately 0.25 s to approximately 0.49 s. Ball size appeared to have little bearing on reaction time.

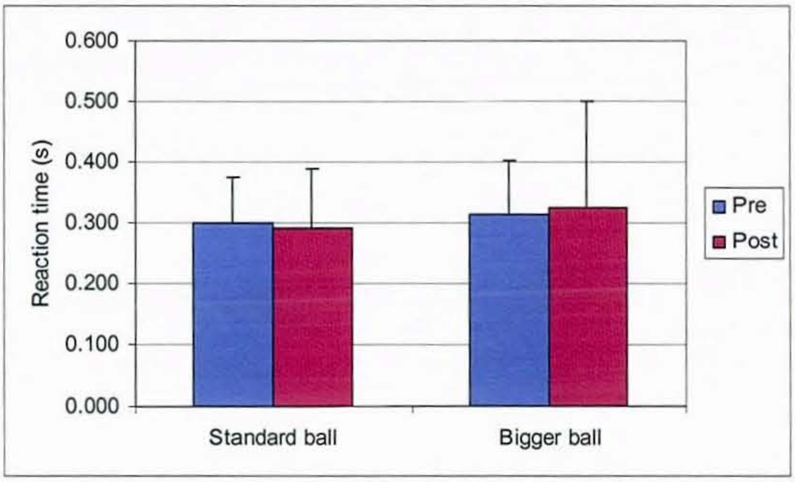


Figure 72: Reaction times observed before and after match play

Rise time was generally slower after the tennis session and the difference was similar with both ball types (Figure 73). There was no difference in the standard and bigger ball post-test values indicating that player fatigue was no greater following play with the bigger ball.

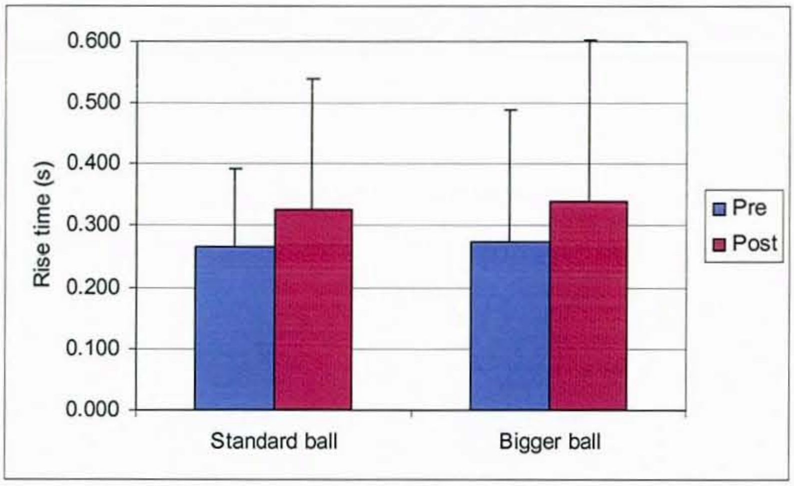


Figure 73: Rise times observed before and after match play

Peak force varied little across testing sessions (Figure 74) and if anything tended to be very slightly quicker post play. The pre-test was performed prior to a warm up and this probably affected the performance. Average peak handgrip force was no different following play with the bigger ball as compared to the standard ball. This suggests that the loading on the arm and shoulder muscles was no greater with the larger ball.

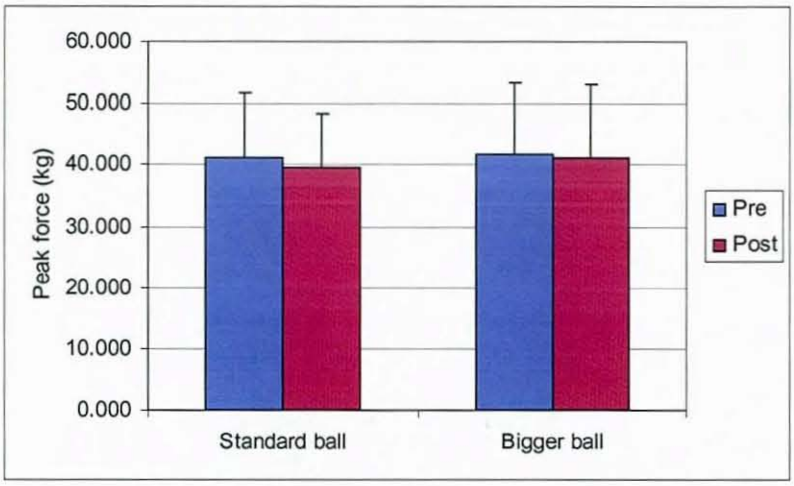


Figure 74: Peak forces observed before and after match play

With reference to Figure 75 it can be seen that the average change in fatigue rate was no different when comparing results from the two ball types.

In summary there was little difference in hand-grip performance following play with the standard and larger ball types. This indicates that the larger ball did not place a greater overload on the arm and shoulder muscles than the standard ball. This statement is true only in the context of this study and the long-term repetitive effects of using the bigger ball should be investigated further.

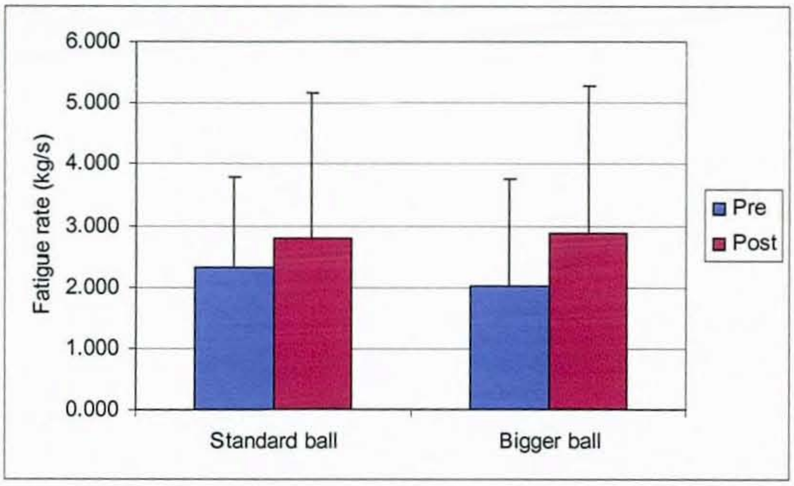


Figure 75: Fatigue rate observed before and after match play

The measures of peak force and reaction time altered little in terms of pre- and post-test values. Rise time and fatigue rate appear to be more sensitive a measure to changes in forearm loading as clear increases in the post-test values can be seen (Figure 73 and Figure 75).

4.4.3 Perceived muscle soreness

Figure 76 and Figure 77 show muscle soreness contour maps, which provide a visual representation of group mean ratings of muscle soreness for the dominant hand. For illustrative purposes the magnitude of soreness for each muscle is depicted by colour. A series of eight soreness groupings are used, with each corresponding to a discrete colour on a blue-red continuum. The greater the muscle soreness rating the more red the colour and the lower the rating the more blue the colour.

These illustrations permit comparisons to be made between standard and larger balls. As for Study A, no condition resulted in a mean muscle soreness rating in excess of 20% maximal muscle soreness.

Reported muscle soreness was increased after playing four 25 minute matches with both the standard and the larger ball, suggesting that the schedule chosen was suitably testing for players of this level (i.e. recreational). The important aspect is whether the players were relatively sorer after playing with the bigger ball. To establish this, a direct comparison of the post-session values is not appropriate as there was a difference in the pre-session reported mean muscle soreness values on the bigger and standard ball days. For this reason difference in muscle soreness (post-session value – pre-session value) was calculated and then compared.

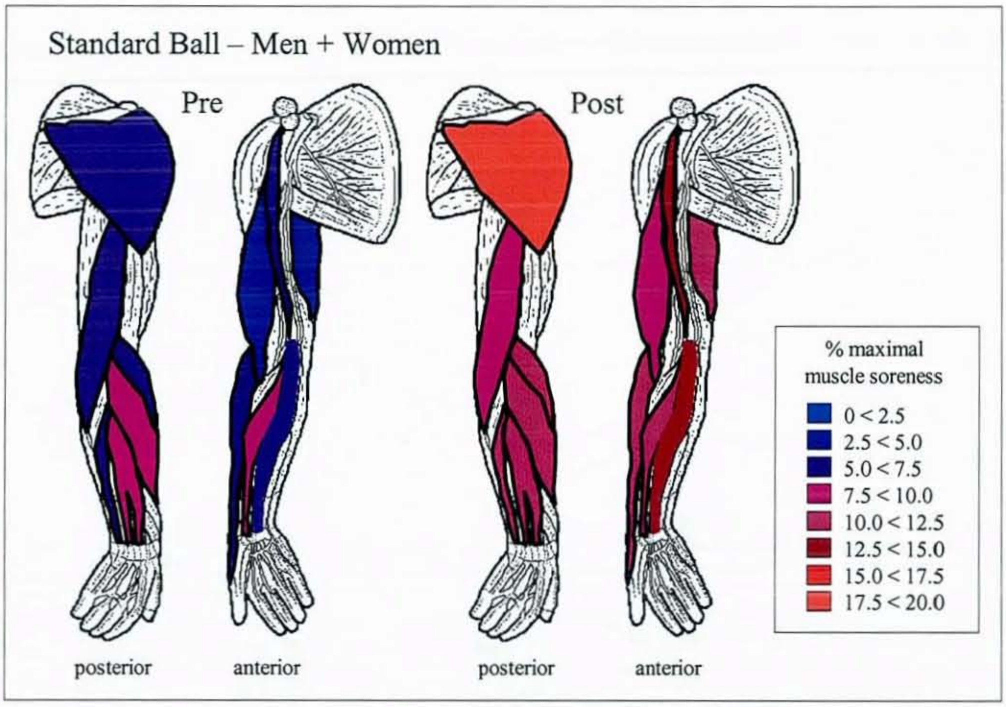


Figure 76: Pre and post session muscle soreness rating with standard ball (men and women)

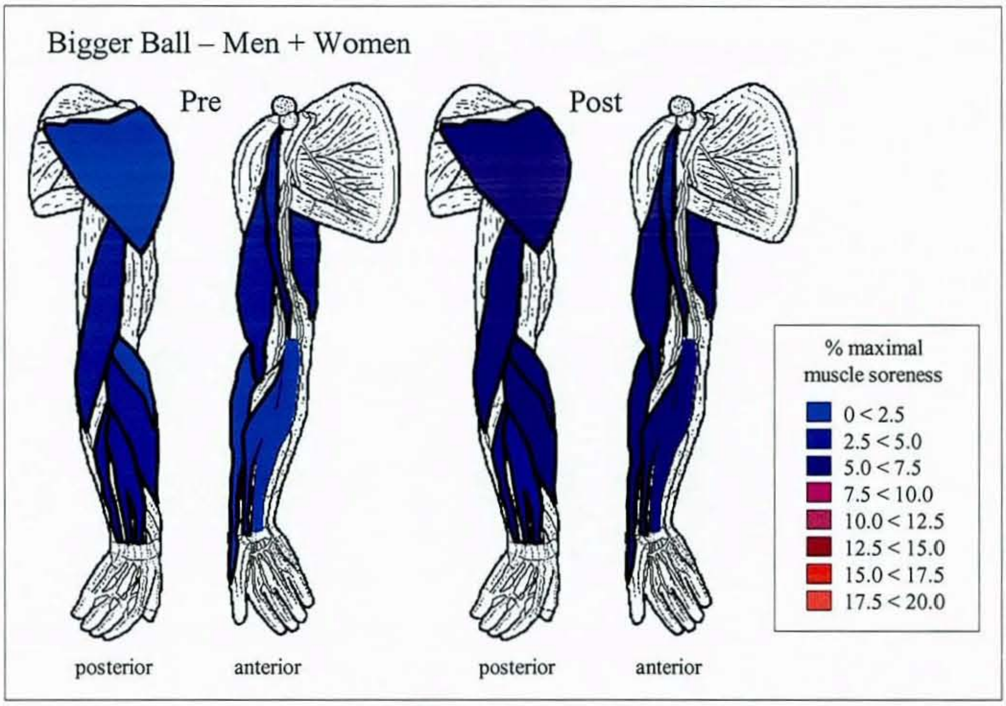


Figure 77: Pre and post session muscle soreness rating with bigger ball (men and women)

With reference to Figure 78 when comparing the difference in muscle soreness (post-session – pre-session) between the bigger and standard ball (for the combined data of men and women), the only statistical difference was in the deltoid muscle. The change in muscle soreness was actually less when playing with the bigger ball. Subject variability was considerable.

Average muscle soreness reported was higher in the males than the females and the change in muscle soreness over the day was also greater in the males, but relatively the same for both ball types. So for this group of subjects, playing with the larger ball did not result in greater levels of muscle soreness when compared to playing with the standard ball.

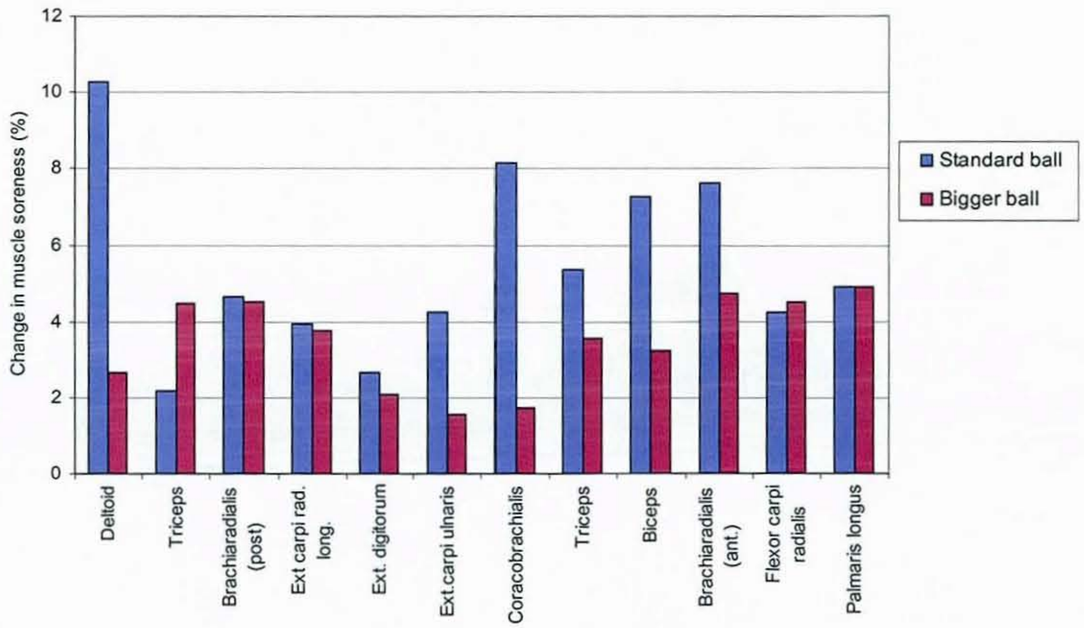


Figure 78: Change in muscle soreness (%) for men and women with both ball types

Early analysis of Sunday play data revealed potential distortion due to recreational players' unfamiliarity with extended play on consecutive days. Further analysis of this effect is recommended for the future. For this reason all the results presented here are from Saturday play data only, when the players were rested.

4.4.4 Point play outcome

The data were entered into a series of Microsoft Excel spreadsheets for analysis. The results were analysed for statistical significance both collectively and by gender using two-tailed t-tests with a P value less than 0.05 indicating significance and between 0.05 and 0.1 suggesting a trend towards significance. Comparisons between 'bigger ball day' vs 'standard ball day' were made using a paired data *t*-test to identify differences between the two ball types. Unless in the following section a comparison is identified as indicating a significant difference, or showing a trend towards significance, it can be assumed to have yielded a P value less than 0.1.

As with the Study A (section 3.5.4), the results are discussed with reference to three possible propositions for the effect of the larger ball (two undesirable, one desirable), as follows:

a) The relative ability of all players becomes less distinct

b) The relative ability of all players becomes more distinct

c) The quality of tennis improves

Point outcome possibilities

A point can be broken down into service outcome and rally outcome. The outcome of a serve can be an ace, double fault, a service return error or it can result in a rally. The outcome of the resulting rally can be either a winning shot, or an error (out, net or mishit) (see Figure 79). For service dominance to be reduced, the proportion of serves leading to rallies needs to be increased. For this to occur, the number of aces, double faults or service return errors must be reduced.

The following results section describes the results of point play in three sections:

- Match overview data
- Service overview
- Rally outcome

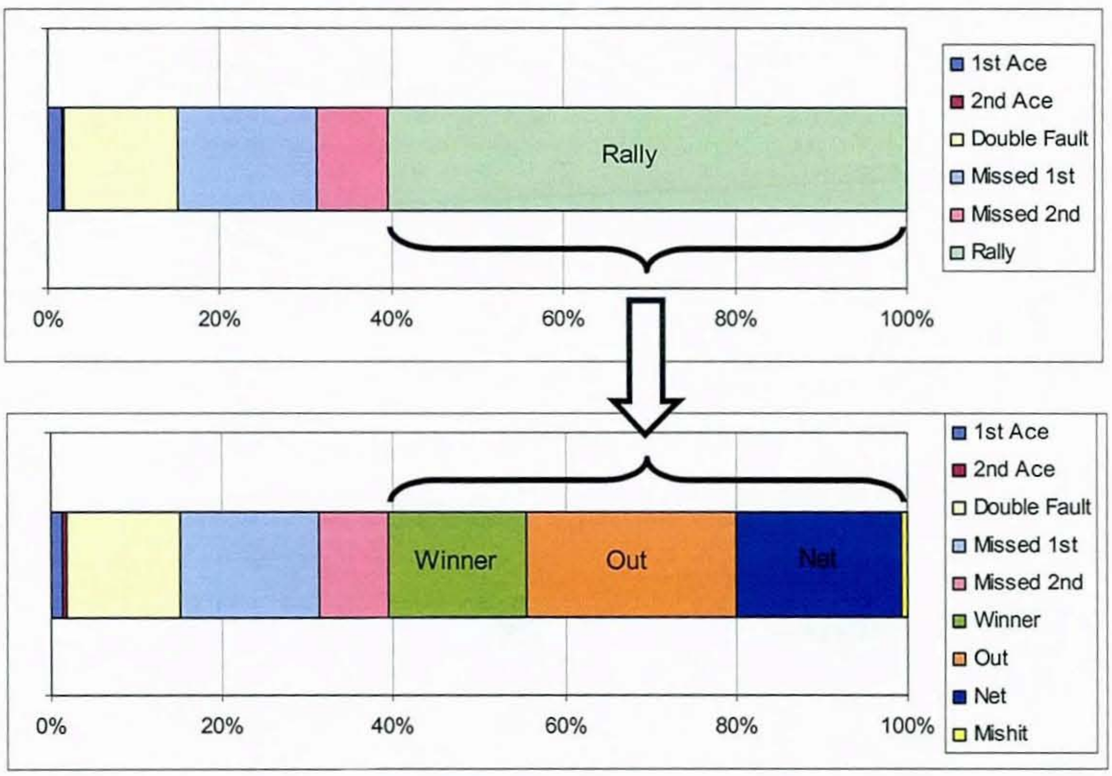


Figure 79: Point outcome possibilities

Match Overview

The match summary data is shown in Table 11. The following results refer to the data collected from the Saturday only of each weekend. Early analysis of the Sunday play data revealed distortion due to recreational players' unfamiliarity with extended play on consecutive days.

Table 11: Match Summary Data

	Standard Ball			Bigger Ball		
	Men	Women	M+W	Men	Women	M+W
Total no. matches	80	40	120	80	40	120
No. matches compared	40	20	60	40	20	60
Total no. games	315	151	466	319	150	469
Average games per match	7.9	7.6	7.8	8.0	7.5	7.8
Total no. points	2015	931	2946	1988	947	2935
Average points per match	50.4	46.6	49.1	49.7	47.4	48.9
Average points per game	6.6	6.3	6.5	6.3	6.4	6.4
Total no. shots	7171	3420	10591	7868	4101	11969
Average shots per match	179.3	171.0	176.5	196.7	205.1	199.5
Average shots per game	23.4	23.2	23.3	25.2	27.9	26.1
Average shots per point	3.6	3.7	3.6	4.0	4.4	4.1

A total of 466 games were played with the standard ball and 469 with the bigger ball. The total number of points played with the standard ball was 2946 and with the bigger ball 2935. A total of 10591 shots were played with the standard ball and 11969 with the bigger ball.

Table 12 shows the statistically significant differences from game, point and shot comparisons when playing with the bigger ball and standard ball. Values with a significant difference at the 95% confidence level are shown by bold text within a shaded box.

Table 12: Statistically significant differences from game, point and shot comparisons between ball types

	% Difference		
	Men	Women	M+W
Total no. games	+1.3	-0.7	+0.6
Average games per match	+1.3	-0.7	+0.6
Total no. points	-1.3	+1.7	-0.4
Average points per match	-1.3	+1.7	-0.4
Average points per game	-3.7	+2.0	-1.9
Total no. shots	**+9.7**	**+19.9**	**+13.0**
Average shots per match	**+9.7**	**+19.9**	**+13.0**
Average shots per game	+7.9	**+20.2**	**+12.0**
Average shots per point	**+11.2**	**+20.0**	**+14.2**

There was no difference in the number of games per match and number of points per game when using the bigger ball as compared to the standard ball (Figure 80and Figure 81). The number of shots per game was significantly increased when playing with the larger ball (Figure 82). This is a positive result as it suggests that the relative ability of the players was not changed by using the bigger ball.

With reference to Table 12, the number of shots per point when playing with the bigger ball is increased by 20% for the women compared to 11.2% for the men. A possible explanation for this might be that in general, recreational standard women tennis players are less competitive than males. The women appeared to be more content with playing a good rally whereas the men tried hard to finish a rally by means of either a winning shot or resultant error.

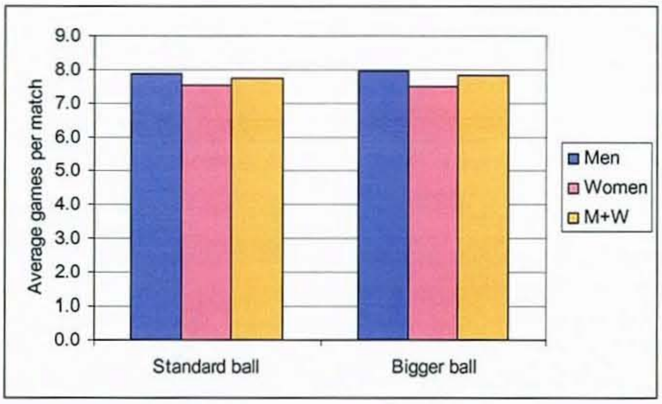


Figure 80: Mean games per match

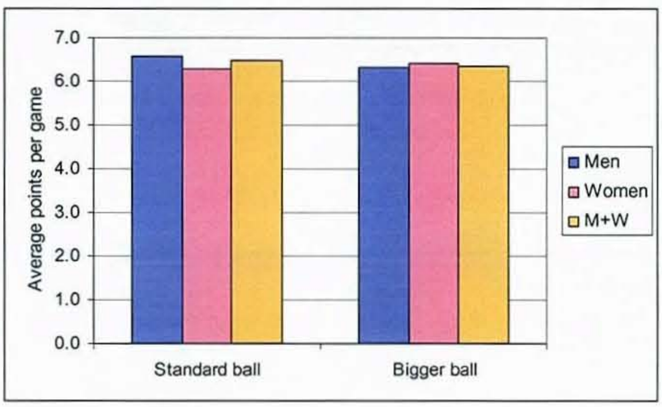


Figure 81: Mean number of points per game

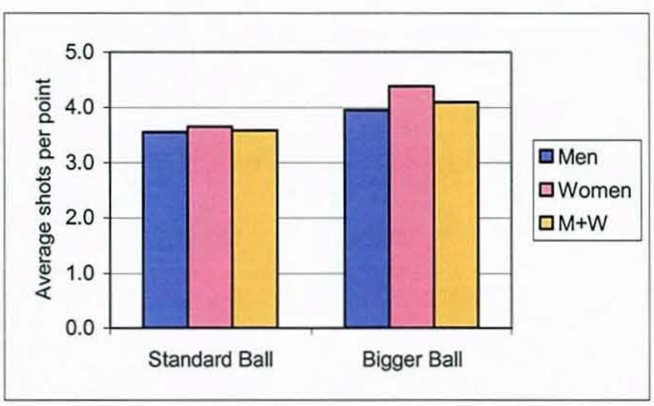


Figure 82: Mean number of shots per point

The statistically significant 14.2% increase in the number of shots per point is in agreement with the 9% increase from the combined 2000 and 2001 studies on University first team players. To reiterate, this supports the proposal that the quality of tennis is improved by playing with the larger ball.

Service Overview

The service outcomes were analysed as for University team players. Table 13 shows the service totals when using the standard and bigger ball. Table 14 shows the percentage differences in service outcome per point when comparing the bigger ball to the standard ball. Values with a significant difference at the 95% confidence level are shown by bold text within a shaded box. Values with a significant difference at the 90% confidence level are shown by normal (non-bold) text within a shaded box.

There was a significant decrease (18%) in the number of missed service returns when playing with the bigger ball. This supports the perception that returning serves with the bigger ball is easier. The effect was more pronounced in the women (26%) as compared to the men (15%).

As a result of this decrease there was a significant increase in the number of rallies when playing with the bigger ball. An overall 16% increase in first serve rallies can be observed (Table 14).

Table 13: Service outcome totals for standard and bigger ball

		Service totals					
		Standard			Bigger		
		Men	Women	M+W	Men	Women	M+W
Aces	1st serve	34	10	44	34	11	45
	2nd serve	7	1	8	6	1	7
	Combined	41	11	52	40	12	52
Double faults		303	92	395	250	90	340
Missed returns	1st serve	308	169	477	268	133	401
	2nd serve	179	61	240	148	37	185
	Combined	487	230	717	416	170	586
Rallies	1st serve	642	368	1010	727	448	1175
	2nd serve	543	230	773	554	227	781
	Combined	1185	598	1783	1281	675	1956
Lets		88	20	108	103	22	125

Table 14: Statistically significant differences from service outcome per point between bigger and standard ball

		% Difference		
		Men	Women	M+W
Aces	1st serve	1.9	+13.6	+4.7
	2nd serve	-15.4	+11.6	-11.8
	Combined	-1.0	+13.5	+2.3
Double faults		-14.9	-3.9	-12.2
Missed returns	1st serve	-12.0	-21.5	**-15.5**
	2nd serve	-19.3	-36.1	**-23.6**
	Combined	-13.8	**-27.3**	**-18.4**
Rallies	1st serve	+15.4	**+19.5**	**+17.0**
	2nd serve	+2.5	-2.9	+0.8
	Combined	**+9.4**	**+10.8**	**+9.9**
Lets		+15.7	+7.0	+1.0

The significant overall decrease in missed service returns and increase in resultant rallies supports the hypothesis that the quality of tennis is improved by using the bigger ball.

The shift in emphasis of service outcome when using the bigger ball can be seen in Figure 83, Figure 84 and Figure 85.

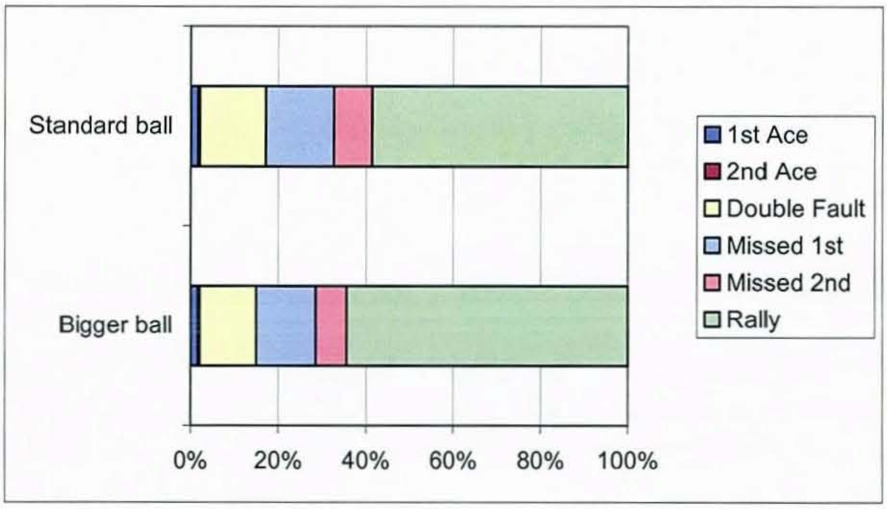


Figure 83: Service outcome per point for men

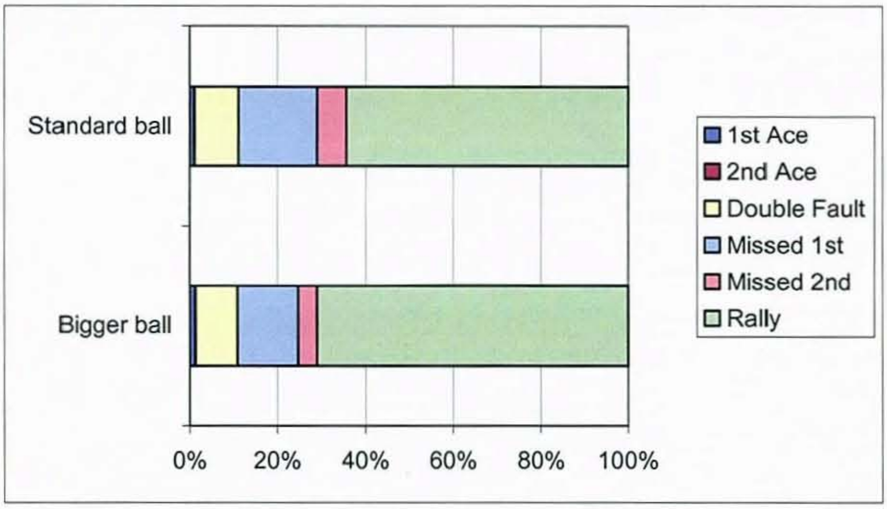


Figure 84: Service outcome per point for women

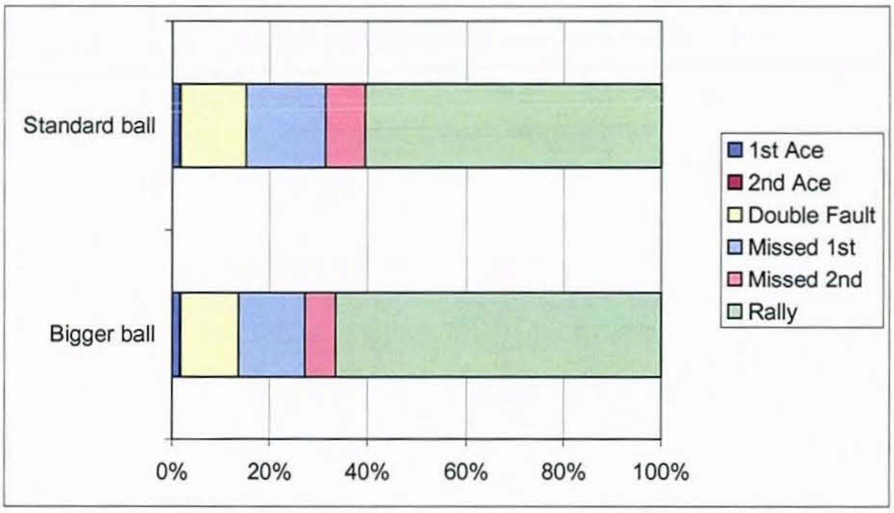


Figure 85: Service outcome per point for men and women combined

Rally Outcome

Although the decrease in service return errors when playing with the bigger ball resulted in proportionally more rallies, when comparing the mean rally outcome (as a percentage per rally) as a result of each ball type, no significant difference was found. The proportion of winners and errors varied little with each ball type. This can clearly be seen in Figure 86. There is however a suggested trend of less balls hit out and more balls hit into the net when using the bigger ball. As suggested in Study A, this is not surprising given the naturally shorter trajectory of the larger ball.

Since the results show no statistically significant differences on rally outcome from playing with the larger ball, it is safe to conclude that only the length and not the nature of the rally outcome is affected by the larger ball.

Figure 86 shows that although the number of rallies resulting in winners and errors increases with the larger ball, due to the increase in total number of rallies, the proportions remain the same.

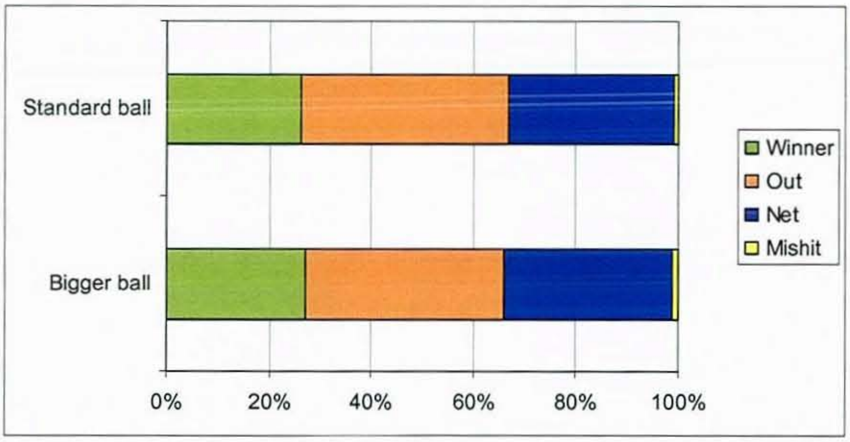


Figure 86: Rally outcome for men and women combined

In summary, when using the bigger ball a greater proportion of points resulted in a rally and the average rally length was increased. It may be harder to hit winners in terms of the effort it takes, but the amount of winners hit was still the same.

4.4.5 Perception

As for Study A (section 3.5.5), the results from the questionnaire are shown as composite bar graphs in the following section. The responses from the men (20 subjects) and women (10 subjects) are indicated using blue and red shading respectively.

The results were analysed for statistical significance both collectively and by gender using two-tailed t-tests with a P value less than 0.05 indicating significance and between 0.05 and 0.1 suggesting a trend towards significance. To do this the five points on the scale were assigned integer values of -2, -1, 0, 1 and 2 from pole to pole respectively.

Racket/ball interaction - Impact severity

When asked to compare the bigger ball with the standard ball in terms of impact severity the responses were inconclusive (Figure 87). 13 players felt the bigger ball was less jarring, 12 players felt it was more jarring and 4 felt they were the same. In the 2000 and 2001 studies there was a trend towards the response that the impact was more jarring.

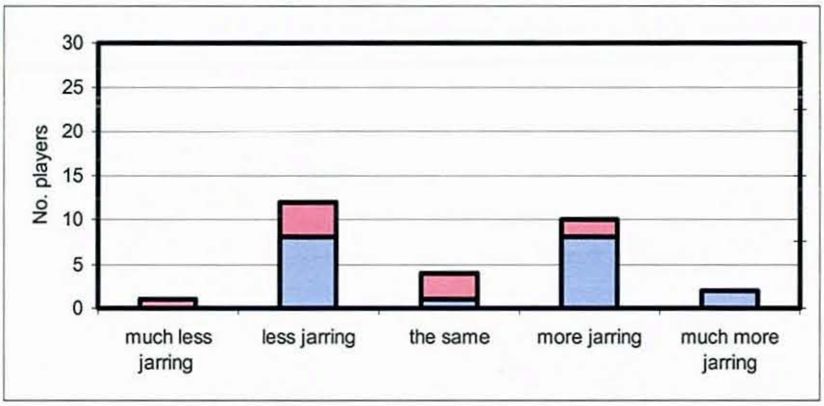


Figure 87: Impact severity

<u>Racket/ball interaction - Impact vibration</u>

With reference to Figure 88, the results indicate no significant difference in perceived impact vibration. 10 players perceived the vibration to be less with the bigger ball, 11 thought the vibration was greater and 9 thought there was no difference. This result was in agreement with the previous study of competitive players. It appears that players of a range of abilities do not feel the bigger ball causes different impact vibration to the standard ball.

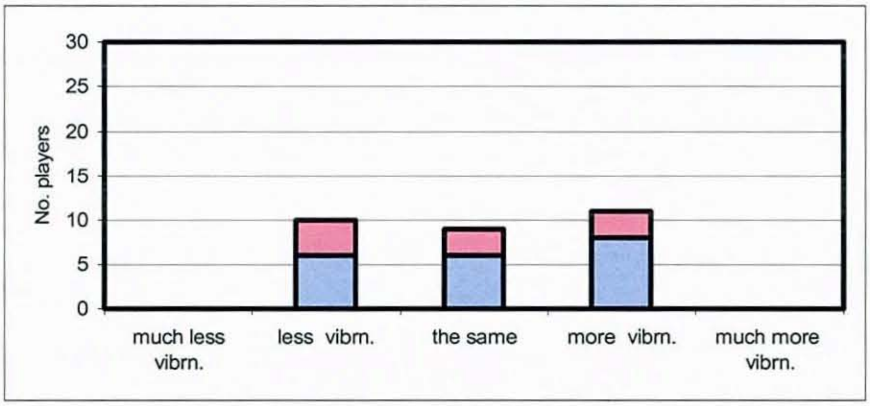


Figure 88: Impact vibration

<u>Racket/ball interaction - Pace generation, control & shot length</u>

Since the larger ball experiences more drag during flight it is not surprising that significantly more players indicated that it was harder to generate pace with the bigger ball (Figure 89). In terms of pace control the players thought the bigger ball was significantly easier to control (Figure 90). In Study A no difference in pace control was reported. When considering the ease with which they could generate shot length, the clear majority (24) indicated it was more difficult (Figure 91).

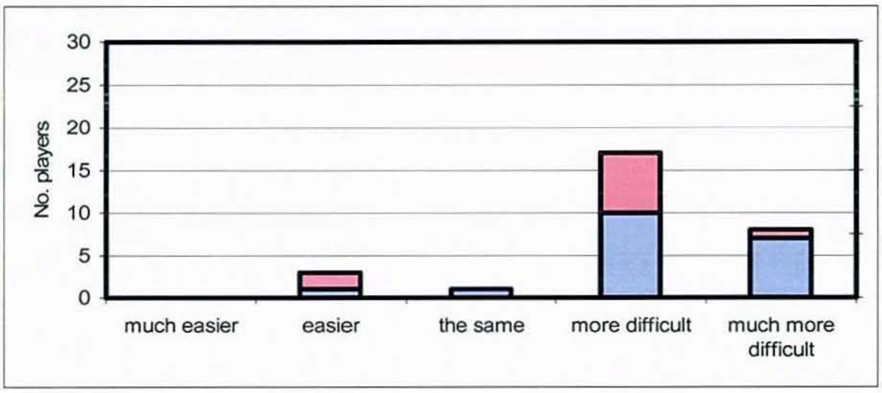


Figure 89: Pace generation

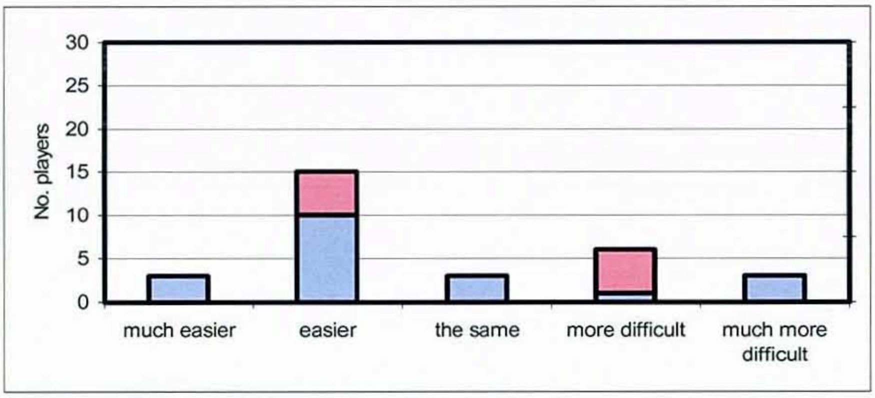


Figure 90: Pace control

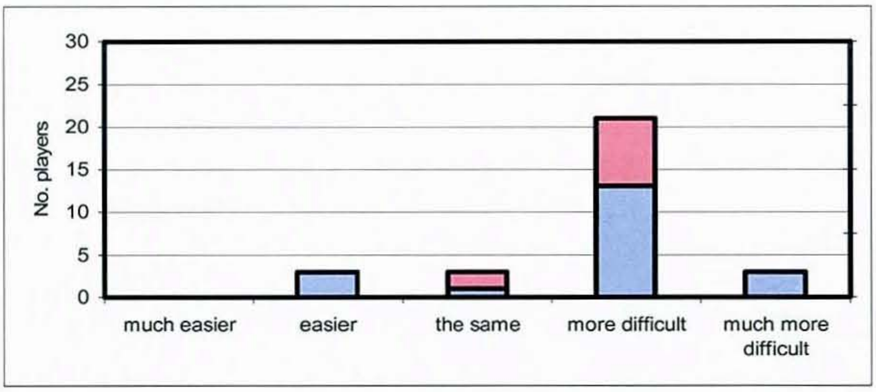


Figure 91: Shot Length

<u>Racket/ball interaction - Spin generation and control</u>

In terms of spin control and spin generation responses were fairly evenly split between easier, the same and more difficult (Figure 92 to Figure 95).

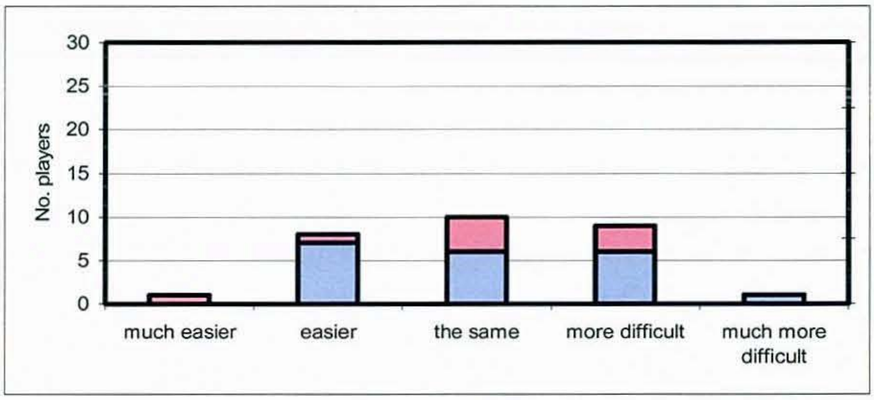


Figure 92: Topspin generation

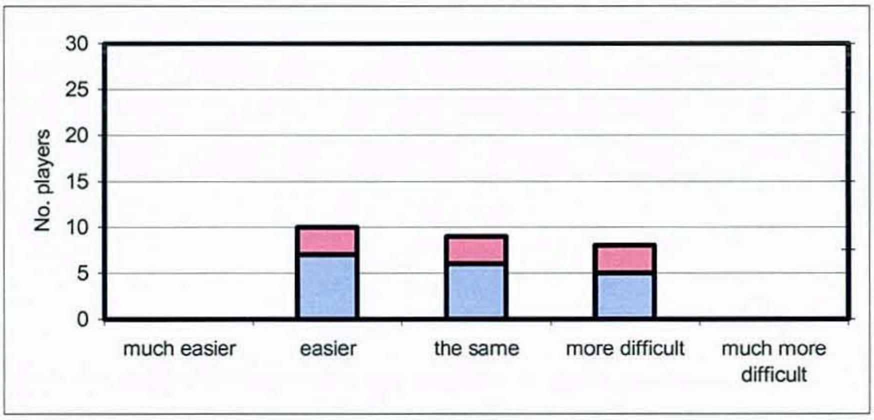


Figure 93: Topspin control

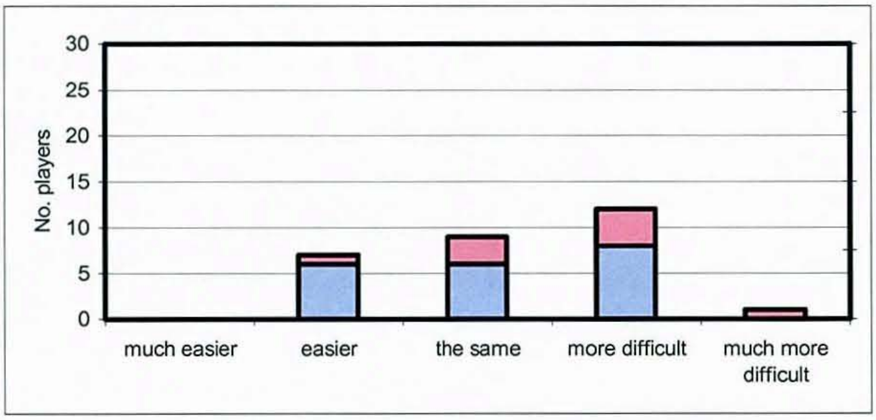


Figure 94: Slice generation

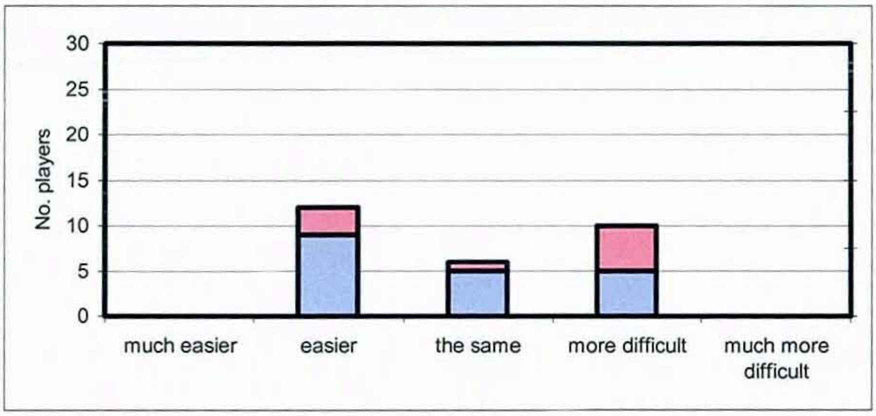


Figure 95: Slice control

<u>Racket/ball interaction - Shot direction & hitting shots in</u>

When asked about their ability to control shot direction with the bigger ball versus the standard ball, no significant difference was indicated, most indicating it was the same (Figure 96). Significantly, more players indicated that it was easier to hit shots 'in' with the bigger ball (Figure 97).

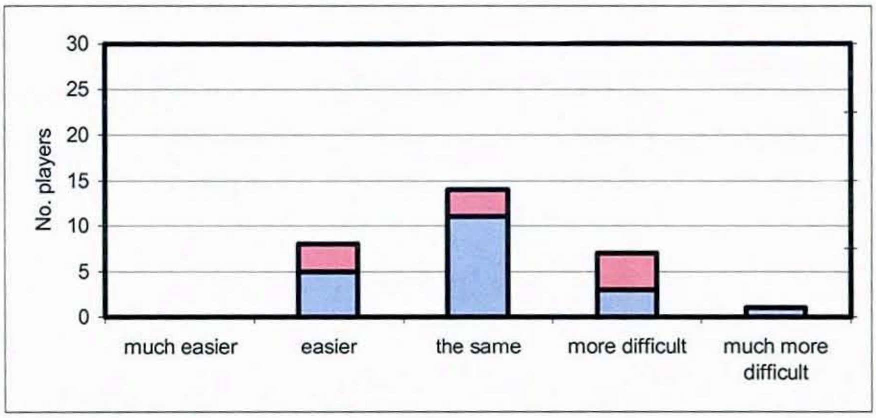


Figure 96: Shot direction

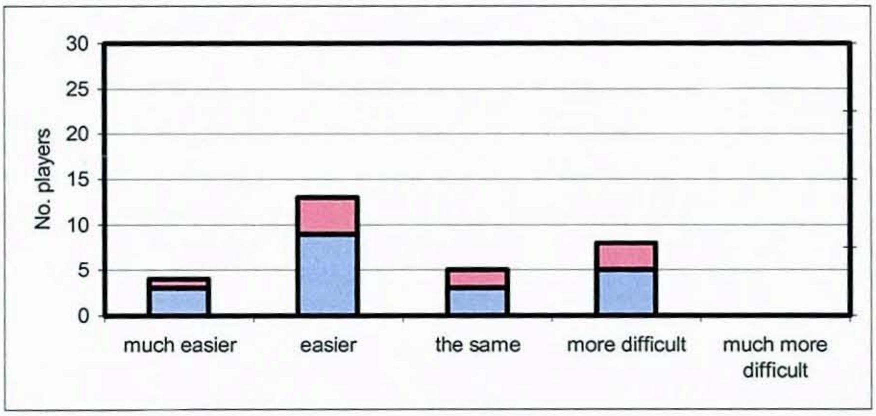


Figure 97: Hitting shots in

Racket/ball interaction - Hit sound

The players unanimously indicated that the bigger ball impact sound was duller compared to the standard ball (Figure 98). There was a significant preference for the sharper sound made by the standard ball (Figure 99).

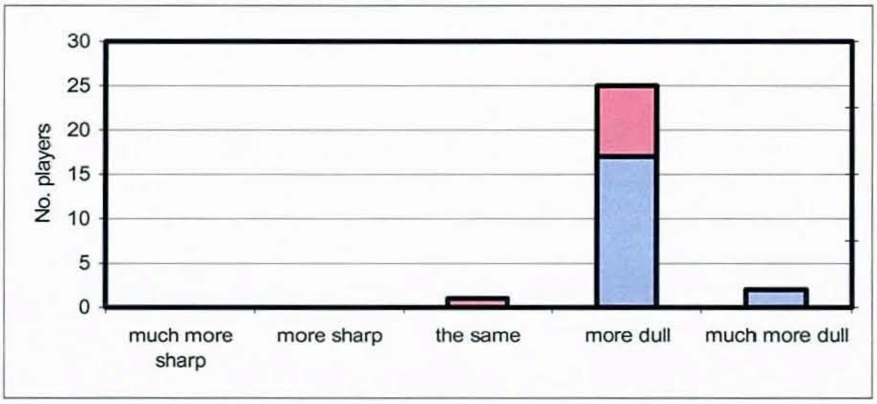


Figure 98: Hit sound

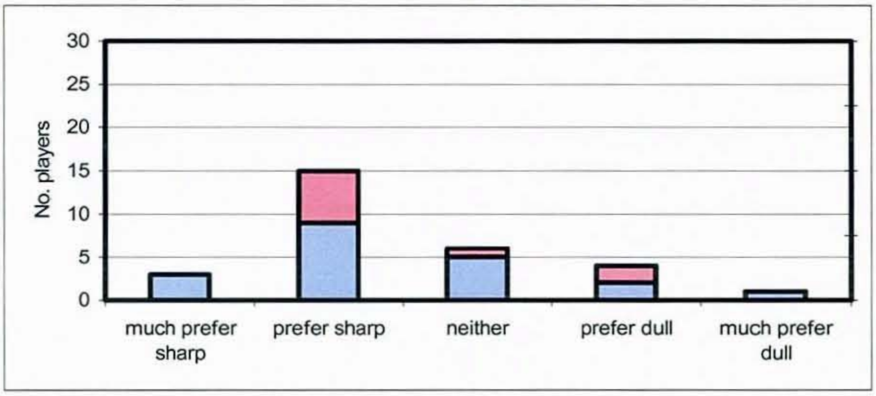


Figure 99: Hit sound preference

Ball/surface interaction - Rebound speed and angle

The players unanimously answered that the larger ball surface rebound speed was slower than the standard ball (Figure 100). Significantly more players felt that the rebound angle of the bigger ball was less steep (Figure 101).

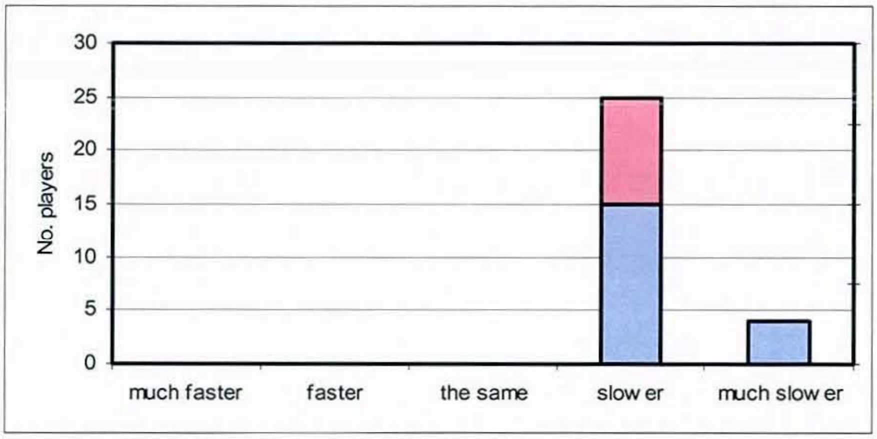


Figure 100: Rebound speed

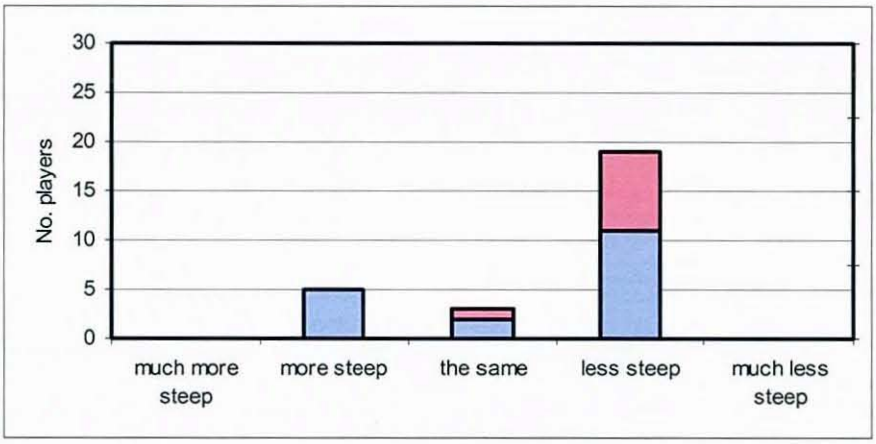


Figure 101: Rebound angle

<u>General properties - Ball mass</u>

The majority of players considered the larger ball to be 'heavier' than the standard ball, although both balls are in fact the same mass (Figure 102).

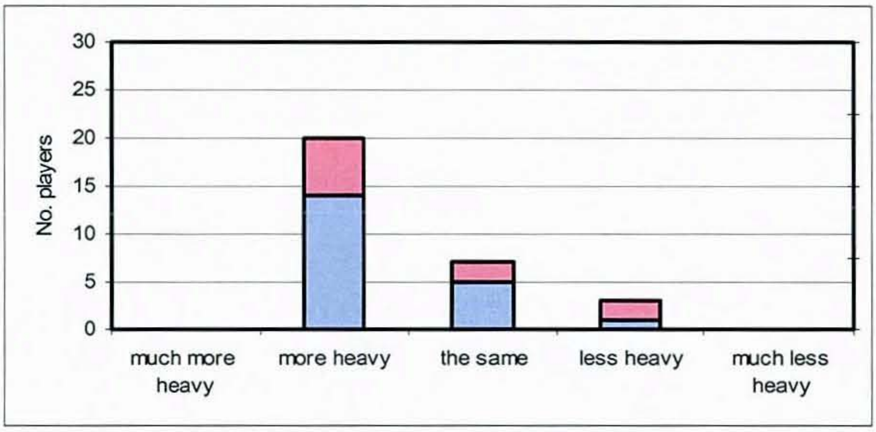


Figure 102: Ball mass

General properties - Ball wear

With responses divided, the players detected no difference in ball durability (Figure 103).

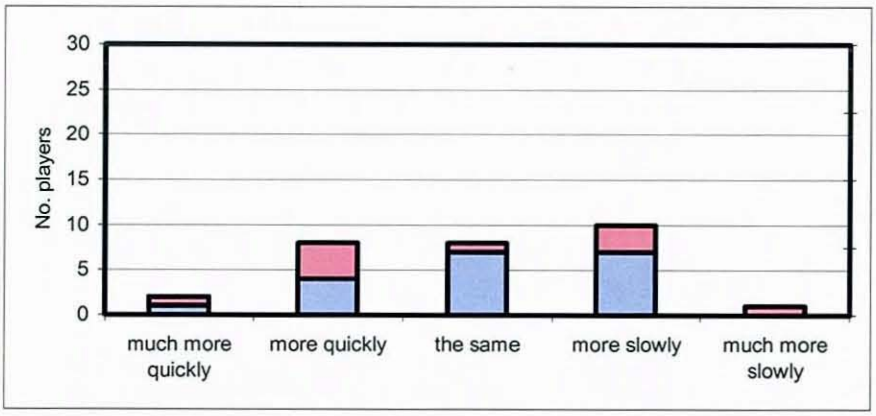


Figure 103: Ball wear

General properties - Ball visibility

Most players (16) indicated that the visibility of the larger ball was the same as the standard ball. 13 players indicated that the larger ball was easier to see (Figure 104). The difference was not significant.

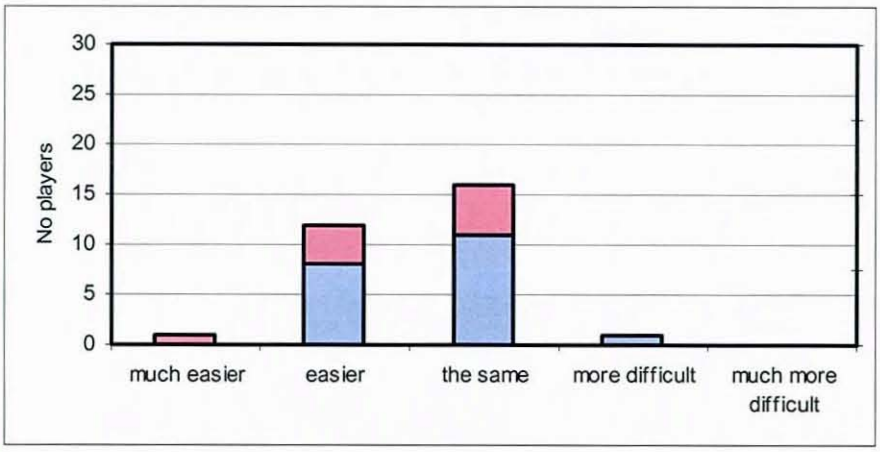


Figure 104: Ball visibility

General properties - Change over time

12 players felt their performance with the bigger ball improved over time, but the majority felt there was no change (Figure 105). Note that 'over time' is defined by the length of the session.

General properties - Ball preference

12 players indicated that they preferred to play with the larger ball, 14 with the standard ball and 4 had no preference (Figure 106). The difference in preference was not significant.

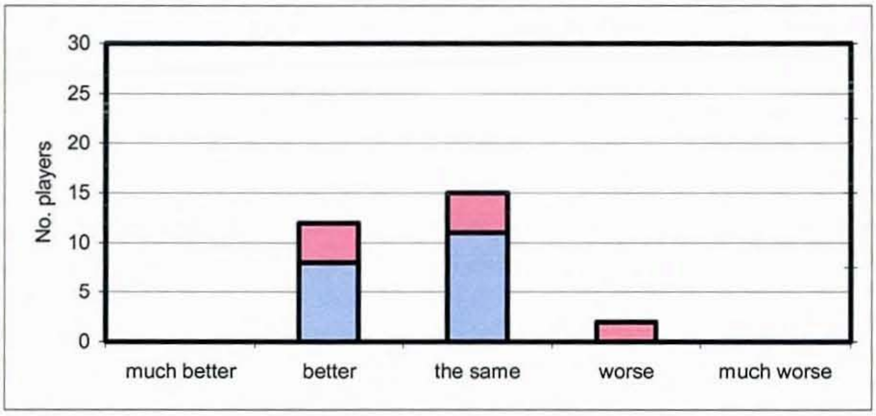


Figure 105: Change over time

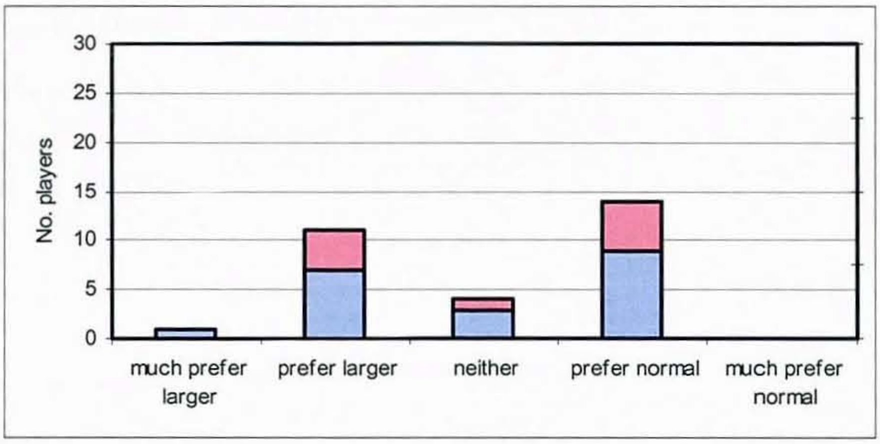


Figure 106: Ball preference

Player Comments

Table 15 lists the additional comments made anonymously by the players about the larger ball on a final section of the player perception questionnaire. The players were asked to comment on what they considered to be the best and worst aspects of the bigger ball. The comments largely mirror the perceptions discussed so far from the questionnaire.

The overall negative view of the ball appears to be that it was hard to hit winners with and required more effort in terms of total shots to do so. The counter argument is that the total number of rally winners actually achieved with the bigger ball was higher due to the greater number of rallies, with the proportion of winners to errors the same for both balls.

The general positive view of the bigger ball was that serves were returned more successfully and the ball was easier to control. There did seem to be a slight difference in overall male and female opinion. In general when asked about the bigger ball the males would answer more negatively with comments such as not being able to hit winners and serves being less effective. The females when questioned generally made positive comments such as serves were easier to return.

Table 15: Player comments with respect to the bigger ball

Positive	*Negative*
"easier to apply spin"	"it felt heavier"
"good for longer and better rallies"	"for hackers"
"could hit at the ball more without it going out which I liked"	"have to hit it harder which makes arms ache after a while"
"had more time to get to the ball"	"hard to hit winners"
"more shots stay in court"	"serves are less effective"
"ball was easier to control and I hit less out"	"hard to put ball away"
"I was more accurate with it"	"hard to hit ball deep"
"I could return the serve much better"	"seemed to lose its bounce"
"I was more consistent with it"	"hard to put pace on it"
"easier to see the ball"	"longer rallies made me tired"
"more of my serves went in"	

4.5 DISCUSSION & CONCLUSIONS

Summary findings from Study B were as follows:

- Ball size appeared to have little effect on either hand-grip performance measures or upper limb muscle soreness in recreational players.
- The number of shots required to determine the outcome of a point was significantly greater with the larger ball.
- The importance of the service game in determining match outcome was diminished when playing with the larger ball.
- Rally composition was independent of ball size, with the proportion of errors and clear winners being unaffected by ball type.
- Match outcome did not appear to be affected by ball size in recreational players playing on acrylic.
- Playing with the bigger ball neither emphasised nor suppressed the distinction between players.
- Players found it more difficult to generate pace with the larger ball.
- Players found the larger ball easier to return, which may be due to the increased time available to prepare for a shot and an improved ability to hit the ball in.

4.5.1 Grip strength

Four aspects of hand-grip performance were measured before and after play with both the standard ball and the larger ball. No significant differences were found in reaction time, rise time, peak force or fatigue rate following play with the larger ball as compared to the standard ball. Peak force values and reaction time values did not vary significantly between the pre and post tests. Rise time and fatigue rate appeared to have increased following the tennis activity, although due to the large standard deviation this finding was not statistically significant. In conclusion, when attempting to detect changes in forearm muscle fatigue, the parameters of rise time and fatigue rate were found to be more sensitive to changes in forearm fatigue than reaction time and peak force. The first team players performed the hand-grip test with greater consistency than the recreational players who exhibited considerable inter and intra-subject variability. This was anticipated and so more than three times the number of subjects were recruited for Study B.

4.5.2 Perceived muscle soreness

Mean muscle soreness ratings did not exceed 20% of maximal soreness, although the inter-subject variability was considerable. When comparing between ball types, the change in muscle soreness (post test value less pre test value) was only significantly different in the deltoid muscle. Mean muscle soreness in the deltoid muscle was lower following play with the larger ball than with the standard ball. The absence of an increase in muscle soreness following play with the larger ball indicated that in the context of this study playing with the bigger ball exerted no additional stress on the arm and shoulder muscles.

4.5.3 Point play outcome

When playing with the larger ball, the number of shots per point was increased. The number of games per match and points per game remained the same. More service returns resulted in a rally ensuing, due to fewer service return errors. The overall proportion of winning shots and errors was unchanged, although there was a trend of fewer balls hit out and more balls hit into the net.

4.5.4 Perception

In general the players' perception of the differences between the bigger and standard balls was in agreement with both theoretical predictions and experimental measures of the ball properties. However, the recreational players in this study as a group were more divided in their responses compared with the subjects of Study A, who were of a higher playing standard. In general the men's responses were more negative about the larger ball than the women's. The players found it harder to generate pace with the bigger ball, but on the whole found it easier to return, particularly in terms of their ability to hit shots in The players found it perceptibly easier to generate spin and to control the bigger ball. Opinion was divided as to which ball the players preferred to play with.

There was notably less evidence at the commencement of the study of negative preconceptions regarding the larger ball in the group of recreational players compared to the first team players in Study A. Whilst some of these players were aware of the existence of the larger ball, they seemed less concerned about how the ball may 'constrain' their efforts and more interested in the potential positive aspects of playing with the larger ball. It is likely that players' opinions on such matters will be related to amongst other things their motivations for playing the game particularly in respect of where they lie on the performance – enjoyment continuum.

4.6 OVERALL DISCUSSION: STUDY A VERSUS STUDY B

Studies A and B provided a valuable insight into the effects of ball size on recreational tennis players, both in terms of player perceptions, the physical demands placed on players and the style of play which results. The studies provided a useful insight into the effects of ball size change on in-play performance, an aspect of testing which is often neglected. The bigger ball appeared to achieve its goals of improving the game without affecting the outcome or increasing muscular soreness. A number of interesting findings have emerged, but design of the studies also possessed a number of limitations that need to be highlighted and addressed.

Firstly, with respect to external validity, it must be remembered that Study A employed a small group of non-professional players, with all tennis played on an indoor acrylic surface. It would therefore be difficult to extend the results obtained under these conditions to professional tour tennis played on grass. In addition, Study A was only able to observe a "first exposure" reaction to the larger balls, although three of the players had used the bigger balls prior to this study and most were familiar with press coverage that the larger ball had received. Whilst it appeared that players adjusted their playing style in response to the different characteristics of the larger ball it was unlikely that this process was completed within the 4 day tennis camp. In other words, prolonged exposure to a larger ball may well yield different results to those obtained in these studies.

Upon commencement of the tennis camps, it became apparent that some of the subjects had already developed negative preconceptions about the bigger ball after reading negative articles appearing in tennis magazines. In general, the male subjects appeared to have more concerns than the female subjects, perhaps because they identify an ability to generate ball speed as more important.

Other factors that should be considered relate to the measures used and the study format. The hand-grip measures, whilst relevant to tennis, only provided an insight into one aspect of muscle function. The endurance characteristics of the arm muscles were not examined.

Furthermore, no direct measures were taken relating to tendon loading or forearm vibration frequencies. In addition, it would be useful to explore upper limb force production across a functional range of movement rather than during a sustained static contraction The problem with taking more functionally relevant measures is that the actual measure can have a fatiguing effect, thereby making it difficult to isolate the effects induced by ball type from those induced by the measurement procedure. In addition, more comprehensive measurement procedures are by definition more intrusive, making player motivation and co-operation more difficult. The study format that was implemented was derived in an attempt to balance sound scientific rigour with a "real tennis" environment. Whilst this was not easy, further attention should be given to ensuring that conditions are standardised when seeking to make standard ball versus large ball comparisons.

In light of the findings of these studies and in an attempt to overcome the limitations outlined, further research was identified as desirable. Conducting research that includes tennis play on grass would provide more transferable data. Ideally a range of players would be utilised to determine whether different levels of player respond differentially to the larger ball. A prospective longitudinal study would allow fully habituated changes to be identified, and increase the certainty with which long-term predictions about risk of injury could be made.

A prospective study is typically used to evaluate the effects of healthcare interventions. In a prospective study, study subjects are divided into groups which are either exposed or not exposed to the intervention(s) of interest before the outcomes have occurred. Randomised controlled trials are always prospective studies whereas case control studies never are. (In contrast to a prospective study, a retrospective study analyses data from previous research.)

Tennis elbow is the most common tennis injury. Due to its high incidence and persistent nature, it should be possible to recruit a group of test subjects with tennis elbow problems to participate in a prospective study to investigate how using alternative tennis equipment might affect tennis elbow. Prospective studies require the ongoing participation and continued commitment of subjects. The duration of prospective studies tends to make them costly to conduct (beyond the scope and resources of this research). Also with prolonged studies it is difficult to maintain adequate control over such factors as diet, conditioning and general health, which requires the use of large sample groups in order to obtain statistically significant results.

The preliminary studies presented in this thesis overcame some of the practical issues associated with prospective studies. Also, there was a concern that the bigger ball might induce greater injury rates, deliberately exposing players to prolonged use would have been unethical without having conducted the preliminary studies.

Future studies may seek to examine both genuine match play scenarios as well as fully controlled research conditions in an attempt to better understand the consequences of playing with a larger ball. This twin track approach is thought most likely to offer the most comprehensive insight into the effects of playing with a larger ball on fast surfaces. It was thus recommended to the ITF that they consider strategic implementation of additional, comprehensive studies, to evaluate and provide information needed to positively promote what appears at first sight to be a beneficial modification to the modern game (i.e. addition of the Type 3 ball).

It is important to remember the context of the findings. The results were relevant to and indicative of the effects likely to be experienced by good quality team players and by recreational players (average age 20). The results were based on exposure to the bigger ball on only two occasions and it was not possible to predict the long-term effects of using the larger ball from these results. The court surface for which the larger ball was proposed and is most suited (grass) was not used in any of the studies. In the case of Study B, the players played for 1 hour 40 minutes in each session, which may not have been long enough for differences in muscle soreness to become detectable.

In the studies, the static hand-grip strength test was used as an indication of level of muscle fatigue. However, this test proved to be insufficiently sensitive and also, particularly in the case of the recreational players, the results showed variability. This was in contrast to previous reports of tennis activity which resulted in reductions in peak grip strength (De Smet and Fabry, 1997; Kramer and Knudson, 1992; McCarthy, 1997; Stratford *et al.*, 1989). The potential reasons for the inconclusive results were identified as (a) insufficient duration/intensity of activity, (b) too much recovery time between finishing the tennis activity and performing the grip test, (c) insincerity/inconsistency of effort (tennis activity or grip test), (d) protocol not specific enough to activity undertaken, (e) device not specific enough to activity undertaken, and (f) no significant difference actually exists between the fatiguing effects of bigger and standard balls.

It was thought important that initial assessment of the effects of playing with the larger ball should be evaluated across a range of issues (grip strength, muscle soreness, point play and player perception). It was also considered that funding/time constraints made necessary simultaneous assessment under realistic tennis play/training conditions. More detailed study of aspects arising from this initial work was always envisaged.

Some of the weaknesses of the initial work are inherent in testing under real play conditions [points (a), (b) and (c)] and may be resolved by adopting a more controlled, simulated play protocol. Other weaknesses [points (d) and (e)] are attributable to the constraints placed on testing using commercially available instruments and may be addressed by developing new devices.

Nonetheless, two studies established that short-term but intense exposure to the larger ball produced no adverse effects on the players, which were measurable using established techniques and commercially available instruments. The benefits to play in terms of point outcome were demonstrated under real play conditions without inducing an adverse perception of playing with the larger ball. All three initial studies (April 2000, Study A and B) discussed have established the scope and direction of further research presented in this thesis and also undertaken by other research groups funded by the ITF and US tennis association.

An improvement in the test protocol would be to carry out the pre test after rather than before the initial warm up.

Although the play period was consistently maintained as a timed period of 30 and 25 minutes for Study A and B respectively, the intensity of play varied depending on the standard and style of play of the opponent. Even against the same opponent, variation was possible between different days of testing. This could not be controlled when part of the study design involved free play. The grip test was not sufficiently tennis specific and was a static test.

Based on the findings of Studies A and B, it was recommended that a test device be developed which is capable of detecting changes in racket hand interaction, especially grip performance during play. Particular attention is to be given to detecting increased fatigue rate (as a potential precursor to injury), although other factors such as changes in shock load or vibration levels due to equipment change are also to be considered. It was considered that such a device might allow inference of possible injury reduction or increase when using alternative tennis equipment.

CHAPTER 5

DESIGN & DEVELOPMENT OF AN INSTRUMENTED TEST RACKET & TEST PROTOCOL

5.1 INTRODUCTION

Research has shown maximal isometric hand-grip strength to be indicative of forearm muscle status. (Bohannon, 1990; Chinn *et al.*, 1974; Strizak *et al.*, 1983). Tennis elbow causes a functional degradation of the forearm muscles, enabling a reduction of maximal hand-grip strength to be used in diagnosis of the condition (Burton, 1984; De Smet and Fabry, 1997; Stratford *et al*, 1989). A reduction in grip strength has also been demonstrated to result from volitional fatigue in a group of skilled tennis players (non-injured) playing simulated match play tennis (McCarthy, 1997). Other studies (Davey *et al*, 2002; McCarthy, 1997; Vergauwen *et al.*, 1998) have shown that shot accuracy decreases as a result of fatigue. Several mechanisms for this have been suggested, one of which is a possible change in hand function due to forearm muscle fatigue.

The research reported in Chapters 3 and 4 was concerned with the effects of playing tennis with Type 3 larger balls as compared with Type 2 standard balls. It was hypothesised that when playing tennis with the Type 3 larger ball, players may experience relatively different (greater) loadings than when playing with the standard ball. If this was the case, then a relative increase in grip fatigue and corresponding decrease in grip strength (or change in other derived measures from the grip force time profile) were expected to occur. The finding that there appeared to be no nett difference indicates there was no relative difference in loading between the two ball types and this was encouraging and important to the ITF. There was certainly no indication for concern regarding playing with the Type 3 larger ball. On the other hand, the tests employed may have lacked sufficient sensitivity to detect small differences.

Whilst the static hand-grip dynamometer test gave promising results, its effectiveness was found to be limited to testing for large changes, for example, reduction of hand-grip strength in situations of high levels of muscular fatigue. It was suspected that it may lack the sensitivity to detect relatively small changes in forearm muscle status and for this reason an improved test was sought. The findings of the earlier studies highlighted an opportunity to direct the project towards researching novel instrumentation and protocols for more sensitively measuring effects of equipment modification on tennis players. A decision was taken to focus on researching the specific effects of equipment changes on muscle soreness and fatigue, as indicated by in-play dynamic grip activity.

The remaining research reported in this thesis has investigated the feasibility of measuring in-play dynamic grip performance during a test protocol designed to induce accelerated localised fatigue. It was proposed that in-play measurements should be more sensitive at detecting changes, since they would eliminate the recovery associated with an off-court test such as the static hand-grip test. Previous tests have indicated that transient elements of grip performance showed greater change than other measures (e.g. peak force) and so a test involving activity specific contraction as opposed to a maximal isometric contraction may well increase the diagnostic potential of the device. Development of a method to sensitively and reliably measure in-play grip activity would enable investigation of the effectiveness of alternative candidate interventions designed to reduce player fatigue. If one piece of tennis equipment can be identified as causing a degradation in grip strength sooner than another, it might be deduced that prolonged exposure to this equipment may exacerbate any contribution to overuse injuries such as tennis elbow. Conversely, design modifications proven to reduce the rate of fatigue may be expected to help prevent injury.

It was proposed that successful introduction of a new measurement method would lead to new knowledge in the area of equipment modification for injury prevention, an area which tennis equipment manufacturers are currently keen to target. Although studies exist that have investigated aspects of in-play grip pressure and vibration, generally only one measure, for example, grip performance, force or vibration has previously been employed at one time and the effects of fatigue have been neglected. The novelty of the approach proposed in this thesis has been to take simultaneous measurements of grip force, vibration and shock loading under controlled conditions of fatigue, leading to a more thorough understanding of the associated phenomena. It is thought likely that most tennis elbow damage occurs when the muscles are fatigued. A particular requirement has been to try and measure changes occurring to grip characteristics as tennis players become tired, something that has not previously been done.

Two aspects were involved in the proposed approach:

1. Selection of instrumentation equipment and the design and development of an instrumented racket.
2. Development of a controlled test protocol designed to induce accelerated fatigue in the functionally relevant muscles symptomatically involved in tennis elbow.

The rest of this chapter provides a detailed description of these two aspects. Chapter 6 then reports on the application of the instrumentation and protocol within a study.

5.2 IN-PLAY MEASURING DEVICE REQUIREMENTS

5.2.1 Introduction

A dynamic, in-play measurement device was proposed as an improvement to the static hand-grip dynamometer test utilised in the ITF sponsored studies. Furthermore, it was proposed that it would be possible to develop an in-play measurement device through the smart application of available technology. The functional requirements for this in-play measurement device are discussed in this section, the main requirements being identified as the ability to:

- measure characteristics of grip pressure in preparation for ball impact and in response to impact
- measure characteristics of racket vibration amplitude and decay in the grip region
- make dynamic, in-play measurements
- quantify effects over time, due to fatigue
- measure the relative effects of alternative equipment, or other variable interventions, for example, ball type.
- a maximum equipment budget of approximately £20,000 was available

These requirements are discussed in more detail below, consideration firstly being given to the measurement of grip pressure and secondly to the measurement of vibration and shock loading.

5.2.2 Requirements for measuring grip pressure

It was a requirement to measure in-play grip pressure exerted on the tennis racket handle. Measurement of grip activity and dynamic grip response during prolonged exposure was required to investigate possible changes under fatigue conditions. Manufacturers of tennis equipment would like to be able to offer equipment that can delay or reduce the onset of these fatigue induced changes. Sensitive and repeatable measurement of grip activity is required to enable investigation of the relative effects of equipment modification, or indeed of any other intervention, for example, technique modification or conditioning regime. A further use for the identification of fatigue induced changes could be to provide an early warning indicator of conditions likely to be damaging, for example, during a training session if a player is particularly tired and would be better advised to rest.

An important requirement for any grip pressure measurement device was that it must be relatively unobtrusive to enable its positioning on the tennis racket handle in a way not to significantly alter the feel or performance of the tennis racket. This required it to be lightweight, not bulky and ideally wireless. In order to detect any sudden changes in grip pressure without loss of information, asampling frequency above a predictable minimum value must be used. The minimum value is termed the Nyquist Limit and the Shannon-Nyquist theorem states that to avoid a loss of information a signal should be sampled at a frequency of at least twice the highest frequency component present in the signal. In this application, sampling frequency should be viewed in the context of the ball-on-racket contact duration, which is typically as low as 4 milliseconds. This would mean that if a sampling frequency of 250 Hz or less is used, at most one sample would be taken whilst the ball is actually in contact with the strings. Following impact with a ball, significant racket frame vibration continues for approximately ten times the contact time, i e. for approximately 40 milliseconds. A sampling frequency of 250 Hz would therefore result in nine or ten samples being taken during this decay period. Whilst consideration of the ball contact time and the frame vibration decay time were important, the grip pressure measurement was primarily designed to measure the changing grip activity of the player. In the context of measuring a player's grip pressure, consideration of the shock loading and vibration resulting from the ball impact were also important.

In selecting equipment to measure grip pressure, the primary requirement was to consider the physical characteristics of the grip itself. Maximum grip strength was important because it determined the required range of the grip pressure sensor. Grip pressure is dependent on grip force and also upon the contact area and distribution profile of that force. Mean grip force reported in the literature for tennis players is typically in the range 50 to 55 kgf for men and 30 to 39 kgf for women (Bowyer *et al.*, 2001; Chinn *et al.*, 1974; Kramer and Knudson, 1992; McCarthy, 1997; Mitchell and Caine, 2000; Mitchell *et al.*, 2001). Another important characteristic was the rise and fall gradient of grip pressure changes. If grip pressure changes from low to high and back to low again very quickly then equipment with a higher sampling frequency would be required than if all changes occur gradually and with few changes of direction. For reference, the NK static hand-grip dynamometer operates with a sampling frequency of 60 Hz. It was considered important to select pressure sensor equipment with a sampling frequency of at least this order of magnitude. Sensor coverage was another important consideration. There is typically a trade off between sensor coverage and sampling frequency, more coverage requires more individual pressure cells and reduces the sampling frequency of each particular pressure cell. At the early stages of instrumented racket development and testing, the main aim was to achieve sensor coverage under the entire hand to enable identification of the regions of greatest activity. Having mapped the pressure across the whole hand, future developments might involve the use and strategic positioning of fewer sensors of greater sampling frequency to provide greater sampling resolution of smaller focussed areas.

To possess adequate sensing capabilities for the measuring task in hand, the selected sensor system had to exhibit several basic characteristics. Sensor resolution determines the physical limit of a sensor's sensitivity and can be considered in four ways. Firstly, the signal resolution of individual sensor cells had to be sufficiently high. All sensor signals, whether digital or analogue, are ultimately processed by a data acquisition system and converted into digital signals. Digital signals only exist at particular discrete levels and signal resolution determines the level of granularity of this signal. Good design practice recommends using sensors with a signal resolution that is at least ten times greater than the smallest increment of change to be measured. Secondly, the spatial resolution of sensor cells across the whole area of the sensor determines the level of localised detail that will be seen on the pressure distribution map across the contact area of the hand on the racket handle. Thirdly, the temporal resolution relates to the frequency at which the sensor is sampled (see above) and fourthly the spectral resolution refers to the ability of a sensor to define fine wavelength intervals.

Sensor repeatability was another important characteristic. The repeatability of a sensor measures its ability to consistently provide the same reading each time the same load is applied. A sensor signal might exhibit a certain amount of erratic error, or it might tend to systematically drift over time, caused, for example, by thermal effects. Repeatability is probably the single most important characteristic for sensors being used in comparative studies.

Sensor linearity describes how proportional a sensor signal is to changes in the input stimulus. If operation of a sensor is based on a physical phenomenon that is non-linear, this can be compensated for by applying a transfer function at the signal conditioning stage. The important consideration about non-linearity is that it can restrict the ability of sensors to working effectively over a particular range.

Sensor accuracy is a measure of a sensor's ability to return a correctly calibrated measurement value. Evidence of a sensor's accuracy may be supported by a manufacturer's calibration test certificate. Some sensors require initial calibration and periodic recalibration may be recommended. Achievement of consistently high accuracy requires good repeatability and correct calibration.

Sensor hysteresis is a measure of the responsiveness of a sensor to a changing input stimulus. A low hysteresis is desirable, which indicates that the sensor can 'keep up' with rapid changes. A high hysteresis results in any sharp peaks or troughs in the signal being reduced in size and 'rounded off'. It also introduces a lag in the measured signal level compared to the actual input stimulus. Suitable pressure sensors must be capable of measuring absolute pressure as opposed to just the transient components.

Ideally grip pressure would be assessed across the whole contact area. In fulfilling this requirement, the pressure sensor was required to accommodate the shape of the tennis racket handle, which is characterised by an octagonal cross-section and flaring to an increased diameter at the butt end.

5.2.3 Requirements for measuring vibration & shock loading

Shock loading refers to the sudden rapid acceleration of the racket-arm system in response to a ball impact. Shock loading results in racket deformation, which causes shock waves and vibrations to be induced in a tennis racket. Following initial ball impact and racket deformation, a significant level of vibration persists for a decay period of typically 40 milliseconds. With reference to the literature, various research has considered the extent to which racket response can be modelled in isolation from a player. Some studies have shown that the tighter the grip pressure, the greater the transmission of the vibration up through a player's arm and the greater the vibration attenuation in the racket. Static studies have shown that vibration magnitude and attenuation correlates with grip firmness. The hypothesis was that an ability to measure changes over time in racket vibration amplitude and decay rate would be indicative of changes in grip firmness and thereby indicate grip fatigue. Furthermore, racket vibration has also been shown to be related to impact location. One of the outcomes of fatigue may be that a greater proportion of shots are mishit, resulting in a greater loading of the muscles. These factors were investigated in the research study by instrumenting a tennis racket with accelerometers.

An important requirement was that the accelerometers had to be relatively unobtrusive and be sited on the tennis racket in a way not to significantly alter its feel or performance. The accelerometers were required to be lightweight, not bulky and ideally wireless. Sampling frequency had to be sufficiently high to detect any sudden changes in acceleration. Returning to the above discussion of ball impact time and subsequent vibration decay period, the time periods involved are very short; approximately 4 milliseconds and 40 milliseconds respectively. Utilising a relatively high sampling frequency of 2000 Hz would still only provide approximately eight samples whilst the ball was in contact with the string bed. A sampling frequency of 2000 Hz was considered to be at the minimum end of acceptability for the purposes of characterising the transient acceleration effects of ball contact. Other considerations of sensor resolution, repeatability, linearity, accuracy and hysteresis also applied to the selection of accelerometers as they did to grip pressure sensors.

5.3 REVIEW OF INSTRUMENTATION TECHNOLOGIES

Over the last decade, rapid advancements have been made in sensor technology and data acquisition systems. On commencing this research study, it was not known if current technology could be found to enable the instrumentation of a tennis racket in a sufficiently unobtrusive manner. However, this work was commenced in the knowledge that if suitable technology does not currently exist, then present rapid advancements in technology will surely mean that it will become possible in the near future. It was recognised that in part this present research investigation was to act as a feasibility study, identifying what is currently achievable but, more importantly, establishing a direction for future developments.

5.3.1 Review of pressure sensor technologies

Pressure sensor technologies were sought which would provide a measure of the pressure distribution across the whole hand in contact with the tennis racket handle. A selection of the candidate technologies are briefly reviewed in this section to provide an overview of the types of systems which are available and the limitations which many exhibit.

Force Sensitive Applications has a pressure sensor system that is based on piezoresistive technology, which means that the resistance changes with applied pressure (FSA, 2003). FSA utilises a proprietary piezoresistive semi-conductive polymer sandwiched between two layers of highly conductive rip stop nylon fabric. This sandwich has a protective cover of polyurethane and the whole is encased in a stretchy Lycra cover. Changes in resistance resulting from different pressures on the semi-conductor are interpreted by an interface module, the pressure map being displayed as an array of coloured cells on a personal computer. The FSA system was unsuitable for instrumenting a tennis racket handle due to its bulk.

The footscan® insole system from RSscan International is a thin and flexible in-shoe pressure measurement device, which is designed for use in gait analysis during, for example, walking, running, skiing or skating (RSScan, 2003). For the purposes of the current research study, a significant feature of the 'footscan' system is its ability to be triggered by a remote controller, allowing testing in real life situations. The user has the choice between a 100 Hz data logger, measuring at 100 Hz during 40 seconds, or a 500 Hz data logger, measuring at 500 Hz during 8 seconds. For use in tennis racket grip pressure measurement, a drawback of the footscan system is that the sensors are foot shaped and a customised sensor would be required. Another shortcoming is that it only supports eight individual pressure sensor cells, which is an insufficient number to enable the total hand pressure to be mapped.

Sensor Products Inc. (SPI) supplies a range of different products to measure pressure (SPI, 2003). One class of product is a pressure indicating sensor film, two different brands being marketed; Fuji prescale film and Pressurex. Both these sensor films are supplied as a large, thin, page-sized sheet of microencapsulated Mylar film. When the sensor film is placed between mating surfaces and force is applied, it instantaneously and permanently changes colour, the shade of this colour being proportional to the amount of force applied, allowing quantification of the contact stress. Although relatively inexpensive and offering excellent spatial resolution (5 to 15 microns) and good accuracy (+/-2%) this class of product has a particular shortcoming of only recording maximum contact pressure as opposed to a pressure-time history. Furthermore, it can only be used once and cannot be reset.

Sensor Products Inc. also supplies an electronic force and pressure indicating sensor, marketed under the trade name Tactilus, which enables contact pressure to be monitored in real-time.

This system offers a sensor pad which can vary in size from 25 mm x 25 mm up to 2000 mm x 810 mm and which is thin (0.48 mm) and said to be flexible, durable and of high resolution. A maximum sensor query rate of 60,000 sensor points per second is possible. Accuracy is claimed to be "approximately +/-10%". This system was not available for trial use and the cost exceeded the project budget. The sensors available were not as well matched to the shape of the racket handle compared to the 'trimmable' sensors offered with the Tekscan system (see below).

Novel Gmbh supplies a system called Pliance, which is specifically designed to measure pressure distribution on and between soft and curved surfaces (Novel, 2002). The system consists of a flexible and elastic measuring mat, multi-channel analyser, calibration device and software package. The measurement mats are available in various sizes, sensor configurations and pressure ranges. The Novel systems utilise capacitive sensors and the individual sensor cells are elastic and arranged in a matrix, which moulds easily to 3-dimensional shapes. There are several different standard shapes of sensor with different numbers of sensor cells and customised sensors can be supplied. A high degree of spatial resolution is possible, for example, one sensor option is a 225 mm x 225 mm mat with 45 x 45 (i.e. 2025) sensor cells arranged on a 5 mm grid. The sensor matrix is connected either to a Novel Pliance mobile electronic hardware, which accepts a maximum number of 256 sensor elements, or to a Pliance-ftm analyser, which accepts up to 12,000 sensor elements. Both these data capture devices sample at a rate of 10,000 sensor points per second, which if combined with a high number of sensor points can result in a low sample rate per sensor per second. A further disadvantage of this system is that the sensor mats have a minimum bend radius of 40mm, which makes them unsuitable for wrapping around a tennis racket handle with its eight flat faces and relatively sharp corners.

Tekscan Inc. has a stated intention of delivering the most advanced thin-film tactile pressure and force sensors, systems, and enabling electronics (Tekscan, 2003). Tekscan's matrix-based systems provide an array of force sensitive cells that enable the measurement of pressure distribution between the two surfaces. A standard sensor consists of two thin, flexible polyester sheets, which have electrically conductive electrodes deposited in varying patterns. Tekscan appears to provide the highest resolution matrix-based products available on the market. Sensing locations within a matrix can be as small as 0.14 mm^2, which equates to a sensor density of up to 170 sensing points per square centimetre. Tekscan has also created sensors covering 1,600 square centimetres with over 100,000 sensing locations. Available sampling frequency is equally impressive. Tekscan has custom manufactured systems which sample 100,000 sensors at 500 Hz, which equates to 50,000,000 sensor point samples per second. Tekscan sensors are thin (approximately 0.1 mm), flexible and can be cut to size to suit the application. Tekscan continues to develop new products, a recent addition being the F-Scan Mobile, which enables pressure/force movies to be recorded without cables extending between the PC and subject The F-Scan Mobile features fast sampling speeds of up to 500 times per second (500 Hz), at a rate of 960,000 sensing elements per second. This is complimented by a large data file recording capacity, providing onboard storage for pressure movie recordings of up to 20,000 frames, equivalent to 40 seconds of activity. Following data capture, data can be subsequently transferred to a PC for analysis via a USB link.

Development of custom-made sensors suitable for this application were available from Tekscan, RSscan and Novel Gmbh but due to time and cost constraints this was not a viable option. In the case of the selected system (Tekscan), if the off-the-shelf sensors showed potential in this study then it would warrant at the next stage of development further investment in a customised sensor specific to the application.

5.3.2 Review of accelerometer technologies

A large portion of commercially available accelerometers are of the piezoelectric or piezoresistive types (Serridge and Torben, 1987). Each of these types of accelerometers uses the electrical properties of its piezoelectric/piezoresistive materials as the primary transducer component. A piezoelectric material is defined as a material that develops an electric charge when subjected to a force. Piezoelectric materials transform mechanical work input into electrical charge and vice versa. Piezoelectric accelerometers may be considered 'active devices' since they generate their own signals, and theoretically don't need to be powered. Since piezoelectric sensors require physical work to generate an electrical output, they cannot respond to steady-state inputs; hence, piezoelectric accelerometers are referred to as AC-response sensors. Most piezoelectric accelerometers will only operate above a certain threshold frequency, and are not suitable for applications in which input acceleration and frequency ranges are both relatively small.

In comparison, piezoresistive accelerometers act as both AC- and DC-response sensors. Piezoresistive materials have the property of changing their resistance under physical pressure or mechanical work. If a piezoresistive material is strained or deflected, its internal resistance will change and will stay changed until the material's original position is restored. In order to detect this change in resistance, an additional power supply is necessary. Piezoresistive accelerometers may be considered 'passive devices', because they don't actively generate an electrical signal in response to an input stimulus. Piezoresistive accelerometers have an advantage over other types, in that they are not as adversely affected by electromagnetic fields. One problem with piezoresistive materials is that they are temperature-sensitive, which adversely affects the repeatability of a piezoresistive accelerometer.

Vibrations can be investigated in the 'time domain', which shows how the amplitude of vibration changes with time, i.e. the time history. Vibrations can also be considered in the 'frequency domain', which describes the vibration in terms of its peak amplitude through the frequency spectrum. Previous research has demonstrated accelerometers are capable of measuring the level and frequency of vibrations experienced at the hand/racket interface, as long as the accelerometer has the correct frequency and dynamic range. In practice, piezoelectric accelerometers are available across wide frequency and dynamic ranges and it should always be possible to find a particular type for any vibration measurement.

Piezoelectric accelerometers were used in this research study to instrument the tennis racket, this type being selected over piezoresistive for practical reasons of cost and availability. The advantage of a piezoresistive accelerometer is that it would have measured the overall acceleration profile of the racket swing (DC component) as well as the AC vibration component. However, the piezoelectric triaxial accelerometer was smaller than the piezoresistive equivalent enabling it to be built into the centre of the grip.

5.4 DESIGN SOLUTIONS

5.4.1 Instrumented racket handle or glove-based system?

Instrumentation of grip pressure could potentially have been achieved by two different approaches, firstly by attaching the grip pressure sensors to the tennis racket handle, or secondly by attaching them to a player's hand. Attaching sensors to a player's hand would most easily be achieved by a glove-based system. This would be an extension of an approach used in several studies in which small sensors were attached to the hand. Some of these studies were industrial in nature and investigated the loading on hands during the operation of machinery (Griffin, 1990). Sensors have also been attached to the hand in golf research, which is appropriate because players generally wear a glove whilst playing golf. In comparison, tennis players do not wear a glove and it was considered that adopting a glove approach to instrumentation may interfere too much with 'feel', which may in turn affect the grip pressure that players exert on the racket during a shot. Furthermore, there was concern that wearing a glove may cause sensory confusion to an extent that it results in the inadvertent adoption of a different grip position, thus distorting the results. Another problem of instrumenting the hand rather than the racket handle is that the racket handle surface is not uniform, being comprised of eight flat faces that meet at angled edges. If a sensor attached to a hand happens to be pressed against an edge, the pressure would be artificially raised. In comparison, golf club grips tend to be of circular cross-section and so this problem would not arise.

A glove system would have the advantage of being more easily transferable between different rackets. It would also cope better with small adjustments to a player's grip, subject to the limitations of the racket handle flat face/edge issue. A glove system would provide better information about where in relation to the hand the loading is occurring, which would help in relating it to possible injury effects. The reality of tennis is that players do adjust their grip according to the shot being played, which would present a problem to a glove-based system.

The ideal situation would be to develop an instrumentation device capable of measuring the continual loading on the hand throughout a 'real' rally of different shots, rather than being confined to a single test shot. Based on the above factors, together with implementation considerations of the available technologies, it was decided to opt for instrumenting a tennis racket handle, as opposed to using a glove-based system.

5.4.2 Pressure sensor implementation

A Tekscan pressure measurement system was selected for use in the research study. An F-Scan system was used in conjunction with a pressure sensor measuring 76 mm x 203 mm and having a matrix of 6 x 16 pressure sensor cells, i.e. a total of 96 cells. The selected sensor was appropriate in size and shape to the tennis racket grip dimensions and had the advantage of being 'trimmable' into six strips. This was an 'off the shelf' sensor and was immediately available and within budget. A sample rate of 200Hz was utilised for each of the 96 sensor cells, this being the highest sampling rate available for this system and sensor. Figure 107 shows a Tekscan sensor.

Figure 107: Tekscan pressure sensor

The potential problem of having to wrap the Tekscan sensor around the edges between successive flat faces of the racket handle was overcome by cutting the sensor into six fingers, which were fitted to six of the eight handle faces. Two of the eight faces of the racket handle were not instrumented. A solution to this limitation was tested whereby two cuffs and two sensors were used simultaneously, providing sensor coverage to all eight faces of the racket handle. This approach was subsequently rejected at the pilot stage as it proved too cumbersome to the player to have two cuffs secured to the forearm during the stroke (see Figure 117 for image of cuff placement on subject arm).

Determination of which two faces to leave out was made on the basis of which faces were least active, which was largely determined by shot type, a single handed slice backhand in this case.

The most common grip for the slice backhand is the Eastern Backhand, with the wrist slightly cocked. The stance should be sideways to the net with the feet parallel at approximately shoulder width. The base knuckle (where index finger meets hand) is placed on the top flat face of the racket handle, with the thumb along the left side face to give support. The most essential element of the stroke is that there is no break in the wrist or forearm at contact. Starting from the cocked position on the backswing, the racket is thrust forward until the arm is completely straight (Roetert and Groppel, 2001).

The slice backhand shot is a useful defensive shot to play particularly when the player is pulled wide off the court; it allows the player more time to get back into position in the centre of the court. It is also an effective shot to use when approaching the net, known as the "chip and charge" strategy, although not as common in the modern high speed game.

Players participating in the study were asked to demonstrate the single handed slice backhand grip they would use and a picture was taken of this and inspected. An example of one of these pictures is shown in Figure 108.

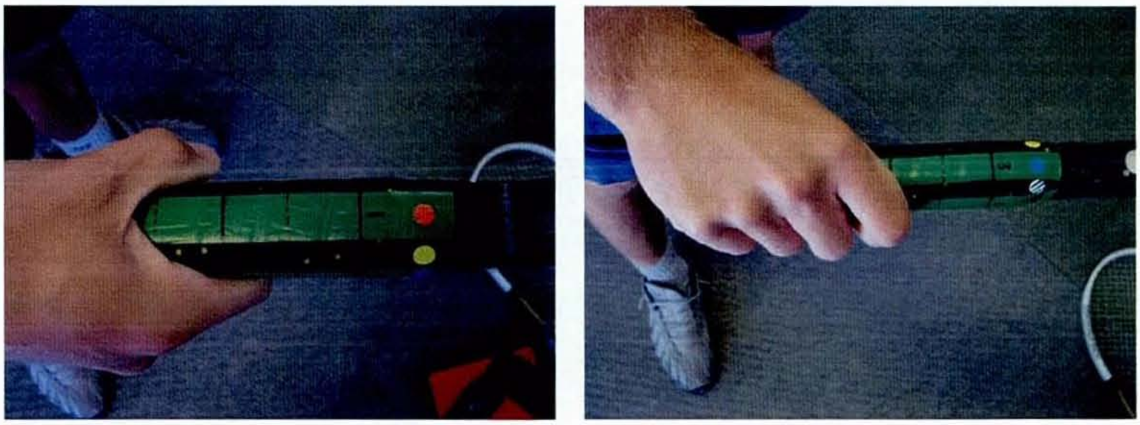


Figure 108: Grip technique for single handed slice backhand

A prototype racket was used for practice placement of the sensor. Six subjects were asked to hit some backhand shots in a laboratory hitting enclosure and various sensor placements were experimented with. Following a period of pilot iteration including a combination of knowledge of technique, inspection of hand placement and advice from the University coach, it was decided that the two faces to leave uncovered should be the bottom face and bottom front face. Relative to the other faces these two were the least 'active' during the slice backhand test shots. Figure 109 illustrates which six of the eight faces of the racket handle were instrumented.

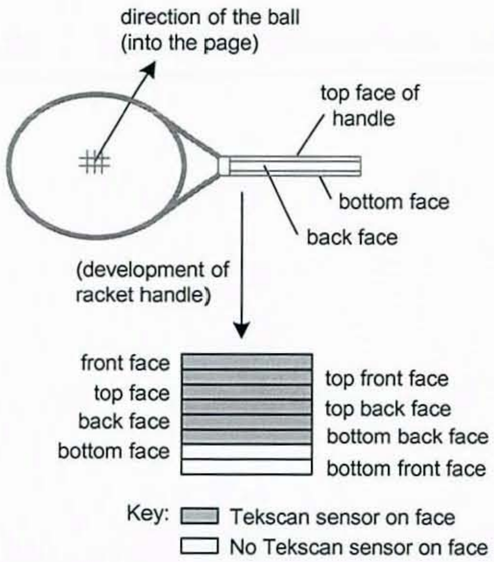


Figure 109: Instrumented faces of the racket handle

Calibration of the Tekscan system was achieved by utilising a special purpose calibration rig, shown in Figure 110.

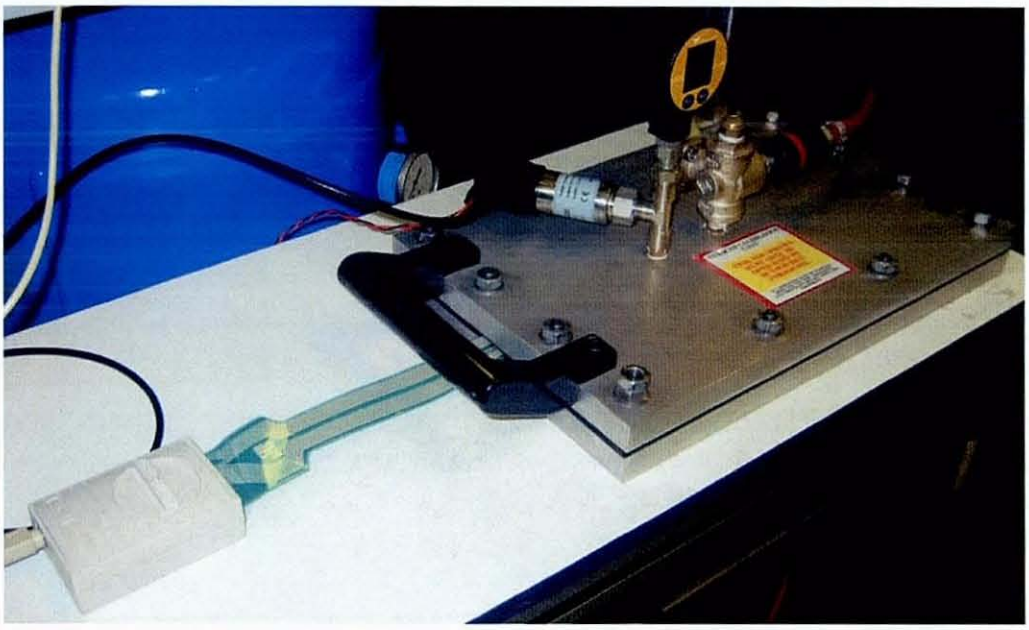


Figure 110: Tekscan calibration rig

Calibration was performed before the sensor was mounted on the racket handle under static rather than dynamic conditions. Static calibration only provides a partial measure of a sensor's performance capabilities. In particular it does not characterise sensor hysteresis, which is a measure of how closely a sensor is able to follow and accurately measure a rapidly changing input stimulus. High sensor hysteresis results in correspondingly slow sensor response and an inability to track changes. The Tekscan sensor specification indicated a hysteresis of 10% at a sampling frequency of 200 Hz. Although not ideal, the benefits of Tekscan sensors (e.g. low profile, adaptability to the grip) still confirm it as the best commercially available technology at the time. Despite problems with hysteresis, the data produced does permit like for like comparison of racket/hand interaction at different levels of fatigue and with different tennis equipment.

To calibrate a sensor it was placed flat in the calibration rig, whilst at the same time attached to the data capture system and PC. Compressed air was used to uniformly apply calibration pressure in a controlled manner. The pressure applied was displayed using a Keller LEO 2 Digital Manometer, a micro-processor controlled measuring instrument accurate to 0.1%. Prior to calibration, each sensor was conditioned by systematically applying uniform pressure up through the sensor's range to its maximum rating of 10.3 bar (150 PSI) and back down again three times. This was carried out to 'break in' the sensor and was recommended by Tekscan before calibration. The software provided with the system included a calibration and 'equilibration' routine.

Slight variation was known to exist between individual cells on any sensor due to the manufacturing process. The F-Scan system provided a method called 'equilibration' to compensate for these variations and thereby minimise system error. In the calibration rig, applying a uniform pressure across the sensor should result in each cell on the sensor providing a uniform output. Equilibration automatically calculated a unique adjustment factor for each cell to compensate for any slight variation (Tekscan, 2001).

A calibration routine was next performed to convert the raw digital output of the sensor to actual pressure units by the application of known pressure loads to the sensor. The calibration software only allowed a sensor to be calibrated at one applied load. This resulted in sensor pressure readings only being accurate around the calibration pressure. To compensate for this, the sensor was calibrated through a range of applied pressures in stepped increments of 0.69 bar (10 PSI) from 0 to 10.3 bar then back down again. At each increment the pressure recorded by the Tekscan system was recorded against the applied air pressure, which was displayed on the digital pressure gauge (Keller LEO 2). The relationship between applied air pressure and corresponding pressure sensor reading was entered into a spreadsheet and used when processing the results data.

Since the sensor was calibrated with load increasing, the resulting in-play data is expected to be most accurate during the active gripping phase of the stroke and least accurate as the player releases their grip post impact. The resulting rise time and peak load measurements are therefore least affected by sensor hysteresis. The grip force decay is affected but is thought less likely to reveal true changes in grip function since, unlike the grip force dynamometer test, the player is believed to relax post impact rather than attempting and failing to maintain pressure.

When applying the pressure sensors to the racket handle, the grip tape was firstly removed, and the sensors were applied directly to the racket frame material using double-sided adhesive tape. A single layer of racket grip tape was applied to the racket over the top of the sensor. From the player's perspective the racket handle felt normal. The only significant change to the racket arising from the addition of the Tekscan sensor was the tail end of the sensor protruding from the head end of the racket handle, this connecting to an interface box, which was strapped to the subject's forearm with a flexible cuff strapping (Figure 117).

In use, the Tekscan system captured 200 frames of grip data per second. Each data frame contained a pressure reading from each of the 96 individual pressure sensor cells. The Tekscan software could be used to graphically view individual data frames or could play back sequences of frames in the form of a movie. Most useful was the ability to export data frames to an ASCII file for subsequent analysis in, for example, Microsoft Excel spreadsheets.

Ideally the Tekscan system would have enabled the 'shock dynamic' to be assessed, but due to the limited sampling frequency of the system (200 Hz) this was not possible. The shock dynamic refers to the immediate response of the grip to the impact shock loading, during the short period of approximately 40 ms following impact. Given a higher sampling frequency and lower hysteresis, it might be possible for a higher performance grip pressure measurement device to detect impact induced shock waves at the racket-hand interface. However, in this study, detection of shock loads was accomplished using accelerometers.

Instead the Tekscan only enabled the 'stroke dynamic' to be assessed. The stroke dynamic refers to the grip pressure through the whole period of the stroke, i.e. how it changes in preparation for impact and the grip response following impact. Re-establishment of grip and control of the racket are factors that are implicated in injury considerations. It was considered that the sampling rate of 200 Hz was appropriate in terms of speed for assessment of the grip activity as it was deemed to be highly unlikely that at this sampling rate any muscular contraction would be missed since human movements occur over a relatively long timeframe.

5.4.3 Accelerometer implementation

Instrumentation of the tennis racket included six accelerometer channels, provided by three Bruel and Kjaer model 4375V (Figure 111) uniaxial piezoelectric accelerometers each weighing 2.4 grams and a single Endevco Model 23 triaxial piezoelectric accelerometer (Figure 112).

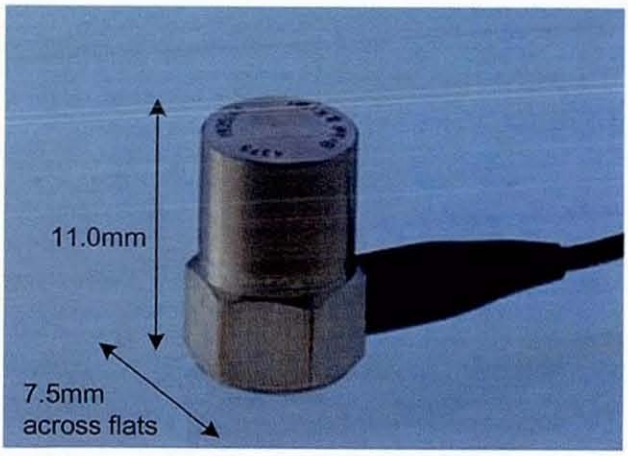


Figure 111: Bruel and Kjaer model 4375V uniaxial piezoelectric accelerometer

The Model 23 accelerometer is marketed as the 'the world's smallest triaxial' and weighs 0.8 grams. Each of the accelerometers are supplied fully calibrated with certificate indicating the required charge sensitivity settings for the charge amplifier and signal analyser.

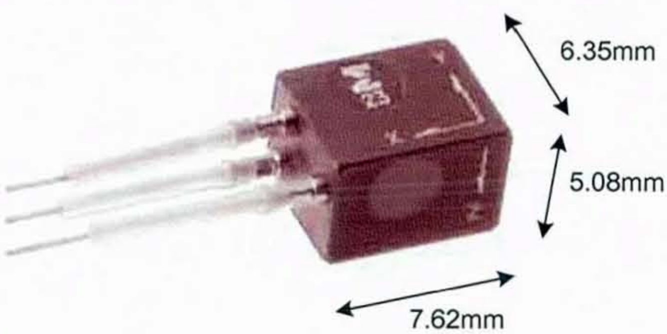


Figure 112: Endevco Model 23 triaxial piezoelectric accelerometer

The three uniaxial accelerometers were mounted on the throat of the racket on an aluminium bracket, which was specially machined to fit the frame in such a way that movement was eliminated, as shown in Figure 113.

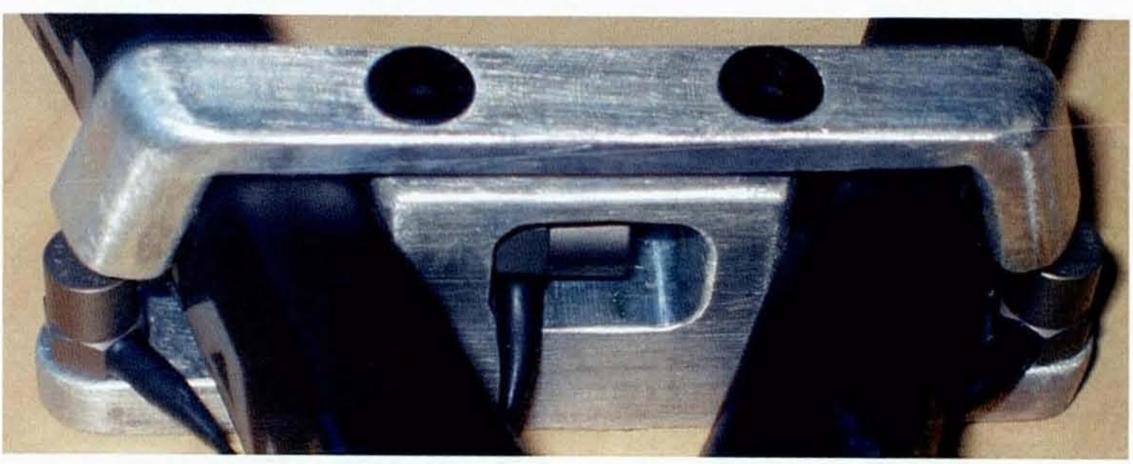


Figure 113: Mounting of three uniaxial accelerometers on the racket throat

The triaxial accelerometer was mounted inside the racket handle. This involved removing the butt cap and machining out a section of the inside of the racket handle to allow the insertion of a polypropylene mounting assembly, which acted as a carrier for the accelerometer. The polypropylene mounting assembly was custom designed and manufactured in three parts, as shown in Figure 114.

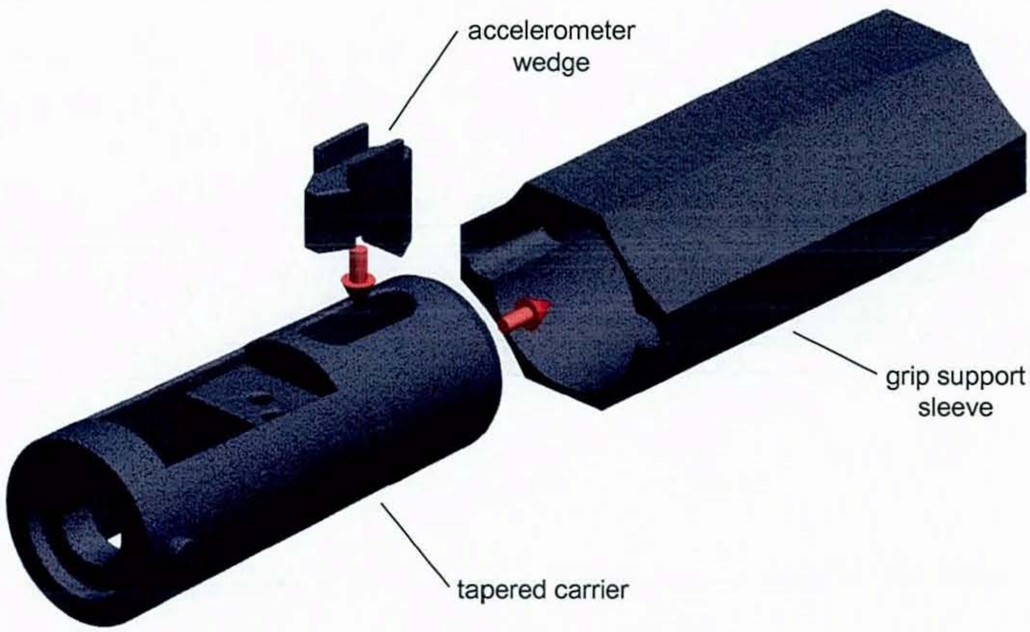


Figure 114: Mounting of triaxial accelerometer in the racket handle

The grip support sleeve (Figure 114) prevents collapse of the machined out grip and was designed with a locking taper and bayonet to take the accelerometer tapered carrier assembly. The accelerometer wedge provides a firm location for the triaxial accelerometer (Figure 112) within the tapered carrier which in turn is held rigidly within the grip support sleeve when it is positioned and locked inside. The two red arrows illustrate the assembly sequence. The grip support sleeve was bonded rigidly inside the racket grip with epoxy resin. The tapered carrier permits the triaxial accelerometer to be removed if necessary. It also prevents movement of the thin connecting wires reducing signal noise.

The number of accelerometer channels and their positioning was selected in order to enable a comprehensive analysis of vibration and shock loading. The positioning of the triaxial accelerometer within the grip enables measurement of the three dimensional acceleration of the grip in the hand environment. Assuming the tennis racket to behave as a rigid body, six accelerometer channels are required in order to fully measure the free body motion in the six degrees of freedom described by x, y, z translation plus rotation about each of these axes.

Figure 115 shows the position and direction of the six accelerometer channels. When executing a shot, subjects held the racket in the orientation shown in Figure 115, i.e. with the left uniaxial above the right uniaxial.

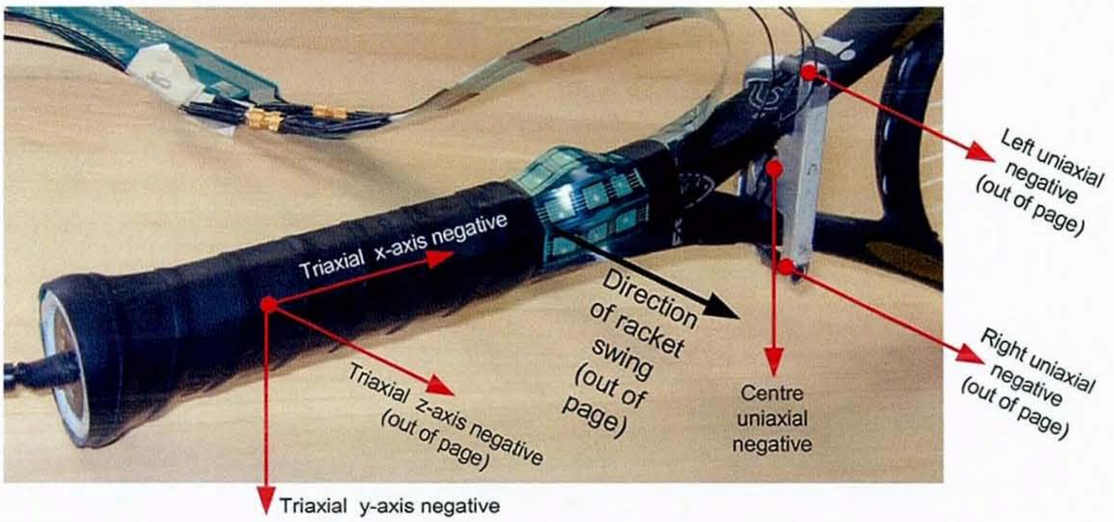


Figure 115: Position and direction of the six accelerometer channels

The six accelerometer channels were positioned to fully measure the free body motion in the six degrees of freedom. In each degree of freedom, acceleration was calculated from the measurements as follows:

- x-axis – taken directly from the triaxial x-axis
- y-axis – estimated from combined effect of triaxial y-axis and centre uniaxial
- z-axis – estimated from combined effect of triaxial z-axis and left and right uniaxials
- rotation about x-axis – estimated from difference between left and right uniaxials with consideration of their spacing
- rotation about y-axis – estimated from difference between triaxial z-axis and mean left/right uniaxials with consideration of their spacing
- rotation about z-axis – estimated from difference between triaxial y-axis and centre uniaxial with consideration of their spacing

Ideally a triaxial torsional accelerometer would have been similarly located within the grip, however this was not available and space was limited. A compromise was achieved by mounting three uniaxial accelerometers remote from the grip, far enough to give angular sensitivity and to avoid affecting the grip, but close enough that the racket can be considered rigid, certainly with respect to the grip. This approach does create problems with delay in shock reaching the triaxial after the uniaxial accelerometers. A potential solution to this would be to adjust the data to compensate for this time delay skew effect. However the delay, with this particular racket was found to be sufficiently small (0.0013s) to justify not adjusting the data.

Wires and Connectors

To provide test subjects with a reasonable degree of mobility, 10 metre long coaxial cables were selected to connect the test racket to the data collection system. Piezoelectric accelerometers can be vulnerable to noise from connection cables, especially if the coaxial layers within the cable become separated, which is possible through movement or bending of the wires. This can cause a charge to be stored, which can appear as noise, interfering with the true signal sent to the charge amplifier. Noise can be minimised by using noise shielded cables, which incorporate a conducting layer in the cable to quickly discharge any unwanted charge stored as a result of any separation of the layers. Through experimentation it was discovered that the wires were most sensitive to movement at the junction between wire and connector. To protect against this, care was taken to secure the coaxial cables to ensure that any movements of the cables at the junctions with the accelerometers and charge amplifiers were minimised.

Signal Conditioning and the Analysis Software

The sensitivity settings of the charge amplifiers were selected to optimise the range of amplification to be applied to the accelerometer signals. The three uniaxial and one triaxial accelerometers (total of 6 channels) were connected to twin Bruel and Kjaer Nexus 2692 4-channel charge amplifiers by noise protected coaxial cable. The sensitivity settings on each channel were adjusted to match the appropriate values for the different accelerometers to achieve optimum charge amplification.

The amplified signals were fed into the Hewlett-Packard E8408A VXI 8-channel digitiser and digital signal processor. The HP data acquisition unit provides analogue to digital signal conversion with built in band-pass filtering to eliminate unwanted high frequency signal content. The HP unit also contains a large data buffer to enable prolonged signal capture at high sampling rates with subsequent download to a controlling IBM compatible personal computer via an IEEE 1394 high-speed serial (firewire) connection.

The controlling PC in this instance was a Gateway Solo Intel Pentium III laptop, equipped with an IEEE 1394 interface and running SignalCalc620 software from the Data Physics Corporation under the Microsoft Windows NT operating system. The SignalCalc620 software enables the user to configure the HP unit via the IEEE 1394 interface in terms off, for example, number of active channels, capture duration, sampling frequency and triggering mode. It also controls subsequent download of the captured data and contains software routines to perform time, frequency and amplitude domain analysis. Suitable unit conversion and overload levels were input to enable, for the purposes of this research, analysis of the acceleration amplitude with time.

By experimenting with trial tennis shots, the analogue to digital conversion indicator levels, which control the full-scale voltage range, were optimised to reduce the chance of an over- or under-loaded signal being produced. Over- or under-loaded signals mean that the captured data suffers either a loss of data or a loss of accuracy. Over-loaded data has exceeded the range of measurement, resulting in a loss of data above the ceiling value, although the rest of the data should be accurate. The amount of data lost is dependant on the extent of the overload. Under-loaded data uses only a small fraction of the available measuring range, and so is prone to loss of resolution and accuracy, compared with what would be possible on a more sensitive range of measurement. SignalCalc provides a high resolution, so under-loaded signals were not of great concern, as long as the signal was sufficient to register significantly. Over-loaded signals were more problematic, since although the majority of the capture would be of a higher accuracy, the peak impact accelerometer data would be lost.

The signal interpreted by the software was DC-coupled to filter out the DC-offset generated by the Hewlett Packard analyser, effectively zeroing the accelerometer readings. DC-coupling allows only the high frequency AC signal to pass. Any readings prior to impact were associated with swinging the racket and were of low frequency, so were prone to filtering out. However, since it was the high frequency impact readings that were of most interest, this did not pose a major problem.

The accelerometer analysis software, SignalCalc 620, was set up to display and save the last time history trace after every capture sequence. Each captured frame was saved in a "run" file in SignalCalc format and then exported as an ASCII file to a separate folder.

5.4.4 Systems integration

Figure 116 shows a system block diagram of the tennis racket instrumented with the Tekscan and accelerometer systems. Although separate PCs were used to host the Tekscan and SignalCalc620 software, the same PC could theoretically have hosted both software systems.

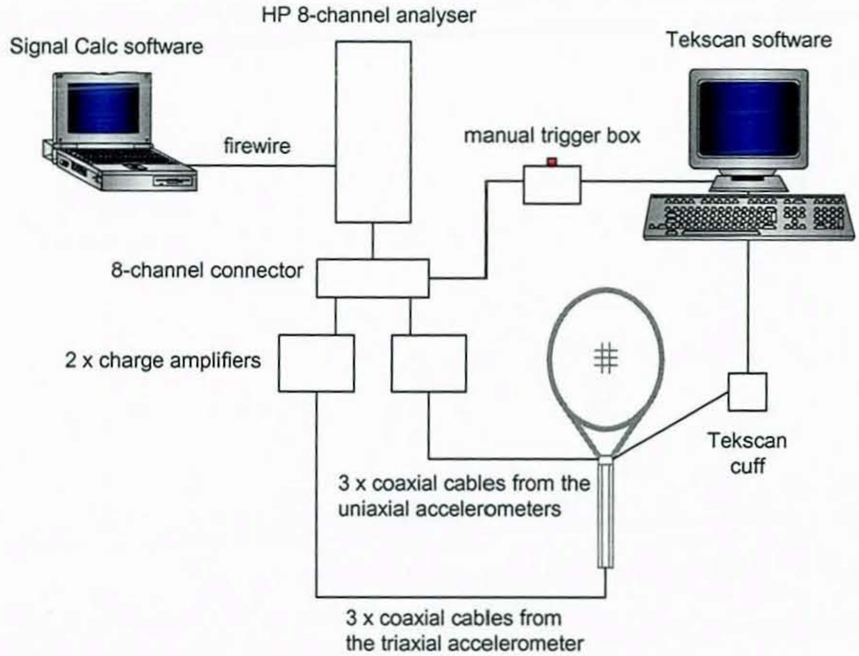


Figure 116: System block diagram

For each test shot, Tekscan and accelerometer data were captured for a period of 1 second. The moment of ball impact could be clearly identified in the accelerometer data, but was less obvious in the Tekscan data. This was overcome by determining the moment of ball impact in the Tekscan data from the accelerometer data, facilitated by ensuring that the streams of data from these two sources could be later synchronised. Synchronisation was enabled by implementing a triggering arrangement.

A trigger box was linked directly to both the Tekscan and SignalCalc620 systems. The trigger box sent a signal via a BNC cable to the 8-channel connector and through to the HP analyser. The analyser buffered the signal, which enabled data collected in advance of the trigger to be retrospectively saved. However, the Tekscan system did not buffer data and could only capture data following receipt of a trigger signal. For this reason, both Tekscan and SignalCalc620 were started manually before impact. The data capture was triggered manually when the incoming ball was seen to bounce. The data capture period of one second was sufficient to extend from the point of ball bounce to a time sufficiently after ball impact for all transient vibrations to decay. The use of light gates to trigger the data capture was considered but rejected as being more intrusive to the subjects who were already surrounded by equipment. After each capture, the SignalCalc620 system automatically reset itself, becoming ready to receive the trigger for the next data burst. In contrast, the Tekscan required a manual reset between each period of data capture.

Figure 117 shows a subject holding the instrumented racket. The Tekscan sensor connects to an interface box strapped to the subject's forearm by a flexible cuff. The three coaxial cables from the triaxial accelerometer leave the racket from the butt end of the handle. The cables from the three uniaxial accelerometers leave the racket along the line of the Tekscan sensor. The cable routes were selected to provide minimum interference with the subject. All signal cables were also attached with a second flexible strapping and tape to the subject's upper arm. During testing an assistant held on to the cables and moved around with the subject, thus keeping the cables off the ground and minimising the risk of entanglement.

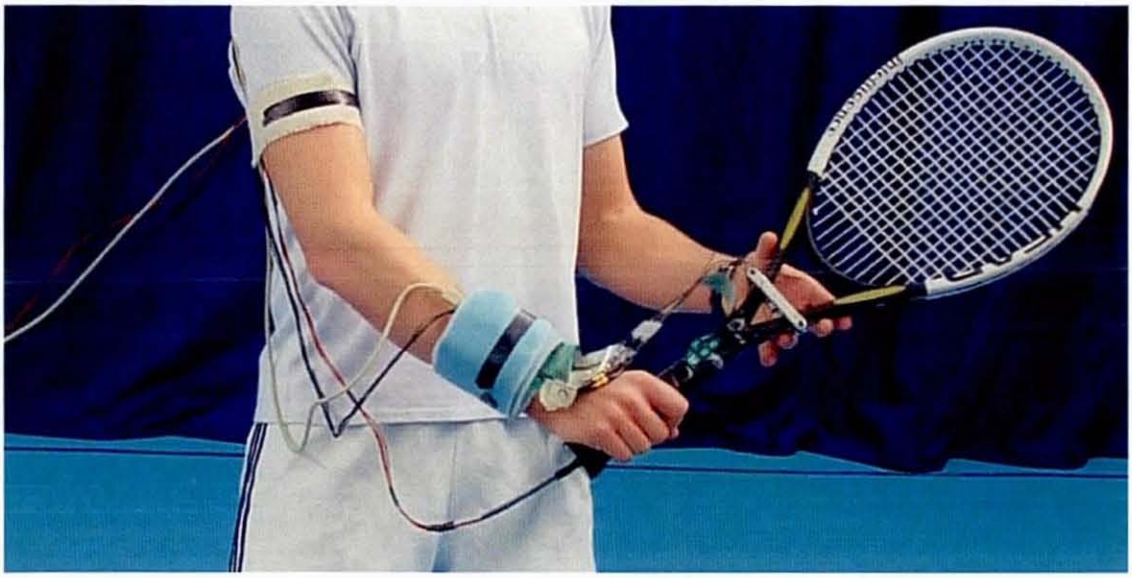


Figure 117: A subject holding the instrumented racket

5.4.5 Preliminary testing of design solutions

The instrumented racket had to be capable of withstanding prolonged use, including over one thousand shots during the test sessions. Practical tests were designed to identify potential problems with its durability in order to refine and make improvements to the design. During test sessions the racket was to be picked up and put down, possibly dropped and had to withstand the repeated shock of ball impact, including some mishits in which the ball contacted the racket frame.

<u>Tekscan</u>

A test racket prototype was utilised to ensure that once the grip pressure sensor was in place on the racket handle and the grip tape placed over it no erroneous or erratic results occurred. It was also necessary to pre-empt any 'in play' issues that might arise, such as:

- slippage of the sensor on the racket handle
- creasing or buckling up of the sensor over time
- heat or moisture from players affecting the sensor
- 'noise' in the results when the sensor tab was jolted during impact (although it was secured to the player using a Velcro cuff to avoid this)

• damage of the tab resulting from repeated impacts during the course of the test sessions

Figure 118 shows the Tekscan sensor tab extending out from the top of the racket handle. This sensor tab was considered to be vulnerable to wear and tear. Various techniques and methods of attaching the sensor to the racket handle and securing the tab and cable to the player were experimented with. The best attempts were then selected and used for a pilot study in the laboratory hitting enclosure. Various players were asked to repeatedly strike the ball using an 'aggressive' technique to test for any of the potential problems identified above. To test for heat and moisture effects players interspersed sets of shots with periods of exercise on either a rowing or cycle ergometer to raise body temperature and stimulate sweat production. No problems were identified either in the nature and quality of the results or in wear and tear or breakage of the sensor.

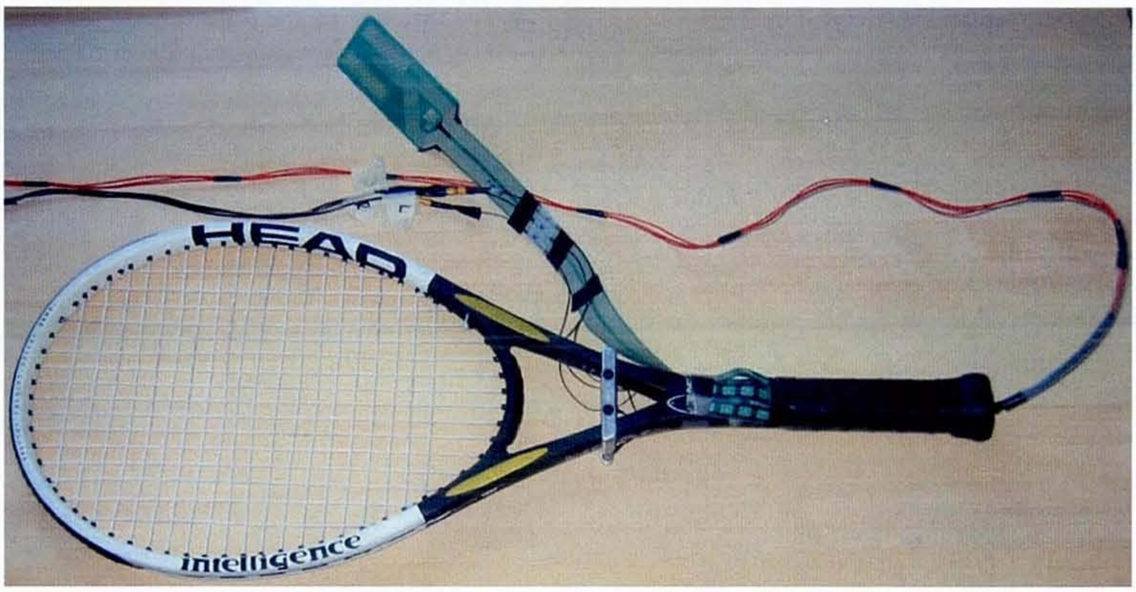


Figure 118: Tekscan sensor tab

<u>Accelerometers</u>

Once the accelerometers had been mounted on the racket throat and within the racket handle it was necessary to perform durability and sensitivity tests on them. When fixing the accelerometers it was important that no independent movement was possible (rattling on impact). It was also important that the accelerometer wires at the end of attachment to the accelerometer were fixed securely, otherwise they might cause noise during a shot or even sustain damage at the connection to the accelerometer. In addition, although care was taken it was necessary to confirm that the triaxial accelerometer had not been damaged whilst fixing it to the mount or positioning the mount inside the racket handle.

It should be noted that the accelerometers were supplied certified as pre-calibrated and that their calibration factors were entered into the charge amplifiers. Neither calibration of the accelerometers nor testing the sensitivity of the instrumented racket were objectives of this equipment test. Instead the equipment test were merely intended to verify the following aspects:

1. that all of the accelerometer channels were live and that accelerometer data could be captured on each of the six channels,
2. that none of the six channels of data were picking up noise: and
3. that the basic 'shape' and magnitude of the data traces from the accelerometer channels were all comparable with other published results.

The instrumented racket was pilot tested on court for durability in the same way as the grip pressure sensor was in the laboratory hitting enclosure. It was necessary to check that under play conditions no erratic acceleration data occurred in any of the six channels and that it would be capable of withstanding the usage required by the testing.

In addition to players striking tennis balls repeatedly and aggressively, a selection of other ball types were introduced in order to test that the equipment was able to discriminate between ball types having grossly different physical properties. The ball types experimented with were a standard Type 2 tennis ball, a squash ball, a golf ball, a cricket ball and a pool ball. Because of the nature of the ball types it was only possible to hand feed them and return speeds were ball dependent (for example the cricket and pool ball were only hit gently to avoid damaging the equipment).

The selection of graphs of accelerometer data shown in Figure 119 to Figure 123 inclusive show a sample of the results obtained for the different ball types. It was found that shots with one ball type typically resulted in graphs with features that were characteristically and consistently different to graphs of data from the other ball types. Figure 119 in particular exhibits a classical response to a tennis ball impact. An initial shock peak is followed by oscillations reflecting dominant excitation of the first and second racket vibration modes. The observed oscillation period is consistent with the known modal response of the Head IS2 racket. Figure 120 mimics this response, as might be expected with a relatively soft rubber ball, but exhibits a lower amplitude consistent with its lower mass.

Figures 121 to 123 exhibit similar behaviour although the rigidity of golf, cricket and pool balls result in a sharper impact that excites the second and higher vibration modes more than the relatively soft tennis and squash balls. The relative shock acceleration magnitudes are consistent with the relative mass of the balls, although distorted somewhat by the need to execute weaker strokes.

The relative and absolute magnitudes internally (comparing channels) and externally (compared with published data) were as expected [Knudson, 1991 #39; Cross, 1999 #192; Kawazoe, 2002 #289]. There was a consistency over prolonged use and no problems with noisy signals were apparent. At the gross level, the conclusion was therefore that the accelerometer data were reliable and the instrumentation capable of showing up differences between distinctly different ball types.

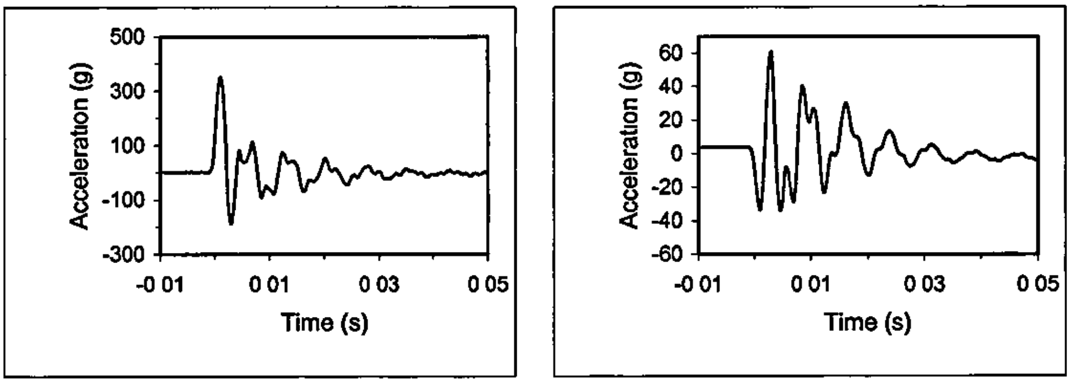


Figure 119: Left uniaxial and 'Y' triaxial accelerometer data with a tennis ball

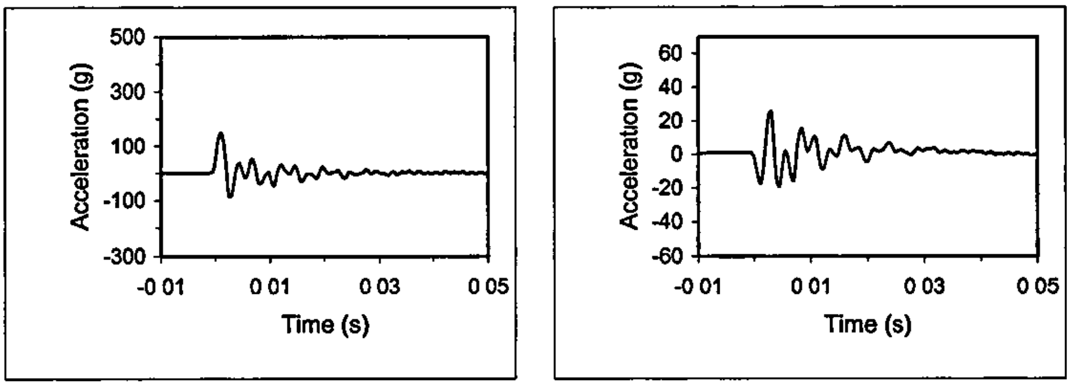


Figure 120: Left uniaxial and 'Y' triaxial accelerometer data with a squash ball

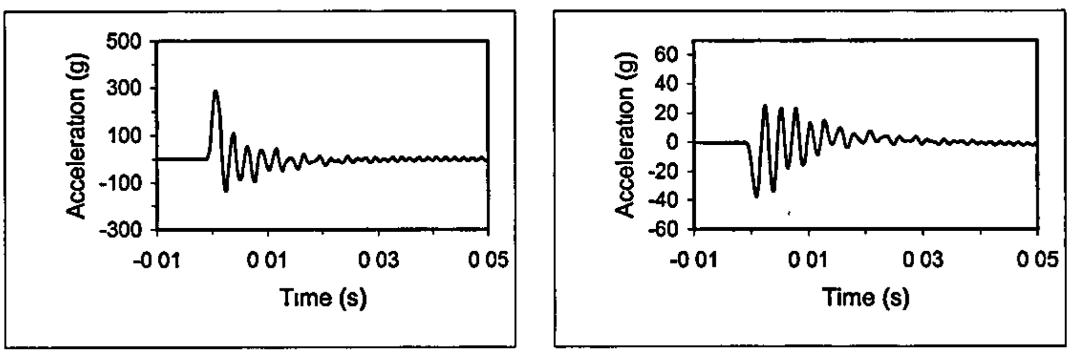
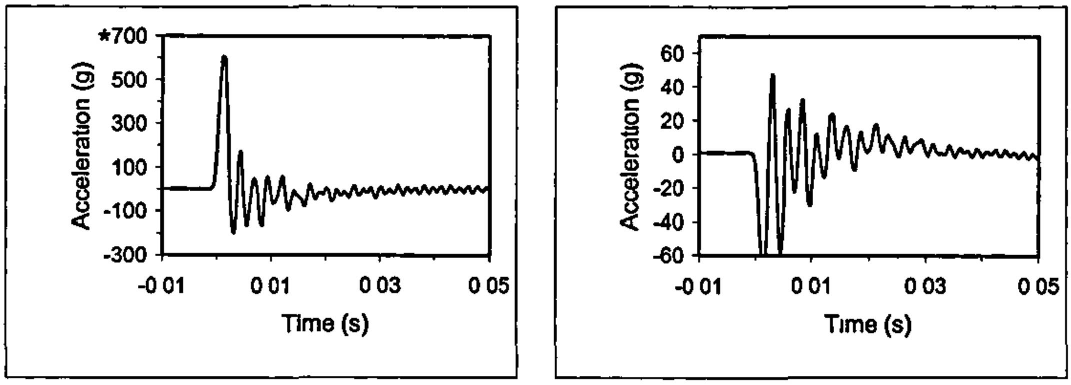


Figure 121: Left uniaxial and 'Y' triaxial accelerometer data with a golf ball



* Note: y axis scale greater than on other graphs

Figure 122: Left uniaxial and 'Y' triaxial accelerometer data with a cricket ball

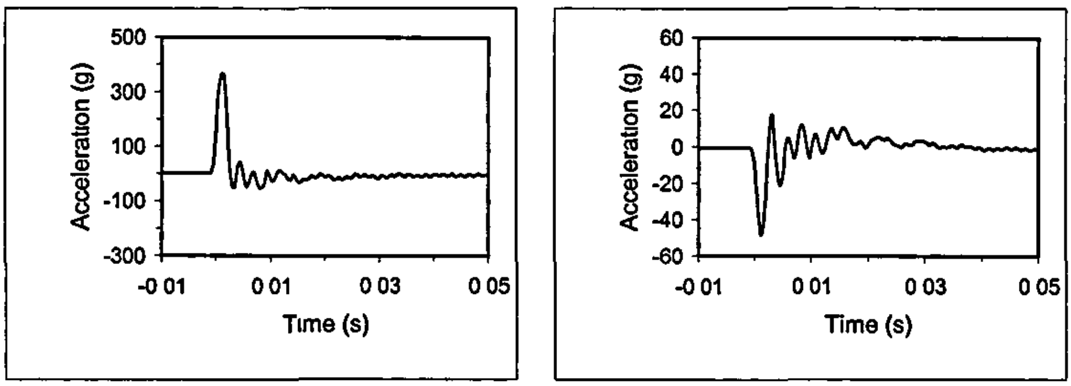


Figure 123: Left uniaxial and 'Y' triaxial accelerometer data with a pool ball

5.5 TEST PROTOCOL REQUIREMENTS

The objective of this research was to develop new techniques to enable in-play measurement of player performance characteristics especially those related to fatigue. The aim of the proposed measurement device was to objectively assess fatigue induced changes in grip activity during actual, realistic tennis play. This would enable the relative effects of interventions, such as equipment modification, to be determined. Tracing fatigue induced changes back to their source muscle groups might also provide new insight into the causes of injury.

Previous research has shown that as a player's fatigue increases his/her shot accuracy reduces. This could be for a number of reasons, one being that fatigue results in a loss of coordination and another being that fatigue impairs hand function. The research aimed to investigate possible mechanisms of this fatigue/accuracy-loss effect; the mechanisms investigated being as follows:

- increased fatigue causes reduced peak gripping forces (leading to loss of racket control)
- increased fatigue causes increased minimum gripping forces (i.e. over gripping and loss of fine control)

The earlier sections of this chapter present the technology aspects and details of the development of an instrumented racket. This rest of this chapter discusses the development of a test protocol within which an instrumented racket can be optimally utilized. It was necessary to develop a controlled test protocol in combination with the instrumented racket in order to achieve the stated objectives of the device. In the development phase of any measurement system it is necessary to expose it to controlled, systematic changes in order to determine its efficacy. The intended application of the instrumented racket was to establish the feasibility of measuring relative changes in grip activity due to tennis play induced fatigue and examine the potential for equipment changes or other interventions to influence this. The activity schedule was designed to induce accelerated fatigue by overloading the muscles involved in executing a single handed backhand.

The main requirements for the accelerated fatigue protocol were identified as follows:

- provision of a realistic play environment, whilst controlling sufficient parameters to enable statistical analysis of results
- to compare the effects of different equipment
- to induce localised muscle fatigue of the forearm
- minimisation of impact location variability, since impact location is a significant factor in impact vibration and shock loading (required in order to investigate the possibility that fatigued players might hit the ball more off centre)

The main requirement of the protocol was to induce fatigue in order to investigate changes occurring as players move from being fresh to fatigued. Investigation included the possibility of different levels of change occurring across different subject populations. The effects of playing with different equipment were also investigated, in order to make inferences about the benefits of alternative equipment designs in terms of performance, injury or comfort.

The aim was to minimise variability due to anything other than forearm fatigue and localised muscle fatigue. The desired outcome was a new measure to determine whether playing with alternative pieces of equipment causes greater or lesser loading on the arm, resulting in greater or lesser fatigue. The instrumented racket was designed to be an improvement over the static hand-grip test used in the earlier studies. The test protocol was designed to induce sufficient fatigue to assess these various effects.

To recap, the aims of the test protocol were to induce accelerated fatigue of the forearm muscles in a real play situation that is controlled and therefore repeatable. A controlled test environment was to be established to investigate how different equipment affects players in terms of vibration, shock loading, grip pressure and fatigue. Successful implementation of such a test environment would enable objective assessment of marketing claims that certain types of equipment can reduce tennis elbow. Other positive outcomes would be the potential for players and coaches to select more suitable equipment, manufacturers to develop more useful modifications, and governing bodies to check newly introduced equipment for possible injury effects.

Whilst the aim was not to simulate match play in terms of the normal activity : rest ratio, it was required that the protocol should try to simulate playing normal shots and pattern of play. The effect of equipment modifications is generally small and quite possibly insignificant initially (i.e. the impact of a few shots may have no distinguishable difference). However, small differences might be found to affect players over an extended period. It was hoped that by designing a test protocol to induce accelerated fatigue, any small differences would become apparent.

5.6 TEST PROTOCOL DESIGN & DEVELOPMENT

5.6.1 Background

The initial studies conducted for the ITF showed no significant difference in the physiological measures taken for the Type 2 and Type 3 balls. One possible cause was the inter and intra subject variability, which could perhaps be attributed to a lack of control in the test protocol. The protocol for the third study required greater control to establish with more confidence whether use of alternative equipment resulted in physiological differences that were discernable.

5.6.2 Participant selection

In the future it is hoped to study effects of the differences between populations of players, including players with a susceptibility to injuries and recreational (low skill level) players. However, for this study the subject population was restricted to high skill, competition players, due to the following benefits:

- shot consistency, therefore fewer mishits and lost data
- shot consistency, therefore muscle isolation
- shot intensity likely to be more consistent
- shot impact position on racket string bed likely to be more consistent
- better conditioned, so able to cope with fatigue without detrimental effects/injury
- ability to provide feedback on protocol

Skilled competitive players hit the ball far more consistently and so by selecting a group of skilled players of similar age and ability this served to naturally reduce the variability. To investigate fatigue induced changes in grip, it was necessary to design a protocol which was physically intense and demanding. Skilled competitive players are familiar with playing and training at high intensity and therefore are sufficiently conditioned to cope with this level of exertion without suffering adverse effects from a test. In the development phase of the protocol, skilled players were also able to offer useful feedback on whether the protocol provided a realistic play environment, i.e. achieved an environment in which the participating players could play their normal game.

Potentially the protocol could have been applied to compare two different populations of players but in line with the aims of the study the selected experimental variables (interventions) were two different ball types and changing fatigue status (fresh versus fatigued). It is worth reiterating that the players were pushed hard to ensure that muscular fatigue was achieved and so only using competitively fit, regular players was considered sensible.

The number of players to be tested was limited by the fact that a large amount of data were generated that needed to be processed within the time constraints of the project. Sufficient players were required to allow statistics to be performed on the data. It was decided that a sample of 6 to 12 players should be tested (each on two occasions). It was anticipated that this pilot development stage of the test protocol would reveal requirements for refinements to the test in terms of number of players to be tested. Consideration of statistical power can assist in determining the number of test subjects to be used in future studies based on this equipment and test protocol.

In statistical hypothesis testing, data is used to make a decision about whether to reject a statistical hypothesis (usually stated as a null hypothesis, H_0) in favour of an alternative hypothesis, H_A. The standard approach is to calculate a test statistic from the data (for example, by using a t-test) and compare its value to the statistics distribution assuming that the null hypothesis is true. The null hypothesis is rejected if the test result exceeds a (user specified) critical value based on the null, otherwise the null hypothesis should be accepted.

Since statistical probability is involved and the test result is only one random and possibly aberrant sample outcome, it is possible that an incorrect decision is made about which hypothesis to accept. If a null hypothesis is rejected when it is actually true, then this is termed a Type I error. Conversely, if a null hypothesis is accepted when it is actually false, then this is termed a Type II error. (The other possibilities are that the null hypothesis has been correctly either accepted or rejected.) The probability of making a Type I error is conventionally designated as α (alpha). By comparison, the probability of making a Type II error is designated as β (beta).

Statistical power, sometimes referred to as simply 'power', is defined as the complement of Type II error (i.e. Power = $1 - \beta$). An alternative definition of statistical power is "the ability of a test to detect an effect, given that the effect actually exists." A test with high statistical power is a goal of a test developer. A test is more effective if it has a higher probability of detecting a difference between the compared means. Statistical power analysis is used to determine how large a sample size an experiment needs and to evaluate the worth of an experiment that retains the null hypothesis.

There are three factors that determine the statistical power of an experiment:

1. **Alpha:** The higher the alpha level, the more likely the null hypothesis can be rejected. The conventional alpha level is 0.05.
2. **Effect size:** The larger the effect size (in actual units of the response), i.e. the larger the difference between the means, then the more likely the null hypothesis can be rejected. Effect size and the ability to detect it are related; the smaller the effect, the more difficult it is to find.
3. **Variation in the response variable:** The smaller the standard deviation, the more likely the null hypothesis can be rejected. A larger sample size and a sample with lower variability will produce a smaller standard error. When designing an experiment a value for standard deviation usually comes from previous research or pilot studies.

Choice of an effective sample size is related to the four parameters alpha, beta, effect size and variation in the response variable. Without some prior knowledge of what to expect in terms of effect size and variation in the response variable, it is not possible to select a sample size to achieve a particular statistical power. Whilst this removes the ability to design an experiment to achieve results of a predetermined statistical significance, it does not prevent the statistics from being calculated and values being established for mean size of effect(s) and variation in the response variable(s). From this perspective, the grip study should be viewed as a large pilot study into the innovative use of instrumentation to measure possible physiological effects of fatigue and equipment changes.

The instrumented racket was set up for testing a single handed backhand. At this stage of development, it was not easily possible to accommodate different types of shots. This was due to limitations of the technology, which made it difficult to reconfigure the instrumentation for the different hand-grip positions used for different shot types. The pressure sensors were limited to only covering 6 of the 8 faces of the racket handle. The accelerometers were limited by having cables connecting them to the data acquisition equipment and so it was important that the players did not twist the racket in their hand, which would have pulled on the cables. Players often spin the racket in their hand unconsciously as they await a shot.

There is epidemiological evidence linking incidence of tennis elbow with the single handed backhand drive (Grouchow and Pelletier, 1979; Knudson, 1991b; Priest *et al.*, 1980a). It is a difficult shot to execute well technically and recreational and beginner players often lead with their elbow and do not 'follow through' smoothly. Players diagnosed with tennis elbow often report aggravation of pain whilst performing particularly the single handed backhand. Executing a single handed backhand isolates the forearm muscles more than performing a forehand shot, which utilises more of the larger muscle groups of the shoulder. A single handed backhand is therefore more likely to be influenced by fatigue and since more skill is required to execute this type of shot, being more fatigued is also likely to have more affect. It has been reported that tennis hitting exerts a force of 45% of maximum grip force at impact in the forehand as compared to 60% in the backhand (Knudson, 1991b). The backhand is therefore tested more often. Although players do not utilise a maximum grip force, the cumulative effect over the duration of a match is likely to be important. Decline in grip strength has been suggested to have a detrimental effect on performance and certainly players who are able to sustain their grip performance later in a match are at an advantage.

In selecting the type of backhand it was decided to specify that the player should perform a slice backhand as opposed to a topspin backhand. The reasons for this were:

- Topspin backhand is rarely executed by those apparently prone to injury. A slice backhand should generate adequate/significant levels of fatigue
- Topspin backhand more often hit two handed, slice backhand single handed
- Topspin backhand more difficult to perform than slice backhand so likely to introduce unnecessary shot inconsistency leading to variability in results masking potentially significant effects

For practical reasons and for consistency, only one racket was instrumented and only right handed players were able to take shots with it.

Only healthy and uninjured players were considered as participants. As the test was designed to be physically challenging it would have been potentially damaging to unfit players, who were not both healthy and injury free. All players were asked to fill out a Health Screen questionnaire about their general health and were questioned about any recent or current injuries. Any player not fully healthy, currently injured, or who had not been in full training for the whole of the previous month were omitted from the test. In addition players filled out a 'Well Being' form on waking on the day before each day of testing, on the day itself and on the day following. This asked the players to describe generally how they felt and directed the players to indicate malaise of any type. This was in case players were coming down with an illness that affected their test performance, but did not become fully aware of the illness until the next day.

Players participating as subjects in the study were all University team players and all fulfilled selection criteria of ability, age, fitness and availability. University team players are naturally placed in groups of similar ability and age and mostly follow the same program of training set by the University team coach. They all play a similar amount of tennis per week and because the University coach (who acted in an advisory role during the testing) coaches them, he was able to confirm their skill rating, capabilities and current fitness level.

5.6.3 Test procedure

The studies reported in Chapters 3 and 4 were concerned with the effects of playing tennis with the larger Type 3 ball compared to the standard Type 2 ball. It initially seemed obvious and would have been interesting to use the same two ball types as variables in this study. Unfortunately it proved impossible to source a sufficient number of the larger Type 3 balls. Since completing the earlier studies, production of the Type 3 ball had been stopped by the manufacturer (Dunlop Slazenger) due to lack of sales. Other manufacturers had also experienced a lack of sales and had ceased production. Feedback from a number of players participating in the Study A reported on in Chapter 4 likened the feel of the larger Type 3 ball to that of pressureless balls, both these ball types being said to feel heavier on the racket than standard Type 2 pressurised balls. It was therefore decided to test the effects of pressureless balls compared to standard pressurised balls.

To compare the effects of two different types of equipment, it is necessary either to repeatedly test one set of subjects on at least two occasions or to test half the subjects with one equipment type and the other half with the other. The latter was rejected due to the study objectives of measurement of relative effects of different equipment. Even if two groups of subjects were closely matched it would make it very difficult to assess the sensitivity of the device if two groups of subjects were tested. In addition, subject variability was a consideration; a larger population would have been required for the alternative study design. Timescales were also a factor, a larger population would mean more testing resulting in more data requiring more time to execute and analyse. A repeat test study design was chosen as the most appropriate in respect of the study requirements.

As the protocol involved demanding activity designed to induce fatigue and overload in the forearm muscles it was necessary to allow sufficient days between the repeat tests to enable the participants to recover fully. One week was both convenient in terms of players' attendance at the weekend and sufficient for recovery, but not too long for their fitness level to change. Each subject took part in two sessions conducted a week apart. The only difference in the two test sessions was that standard tennis balls (pressurised) were used in one and pressureless balls in the other. In this type of repeat study design it is important that the two sessions are completed at the same time of day to control variation in performance due to circadian rhythms (Atkinson and Reilly, 1996).

The use of a crossover study design was considered, but rejected. In a crossover design half the subjects would have used one type of ball first and the other half the other type. Instead, all of the testing in Week 1 was conducted with the standard pressurised ball and all in Week 2 with the pressureless ball. This clearly introduced the possibility of systematic differences being introduced, for example, the 'learning effect' of participating in the Week 1 test may have carried over to alter a player's performance responses in Week 2, irrespective of the possible influence of any equipment change.

There were two main reasons for not adopting a crossover design. The first related to the relative expectation of success in detecting changes caused by the two variables that were experimented with, i.e. ball type and fatigue status. Of the two variables, fatigue status was expected to produce changes of greater magnitude. The experiment would ideally have been conducted to compare the effects of the larger Type 3 ball with those of the standard Type 2 ball, as per the earlier studies for the ITF. The physical differences between these two ball types are more distinct than differences between the Type 2 pressurised and pressureless balls that were actually used. When supply of the Type 3 balls became unavailable it was recognised that any differences in the measured responses between the Type 2 pressurised and pressureless balls were likely to be either small or undetectable. It was therefore decided to focus on measuring the effects of fatigue, which was expected to show a greater response and have a higher statistical power.

A second reason for adopting a non-crossover design was concern over possible failure of the instrumented racket. Although the instrumented racket was successfully put through a period of pilot testing, it was recognised that any failures during the main study would have effectively split the results into those collected before and those after the failure. Had racket repairs proved to be necessary, it would have cast doubt on the consistency of results before and after any repair. For example if the grip pressure sensor required changing the sensor itself would have been slightly different, as would its positioning on the racket handle. By adopting a non-crossover design, it was considered that any such split of the data would result in larger groups of data for any one ball type, either side of the split. This would give higher statistical power to the individual groups of data. This design was therefore considered more appropriate for primarily investigating the effectiveness of the instrumentation in measuring fatigue induced changes.

5.6.4 Test schedule

Published research, for example, Knudson (1988), Knudson and Blackwell (2000), (Knudson, 1991a) and Kawazoe *et al.* (2002) indicates the ability of such instrumentation to detect different strokes, different racket types, different racket impact locations. There is a confirmed inability of present devices to detect differences in modest equipment change (see Chapters 3 and 4 studies concerning Type 2 versus Type 3 ball) under short duration exposure. The pilot testing of the instrumentation has indicated an ability to detect differences between grossly different ball types. It is most likely that this would be the case with grossly different rackets. What is not apparent is whether modest equipment change induces significant physiological change with prolonged exposure that can be detected by these instruments.

The test schedule design, developed by Davey *et al.* to simulate tennis match play in a controlled environment was used as the basis for the protocol (Davey *et al*, 2002; McCarthy, 1997). This research was responsible for devising the 'Loughborough Intermittent Tennis Test' (LITT), which enabled investigation of the influence of, for example, training and dietary intervention on performance. The LITT schedule consisted of bouts of 4 minutes work plus 40 seconds recovery, repeated to volitional fatigue, with a stroke skill test performed before and afterwards. During the test, balls were fed randomly to either side of the court and the player had to run from side to side, thus simulating real match play in which the player does not have the ball fed to their feet.

In the present study, it was decided to feed the ball repeatedly to one position. Whilst acknowledging that this removed an element of the real match play environment, it was preferred for a number of reasons. The main requirement was to load the forearm, inducing localised muscle fatigue. It was felt that by removing the element of side to side movement, the total number of shots that a player could manage would be increased, so increasing the loading on the arm. A further reason was to minimise impact location variation due to any reason other than hand function change resulting from localised muscle fatigue (because impact location influences vibration, shock loading and grip pressure). From a practical perspective, the cable connections to the instrumented racket limited the range of movement of the player. 10 metre long cables were used to provide scope for some movement.

Whilst the aim was to fatigue the forearm muscles by repeatedly performing a single handed backhand, it was considered that asking the players to just hit backhands would be unrealistic in terms of normal tennis play and excessive in terms of overload on one side. During the periods of Controlled Play Activity (CPA), players were asked to hit one forehand to every two backhands, thus putting the emphasis on the backhand muscles whilst balancing play with some forehand shots. This added realism by causing the players to adjust their grip according to the shot and also relieved the potential for participant boredom.

A pilot test of the proposed test schedule was carried out with a player (not included in the main study) from the same population group as the study participants. The University coach assisted selection of this player as being of similar ability and fitness level to the players taking part in the main study. The objective of the pilot was to check that the activity to rest ratio was appropriate and would achieve the desired levels of forearm fatigue.

In summary, the pilot utilised repeated 4 minute periods of work and 40 seconds of recovery until fatigued (which had occurred at about 35 minutes in the study of Davey *et al.*). Balls were fed to the same place rather than randomly side to side and the player was asked to repeatedly play one forehand to every two backhands, stepping round the ball as necessary for the duration of the work period. Based on the results of the pilot and on the advice of the coach, it was decided to reduce the activity periods from 4 minutes to 3 minutes with 1 minute of recovery and that the target would be to complete a total of nine of these activity periods within each test session. The periods of 3 minutes of activity were referred to as 'Controlled Play Activity' (CPA). In terms of total activity duration, this was in line with Davey *et al.* and based on the pilot was expected to sufficiently load up and fatigue a player's forearm, but without causing a potentially damaging overload.

The activity-recovery schedule for the test was developed in consultation with the advice of the University team LTA qualified tennis coach, who coached all of the players participating in the study. The coach had experience of all the players' ability and current level of fitness.

The test racket was only configured to perform backhands and so a non-instrumented standardised racket was used during the CPA. The instrumented racket was used by the players at regular intervals during the test to perform sets of 15 single handed slice backhands aiming at a target box. These sets of 15 shots with the instrumented racket were referred to as Data Collection (DC) shots and were a further development of the test protocol.

A set of DC shots was performed at the beginning of the test and subsequently after every 9 minutes of CPA. Each test session comprised 27 minutes of CPA, interspersed with 4 sets of 15 DC shots. The aim was to collect data from a sufficient sample of good shots to indicate grip status at that point. When a player used the instrumented racket there was a slight interruption caused by having to secure the Tekscan cuff around their wrist and make sure that the cables were fed over their shoulder, out of their way but with enough freedom to swing without tugging at the cables. Securing of the cuff took place within the timed recovery period between activity periods (see Chapter 6).

How many sets of DC shots were taken in each test session was determined by balancing two issues; too many might have been annoying and broken the players' flow; too few might have resulted in failure to identify trends which might otherwise have become apparent. In line with the static dynamometer test utilised in the previous studies, just taking a set of DC shots at the start and end of the test session would have been adequate to simply investigate the possibility of fatigue induced changes. However, two intermediate sets of DC shots were also taken. This was considered useful in terms of refinement of the protocol for use with populations of players other than skilled regular players. The ideal situation would be to develop an instrumented racket that is sensitive enough to detect changes before a player reaches high levels of overload and fatigue. A diagnostic tool would be more useful if it could be used to track changes and indicate the moment they occur.

Figure 124 shows the layout of the tennis court used for the testing. It shows the positions of the player and a Bola ball launch machine and the position of two target zones. In each dimension, the Accuracy target zone was one quarter of the area of the Consistency target zone. It can be seen that the target zone was positioned to elicit a 'cross court' backhand shot as opposed to a shot 'down the line'.

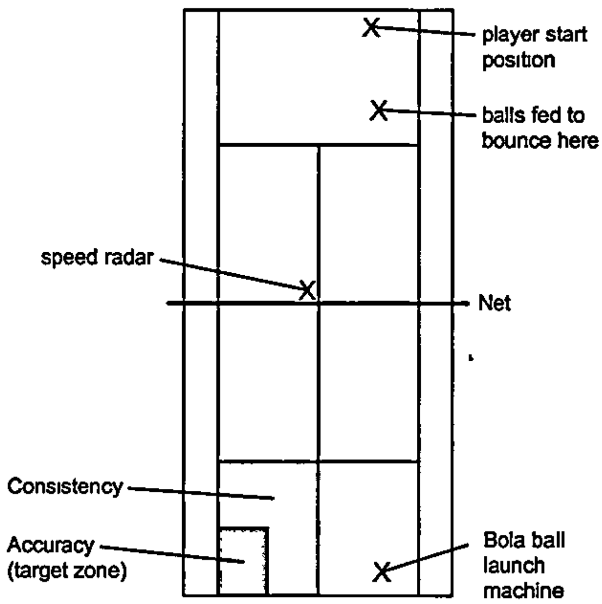


Figure 124: Layout of the tennis court used for testing

<u>Ball feed</u>

Balls were fed to the test player at the same court position using a Bola ball launch machine. The Bola had previously been assessed for accuracy of delivery in terms of consistency and repeatability of both velocity and dispersion. The amount of ball wear caused by the Bola and the corresponding maximum Bola deliveries per ball had also been established previously. A ball delivery velocity of 17.9 metres per second (40 miles per hour) was chosen, this was considered to be representative of good groundstroke pace for the level of players participating and verified by the LTA coach. The rate of ball feed during the CPA was 30 balls per minute as per the LITT. This rate worked well in the pilot study and the coach felt it to be sufficiently challenging but readily achievable. The rate of feed during the DC was 15 balls per minute, the reduced rate being selected to maximise consistency and 'naturally' reduce variability.

For each test it was decided that ninety fresh balls would be used. This relatively high number was required to minimise variability due to ball wear. Wear rate is significantly increased by launching balls out of the Bola machine, which works by two big rotating wheels that squeeze the ball to almost flat before ejecting it. Ninety balls meant that each ball was used about ten times during the test, which ensured the balls remained fresh and consistent, which was important when directly comparing the effects of alternative ball types. Having plenty of balls in circulation for each test also made it logistically easier to keep the Bola ball hopper replenished.

The racket used in the CPA was the same make and model as the instrumented racket so as to not disrupt timing or feel of the players. The racket used was a Head Intelligence I.S2 Mid Plus strung at 25 kgf. It was selected as being a good quality, medium sized, 'suit all' racket. Also, its light weight meant that any additional mass added by the instrumentation would still leave it in the normal weight range of rackets. It was decided that the players should do the CPA part of the test with a racket of their normal grip size and so a number of rackets (identical except range of grip sizes) were available for the subjects to select for use during the CPA. Overloading their grip whilst using a racket with a different grip size to their own personal racket was considered to present a potential injury hazard.

Prior to testing, subjects completed a controlled warm up that was developed with advice from the tennis coach. It was based on what the players would normally do as a warm up and was a balance between warming them up sufficiently without tiring them. The warm up consisted of a four minute jog to raise the subject's temperature, followed by a series of appropriate warm up stretches. Subjects then completed a timed 5 minute on court warm up, returning balls delivered at the test velocity of 17.9 meters per second at a rate of initially 15 balls per minute, increasing to the CPA rate of 30 balls per minute. The on court warm up provided a familiarisation and 'settling in' period for the subject to the test protocol, instrumentation and ball delivery.

5.7 TEST MEASURES

5.7.1 Introduction to test measures

The test measures included in the protocol are listed in Table 16 and the reasons for their inclusion are discussed below. The main test measures have been subdivided into Primary and Secondary measures. In order to fulfil the requirements of the protocol, a series of control measures were necessary in addition to the actual test measures.

Table 16: Table to show study test measures

Primary measures	Secondary measures	Control measures
Grip pressure	Static hand-grip strength	Shot outcome/accuracy
Racket vibration	Perceived muscle soreness	Shot velocity
Shock loading	Perception	Heart rate
		Rate perceived exertion
		Additional

5.7.2 Primary test measures

The primary test measures were those taken with the instrumented racket; i.e. in-play grip pressure, shock loading and racket vibration. The motivation for measuring in-play grip pressure was to investigate if any changes occur in any aspect of grip activity under conditions of player fatigue or equipment change. Accelerometer data was expected to be an indicator of more off centre impacts or of mishitting more shots. Lower vibration damping might be linked to grip changes, possibly due to grip fatigue. Of particular interest to the current study was investigation of the changes that may occur at the player-racket interface as players become fatigued compared to when they are fresh.

Figure 125 shows an example of an accelerometer data profile showing the peak shock load and a curve fitted through the local peaks in order to calculate the decay rate.

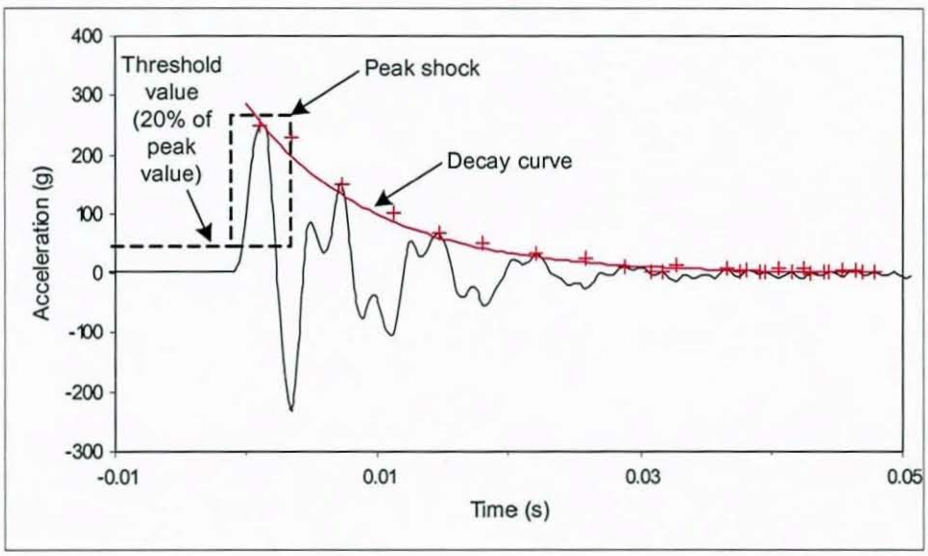


Figure 125: Example of an accelerometer data profile

In summary, the following test measures were taken:

Acceleration

- Peak shock on each of 6 accelerometer channels
- Decay rate on each of 6 accelerometer channels
- Root Mean Square (RMS) on each of 6 accelerometer channels

Grip pressure

- Peak grip force
- Individual sensor cell peak pressure
- Grip force rise rate pre-impact
- Grip force decay rate post-impact
- Individual cell rise rate pre-impact
- Individual cell decay rate post-impact
- Pressure distribution

5.7.3 Secondary test measures

The following recommendations were made in Chapter 4 about the weaknesses of the static grip test and why it did not show up significant changes between the measurements taken before and after activity:

- the stimulus in terms of amount of activity was not sufficient to result in changes
- the post test was not carried out immediately after completion of the activity, allowing the subject to recover therefore losing any potential decrease in static test performance
- the pre test was conducted prior to the subject completing an on court warm up, which could have suppressed the performance therefore reducing any potential difference between the pre and post test values

In comparison with the ITF studies presented in Chapters 3 and 4, the protocol of this study was much more fatiguing. Subjects were asked to perform the static hand-grip test before and after the activity session in the same way as in the previous studies. In this study, players performed the first static grip test following an on court as well as off court warm up. Also, because only one subject was tested at a time, it was possible to perform the second static grip test immediately following the activity (starting within 15 seconds of end of activity). The static hand-grip test was included as it provides a baseline for comparison with previous studies and other published research. It was hoped that the instrumented racket would show more in terms of indicating any hand-grip differences due to fatigue than the static hand-grip strength test, so the aim was to compare the results of both measurements.

It was decided to also include the perceived muscle soreness questionnaire and the perception questionnaire for the same reasons they were included in the previous Type 3 ball studies. The perception questionnaire was used to gain subject player feedback on the performance of the balls used (Appendix 2). Potentially this would enable any perceived differences to be correlated with the objective primary measures. Subjects were asked to complete the perception questionnaire following completion of each test session (therefore on two occasions in total). In the previous studies, the subjects played with the two balls under investigation on consecutive days and then at the end of the two days were given a questionnaire asking them to compare the performance of the two balls (and so they had to recall from the previous day how the ball felt). In this study, the two tests were completed a week apart, which was considered too long a period to ask the players to recall how the ball felt, particularly as they were likely to have also played during the week with other balls. This was solved by altering the wording of the questionnaire so that the subjects were asked to compare the performance of the ball they used in the test to the performance of balls with which they generally play. This was a weakness because the players would normally play with different balls, maybe a mixture of balls, and balls of various age and wear.

The muscle soreness questionnaire provided subjective feedback from the players about levels of perceived muscle soreness (Appendix 1). A refinement to this process (from the big ball studies) was that in addition to completing this questionnaire before and after the test, the players were asked to complete the questionnaire a further two times, in the morning and evening of the day after the test session. This was to assess levels of 'delayed muscle soreness'. Muscle soreness during and immediately after exercise usually reflects fatigue, caused by a build up of the chemical waste products of exercise (Abraham, 1987). Delayed onset of muscle soreness is common following strenuous activity to which a person is unaccustomed and the soreness worsens in the period of 12 to 48 hours after the activity. Generally this is not indicative of any problem and is usually fully gone after a few days of rest, or better still, light recovery activity. It is just part of the body's adaptation process, which is the basis for training in that, during the recovery period after exercise, the body becomes stronger in response to exertion.

5.7.4 Control measures

It was decided to have the players aim all shots at a target box marked on the court in the far corner and to record the outcome of each shot (Figure 124). Controlling the shot target zone was intended to improve the players consistency in terms of the stroke, impact location and intensity of the shot. A main requirement of the test protocol was to naturally reduce variability, a main contributor to which comes from differences in impact location. Reduction in accuracy has been reported in players playing to fatigue. Having a record of the shot outcome also helped in tracing the reason for any unusual data showing up on later processing the instrumented racket data. For instance having recorded that a shot was a mishit, the vibration associated with that shot might be expected to be different. The size and placement of the target box was based on a combination of what was used during the 'Loughborough Intermittent Tennis Test', advice of the University Coach and what happened in the pilot study. The test was not a 'skill test' and so the target size did not need to be very small; too small and the players were likely to trade off speed for accuracy, which would diminish the fatigue overload effect that was being sought. It was also important that the players remained well motivated, in order that they push themselves to their best ability. If they were generally able to hit the target, this was expected to improve their motivation. A data sheet was used to record the outcome of each shot, as being in the target box (accuracy), near the target box (consistency), out, in the net, a mishit or complete miss of the ball. This was the same approach taken as in the study by McCarthy (1997).

Return shot speed was recorded for each shot using a 'Speedchek' sports radar system, positioned at the net facing the subject (so the ball passed over it during the shot). Shot speed was recorded for a number of reasons. The magnitude of the vibration and grip pressure recorded by the instrumented racket were influenced by how hard the subjects hit their shots. It was important to encourage the subjects to hit consistently during each test session and through the whole duration of the test session (for the sake of comparison). As the subjects became tired it was thought that they may start to hit more slowly. The speed radar provided immediate feedback to the players during the session to encourage them to hit consistently and provided a measure of the return ball speed to indicate fatigue, lack of motivation or influence of ball type.

Although monitoring ball return speed helped motivate the players and maintain localised muscle exertion it was necessary to measure how exhausting the activity was to ensure that each subject was not being over exerted and to ensure consistency across test sessions. To make inferences about different equipment causing different levels of fatigue, it was necessary that each player worked equally hard with each. The requirement was for a quick and unobtrusive means of assessing level of exertion. The whole thrust of the approach was to examine whether non-invasive methods could detect change. These could be correlated with invasive physiological measures if apparent. Heart rates were recorded during each test session using a Polar Sports Tester telemetric transmitter worn around the chest in combination with a receiver wrist watch. This recorded and stored heart rate at five second intervals. Recorded data were subsequently downloaded onto a computer for later analysis. Heart rate is an accepted indicator of intensity of effort (Laukkanen and Virtanen, 1998). During the testing, heart rate was monitored visually after each activity period of the test session to ensure that each subject was working at an appropriate level, which was neither too high nor too low. Because the test was designed to be physically challenging it was necessary to monitor the well being of the subjects in order to prevent them from exerting themselves detrimentally.

As a further measure of exertion, after each activity period subjects were asked to indicate their perceived rate of exertion on the standard Borg scale (Borg, 1970). This is an ordinal scale with values ranging from 6 'no exertion at all' to 20 'maximal exertion'.

Steps were taken to ensure consistency between test sessions that were conducted a week apart. Subjects were asked to ensure that their activity levels, sleep pattern and dietary intake were as similar as possible in the two days prior to each test session. To assist them in this task they were issued with an activity log and dietary intake diary, which they were instructed to fill out in the two days before the test. In the two days before the second test the subjects were encouraged to refer to their log from the previous week to enable them to replicate conditions as closely as possible. On the morning of each test day the subjects were asked to indicate on a written sheet how they generally felt in themselves that morning. This was to monitor for any signs of ill health, general malaise, start of an illness, etc. that may have influenced their level of performance. Each test session was video recorded for possible use in the investigation of unusual results.

CHAPTER 6

DYNAMIC GRIP MEASUREMENT STUDY

6.1 INTRODUCTION

This chapter reports on the final experimental study that was carried out to measure various parameters of in-play dynamic grip performance in a group of skilled players within a protocol designed to induce repeatable accelerated forearm fatigue whilst maintaining realistic play conditions for players. The method reported in section 6.2 is based on the issues raised and decisions described in Chapter 6. The aims of the experiment were twofold:

- to prove the effectiveness of a more sensitive instrument (a fully instrumented tennis racket for use in-play compared with a static hand-grip test)
- to investigate the influence of equipment modifications on player performance and player fatigue

The objective was to determine whether one or more quantitative measurements made with the instrumented racket change with fatigue status and so would enable the effect of equipment modification on fatigue status to be assessed.

In assessing the effectiveness of alternative measurement parameters it was necessary to determine the inter and intra-subject variability. The requirement was to provide a realistic play environment, i.e. not laboratory based, whilst at the same time providing sufficient control for practical test sessions to be repeatable and comparable. In particular, the aim was to investigate a series of parameters and derived measures that are sensitive to changes in grip performance due to fatigue or muscular overload in tennis.

The remainder of this chapter is divided into two main sections that describe the methods and present the results that are discussed further in the final section.

6.2 METHODS

6.2.1 Participants

Nine male University Team players, from the first, second and third teams, were chosen as participants for the study. Their ages, basic physical characteristics, experience and current tennis ratings are shown in Table 17. Two participants were left handed and could not use the instrumented racket during the periods of data collection because the positioning of the un-instrumented grip faces made it suitable for use by right handed players only. The Tekscan sensors would have needed to be positioned differently for left handed players but to ensure consistency of results the decision was made to take measurements for all subjects using the same unaltered instrumented racket. The two left handed players followed the same protocol as the right handed players and all measurements were taken with the exception of measurements from the instrumented racket. This increased the sample size for the control and secondary measures data.

The selection criteria for subjects were that they were male, of age 18-24, and of University team standard. They were all screened for health, in full training and had no pre-existing signs of injuries. Only subjects that used a single handed backhand were selected, although four of the subjects reported using a combination of double and single handed backhands during normal play.

Table 17: Participant mean details

Sex	N	Age (yr)	Height (m)	Mass (kg)	Time playing tennis (yr)	LTA rating	Maximum heart rate (bpm)	Resting heart rate (bpm)
Male	9	20.1±0 6	1 81±0 06	75 2±9 1	10.5±2.5	2.4±0.6	194±5	57±7

6.2.2 Procedure

All testing took place on indoor acrylic courts situated in Loughborough University's Dan Maskell Tennis Centre. The venue was chosen for a number of practical reasons. It provided a uniform playing surface and controlled playing conditions for all test sessions. Being indoors negated the effects of weather and afforded convenient access to power sockets for the test equipment. In the future, it would be useful to investigate the effects of different court surfaces.

Each subject took part in two sessions conducted a week apart. The only difference in the two test sessions was that standard tennis (pressurised) balls were used in one and pressureless balls used in the other. The two sessions were completed at the same time of day.

Penn supplied both the standard balls (pressurised) and the pressureless balls. Ninety balls were used for each test session, all ninety balls being replaced with new ones at the start of each subject's test session.

Prior to testing, subjects completed a controlled warm up that was developed with the advice of the University LTA qualified team coach. This consisted of a jog to raise the subject's temperature followed by a series of appropriate warm up stretches. The subject was required to use a standardised racket for the test, a Head Intelligence I.S2 mid plus strung at 25 kgf. A selection of standardised rackets were available in a range of grip sizes. Subjects were asked to choose one with a grip size they were comfortable with. Subjects then completed a timed 5 minute warm up on court returning balls delivered at a launch speed of 17.9 ms^{-1} (40 mph) at a rate of initially 15 balls per minute increasing to the test rate of 30 balls per minute. A manually operated Bola ball launch machine was used to deliver balls to the subject in a consistent and reproducible manner.

Three minutes after the warm up the subjects performed a pre test maximal hand-grip test using a digital hand-grip dynamometer (NK Biomedical). This involved three separate three second maximal isometric contractions using alternate hands. This was repeated immediately on completion of the test.

All sessions were video recorded to enable playback observation of the tests.

6.2.3 Test schedule

The test session was designed to induce accelerated fatigue of the subjects by overloading the muscles associated with playing a single handed backhand. The total duration of the test session was 41.5 minutes inclusive of activity and recovery periods. The subjects were informed that the activity would be of a challenging intensity and duration and that they could stop the test at any time. After each activity period the player's heart rate response to the activity was monitored and the subject was asked to indicate their perceived exertion on the standard Borg scale.

The sequence of events in the test schedule is illustrated in Table 18.

During data collection, using the instrumented racket the subject returned 15 single handed slice backhands aiming at the target box (see Figure 124). In the case of mishits or suspected sub-standard shots the player simply moved on to the next shot. A total of 15 balls were fed for each DC period, whatever the shot outcome. A requirement was for each player on each test occasion to be in play for exactly the same total time. The ball was delivered to the subject from a Bola ball launch machine consistently at 40 miles per hour at a rate of 15 balls per minute. This process was repeated by the subject on four occasions during the course of the test session, each occasion being referred to as a DC (data collection) and being numbered consecutively from one to four. The pre test data collection was referred to as DC1 (or pre), the data collection occurring after three periods of Controlled Play Activity (CPA) was referred to as DC2, occurring after six periods of CPA was referred to as DC3 and occurring after nine periods of CPA was referred to as DC4 (or post).

During controlled play activity (CPA), using a standardised racket (non instrumented) the subject returned balls delivered at 17.9 ms^{-1} at a rate of 30 balls per minute. The subject repeatedly returned the ball using one forehand to two consecutive single handed backhands aiming at the target box marked on the court. The ball delivery remained the same throughout the CPA, the subject stepping round the ball to change from forehand to backhand. The player performed this activity continuously for three minutes followed by one minute recovery. In total the test consisted of nine periods of CPA.

Table 18: Test schedule sequence of activities

Phase	Step	Duration	Activity
Pre-test	1	-	Subject to submit 'Subject General Information Form' (wk 1 only)
	2	-	Subject to submit 'Test day well-being Form'
	3	-	Subject to submit 'Dietary Record'
	4	-	Subject to complete 'Muscle Soreness Questionnaire'
	5	10 mins	Off court warm up - e.g. jog/stretch (self operate)
	6	-	Instrumentation familiarisation and instruction
	7	5 mins	Controlled on court warm up
	8	3 mins	Rest
	9	-	Isometric hand-grip test (pre-test)
	10	2 mins	Recovery
DC1	11	1 min	Data Collection with instrumented racket
CPA1-3	12	30 secs	Recovery
	13	3 mins	Controlled Play Activity 1
	14	-	RPE indication (Rate of Perceived Exertion)
	15	1 min	Recovery
	16	3 mins	Controlled Play Activity 2
	17	-	RPE indication
	18	1 min	Recovery
	19	3 mins	Controlled Play Activity 3
	20	-	RPE indication
	21	1 min	Recovery
DC2	22	1 min	Data Collection with instrumented racket
CPA4-6	23-32	12.5mins	Repeat steps 12 to 21
DC3	33	1 min	Data Collection with instrumented racket
CPA7-9	34-43	12.5mins	Repeat steps 12 to 21
DC4	44	1 min	Data Collection with instrumented racket
Post-test	45	-	Isometric hand-grip test (immediately after DC4)
	46	-	Muscle Soreness Questionnaire (after hand-grip test)
	47	-	Perception Questionnaire (after Muscle Soreness Q.)
	48	-	Muscle Soreness Questionnaire (next morning)
	49	-	Muscle Soreness Questionnaire (next evening)

6.2.4 Test measures

6.2.4.1 Primary test measures

The primary test measures were racket vibration and grip pressure. Details are provided in section 5.7.2.

In-play grip pressure measurements were made using the instrumented racket during the four data collection periods. Grip pressure data was recorded at a sampling frequency of 200 Hz for 1 second and triggered manually approximately 0.3 second prior to the ball impacting with the racket. Acceleration measurements were also made using the 6 accelerometer channels mounted on the instrumented racket. Acceleration data was recorded at 2048 Hz and was triggered simultaneously with the grip pressure allowing synchronisation of this data.

6.2.4.2 Secondary test measures

<u>Static maximal hand-grip test</u>

Subjects performed a maximal hand-grip strength test before and immediately after the test session (section 3.4.2).

<u>Perceived muscle soreness</u>

Subjects filled out a muscle soreness questionnaire before each test session, after each test session, the morning after the test session and the evening of the day after the test session (Appendix 1). This questionnaire was designed to enable subjects to record perceptions of muscle soreness (section 3.4.3).

<u>Perception</u>

Subjects filled out a perception questionnaire at the end of each session (Appendix 2 and section 3.4.5).

6.2.4.3 Control measures

Two active control measures were included in the study design to maintain data quality:

- Shot outcome
- Shot speed

The outcome of all shot returns were recorded during the test on a prepared data sheet. The subject was instructed to aim at a target box (see Figure 124) marked on the court and the outcome of each shot was recorded as landing in the target box, 'near' the target box, out, in the net or a mishit. For the purposes of analysis, a rating of 'accuracy', 'consistency' and 'out' was calculated as the percentage of, shots landing in the main target box, shots landing in the extended target box, all other shot outcomes, respectively.

The speed of every return shot hit by the subject was recorded throughout the test session using a Speedchek Sports Radar. The speed of the shot was immediately displayed, providing feedback to the subject. The subject was asked to maintain the pace of the returns throughout the test and was verbally encouraged to do so. Consistent pace was considered to be ±10% of the subject's predetermined 'good' backhand match pace. This pace was established during a training session prior to the test by the University Coach.

Players were encouraged to maintain their level of effort and concentration throughout the test. Monitoring the shot outcome and return speed during the session gave instant feedback to the testers of a change in performance, indicating if the player was getting tired and starting to struggle to maintain their performance level or if they were losing concentration or motivation. In either case, providing the players with encouragement helped.

The passive controls (section 5.7.4 for details) included as test measures were:

- Heart rate
- Rate of perceived exertion (RPE)
- Additional controls

Throughout the test the subject wore a Polar Sports Tester telemetric transmitter and receiver and heart rate was recorded throughout the test at 5 second intervals. This data was downloaded to computer for analysis on completion of the test. After each activity period, the subject's heart rate was checked as part of the monitoring activity to ensure subject well being.

After each activity period the subjects were asked to indicate their perceived exertion on the standard Borg scale.

Steps were taken to control for non target variables to ensure consistency between test sessions, which were conducted a week apart.

6.2.5 Data processing

6.2.5.1 General

Data processing involved extracting data from the data capture device or host software and where appropriate applying any calibration factors and presenting the data in a form which was convenient for performing data analysis.

6.2.5.2 Accelerometer data

The data from the 8-channel Hewlett Packard analyser was stored in ASCII format by the SignalCalc620 software. A total of 780 shots of data were captured, based on 60 shots for each of 6 subjects repeated on two occasions, plus 60 shots for one subject who only completed one week. An Excel spreadsheet template containing all of the calculations required to process the shot data was constructed to automatically generate a series of parameters that were chosen to characterise the shot data. For each shot, a new, duplicate copy of the spreadsheet was first created, into which the ASCII data file was imported. Due to the fixed format nature of the

ASCII data, all of the calculations were then performed automatically, based on the fixed cell positions of the data. Some of these data manipulations were outside the capabilities of the standard Excel functions. It was therefore necessary to write a number of Excel macros to provide the requisite functionality. A table of output data and a series of graphs were automatically generated, which characterised the main features of the shot and provided an instant visual representation of the shot data.

The following paragraphs provide a list and brief description of the parameters that were calculated to characterise the accelerometer data. Each parameter was calculated for each of the six channels of accelerometer data for each shot. Statistical tests were performed on these parameters to determine whether changes occurred due to either ball type or fatigue level. The different parameters could be broadly classified under three different headings of translational shock, angular shock and vibration decay, as follows:

Translational shock

- Peak acceleration (g)
- Impact time
- Peak time
- RMS (PI)
- Area (PI)

Angular shock

- Angular acceleration (peak)
- Angular acceleration RMS (PI)
- Angular acceleration Area (PI)

Vibration decay

- Attenuation filter method
- Exponential attenuation parameter 'a'
- Exponential attenuation duration

Peak acceleration (g) was found by simply searching through the data points and finding the point with the greatest magnitude, either positive or negative.

Impact time was defined as the first time at which acceleration of the left uniaxial accelerometer exceeded 20% (flexibly coded) of the peak value. The left uniaxial was chosen because it exhibited a characteristic rapid rise to an initial high peak. The right uniaxial could have equally well been chosen. A uniaxial was also chosen in preference to any of the triax channels to overcome any potential time delay of the vibration transmission from racket throat (uniaxial location) to racket handle (triax location).

The peak interval was defined as the interval of the graph, in the region of the peak acceleration value, that extends from threshold values equal to 20% of the peak value, before and after the peak. With reference to Figure 125, the peak interval is shown enclosed by the dashed box marked 'peak shock'.

The Root Mean Square (RMS) of the peak interval (PI) was calculated. RMS was calculated since it provides a measure of the magnitude of a set of numbers and is roughly the same or a little larger than the average of the unsigned values.

The area under the same peak interval of the graph was calculated, i.e. extending from the point at which the acceleration rises above 20% of its peak value to when it drops below 20% again. Like the RMS, the area under the graph was calculated to provide an alternative physical characterisation of the acceleration plot. The area corresponds to the change in velocity occurring over the peak interval. Velocity is a measure of physical significance since with reference to the mass, it determines both momentum and kinetic energy. Moreover, since the mass of the system is unchanging, the change in velocity is a measure of the initial impulse experienced. Harder impacts or off centre shots could be expected to generate larger grip impulses.

The Angular Acceleration was calculated around each of the three mutually perpendicular axes defined as X, Y and Z.

The rate of decay of the accelerometer vibration was calculated in two separate ways. The first involved fitting an exponential decay curve to the data and comparing decay curve indices. The attenuation time was then calculated as the time taken to fall to a (flexibly coded) percentage of the peak value. The second method of characterising the rate of decay, which was called the attenuation filter method, involved smoothing the data by applying a running average filter of 16 data points. 16 was chosen after carrying out some frequency analysis on the accelerometer data which indicated that the fundamental vibration frequency of the instrument racket was in the region of 128 Hz. Given that the sampling frequency of the accelerometers was 2048 Hz, a span of 16 data points appeared to provide the best match to the cycle length of the main oscillation.

A 'summary spreadsheet' of the individual shot processing spreadsheets was constructed and populated, to perform group statistics. Given the large number of individual shots (780), cutting and pasting summary data from each individual template processing spreadsheet to the summary spreadsheet would have been unduly time consuming. Instead the summary spreadsheet was constructed with flexible links to the individual shot spreadsheets that were specified dynamically by simply typing in the workbook and worksheet names of the individual shot spreadsheets.

For the benefit of readers who may wish to replicate this data processing activity an example of the spreadsheets and code listing of the Visual Basic macro code used is provided in Appendix 10.

6.2.5.3 Grip pressure data

The Tekscan grip pressure data were initially stored as Tekscan movie files, data from each individual shot being stored as a separate file. As with the accelerometer data, data was captured for a total of 780 shots. To process the data, each movie file was first exported from the Tekscan host software as an ASCII file and then imported into an Excel spreadsheet template. Each movie file contained 200 frames of data, which was equivalent to 1 second. The exported ASCII file only contained 101 frames of data, the 'missing' frames having been removed to achieve data alignment between all of the different shot files. Each Tekscan ASCII file was trimmed so that it contained data frames corresponding to 0.075 seconds before ball impact to 0.425 seconds after impact. Alignment was achieved by checking the accelerometer data for the shot and finding the time period between the manual trigger and the ball impact, as indicated by a rise of the left hand uniaxial accelerometer.

As with the accelerometer data, a template processing spreadsheet was constructed to automatically process the data and calculate a series of parameters chosen to characterise the grip pressure data for the shot. These parameters fell into the following categories:

- Peak grip pressure
- Grip force rise rate pre-impact
- Grip force decay rate post-impact
- Overall grip activity level
- Pressure distribution

For each test shot, each parameter was calculated twice, firstly for the average pressure signal across all of the sensor cells and secondly for the single sensor cell that achieved the highest peak pressure during the shot. For each shot, the peak pressure cell was identified from the data collected for that shot and so the peak pressure cell was liable to change from shot to shot.

Peak grip pressure was found by simply searching through the data points and finding the data point with the greatest magnitude. For each shot, two separate peak grip pressures were identified, firstly the peak before ball impact and secondly the peak after ball impact. The data points immediately around the ball impact time were disregarded due to suspected noise.

Prior to ball impact it was observed that the grip pressure typically built up to a maximum value at or around the moment of ball impact from when it subsequently reduced. Furthermore, the pre-impact rise in pressure was observed to consistently follow a straight line. The rise rate was therefore characterised by automatically fitting a straight line segment to the pre-impact portion of the pressure curve and automatically generating a data value for its gradient.

After ball impact the grip pressure typically reduced. However, considerable variability occurred in the basic shape of the decay curve, which meant that attempting to automatically fit it with a particular type of curve from which decay indices could be derived was not possible. Instead a number of alternative measures were calculated to characterise the percentage decay that occurred. This was done in two alternative ways, both of which were based on reductions occurring in the post-impact peak level of grip pressure. Firstly, time periods were calculated that corresponded to a range of different percentage reductions in the post-impact peak (Figure 126). Secondly, working in the other dimension, the percentage reductions in pressure compared to the post-impact peak were calculated at particular (periodic) time intervals after ball impact (Figure 127).

To obtain a measure of the overall level of grip activity, the area under the grip pressure curve was calculated for the period from 50 milliseconds before ball impact to 100 milliseconds after ball impact. This was a shorter period than the 0.075 seconds before ball impact to 0 425 seconds after impact for which data was available. However, a shorter period was selected to focus on the region of peak pressure. Additional data processing would be possible to calculate the area under different portions of the curve.

To obtain a picture of the overall pressure distribution across the hand, a separate chart was produced for each shot showing the average pressure value occurring in each pressure cell through the data capture period, i.e. plotting "pressure versus pressure cell number" as opposed to the "pressure versus time" view taken for all the other above measures.

Statistical tests were performed on all the parameters to determine whether changes occurred due to either ball type or fatigue level.

Had all eight faces of the racket handle been instrumented, it would have been interesting to try and resolve the normal forces acting on each handle face and thereby calculate whether any nett forces were present. The presence of nett forces might be expected to indicate racket handle acceleration and trying to correlate nett forces with known movement would have been challenging. However, this line of investigation was unavailable since only six of the eight faces of the racket handle were instrumented.

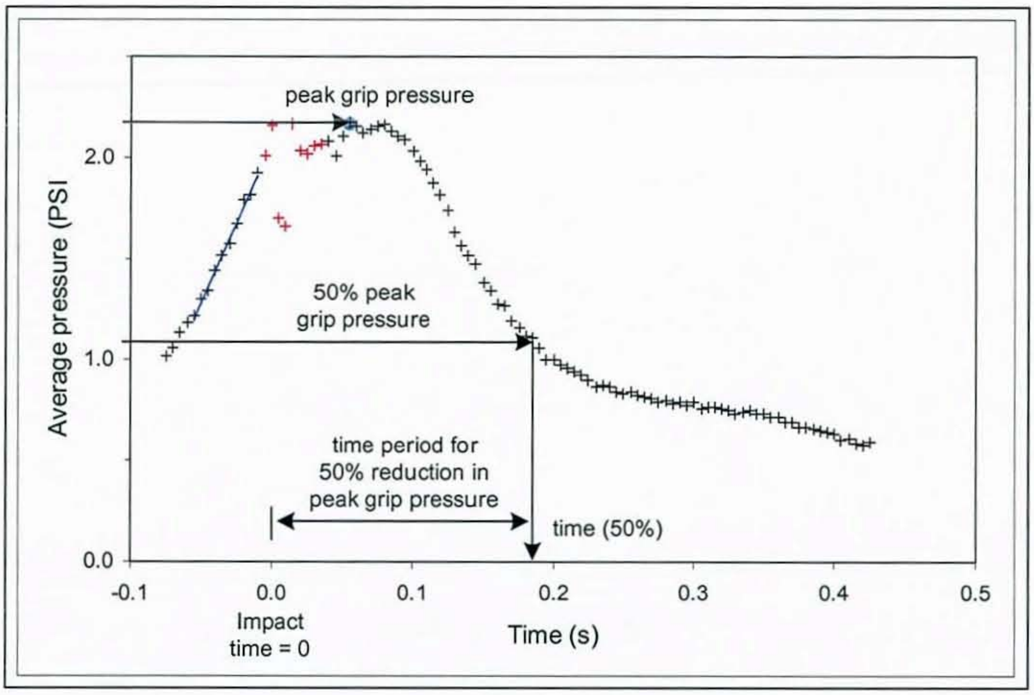


Figure 126: Time period for percentage reduction in grip pressure peak

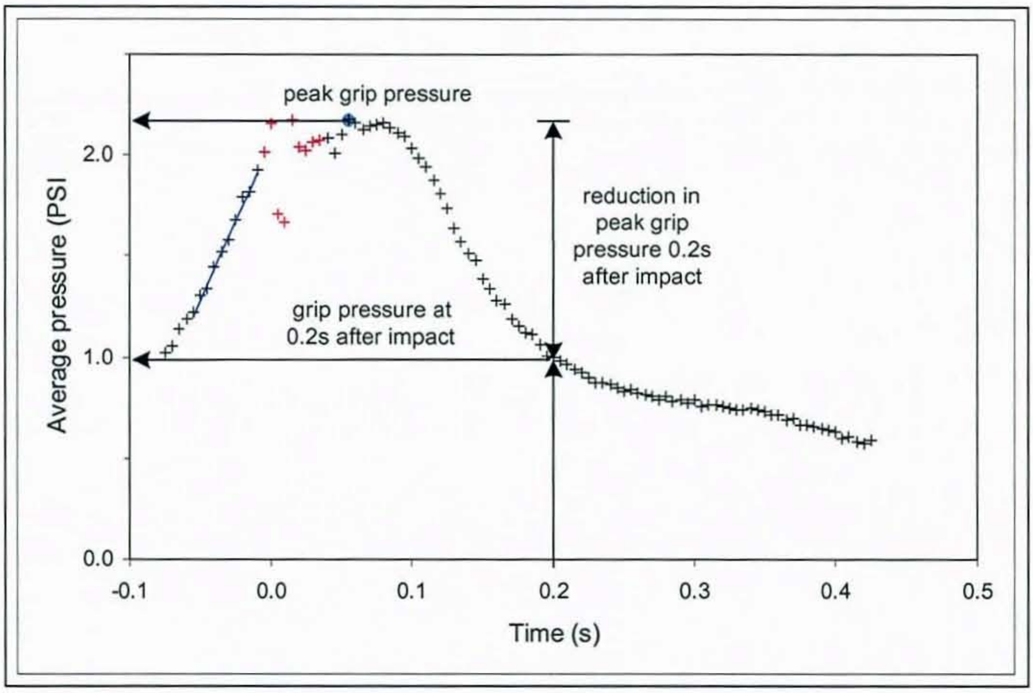


Figure 127: Percentage reduction in peak grip pressure a certain time after ball impact

When the raw ASCII shot data were imported into the spreadsheet, the spreadsheet first applied the calibration scaling factor to each cell, as previously determined by the calibration activity. Each of the 101 data frames contained in the ASCII file contained a pressure value for each of the 96 pressure cells. Two main measures of the pressure data were considered. Firstly, the average pressure of all 96 cells. Secondly, the value of the individual cell that reached the highest peak pressure, although all pressure values for the 40 milliseconds following ball impact were discounted on the basis that during this period racket vibration was affecting the grip pressure readings. Time history plots of the average pressure reading and the peak cell pressure reading were automatically generated to give an instant visual representation of the shot data. A range of parameters to characterise the shape of these plots were automatically calculated.

As with the accelerometer data, a 'summary spreadsheet' of the individual shot processing spreadsheets was constructed and populated, in order for group statistics to be performed. Again, this summary spreadsheet was constructed with flexible links to the individual shot spreadsheets that were specified dynamically by simply typing into the summary spreadsheet the workbook and worksheet names of the individual shot data spreadsheets.

6.2.6 Data analysis

Similar approaches were used for analysis of the accelerometer data and grip pressure data. Summary data for each shot was copied from its single shot processing Excel spreadsheet into a combined summary spreadsheet, a different summary spreadsheet being used for the accelerometer data and for the grip pressure data. Through the use of standard Excel filters, a variety of alternative views of the data were displayed and copied to form other tables containing subsets of the data, for example, all shots from week one, or all shots from DC1. Statistical tests were applied to the data in different ways to examine for any similarities, trends, key differences or changes in the data. Statistics were gathered at the single subject and group level within these summary spreadsheets.

Data were analysed and statistics produced at the level of individual subjects and whole group to investigate the effects due to fatigue over time (DC1 to DC4) and due to different ball type. Analysis included statistical tests on the two different ball types individually, and also on the combined data for both ball types (i.e. data for the standard pressurised ball from week 1 combined with data for the pressureless ball from week 2). Mean and standard deviation were calculated. Coefficient of variability was used to assess the variation observed either within or across a group and is given by the formula:

$$CV=\left(\frac{SD}{Mean}\right)\times 100$$

From initial inspection of the data displayed in bar charts it was observed that many of the differences occurring over time were relatively small in comparison to the amount of intra-sample variability. For this reason, the majority of the statistical analysis concentrated on testing for differences between DC1 and DC4, rather than also involving the intermediate values, DC2 and DC3. In the case of comparing two means, a paired two-tailed t-test was appropriate. An additional reason for using this approach was to enable the large amounts of data generated by the research study to be processed within an acceptable timescale. The paired t-tests were processed automatically by the Excel spreadsheets using the in-built functions for statistical analysis.

More advanced statistical analysis was also performed using an Analysis of Variance (ANOVA) test. The ANOVA test was used to test for significant differences between each of the four sets of data DC1, DC2, DC3, and DC4. The ANOVA test was not available within Excel and was instead performed using the statistical analysis package SPSS (version 11). Due to the time consuming nature of applying the ANOVA test to all data files, it was only used selectively in situations where observation of the charts suggested that differences might exist (where error bar graphs overlap).

A repeated measures ANOVA test was applied using SPSS. The repeated measures version of the ANOVA test is specifically designed for use when the levels of the independent variable have a meaningful order. In this case DC1, DC2, DC3, and DC4 occurred at successive points in time. Bonferroni corrected output statistics were selected as being most appropriate for use with a repeated measures ANOVA. A significance level of 0.05 (95% confidence level) was set for the *post hoc* tests. When checking the significance of the output statistics, care was taken to check if the assumption of sphericity had been violated, and where it had the Greenhouse-Geisser correction, Huynh-Feldt correction or Stevens correction was applied. The table of *post hoc test* output statistics produced by SPSS contained values for each of these corrections, and after each test the appropriate value was selected for the given sphericity value.

As well as being used to test for possible fatigue induced changes, a paired two-tailed t-test was used to test the effect of changing the ball type. Thus, a whole range of data were compared at corresponding times between the week 1 test with the pressurised ball and the week 2 test with the pressureless ball. Within a fixed group of subjects, the paired two-tailed t-test was an appropriate test because by matching pairs of results for each subject it removed the effect of any systematic differences between subjects.

6.3 RESULTS

6.3.1 Introduction

The results presented in this chapter represent a selection of key results that exhibit differences. Differences are referred to as either trend differences (90% confidence level) or significant differences (95% confidence level). Where bar charts are used to present means and standard deviations, it should be noted that the error bars represent one standard deviation.

Eight of the nine participants completed the study. One participant was unable to undertake the second session due to illness, the incomplete set of data obtained from the withdrawn subject was not used in the ensuing analysis. Two of the subjects were left handed and could not use the instrumented racket, which was set up for right handed players only. For this reason the results presented and discussed for the 'vibration' and 'grip pressure' measurement sections refer to only six of the eight subjects, the other results sections were obtained from eight participants.

6.3.2 Vibration measurement

Figure 128 to Figure 131 inclusive provide examples of characteristic traces that were obtained. These plots show accelerometer data over the time period from 0.01 seconds pre-impact to 0.05 seconds post-impact. The duration that the ball remains in contact with the string bed during impact is approximately 0.004 seconds with the ensuing racket vibration lasting for approximately 0.04 seconds. Each figure consists of six plots, each corresponding to the output of a different accelerometer channel of the same single shot (see Figure 115 for positioning of accelerometers). The six plots show acceleration in terms of the gravitationally constant g. The data from the individual shots were processed to obtain mean data at the level of both individual subjects and at group level for statistical analysis.

The traces are comparable with published data in terms of peak values and attenuation (Brody *et al.*, 2002; Cross, 1999; Kawazoe *et al*, 2002; Knudson, 1991b). The relative magnitude of acceleration in the uniaxial channels (positioned on the throat of the racket) is in the order of approximately six times greater than the triaxial accelerometer channels (within the racket handle). This is to be expected because the vibration attenuates as it travels down the racket towards the hand. The left and right uniaxial traces are in the hitting plane and as a result are greater in magnitude than the centre uniaxial, which is in the slice plane. The z triaxial channel is in the plane of impact and so of the three triaxial channels would be expected to generate the largest values. Triaxial y, which is in the slice plane (transverse), might be expected to exhibit the next largest triaxial signal. It is surprising that the amplitude of vibration on the x channel is quite so large, larger than the y channel for the examples shown.

The trace for each channel is characteristic of the placement of the accelerometer it is associated with and can be seen to be fairly consistent across subjects. This is because the vibration is driven by the response of the racket and as a result of the controls imposed the shots are all similar (type and direction of shot, return speed). The variation in the magnitude of the vibration represents slight differences in shot execution, for example, hitting velocity and/or impact location. The relatively small variation across subjects was indicative of the relative dominance of the racket characteristics in determining the vibration characteristics of the complete racket-arm system. Off centre shots were reflected in a relative difference between the left and right uniaxial accelerations, which was indicative of angular rotation about the longitudinal axis of the racket.

The vibration plots exhibit classical attenuation. To characterise the rate of this attenuation, Figure 131 shows how an exponential curve was automatically fitted to the plots. Automatic curve fitting was carried out for all plots to enable statistical analysis of the exponent and hence rate of decay. Referring to Figure 131, the data points marked by the red crosses were automatically calculated as the local peak values, negative peaks being made positive. An exponential decay curve was automatically fitted through the local peak values and the equation of the exponential curve automatically generated for use in the subsequent statistical analysis.

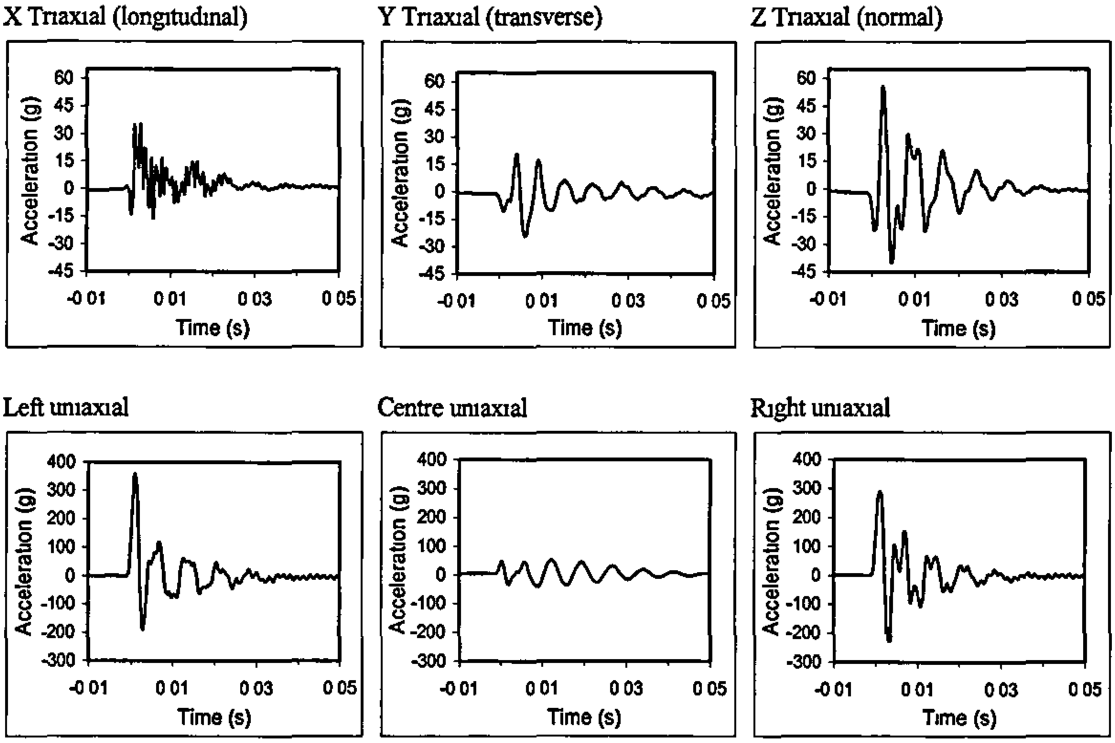


Figure 128: Accelerometer data for Subject 3, pressureless ball, DC1, shot 6

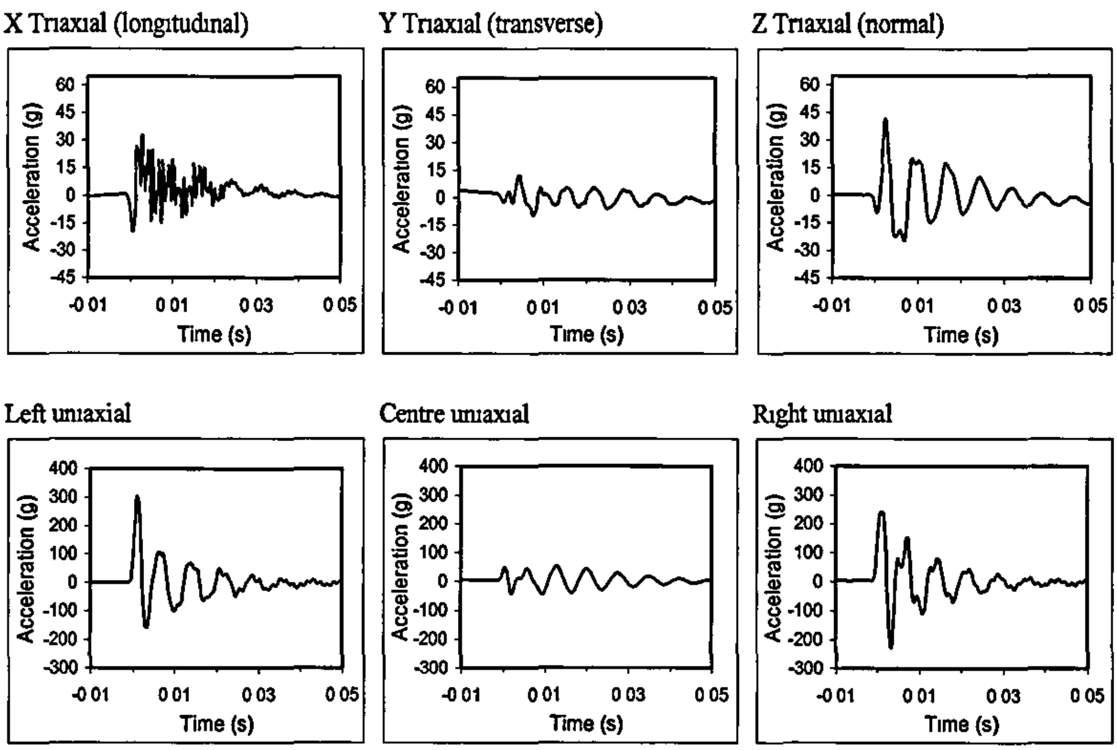


Figure 129: Accelerometer data for Subject 7, pressureless ball, DC3, shot 7

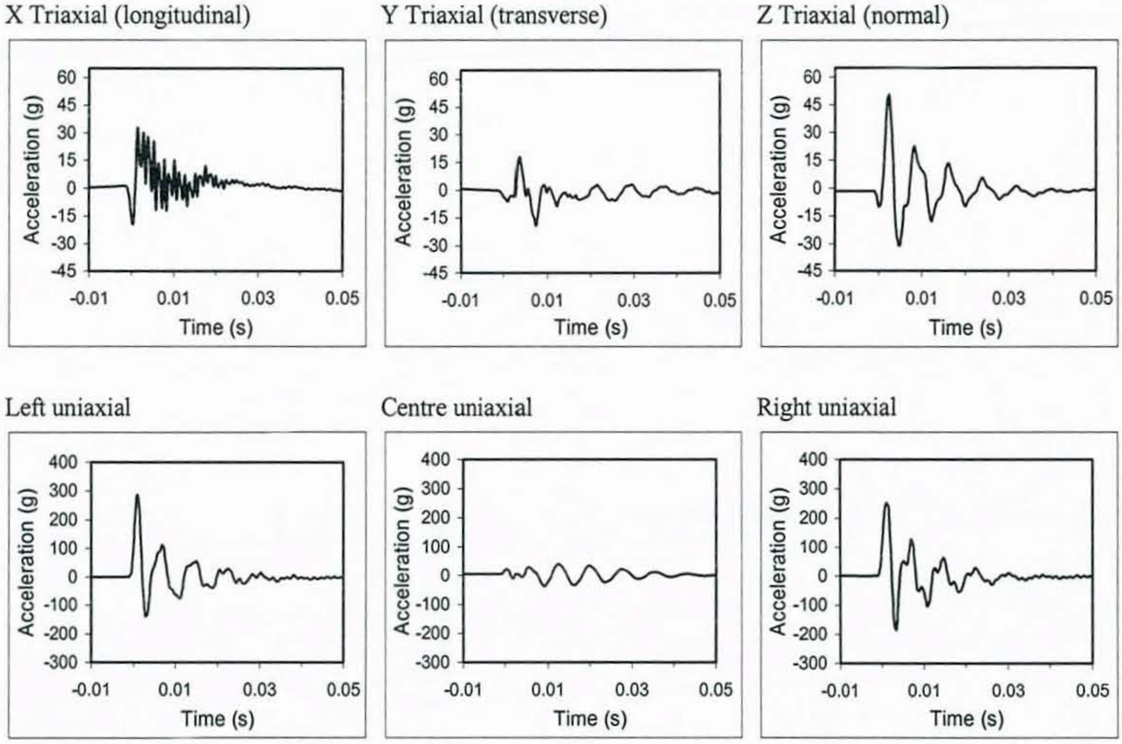


Figure 130: Accelerometer data for Subject 2, pressureless ball, DC4, shot 1

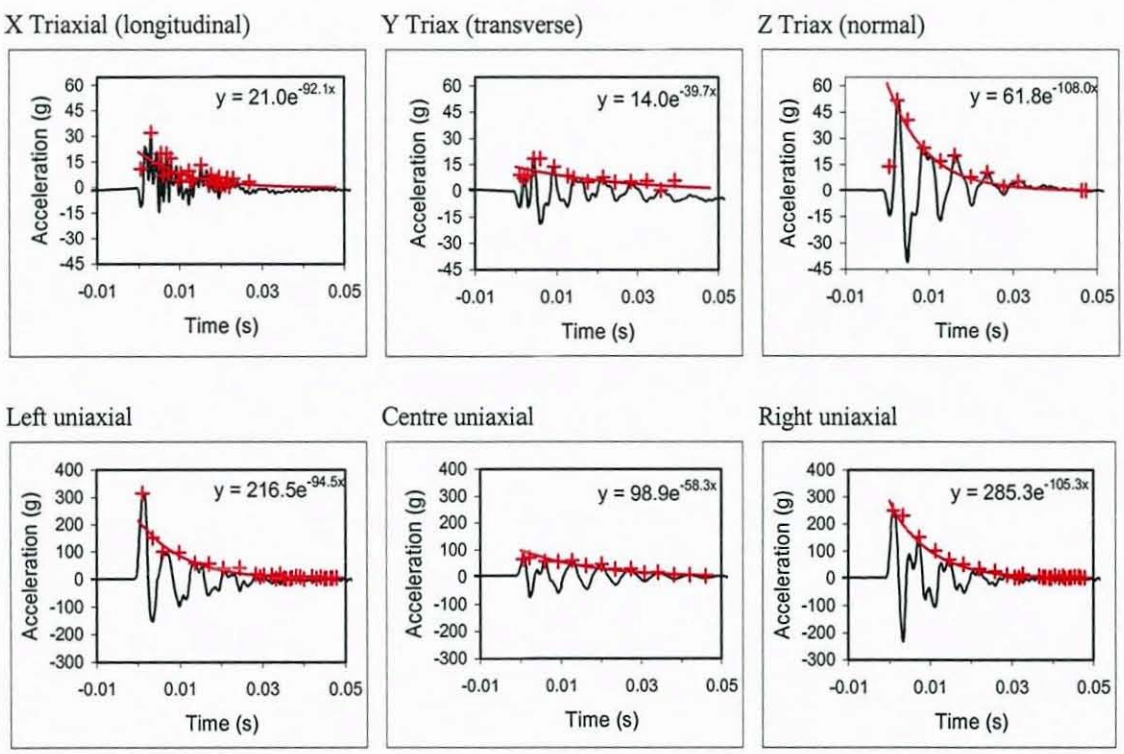


Figure 131: Accelerometer data for Subject 3, standard ball, DC2, shot 3

Each of the parameters identified in section 6 2.5.2 were calculated to characterise the accelerometer data for each of the six channels at both the individual subject and group level. Statistical tests were performed on these parameters to determine whether changes occurred due to either ball type or fatigue level. With the exception of those results that are presented in the rest of this section, the other parameters showed no systematic differences (see Appendix 11).

Figure 132 shows bar charts for the group peak acceleration for each ball type and Figure 133 shows group peak acceleration for the combined data of both ball types. Figure 134 to Figure 139 show peak acceleration data for six of the individual subjects[5]. Peak acceleration was the only vibration parameter to exhibit systematic differences over time (due to fatigue). There was no difference when comparing peak acceleration values for the standard pressurised ball compared with the pressureless ball. The trend of these results appears to be a reduction of peak value over time on three accelerometer channels; triaxial axis-y, triaxial axis-z and the uniaxial centre axis. A mean reduction of approximately 15% occurred, although due to variability of results these reductions were not statistically significant. Upon examination of the mean results for the individual subjects, it was found that the reductions in peak acceleration were particularly noticeable for three of them (Figure 135, Figure 136 and Figure 139). However, a repeated measures ANOVA test only revealed the following significant differences, all relating to subject 3 peak acceleration (Figure 135)

- for the standard ball (week 1) DC1 v DC3 and DC1 v DC4
- for the pressureless ball (week 2) DC1 v DC2, DC1 v DC3 and DC1 v DC4

A reduction in peak acceleration in the centre uniaxial may be explained by the player applying less slice, a reduction in the chopping action of the shot. The absence of a change in the left and right uniaxial channels is interesting as a hypothesis could have been that as a player becomes more tired they might be expected to hit more shots off centre. If this had been the case then the left or right peak uniaxial acceleration would have been expected to increase from DC1 to DC4. This did not occur suggesting in the case of this study that fatigue did not result in players hitting more off centre shots. In addition this is borne out by the absence of any decrease in shot outcome over time (see Figure 159 to Figure 162 inclusive). A reduction in peak acceleration was not reflected by a corresponding reduction in the return shot velocity data (see Figure 163 and Figure 164).

[5] The abbreviations 'stand' and 'press' within the charts refers to standard pressurised and pressureless ball data.

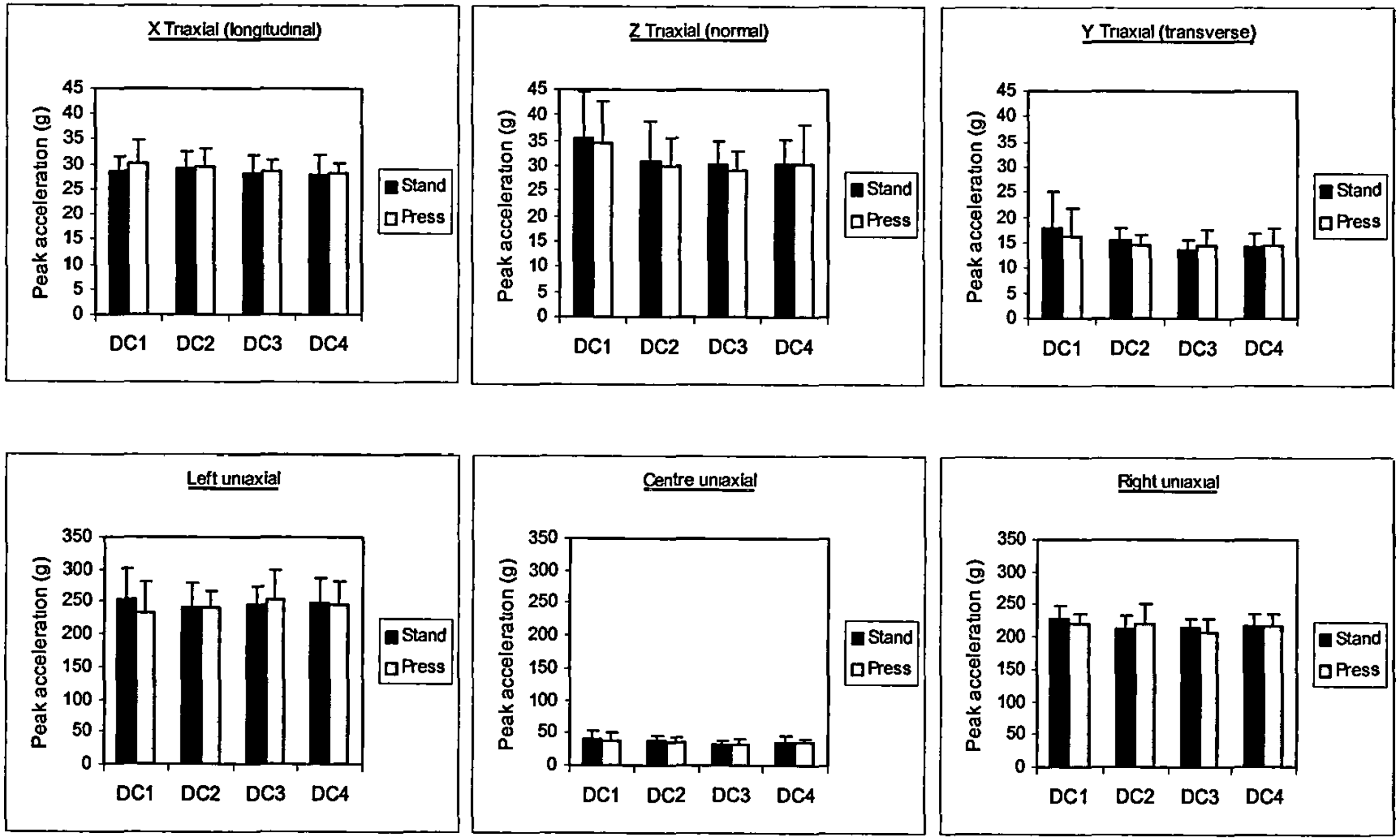


Figure 132: Bar charts showing group peak acceleration

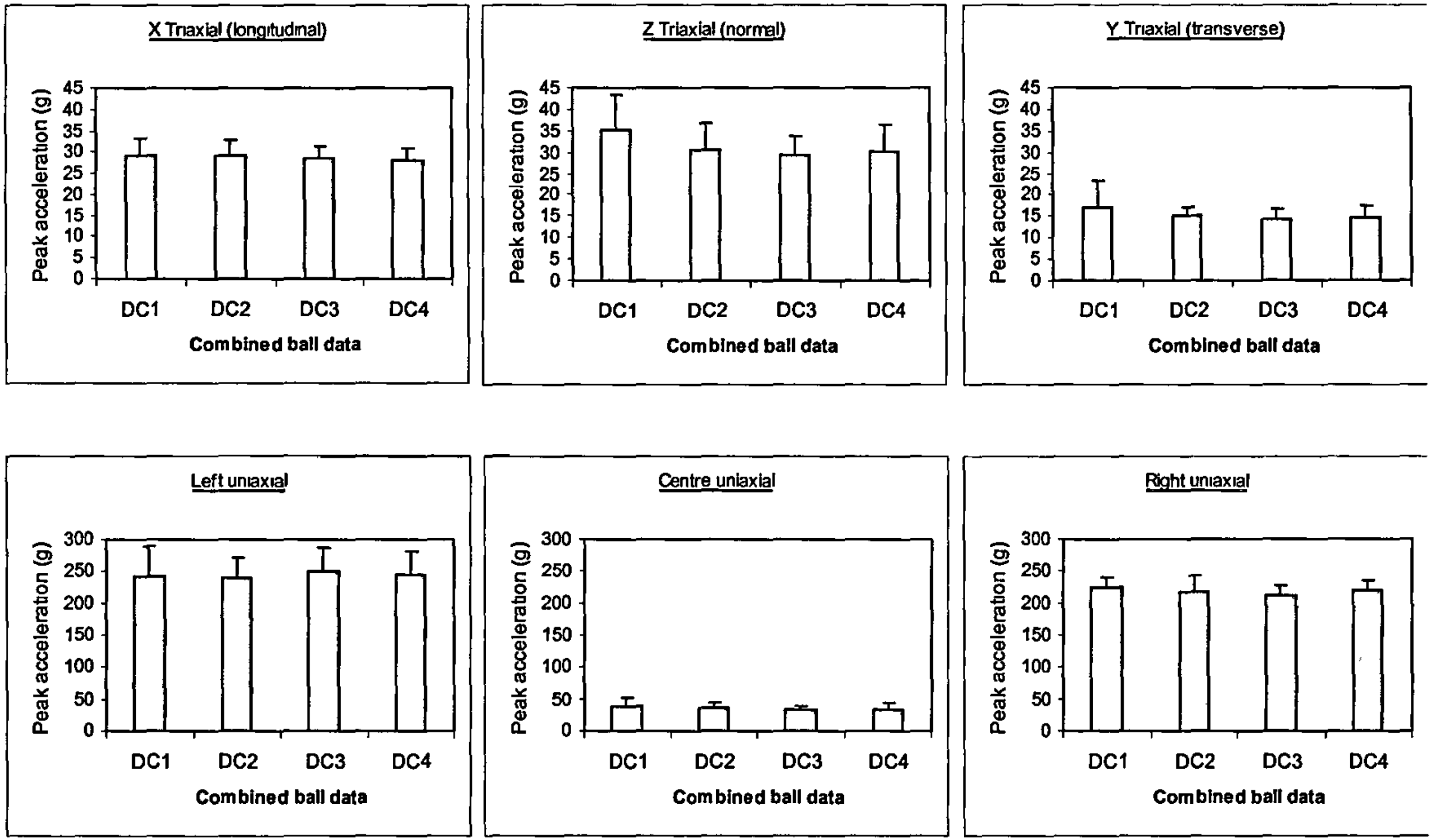


Figure 133: Group peak acceleration for combined ball type data

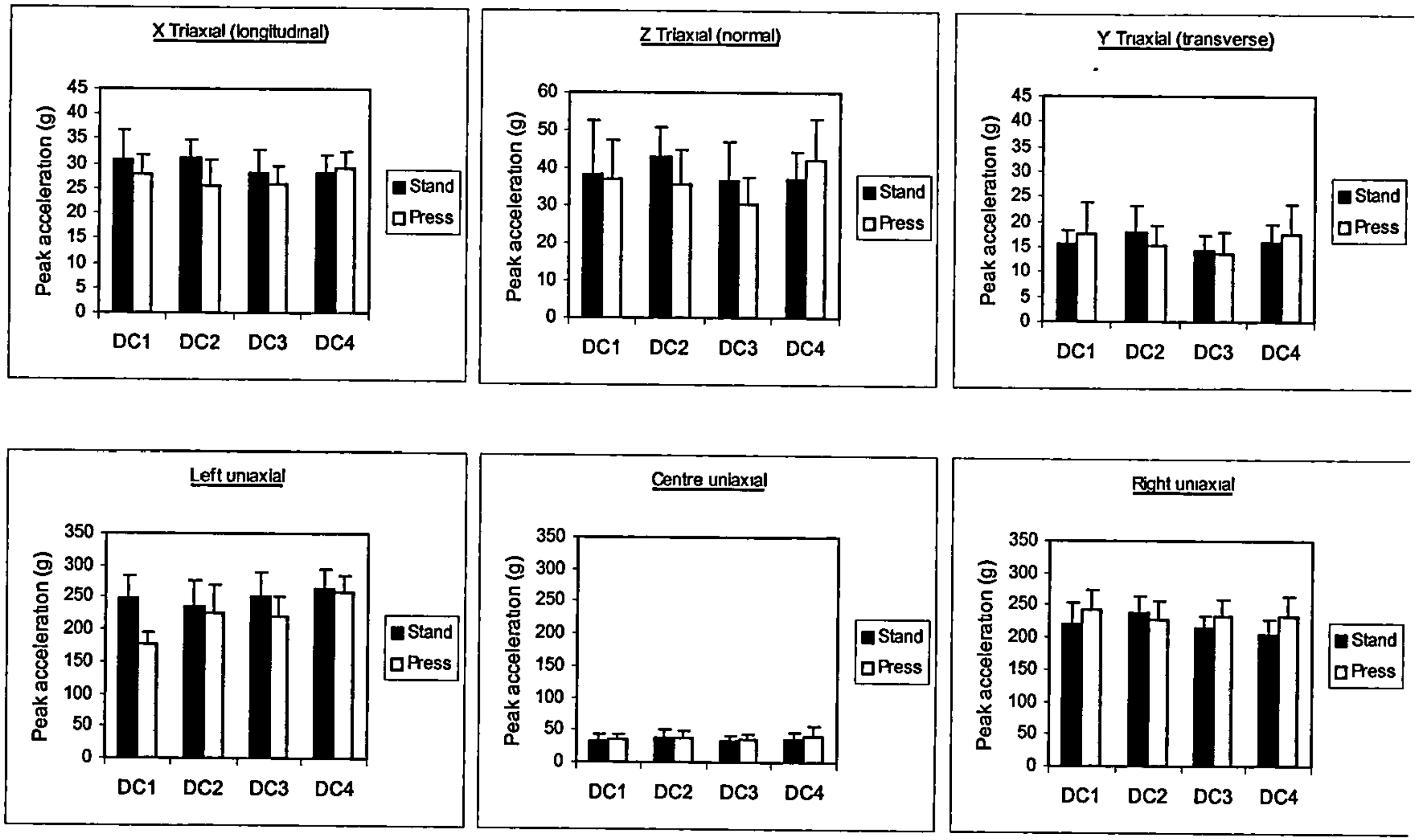


Figure 134: Bar charts showing Subject 2 peak acceleration

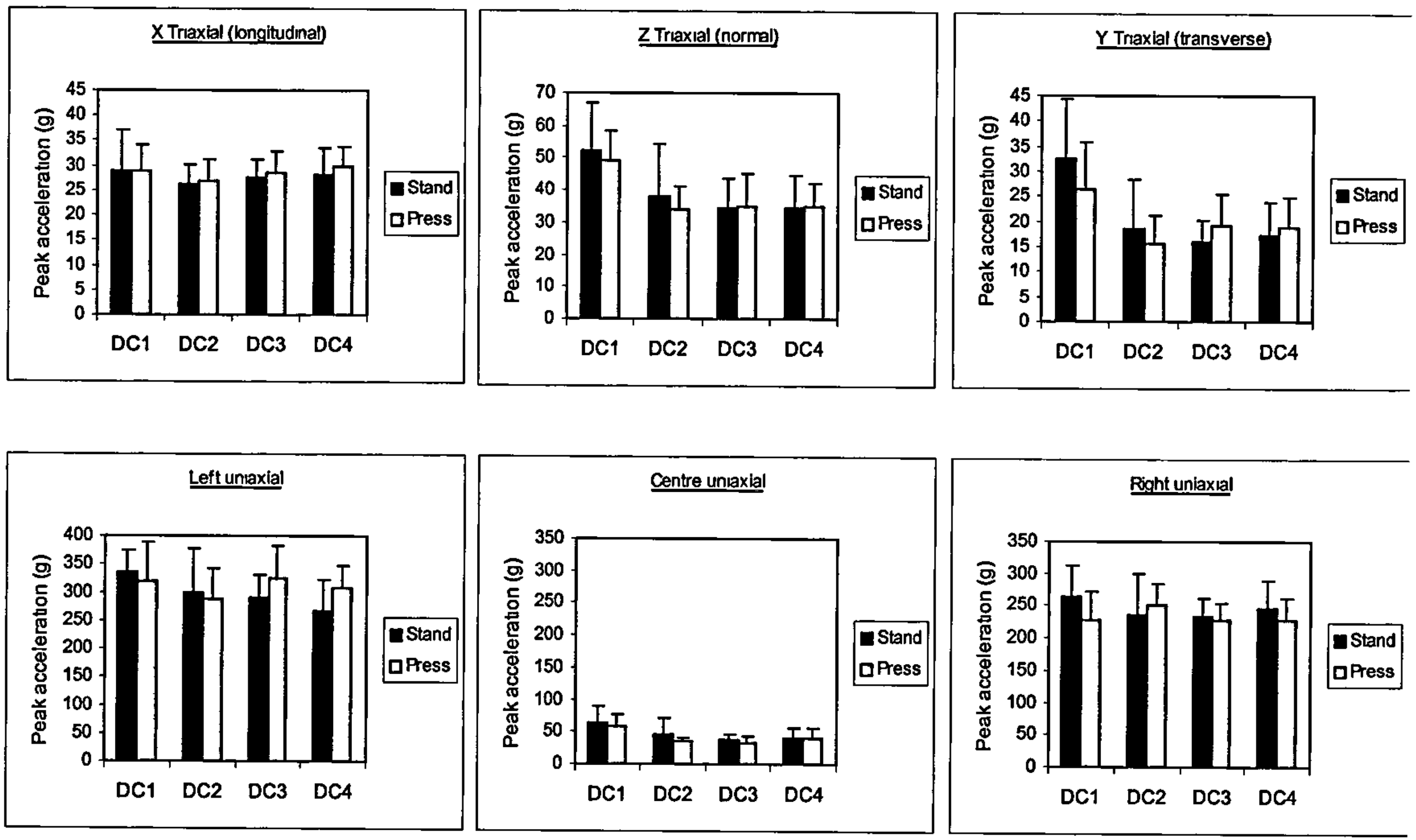


Figure 135: Bar charts showing Subject 3 peak acceleration

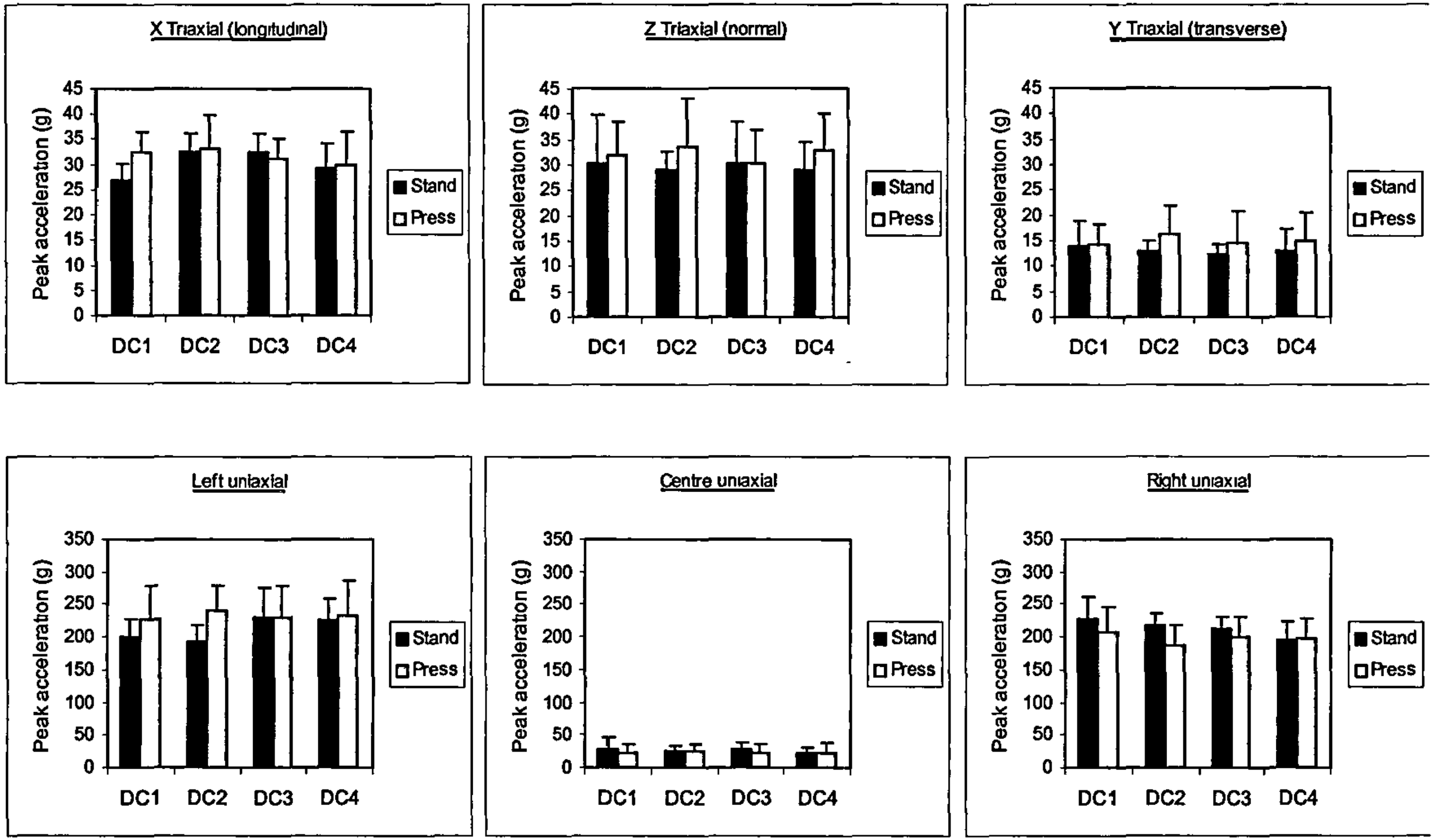


Figure 136: Bar charts showing Subject 4 peak acceleration

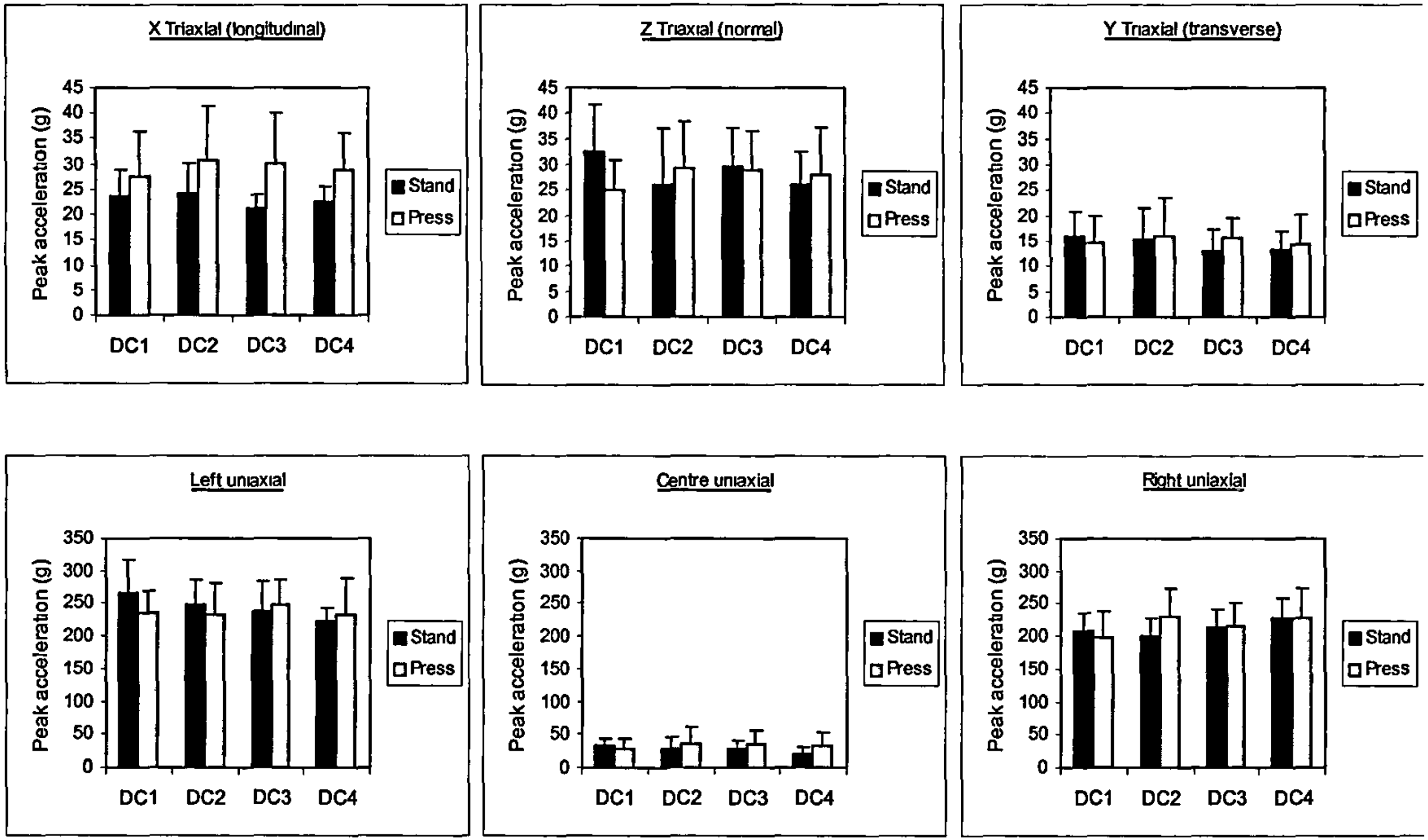


Figure 137: Bar charts showing Subject 5 peak acceleration

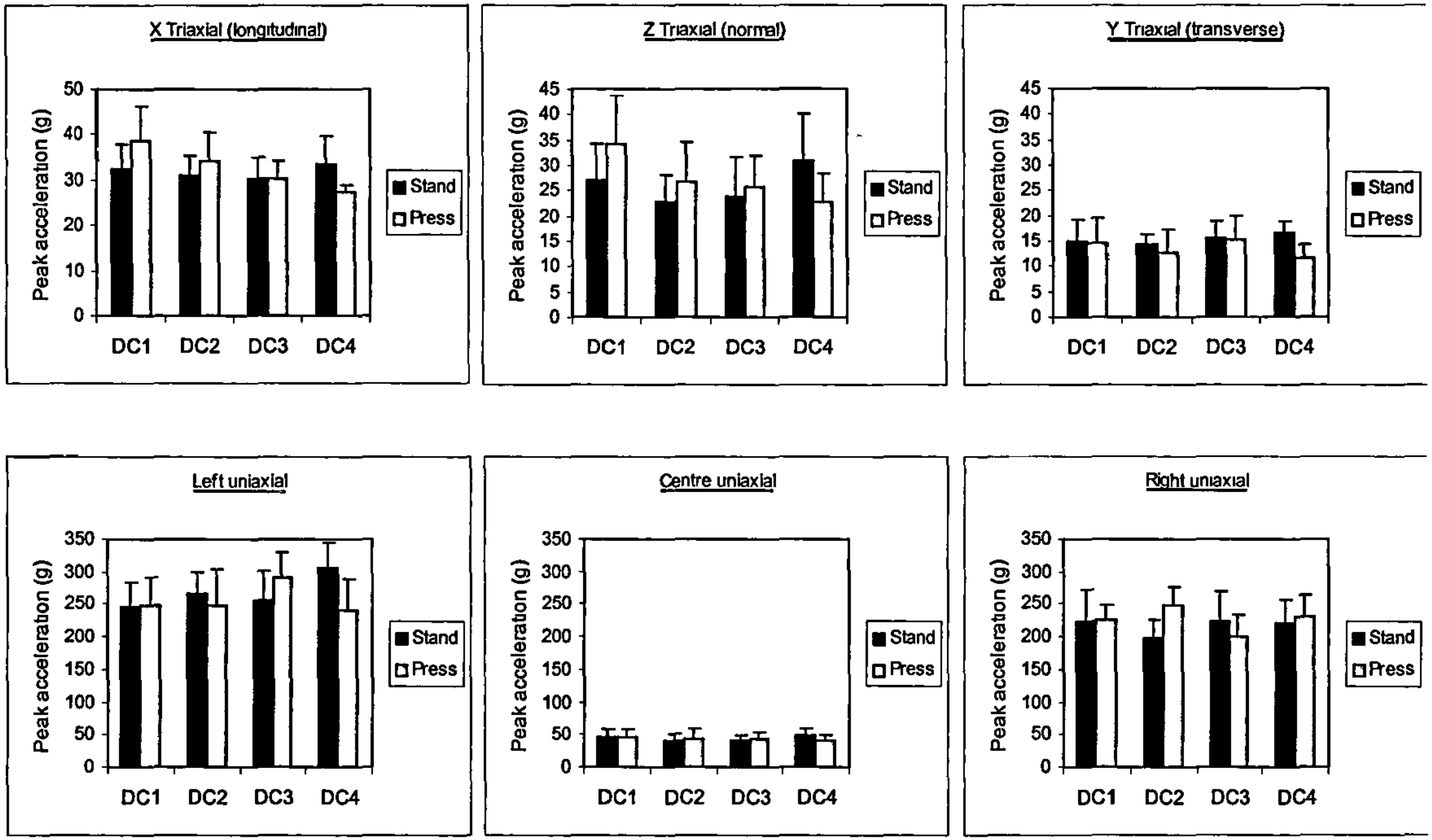


Figure 138: Bar charts showing Subject 7 peak acceleration

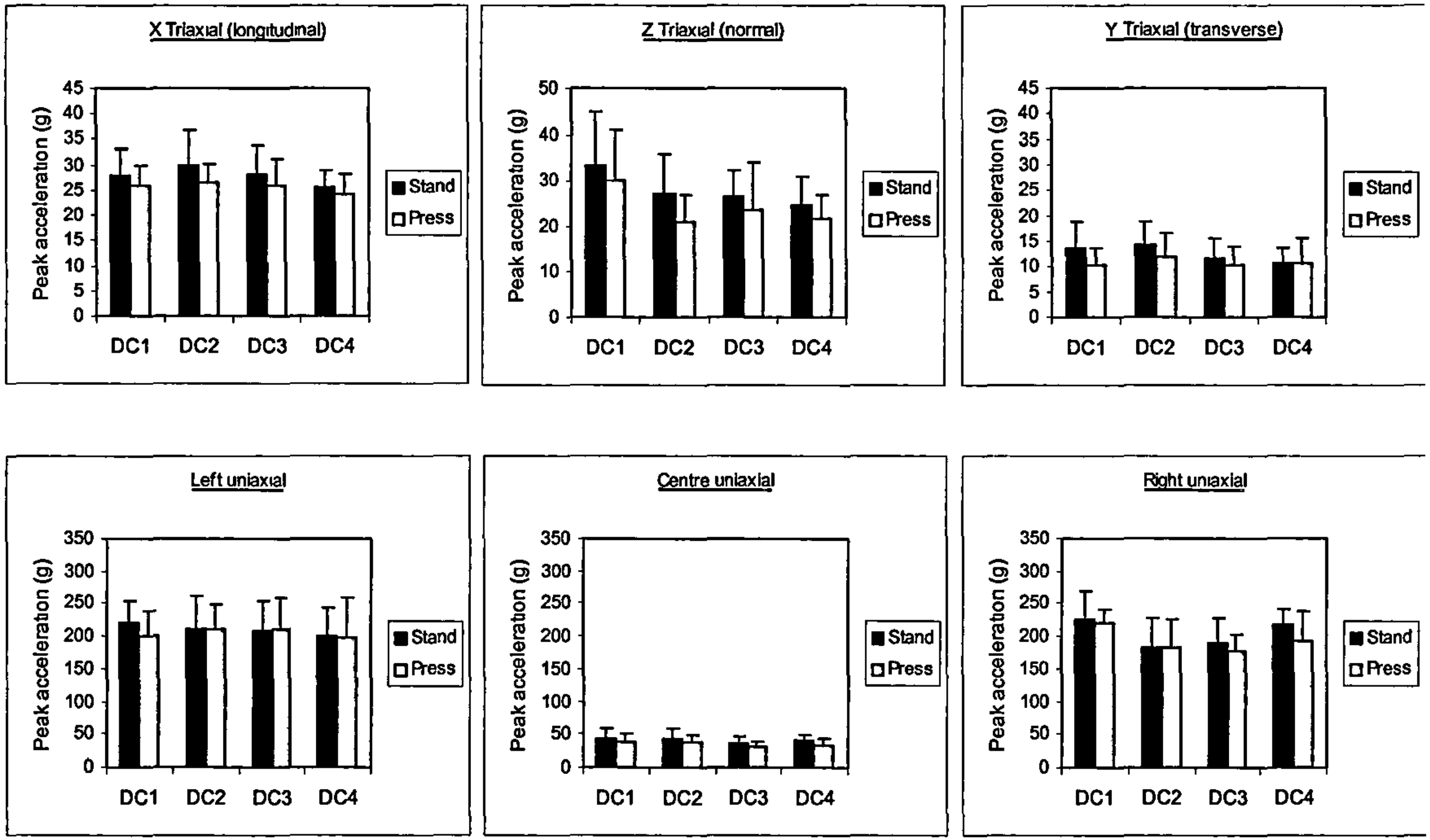


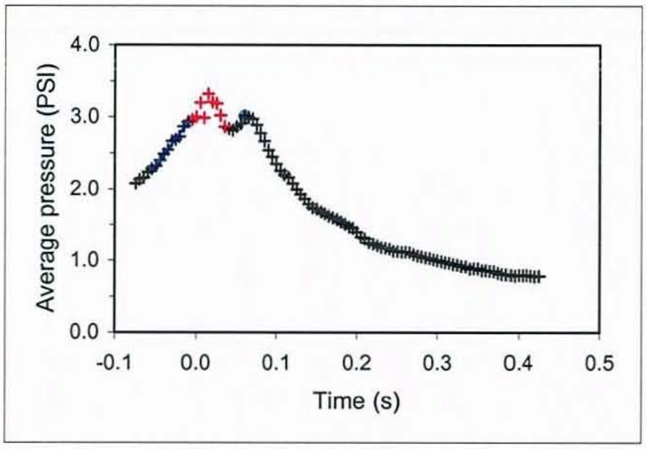
Figure 139: Bar charts showing Subject 8 peak acceleration

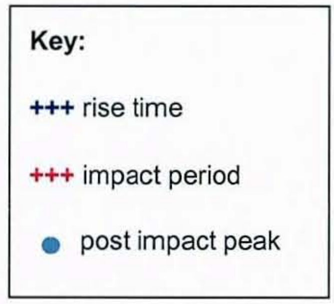
6.3.3 Grip pressure measurement

Figure 140 and Figure 141 each consist of two sample graphs and a colour chart for a single shot. The first graph (a) shows the average adjusted whole sensor pressure over time. Each point on this graph corresponds to the mean value of all 96 pressure cells on the sensor for each frame of captured data (nett pressure). The second graph (b) shows the pressure over time plot of the pressure on the single cell that achieved the highest peak pressure during the whole data capture period of the shot, although discounting all values in the 'noisy' data frames in the 'impact zone'. 'Noisy' data is where the sampling rate is too low to fully capture the high frequency grip vibrations seen in previous acceleration graphs. Insufficient sampling frequency gives rise to apparently chaotic data. The impact zone is indicated by red crosses on the graphs and corresponds to a zone of noise caused by the ball impact and associated racket vibration. The impact zone was taken as extending from 0 01 seconds before ball impact to 0.04 seconds after ball impact, the data frames at these boundary values not being included in the impact zone. The duration of the impact zone was determined from observation of the data and also agreed with values reported in the literature (ball impact time approximately 4 milliseconds and subsequent vibration decay period and 40 milliseconds). It was only necessary to ignore data values in the impact zone because the sampling rate of the Tekscan system was insufficient to measure the transient values caused by vibration and shock loading. In an ideal situation the Tekscan equipment would have been able to accurately to track the grip pressure profile throughout the impact zone. Graphs (a) and (b) are similar in shape but the magnitude of the values in the average whole sensor pressure (a) are lower because of a number of inactive cells on the sensor.

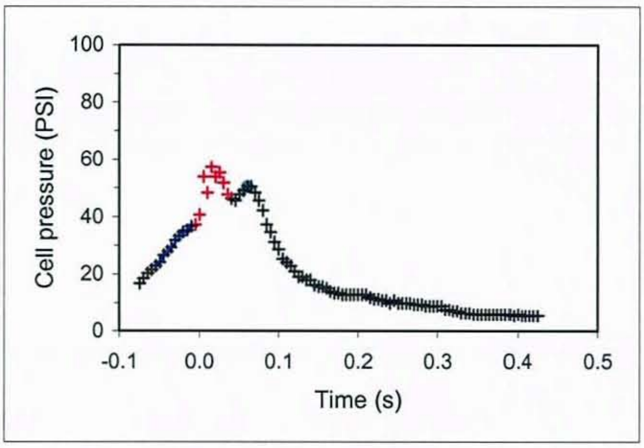
Both graphs exhibit a number of common features across shots. Grip pressure increases in preparation for ball impact and the rise was typically fairly linear. This enabled the profile through the rise time to be characterised by fitting the data with a straight line. The linear fit is represented on the graphs by blue crosses. Following impact, the grip pressure remains elevated and in some cases continues to increase for a short period.

For some shots the rise rate is a negative value (e g. the single peak pressure cell profile in Figure 142), indicating that pressure is falling just prior to impact. Further investigation shows that a negative rise rate only occurs on the single peak pressure cell profile and is probably attributable to movement of the hand across the sensors during the shot. In Figure 142 it can be seen that the corresponding average whole sensor pressure profile has a positive rise rate.

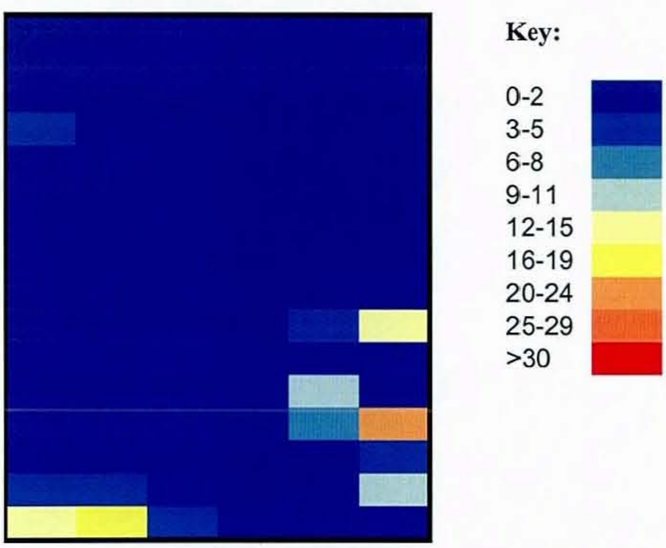




(a) Graph of average adjusted whole sensor pressure

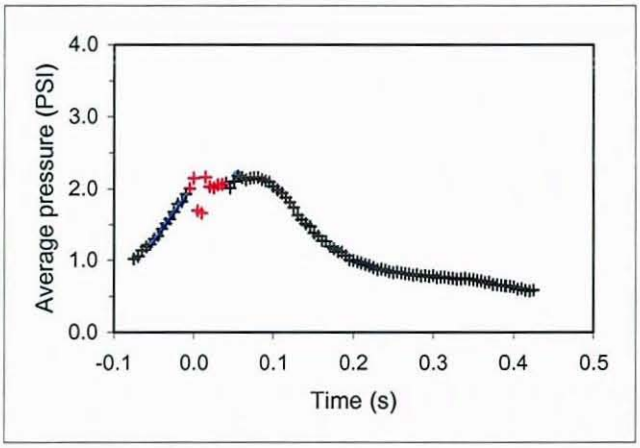


(b) Graph of pressure on the single cell with highest peak pressure

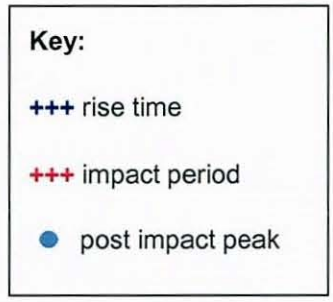


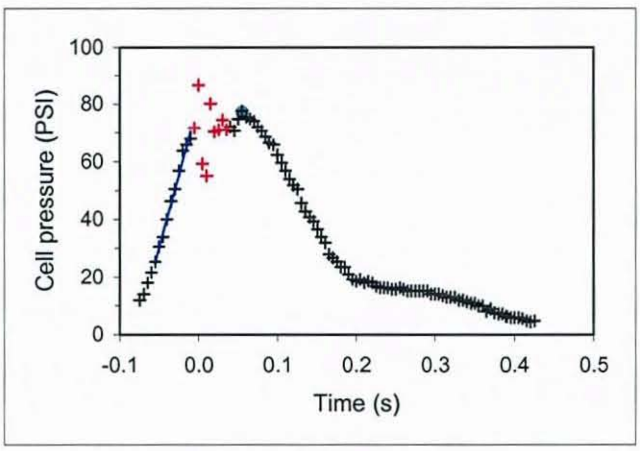
(c) Average pressure (PSI) for each individual cell for one shot

Figure 140: Grip pressure data for Subject 5, standard ball, DC1 shot 14

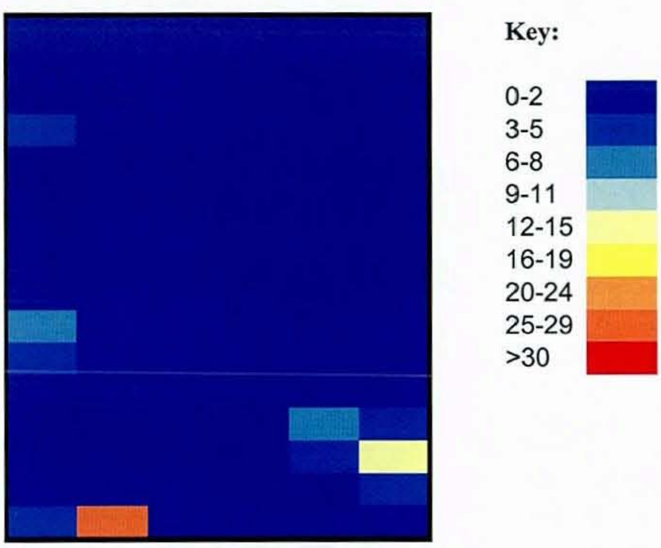


(a) Graph of average adjusted whole sensor pressure





(b) Graph of pressure on the single cell with highest peak pressure



(c) Average pressure (PSI) for each individual cell for one shot

Figure 141: Grip pressure data for Subject 2, standard ball, DC4 shot 14

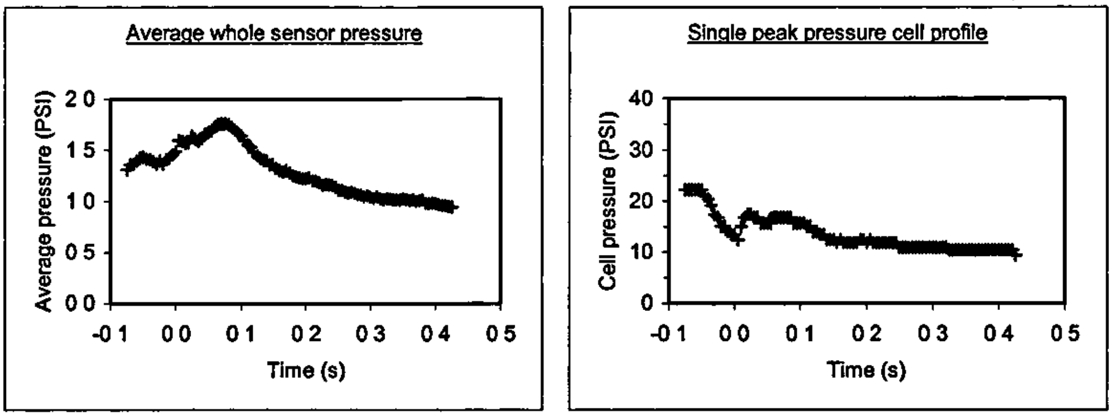


Figure 142: Example single shot exhibiting negative 'rise' rate

For the majority of shots rise rate is a positive value. It is considered that the pressure profile of the single cell with the highest peak pressure may be less reliable due to the possibility of slight changes to the grip position during the shot. Whereas it is considered that the pressure profile of the whole sensor pressure will be less affected by grip changes due to an averaging effect.

The sky blue marker on the graphs (Figure 140 and Figure 141) indicates the post-impact peak data point, which was one of the parameters calculated from the data for the purposes of analysis. The post-impact peak may be due to either; passive recoil of the hand due to impact, active tightening of the hand in response to the impact shock or mistimed active tightening of the hand in expectation of impact. Given the short time duration between the impact shock and the post-impact peak, the latter seems most probable. It seems unlikely that a player could consciously respond within such a short time duration. Grip pressure decay occurs at approximately the same rate as the rise rate.

The colour chart shows the average pressure for each individual cell over the 0.5 second period of the trimmed Tekscan data, which extends from 0.075 seconds before ball impact to 0.425 seconds after ball impact (Figure 140 and Figure 141). The chart shows the 'hot spot' cells which exhibited significant pressure activity through the period of data capture. In the colour charts shown, the bottom of the chart corresponds to the end of the sensor at the butt end of the racket handle. Considering the racket when held in the orientation to take shots, the left column of the colour chart corresponds to the pressure sensor strip on the front face of the racket handle. Moving from left to right across the chart corresponds to moving from the front face of the racket handle, up over the top of the handle and then down the back of the handle to finish at the bottom back face. No pressure sensors were present on either bottom face or bottom front face.

It was generally observed that there were two characteristic areas of hot spot pressure activity. The first area of activity at the bottom left of the colour chart corresponds to contact of the flare on the butt end of the racket handle with the hypothenar eminence (the prominent part of the palm of the hand below the base of the little finger). This is one of the two zones of the hand investigated in studies undertaken by Knudson and Cross. The second area of activity on the lower right hand side of the colour chart corresponds to contact of the ends of the fingers on the lower back and back faces of the handle, this is an area not investigated in the studies by Knudson and Cross. Due to differences in hand size and hand placement of the different subjects and the low spatial resolution of the matrix of sensor cells no detailed analysis of hand positioning was attempted.

A number of parameters were calculated to characterise the grip pressure data (Appendix 12). Each parameter was calculated for the average whole sensor pressure and for the peak sensor cell at both the individual subject and group level. Statistical tests were performed on all the parameters to determine whether changes occurred due to either ball type or fatigue level. With the exception of those results that are presented in the rest of this section, the other parameters showed no systematic differences.

Figure 143 and Figure 144 each show four graphs of group mean values of selected parameters of grip pressure. Figure 143 refers to the average whole sensor pressure (AWSP) and Figure 144 to the peak pressure cell. Although not statistically significant, Figure 143 shows a trend reduction in values when comparing week one to week two. It is likely that this was due to a learning effect rather than due to ball type. Applying a repeated measures ANOVA test revealed no significant differences to have occurred through the duration of the test (DC1 to DC4) at the group level.

At the individual subject level, half of the subjects showed significant reductions in grip pressure over time whilst the other half did not. Figure 145 to Figure 150 inclusive show a series of charts for three of the subjects who showed a significant reduction in grip pressure over time. The biggest change typically occurred between DC1 and DC2, the decrease continued through DC3 and DC4 but not as steeply. Table 19 presents a summary of all the significant reductions in grip pressure that were identified at the individual subject level.

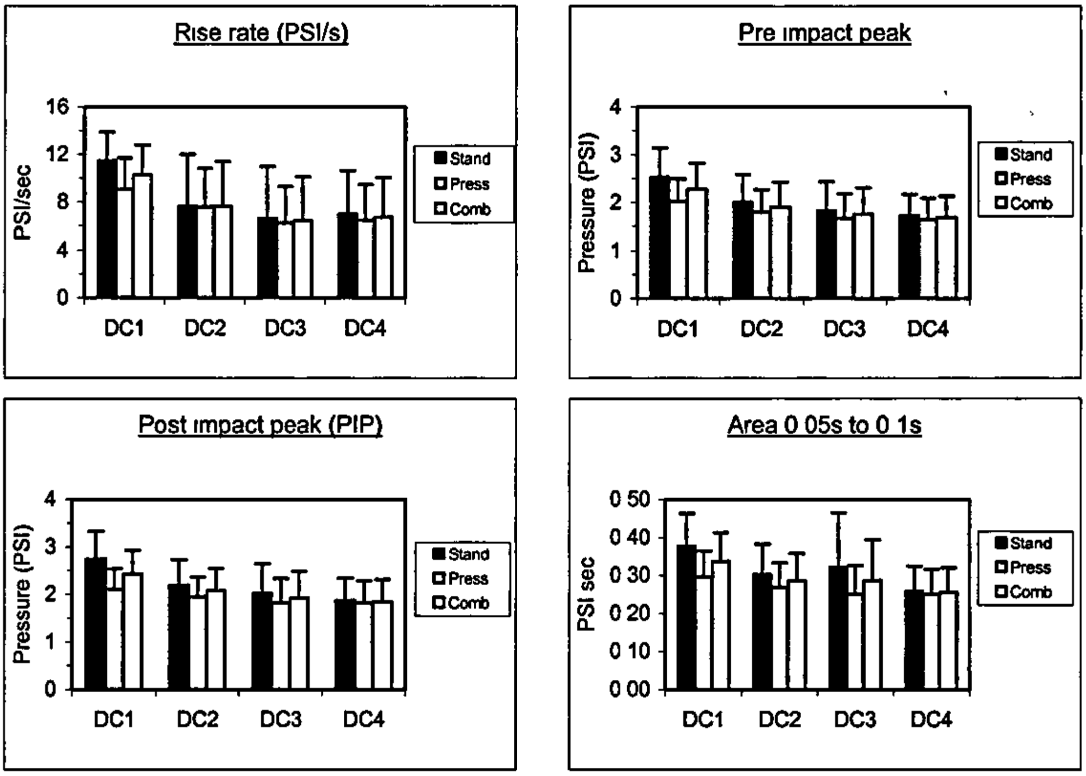


Figure 143: Selected group mean parameters of whole sensor pressure

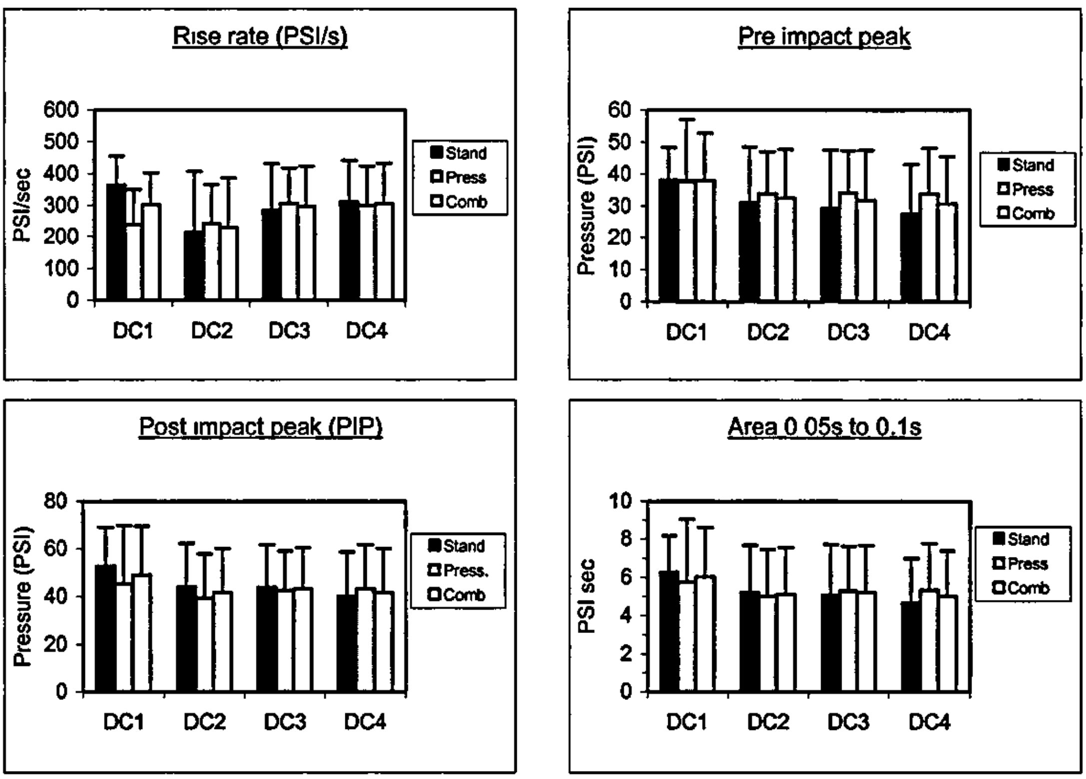


Figure 144: Selected group mean parameters of peak pressure cell

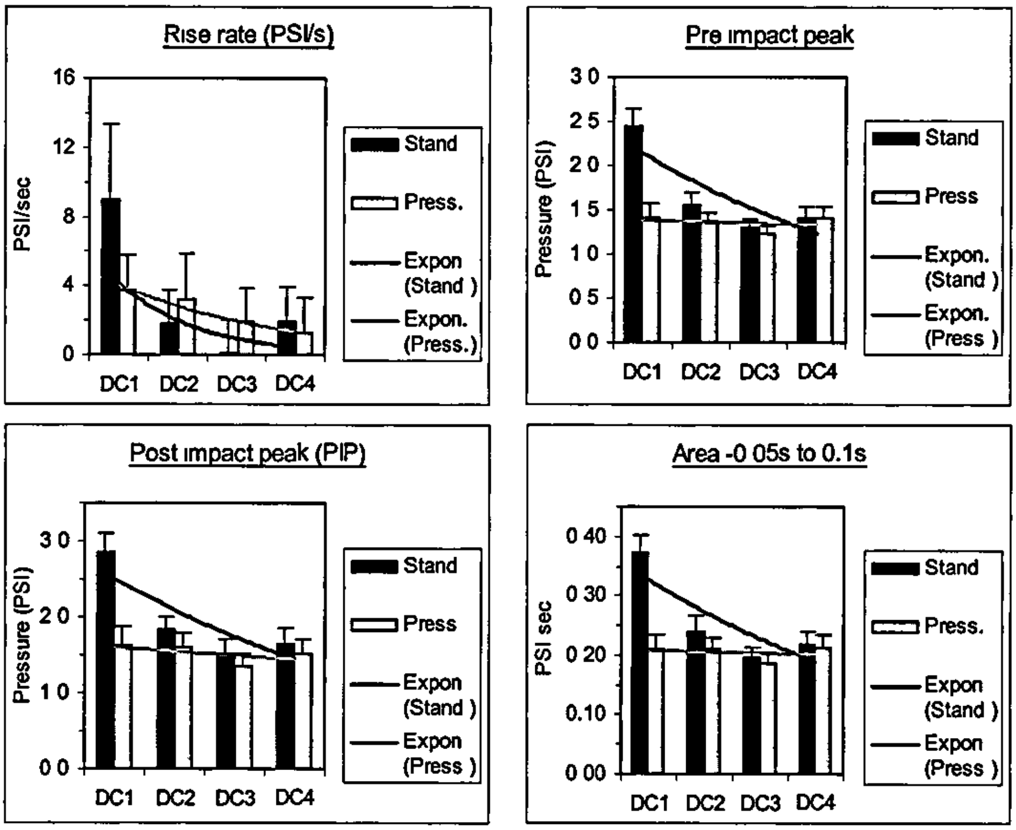


Figure 145: Selected mean parameters of whole sensor pressure for Subject 8

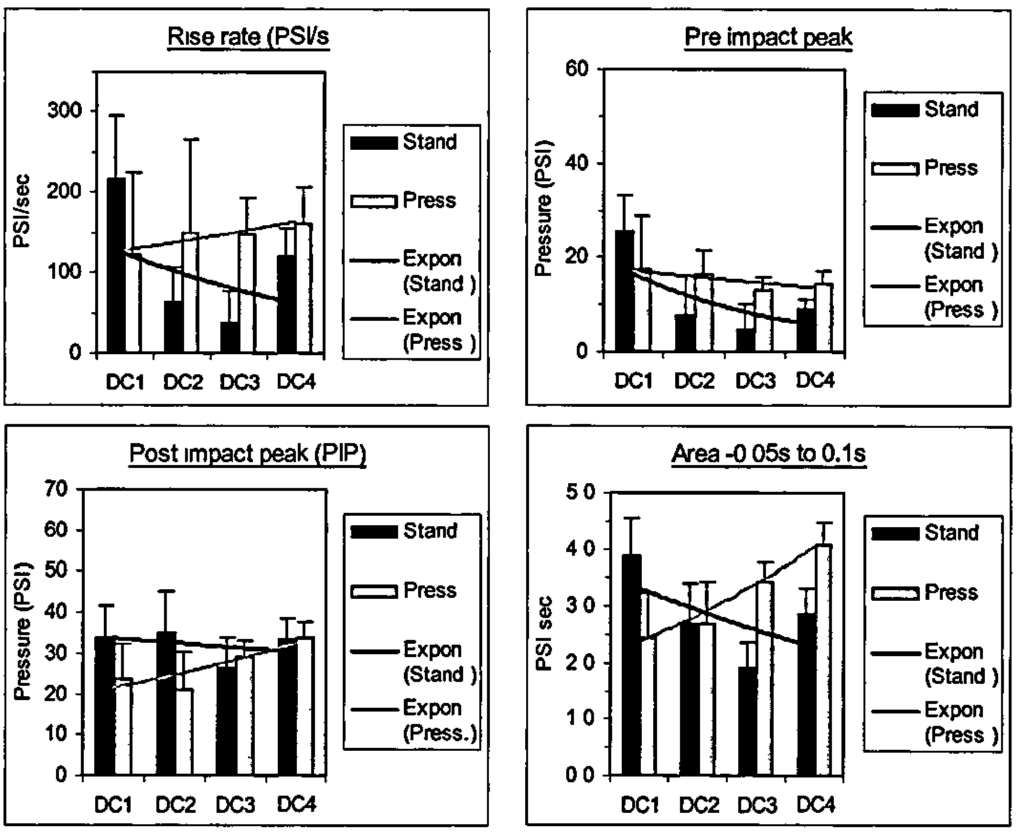


Figure 146: Selected mean parameters of peak pressure cell for Subject 8

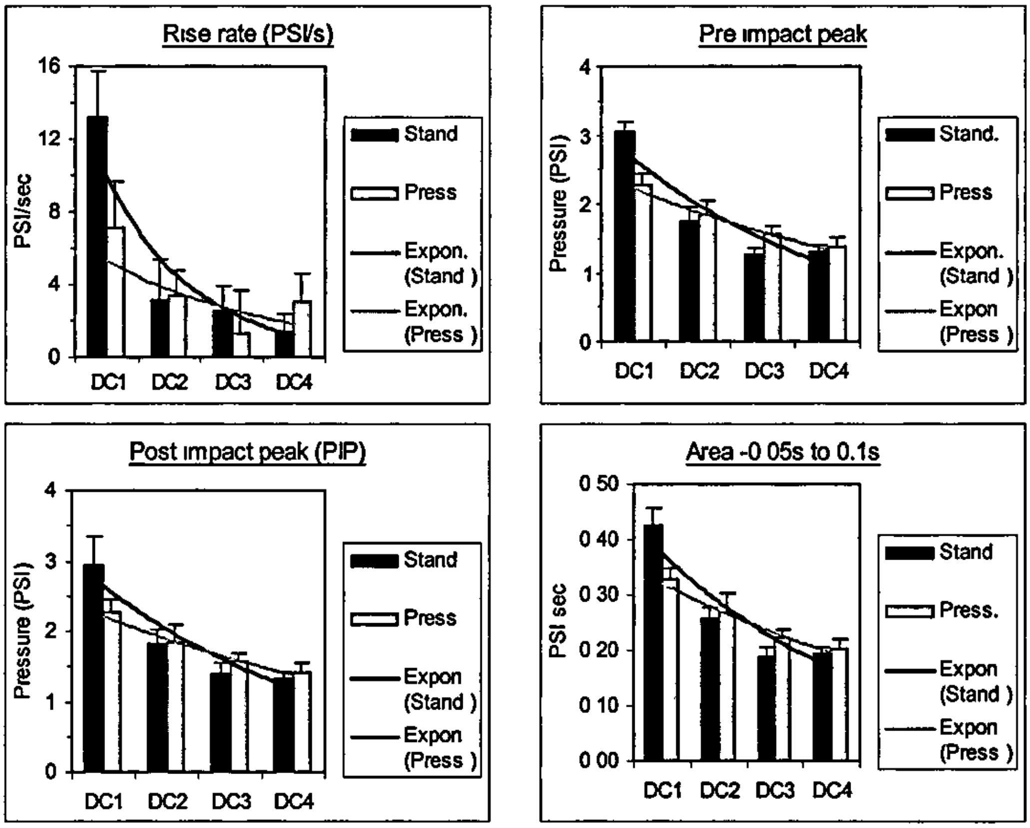


Figure 147: Selected mean parameters of whole sensor pressure for Subject 3

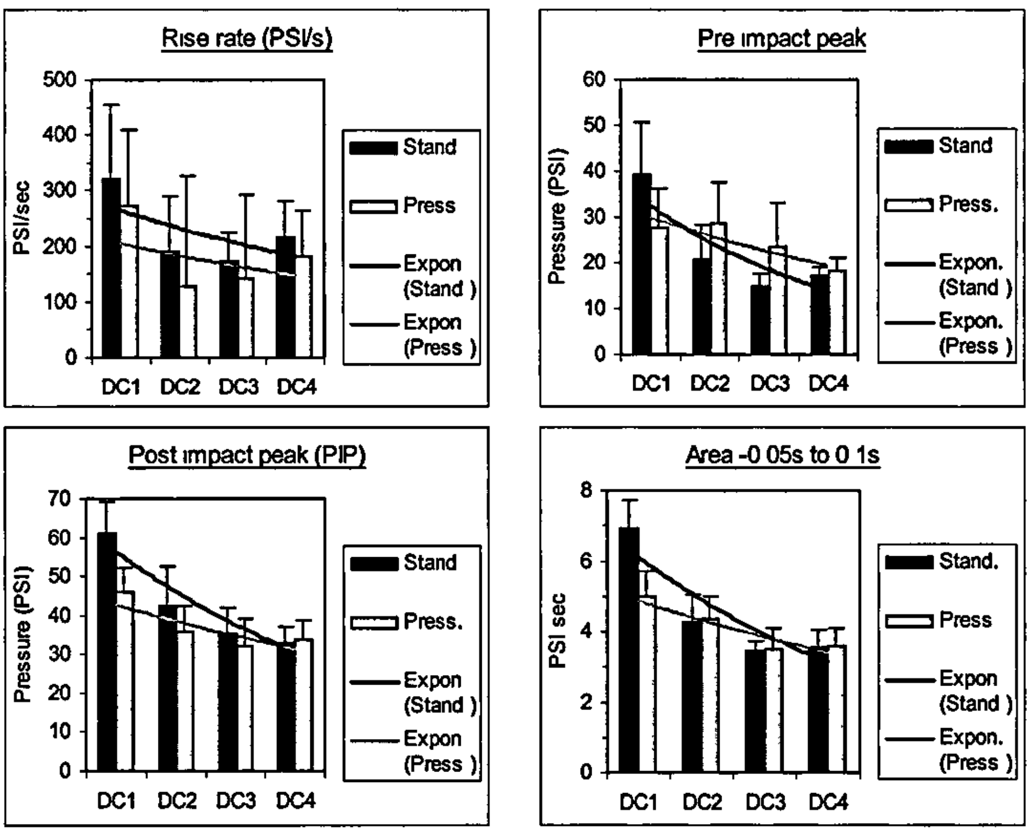


Figure 148: Selected mean parameters of peak pressure cell for Subject 3

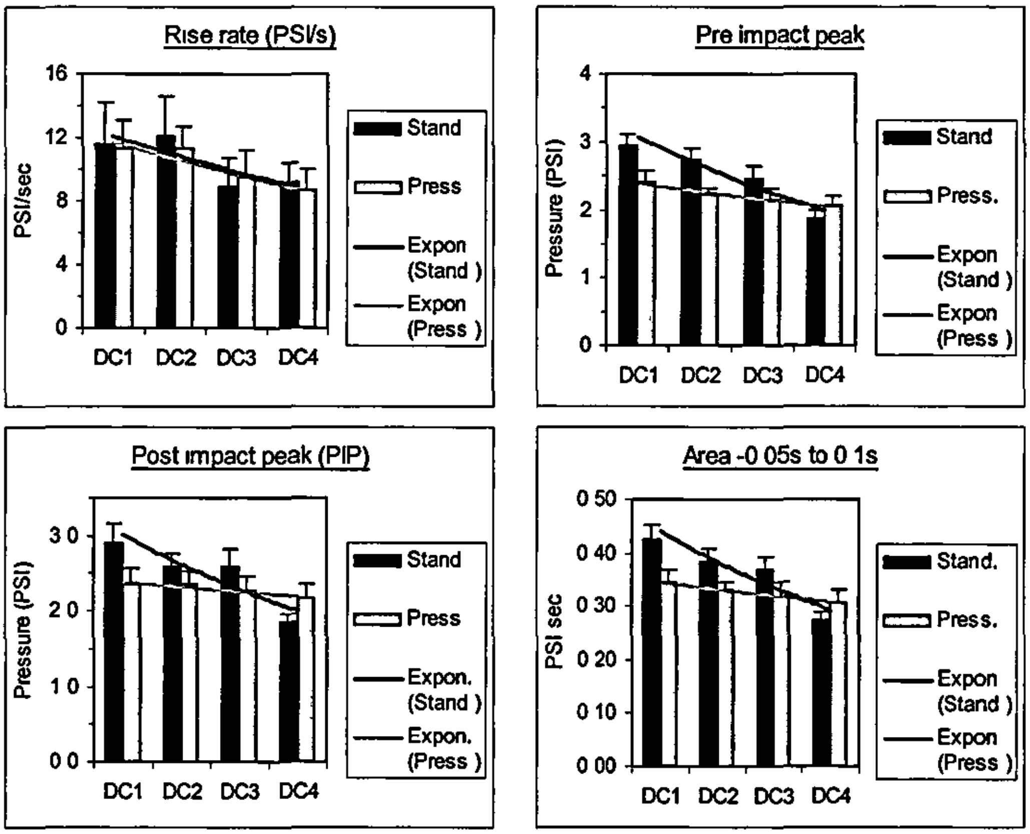


Figure 149: Selected mean parameters of whole sensor pressure for Subject 5

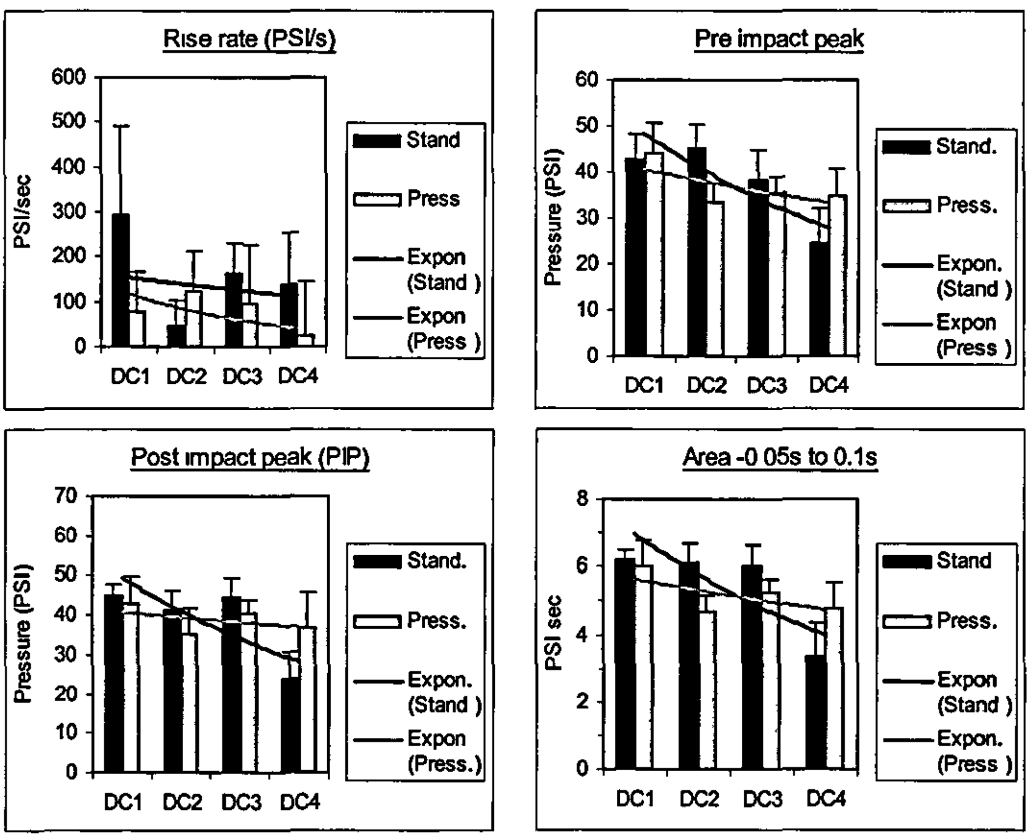


Figure 150: Selected mean parameters of peak pressure cell for Subject 5

Table 19: Statistically significant differences in single subject grip pressure parameters

ANOVA results - Statistical differences at 95% confidence interval					
		Whole sensor pressure		Peak pressure cell	
Subject	Parameter	Standard pressurised ball	Pressureless ball	Standard pressurised ball	Pressureless ball
3	Rise rate	DC1vDC2 DC1vDC3 DC1vDC4			
	Pre impact peak	DC1vDC2 DC1vDC3 DC1vDC4 DC2vDC3 DC2vDC4	DC1vDC2 DC1vDC3 DC1vDC4 DC2vDC3 DC2vDC4	DC1vDC2 DC1vDC3 DC1vDC4 DC2vDC4	DC1vDC4
	Post impact peak	DC1vDC2 DC1vDC3 DC1vDC4 DC2vDC3 DC2vDC4	DC1vDC3 DC1vDC4	DC1vDC2 DC1vDC3 DC1vDC4	DC1vDC3 DC1vDC4
	Area	DC1vDC2 DC1vDC3 DC1vDC4 DC2vDC3 DC2vDC4		DC1vDC2 DC1vDC3 DC1vDC4	DC1vDC3 DC1vDC4
5	Rise rate		DC1vDC4		
	Pre impact peak	DC1vDC4	DC1vDC3 DC1vDC4	DC1vDC4	
	Post impact peak	DC1vDC4		DC1vDC4	
	Area	DC1vDC3 DC1vDC4		DC1vDC3 DC1vDC4	DC1vDC2 DC1vDC3
8	Rise rate	DC1vDC2 DC1vDC3 DC1vDC4		DC1vDC2 DC1vDC3 DC1vDC4	
	Pre impact peak	DC1vDC2 DC1vDC3 DC1vDC4		DC1vDC2 DC1vDC3 DC1vDC4	
	Post impact peak	DC1vDC2 DC1vDC3 DC1vDC4			
	Area	DC1vDC2 DC1vDC3 DC1vDC4		DC1vDC2 DC1vDC3 DC1vDC4	DC1vDC4

6.3.4 Static maximal hand-grip test

The aim in performing the static hand-grip test during this study was two fold. Firstly performing a static hand-grip test enabled direct comparison with the results of the dynamic, in-play hand-grip test. Secondly to follow up weaknesses in implementation of the static grip test identified in the two studies reported in Chapters 3 and 4. It was felt that in the previous studies the pre-test values may have been suppressed, due to subjects not being sharpened from a full on court warm up. Furthermore, it was considered that the post-test values may have been elevated by subject recovery during the delay period before the post-session test. Both these factors would reduce any differences between the pre- and post-test values. On this occasion the pre-session test was performed following an on court warm up in addition to the off court warm up. The post-session test was performed immediately on completion of the session to prevent associated recovery.

A series of charts follow to illustrate pre- and post- session values for a range of hand-grip related measures (Figure 151 to Figure 154). All measures are group mean values (n=8) obtained for both the dominant (marked as Dom on the figures) and non-dominant (Non-dom on figures) hand for both test sessions. In this context, dominant hand refers to the hand in which the subject holds the racket. Inter-subject coefficients of variability were large and on average 13%, 38%, 49% and 76% for peak force, reaction time, rise time and fatigue rate respectively. The latter is particularly high and all are of similar magnitude to that of in Study A and B reported in Chapters 3 and 4.

There were no significant differences between post- session values for any of the measures obtained. In addition, with the exception of non-dominant peak hand-grip force ($p<0.01$) there were no significant differences between pre- session values for any of the measures obtained. Furthermore, with the exception of non-dominant peak hand-grip force obtained using the standard (pressurised) ball, there were no significant differences between pre- and post- session measures for both standard pressurised and pressureless ball conditions.

Although pre and post values are in the main not significantly different for the measures obtained there are some trends worthy of note. Peak force post- session values were marginally lower than pre- session equivalents for the dominant hand. This trend was not reflected in the non-dominant hand values. Reaction time was slightly slower on average for the post- session tests compared to the pre- session test values for the dominant hand. However, reaction time was quicker post- compared to pre- session test in the non-dominant hand. With reference to Figure 153 it can be seen that rise times were generally slower post- session compared with pre-session, again this was not reflected in the non-dominant hand values. The parameter of fatigue rate demonstrated the most pronounced variability. Fatigue rate comprises two components. Positive fatigue is observed where the subject achieves a peak force quickly and then subsequently fatigues as demonstrated by decay of the force profile. Negative fatigue equates to an increase in force over the contraction, such that the force observed at the end of the contraction is greater than the initial 'peak'. This phenomenon occurs when a subject reaches a false peak followed by a subsequent rise in force. This pattern of muscle contraction indicates an inability to generate a maximal force quickly and is consistent with fatigue of fast twitch muscle fibres.

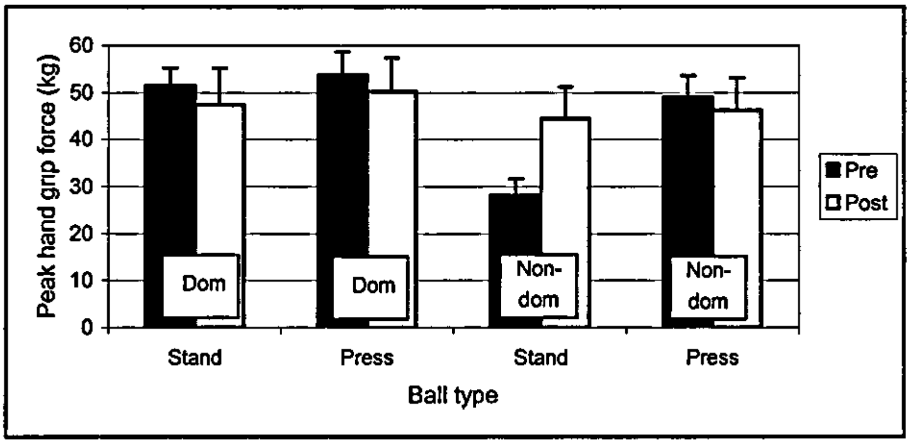


Figure 151: Group mean static grip peak force values pre and post activity

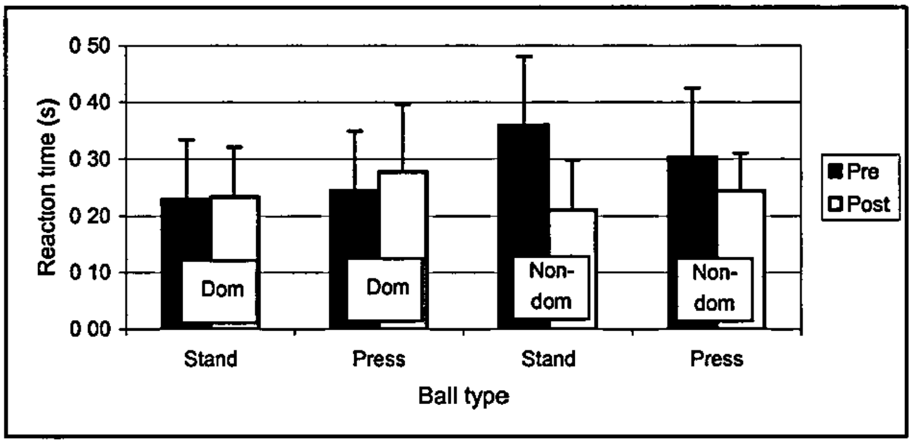


Figure 152: Group mean static grip reaction time values pre and post activity

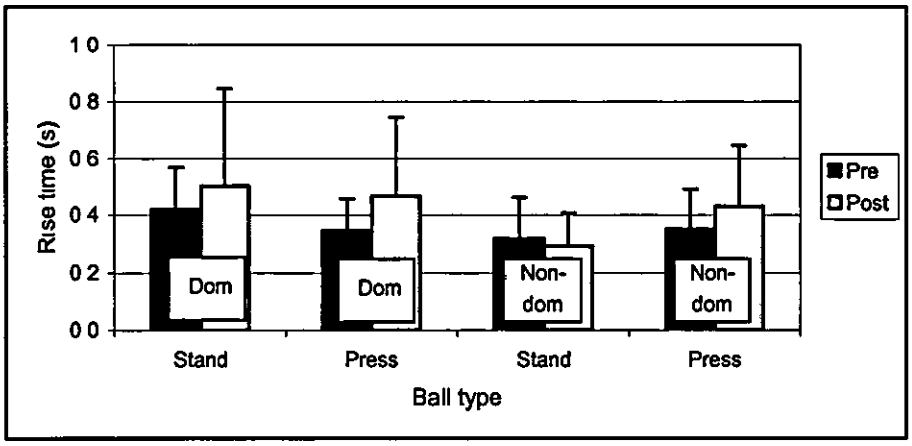


Figure 153: Group mean static grip rise time values pre and post activity

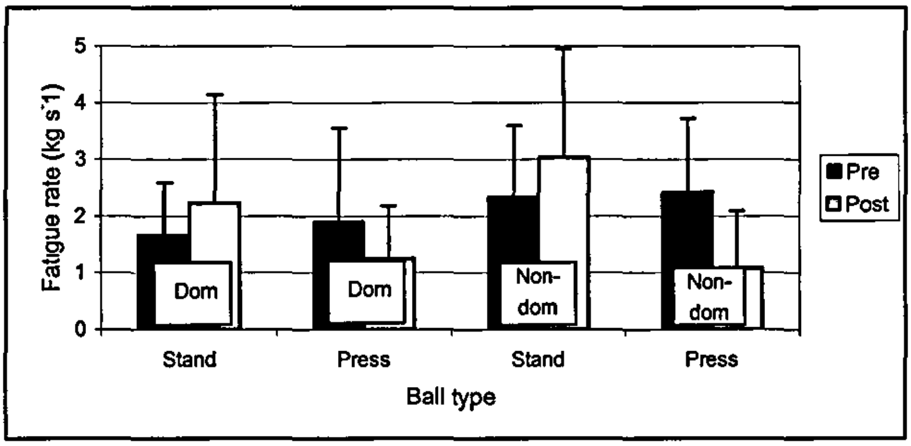


Figure 154: Group mean static grip fatigue rate values pre and post activity

6.3.5 Perceived muscle soreness

A series of muscle soreness charts follow, they provide a visual representation of group mean ratings of muscle soreness 'pre' (after warm up), 'post' (within 10 minutes of completion of the session), 'post am.' (the morning after the day of the session) and 'post pm.' (the evening of the day after the test session). Figure 155 and Figure 157 refer to muscle soreness reported in the dominant and non-dominant hand respectively from test sessions conducted with the standard pressurised ball, whilst Figure 156 and Figure 158 are obtained from test sessions using the pressureless ball.

It can be seen that muscle soreness prior to testing was present albeit at a modest level (<8% maximal muscle soreness). There was a statistically significant increase in levels of muscle soreness reported in muscles of the dominant arm when comparing pre levels to all three post test levels (i.e. post, 'post am', and 'post pm'), with both ball types. Peak levels of muscle soreness were reported in the muscles of both the dominant and non-dominant arms 'post am' and generally did not rise any further 'post pm'. It can be seen that muscle soreness was greatest in the muscles of the upper arm and shoulder area. Levels of muscle soreness were significantly greater in the muscles of the dominant arm as compared to the non-dominant arm at all times other than pre test. There was a trend of slightly raised pre-existing levels of muscle soreness in the dominant as compared to the non-dominant arm. Interestingly 'post am' and 'post pm' levels of muscle soreness were significantly greater following play with the standard pressurised ball (week one) compared to the pressureless ball (week 2). It is possible that this was as a result of the ball differences, but was more likely due to unfamiliarity of the test session and activity during week one. This demonstrates the limitations in attributing differences to equipment changes resulting from a study that does not use a crossover design.

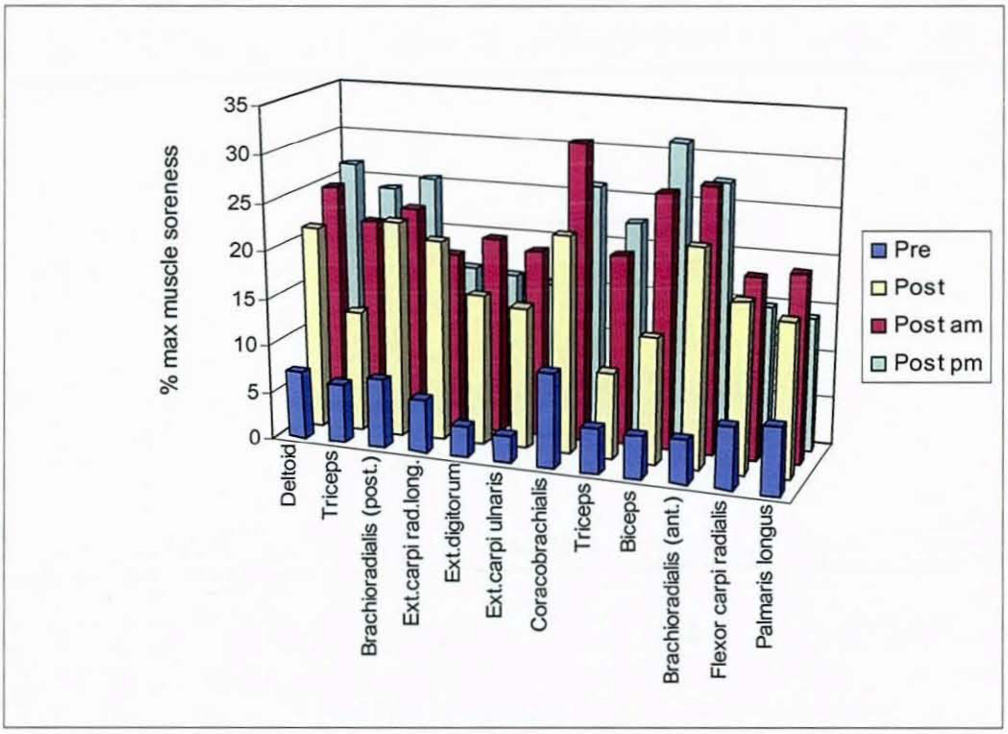


Figure 155: Dominant arm muscle soreness values obtained using the standard ball

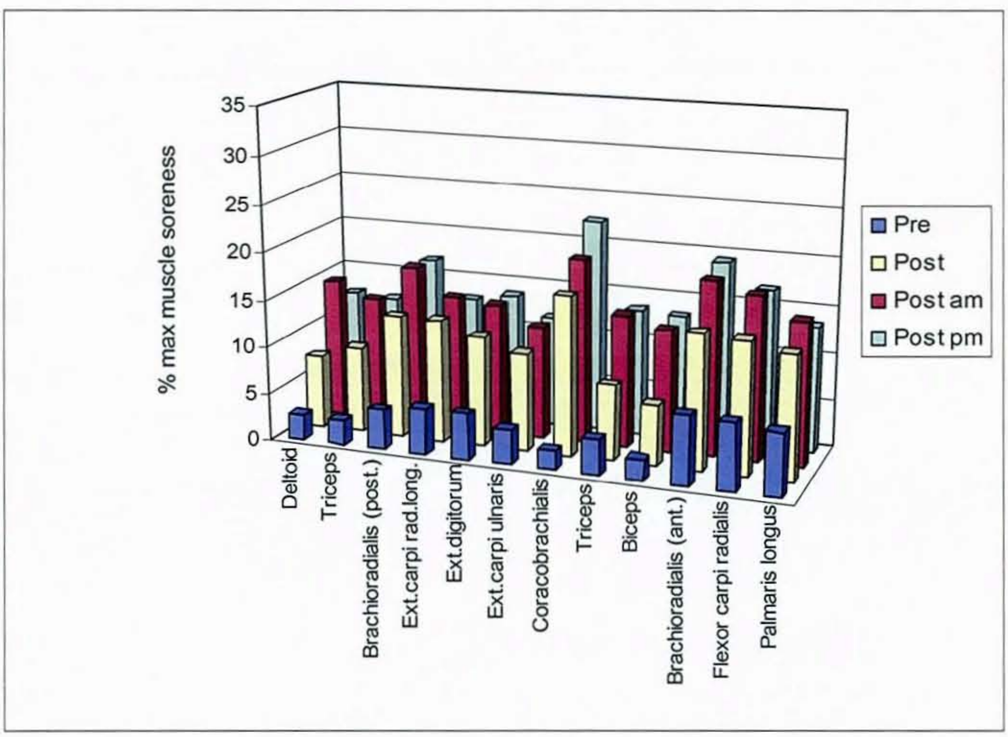


Figure 156: Dominant arm muscle soreness values obtained using the pressureless ball

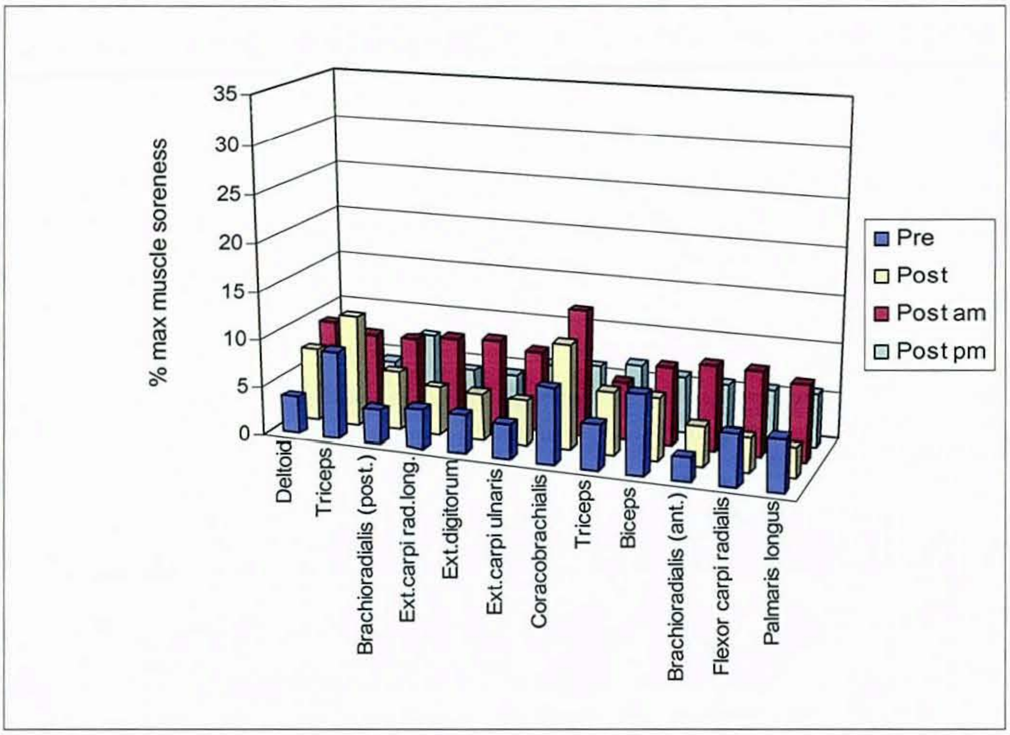


Figure 157: Non-dominant arm muscle soreness values obtained using the standard ball

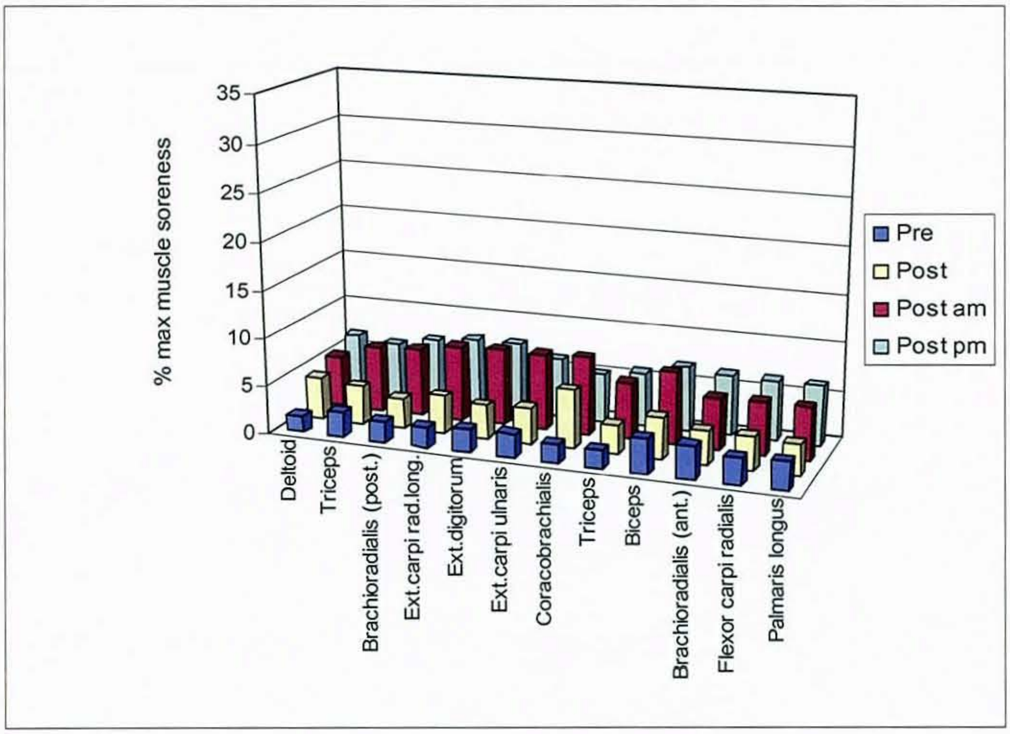


Figure 158: Non-dominant arm muscle soreness values obtained using the pressureless ball

In order to make a statically significant comparison between the effects of playing with alternative equipment it would be necessary to give the players more time to become familiar with performing the test. This might involve repeating the test several times and only looking for differences between the results of later tests. Each week of tests should also utilise a crossover design. To do this the players would be divided into two groups, A and B. On each test occasion, Group A would play with the alternative equipment to Group B and on every successive test occasion each test group would switch to the alternative equipment.

6.3.6 Perception

There were no major differences in players' perception of the performance of either ball type. On balance players expressed a preference for the standard pressurised ball but not strongly so. The majority of the players reported difficulties in answering fairly some of the perception questions because they were playing with a racket they were not used to for the test sessions. The players felt that it was hard to decide if any differences they were feeling were due to the unfamiliar racket or the ball and therefore they could not accurately assess the feel of the impact without the reference they would have from playing with their regular racket. As the perception element to this study was not key it was decided not to analyse the perception results in any more detail.

6.3.7 Shot outcome

Figure 159 and Figure 160 refer to the outcome of shots during the nine sets of three minutes of controlled play activity (total of 90 shots during each CPA). The figures show the group average shot outcome expressed as a percentage. Note that during the periods of controlled play activity the player performed two backhand strokes to one forehand stroke and the percentage outcome figures presented are calculated from the combined outcome of both types of strokes. Figure 161 and Figure 162 refer to the outcome of the four sets of 15 backhand shots executed with the instrumented racket.

Although not statistically significant when comparing week two with week one, accuracy is slightly increased, this is more evident in the DC shots (Figure 161 and Figure 162) than the CPA shots (Figure 159 and Figure 160). It is likely that this represents a learning effect and that despite efforts to ensure the participants felt as comfortable as possible, the subjects were likely to have been more anxious during the first test session and more relaxed during the second test session when they were familiar with the process.

The group average accuracy (inclusive of accurate and consistent shots) for both test sessions was 72.3% $\pm$ 3.4, which reflects the high skill level of the players. It is interesting that despite in-play grip pressure changes, accuracy remained consistent throughout the course of each test session when it was expected that accuracy would decrease over time. There was no difference in accuracy when comparing rates during CPA to rates during DC. This demonstrates that players' performance was not negatively affected by switching to the instrumented racket to perform the DC shots and also that they could perform as well with the instrumented racket as they could with the regular standardised racket.

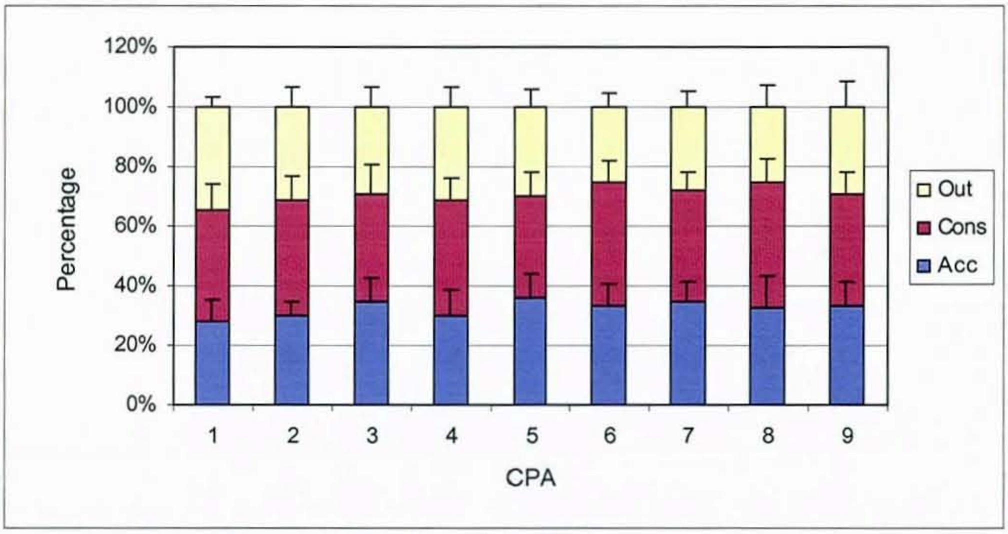


Figure 159: Group mean accuracy during CPA with the standard ball

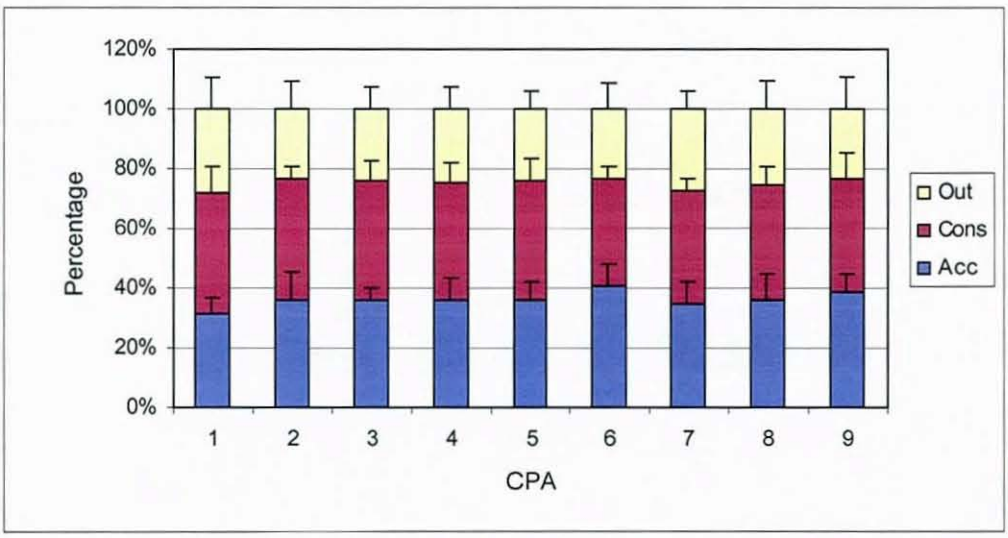


Figure 160: Group mean accuracy during CPA with the pressureless ball

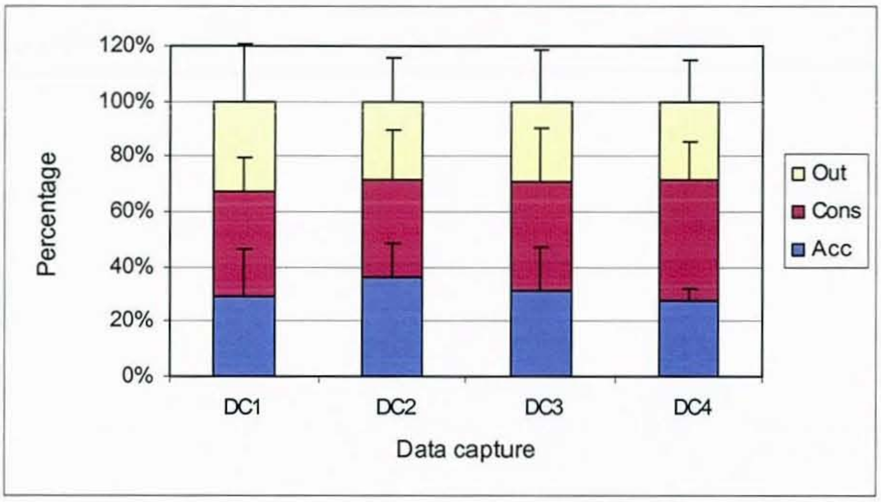


Figure 161: Group mean accuracy during DC with the standard ball

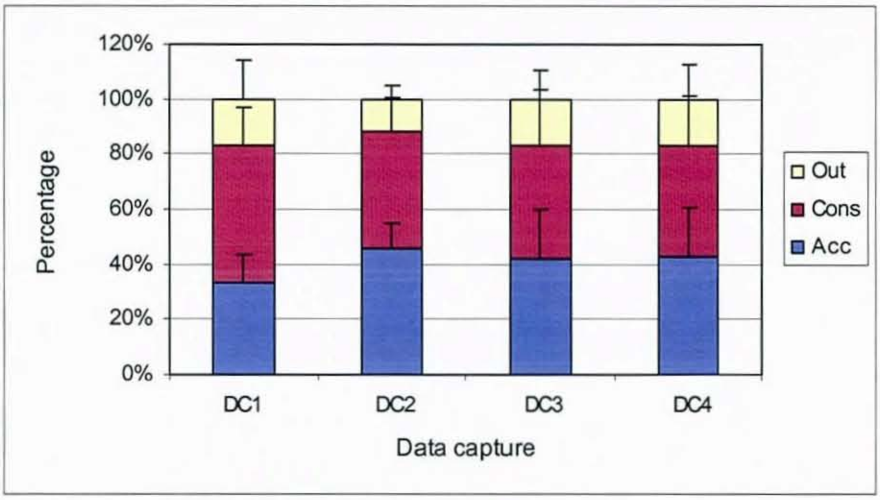


Figure 162: Group mean accuracy during DC with the pressureless ball

6.3.8 Return shot velocity

The figures below illustrate the return shot velocity data at both the group (Figure 163) and individual level (Figure 164).

Figure 163 shows the group data for average return shot velocity for each of the four data collection periods with each corresponding ball type. There was no statistical difference between the return shot velocity played with either ball type for any of the data collection periods. There was no statistical difference in return shot velocity over time during the session on either of the two test occasions.

Individual average return shot velocity for data collection shots ranged from 18.1 ms^{-1} to 23.6 ms^{-1} (40.4 mph to 52.9 mph) (Figure 164). The intra-subject variability was low indicating that subjects returned shots at consistent velocity on the two test occasions. Figure 163 and

Figure 164 demonstrate that whilst inter-subject variability occurred in return shot velocity each subject was consistent on the two test occasions permitting fair comparison of the primary test measures across weeks

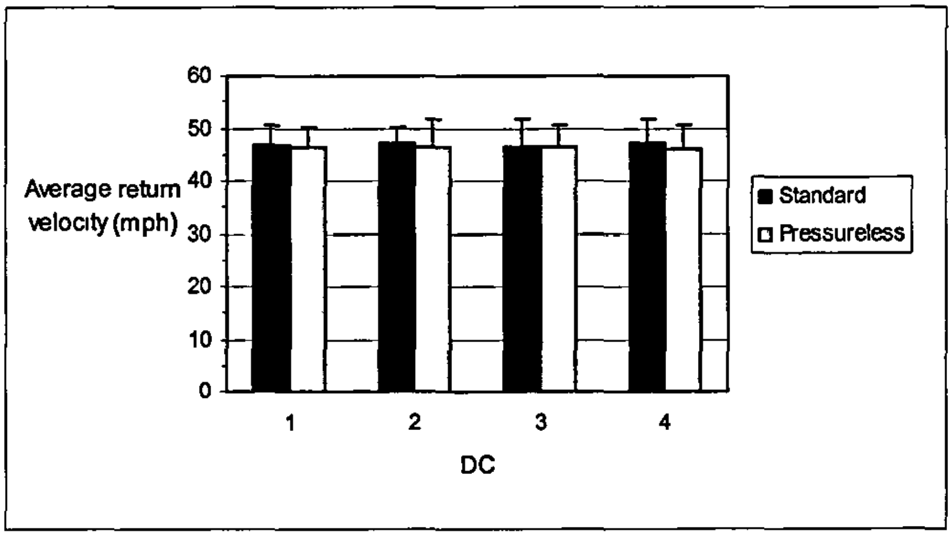


Figure 163: Group average return shot velocity for each data capture period

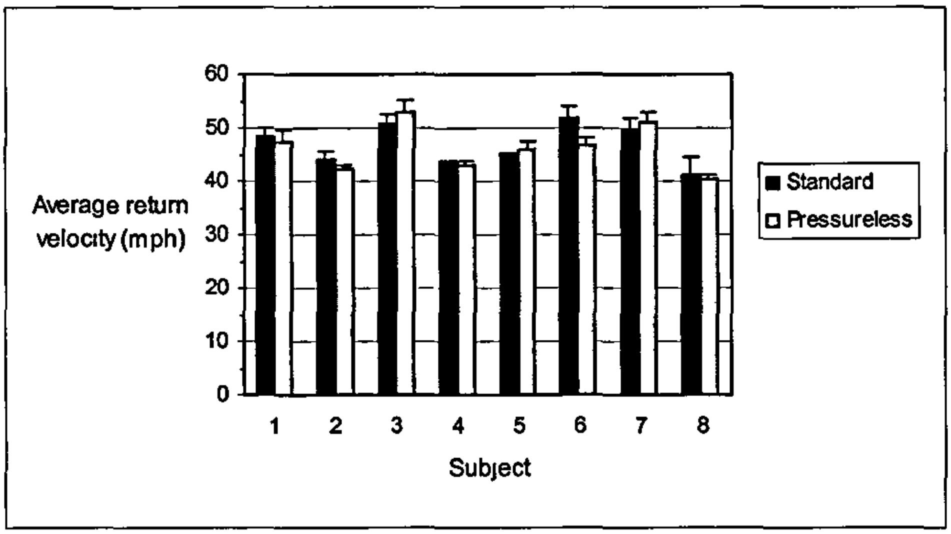


Figure 164: Individual average return shot velocity for each ball type

6.3.9 Heart rate

Heart rate was sampled and stored every 5 seconds throughout the test. Figure 165 provides an example characteristic trace obtained during Subject 1's second week session. The trace exhibits nine clear 'humps' corresponding to each CPA, with heart rate increasing during the three minute activity period and then falling during the recovery. Typically heart rate rose fairly rapidly during the early part of the three minute period and then fell steeply during the recovery. There was a slight delay (5 to 10 seconds) on the completion of the CPA and initiation of the recovery period before heart rate fell.

Figure 166 shows mean group heart rate values on immediate completion of each CPA obtained using both the standard (pressurised) and pressureless ball. Figure 167 shows mean group heart rate values after each CPA recovery period (i e. just prior to the start of the subsequent CPA). For some individuals increasing levels of fatigue may be more reflected in a reluctance of the heart rate to fall on recovery between bouts of activity than in the peak value that the heart rate reaches during the activity. Group heart rate values did not differ through the course of the test session (i e. CPA 1 to CPA 9) during either week. Although not statistically significant there was a trend of slightly lower heart rate values during the week 2 test (pressureless ball) compared with the week 1 (standard pressurised ball) heart rate values. This trend was reflected to some extent in the RPE values. It is worth noting that the significant increase in RPE during the test sessions was not reflected in the heart rate values.

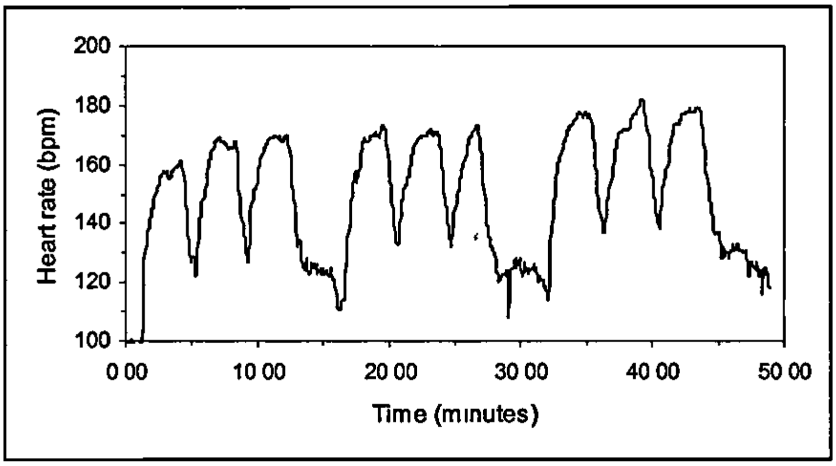


Figure 165: Graph of heart rate for Subject 1 during week 2 session

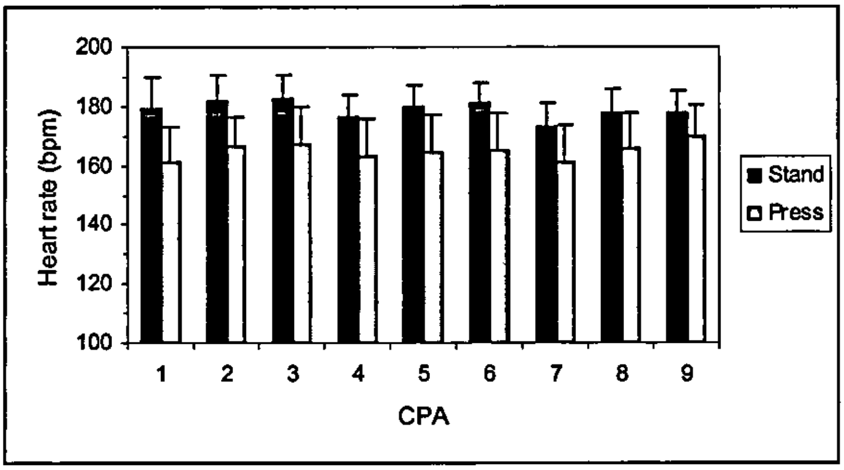


Figure 166: Group heart rate values on completion of each CPA

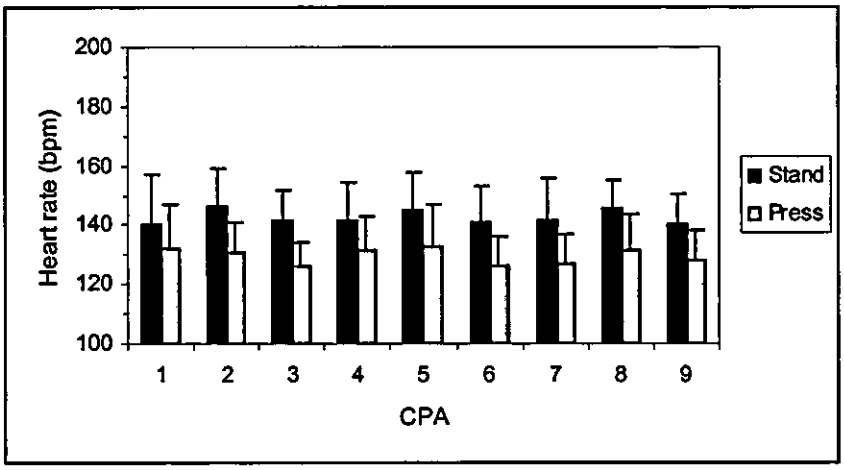


Figure 167: Group heart rate values after each CPA recovery period

6.3.10 Rate perceived exertion

Players were asked to indicate their rate of perceived exertion (RPE) from a scale presented immediately on completion of each of the nine periods of controlled play activity (CPA). Group average RPE for each period of the test session for each week is presented in Figure 168. A statistically significant increase in average group RPE occurred during both weeks of test sessions from an average of 11.9 to 15.0 when using the standard (pressurised) ball and from 9.8 to 15.0 when using the pressureless ball. The scale description corresponding to an RPE indication of 9 on the scale is 'very light'. An RPE rating of 15 corresponds to an indicated perception that the individual is exercising at an intensity described as 'hard (heavy)'.

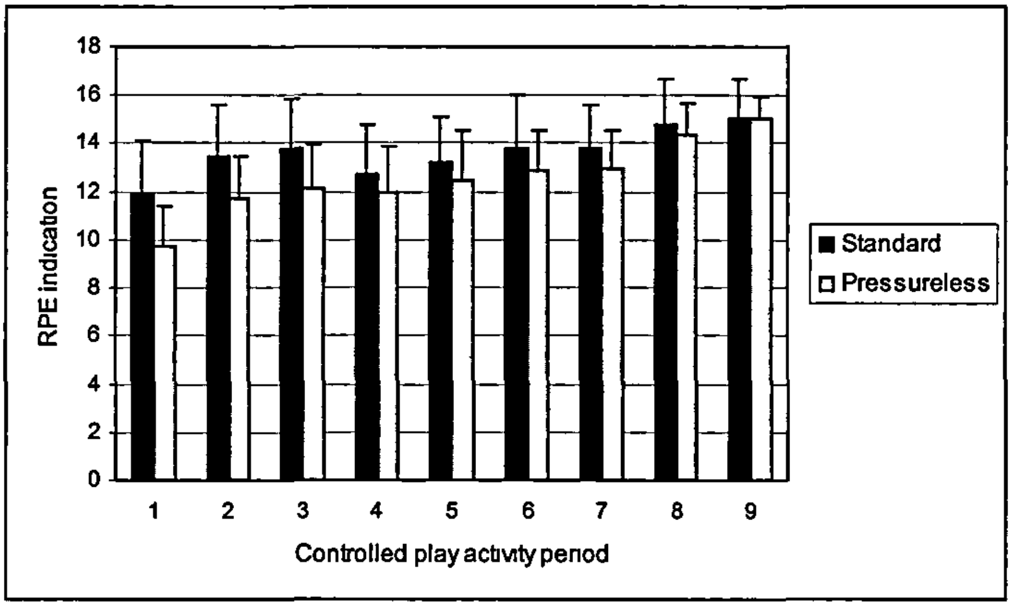


Figure 168: Average group RPE indication after each 3 minute CPA period

Average RPE was not statistically different when comparing between test sessions (across weeks/ball type) following any of the 3 minute activity periods. Indeed the group average RPE after the final activity period was 15 0 on both occasions. It is interesting that during the first three periods of controlled play activity the average RPE is lower (not statistically significant) when comparing the week 2 test session (pressureless ball) with the week 1 test session (standard ball). It is likely that on the first occasion the subject was tested they were initially slightly nervous due to not knowing quite how hard the session would be. It is possible that this initial apprehension influenced their perceived exertion rating elevating it slightly. On week two the subjects knew what to expect and were therefore a lot more relaxed which was likely to reduce their RPE levels relative to those of week one.

6.3.11 Additional controls

Activity logs, dietary intake lists and 'test day well being' forms were analysed and compared to identify any non target variables that may have unduly influenced the subjects' performance during the test sessions. With the exception of the one participant who was unable to attend the second test session due to illness, all subjects remained healthy and well throughout the period of the study. Activity levels, dietary intake and sleep patterns remained consistent in the 48 hour period prior to each test session. Reported well being on the morning of the two test sessions remained unchanged.

6.4 DISCUSSION OF RESULTS

This study achieved the objective of simultaneous measurement of in-play grip vibration, shock loading and grip pressure in tennis whilst in addition incorporating the component of fatigue.

This was achieved by the design, development and assembly of an instrumented racket utilising existing technology appropriate to the application.

A test protocol was designed and developed (Chapter 5) to induce accelerated fatigue in the functionally relevant muscles symptomatically involved in tennis elbow. This was necessary in order to field test the instrumented test racket within an appropriate environment. The primary requirements of the protocol were to:

- Induce accelerated fatigue
- Compare the effects of equipment
- Provide play realism
- Provide control

To properly compare the effects of different equipment it would be necessary to utilise a crossover study design. To do this the players would be divided into two groups, A and B. On each test occasion, Group A would play with the alternative equipment to Group B and on every successive test occasion each test group would switch to the alternative equipment. A crossover design was not used primarily due to concerns about the durability of the instrumented test racket (see section 5.6.3).

Fatigue status was selected for manipulation because of the potential end use of this type of measurement device, i e. to determine relative effects of equipment in terms of fatigue and injury. It is beyond the scope of this thesis to attempt a discussion on the mechanisms of fatigue. Fatigue due to prolonged exposure use was expected to invoke a response that was sufficiently large to be measurable.

The reported rate of perceived exertion (RPE) and perceived muscle soreness results demonstrate that the protocol successfully achieved sub-maximal levels of fatigue in the players. Reported RPE increased significantly during the nine periods of Controlled Play Activity (section 6.3.10: Borg RPE scale: 11.9 pre to 15.0 post with the pressurised and 9.8 pre to 15.0 post with the pressureless ball). The values indicate evidence of a learning effect in that there is a trend towards lower reported RPE values in week 2. This is most evident during the first three periods of CPA, following the final period of CPA, notice that the average group RPE was exactly the same (15.0) in week 1 and week 2. This indicates that the protocol successfully controlled the overall total activity intensity.

Perceived levels of muscle soreness were obtained on four occasions for each test session: pre (prior to the test session but following the warm up), post (immediately on completion of the test session), 'post am' (the morning of the day after the test session) and 'post pm' (the evening of the day after the test session). There was a statistically significant increase in levels of muscle soreness reported in muscles of the dominant arm when comparing all three post test levels (i e. post, 'post am', and 'post pm') to pre levels, with both ball types (figures 40-43). In addition, there was a statistically significant increase in soreness of the muscles of the non-dominant arm the day after the test session ('post am' and 'post pm') but not immediately on completion of the session (post). The greater levels of muscle soreness in muscles of the dominant arm compared with the non-dominant arm confirms that the repeated loading was sufficient to induce expected changes. The fact that muscle soreness increased in even the non-dominant arm confirms that the intensity and duration of the activity was physically challenging. Peak levels of muscle soreness were reported in the muscles of both the dominant and non-dominant arms 'post am' and generally did not rise any further 'post pm'. This is in accordance with delayed onset of muscle soreness.

Heart rate showed no increase throughout the duration of the test session (Figure 165 to Figure 167). The heart rate was not expected to reflect increasing levels of localised fatigue of the forearm muscles resulting from the repeated shot loading during the test session. It may however have been expected to reflect the reported RPE values, though in this study this did not occur.

McCarthy (1997), established a link between increasing player fatigue and reducing accuracy, utilising a controlled simulated match play protocol in which subjects played to volitional fatigue. In view of this it was expected that shot accuracy would decrease over time during the test session reflecting increasing player fatigue, but this did not occur (Figure 159 to Figure 162). This either suggests that reduction in accuracy only occurs at the point of volitional fatigue or that the reduction in accuracy is not due to change in hand function due to fatigue. Players in the McCarthy study were required to move across the court between shots. In contrast, the focus of this study was on inducing localised muscle fatigue in the forearm and the players remained relatively stationary, only being required to move round the ball to switch between making backhand and forehand shots. The reported reduced accuracy may have been due to a slowing of the player moving across the court resulting in a reduced ability to get the racket onto the ball with as much precision. This would mean that subjects were hitting more shots off centre which may have resulted in greater shock loading and vibration than if they were hitting the ball 'sweetly'.

Trend changes (not statistically significant) occurred in selected in-play grip pressure parameters (reduced), shot accuracy (increased), muscle soreness (reduced), and heart rate values (reduced) when comparing week 1 results to week 2 results. Due to necessary limitations of the design of the experimental study (i.e. that a crossover design was not used) these differences cannot be readily attributable to change in ball type. The reasons for choosing not to adopt a crossover design of experiment have already been discussed in section 5.6.3. This clearly introduced the possibility of systematic differences being introduced, for example, the 'learning effect' of participating in the week 1 test may have carried over to alter a player's performance responses in week 2, irrespective of the possible influence of any equipment change.

The trend changes will also have been contributed to by the increased anxiety during the first test session compared with the second test occasion. This effect is documented in the literature and commonly referred to as the 'white coat' effect (Lantelme, 1998). Although efforts were made to ensure the participants were made to feel as comfortable and at ease as possible and they were fully informed about all aspects of the session in advance, the subjects would have been naturally more apprehensive during the first week. On week two the subjects knew what to expect and were therefore a lot more relaxed, which is reflected in the various physiological measures.

In order to make a statically significant comparison between the effects of playing with alternative equipment it would be necessary to give the players more time to become familiar with performing the test. This might involve repeating the test several times and only looking for differences between the results of later tests. Each week of tests should also utilise a crossover design.

Performance measures of in-play grip pressure, vibration and control measures indicated consistency of results between weeks, confirming that controls had been successfully applied to ensure consistency of the results obtained from the primary and secondary test measures. Return shot speed remained consistent across test sessions as did various parameters of grip vibration indicating that similar levels of performance in terms of effort, intensity and motivation were achieved on both test occasions permitting comparisons to be made.

Compared with previous studies concerned with measuring aspects of dynamic grip pressure and vibration, this study achieved significantly greater play realism. Previously reported research has typically adopted a case study approach involving a single player performing a small number of shots (less than 20) and generally not taking place on an actual tennis court. This study utilised a much greater number of shots and during the periods of controlled play activity the players alternated between one forehand and two backhand strokes. A total number of 870 shots per test session per subject were performed, of which 60 were data collection (DC) shots. This number of shots is much more similar to the number of shots performed in regular tennis play and is much greater than the number of shots utilised in previous research studies.

Considering vibration, processing of the accelerometer data yielded a range of parameters to characterise the shape of each acceleration-time plot. Parameters were calculated for the six channels of accelerometer data for each of the 720 Data Collection (DC) shots. Statistical tests were performed on these parameters to determine whether changes occurred due to either ball type or fatigue level. The majority of these parameters showed no systematic differences caused by either ball type or fatigue level changes.

It seems likely that the failure to detect any discernable, functional difference due to the ball types used not being sufficiently different. The study used standard pressurised and pressureless balls. It is acknowledged that it would have been better to compare the effects of the standard sized Type 2 ball with the Type 3 oversize ball for reasons of consistency with the two studies reported in Chapters 3 and 4 to shed further light on the Type 3 ball issue. The Type 2 and Type 3 balls may have been expected to show greater differences. However, introducing the Type 3 ball and insisting on the same shot speed would have artificially raised the shock/grip levels as players would need to hit the ball significantly harder to achieve this. For this reason alone it might have showed more rapid onset of fatigue and the task would still exist to investigate if this is the case within the normal play context or whether players eventually adapt their playing technique.

Previous research has shown that a firmer grip increases transmission and transfer of vibration from impact to the arm and this has been implicated in injury Hatze (1976). An increase in grip firmness is also related to greater coefficient of restitution and therefore greater return ball speed Plagenhoef (1970) and Hatze (1976). To generate more ball speed, elite players are generally advised to grip firmly, the corresponding concerns over injury being reduced by an elite player's ability to hit the ball more centrally on the racket. Conversely, recreational players are normally advised to grip less firmly, more off centre shots being likely.

Following on from this general knowledge, it was hypothesised that a fatiguing grip might have reduced the grip pressure and thereby reduced the damping effect of the hand and arm. This in turn might have been expected to alter the profile of the accelerometer data. Whilst a fatiguing grip was evidenced by the in-play grip pressure data, statistical analysis of the group results showed no significant reduction in the mean peak value of acceleration across any of the six channels as players became fatigued. Furthermore, the rate of decay of the racket-arm system vibration remained independent of overall fatigue, as shown by the following results.

Figure 169 shows the attenuation time to fall to 5 percent of the peak value, which was calculated by fitting an exponential decay curve to the data and comparing decay curve indices. It can be seen from the results that increasing levels of fatigue (DC1 to DC4) caused no corresponding trend change in vibration attenuation.

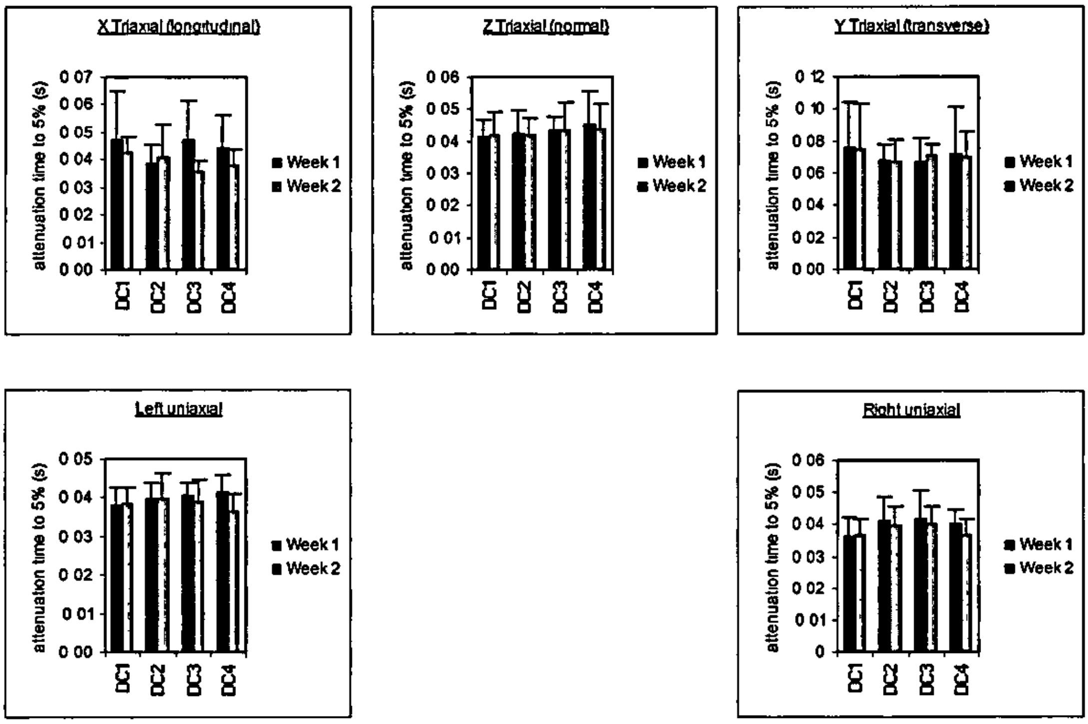


Figure 169: Attenuation duration to 5% of peak value

Failure to find any difference in the rate of decay of the racket-arm system may be due to this effect being dominated by the physical characteristics of the racket. Indeed, some research suggests that it is reasonable to model a racket as a free body (e.g. Hatze, Brody). Perhaps no relationship was detected because relatively large changes in grip pressure only result in relatively small changes in vibration characteristics. It is likely that if vibration of the wrist had been measured it would have altered with changes in the grip pressure. However, such measurement would have been difficult to achieve in this protocol due to the longer rest periods that would inevitably be required. It is likely that an accelerometer would need to be re-fixed for each data collection period. It is difficult to fix a sensor onto part of the body and it needs to be fixed securely onto a bony protrusion in order to prevent movement. This technique can restrict blood flow and be uncomfortable to the subject.

Although not statistically significant, some trend changes in the accelerometer data were observed. A trend reduction of the peak value over time appeared to occur on three accelerometer channels; triaxial axis-y, triaxial axis-z and the uniaxial centre axis. The mean level of this reduction was approximately 15% from DC1 to DC4. Upon examination of the mean results for the individual test subjects, it was found that the reductions in peak acceleration were particularly noticeable for three of them (numbers 3, 5 and 8) although again this was not statistically significant. The reductions were not accompanied by any observable reduction in return ball speed. Based on subjective observations of the test sessions, it was considered that subjects 3, 5 and 8, for whom trend changes in the accelerometer data were observed, were the three players who became most tired by the end of the test sessions. This was also borne out by the various physiological measures of player fatigue, i.e. heart rate, perceived exertion and muscle soreness.

These results indicate the potential for the accelerometer data to detect differences between players that are greatly fatigued compared with players that are somewhat less fatigued. However, all players involved in this study reported that they experienced levels of localised muscular fatigue that were in excess of any fatigue they might typically encounter during normal tennis matches or training sessions. It is therefore questionable how useful in-play accelerometer data is in respect of detecting the effects of alternative equipment on localised fatigue rates under normal playing conditions. It is still likely that accelerometer data would reveal a greater tendency to mishit under more generalised fatigue conditions.

Considering grip pressure, it was hypothesised that the periods of CPA would fatigue the hand sufficiently to result in a measurable reduction in the in-play grip pressure. A repeated measures ANOVA test showed that differences in some of the parameters of grip pressure (statistically significant at the 95% level) were observed through the duration of the test (DC1 to DC4). The parameters of dynamic grip pressure that were identified as being the most sensitive to fatigue induced changes in grip performance were; rise rate, pre-impact peak, post-impact peak and area under the grip pressure curve between 0.05 s before impact and 0.1 s after impact (Figure 143 and Figure 144). Each of these parameters significantly decreased over time as a player became increasingly fatigued. At the individual subject level, three of the subjects showed clear reductions in grip pressure over time (Figure 145 to Figure 150) whilst the other three did not. Interestingly, the three players showing these more marked reductions in grip pressure were numbers 3, 5 and 8, who were the same three that appeared to become more fatigued and that showed trend reductions in accelerometer values.

The largest reduction in grip pressure occurred between the first and second periods of data collection (DC1 to DC2). This early onset of reduction in grip pressure suggests that there was either an initial settling-in period, during which players naturally relaxed their grip, or that significant grip fatigue occurred during the first nine minutes of Controlled Play Activity (i.e. the first three periods of CPA). It would be interesting to investigate the early stages of grip fatigue onset in more detail.

Despite the resulting change over time in dynamic in-play grip pressure, the static hand-grip test failed to reveal any significant differences for the dominant hand. This was despite addressing the perceived implementation weaknesses of this test when applied in previous studies. Significant differences were neither caused by use of an alternative ball type, nor by player fatigue induced by the periods of CPA. Certain trend changes were observed that might have been expected and therefore added confidence to the overall reliability of the results. These trends suggested some lowering of measures for the dominant hand, in line with expected effects of fatiguing, which were not shown for the non-dominant hand. In conclusion, the stated objective of developing a more sensitive test device than the static hand-grip test, capable of detecting fatigue induced changes was achieved.

A key finding was that despite the presence of fatigue, the resulting statistically significant changes in dynamic in-play grip pressure were not reflected by any change in the measures or derived parameters of either vibration or static grip pressure. No differences being found in the measures of vibration and static grip pressure either meant that there were indeed no differences, that any differences were not successfully measured (perhaps due to lack of sensitivity of the measuring techniques or failure to measure the correct parameters), or due to the occurrence of a statistically aberrant (freak) result. An appreciation of statistical power (see section 5.6.2) provides insight into these various possibilities and indicates the unlikelihood of a failure caused by the statistical analysis.

It is acknowledged that variability in the results reduces the chances of significant differences being found. This variability, to a large extent, was contributed to by the inevitable variation in impact location during the shots. A main requirement of this testing was that conditions should remain as 'real' as possible, allowing players to play as they would normally rather than testing them in artificial conditions. There is an obvious trade off between 'real' conditions and scientific control for the purposes of reliability and repeatability of testing. This dichotomy is the main difficulty of this research problem. By using only skilled players, controlling the speed and direction of the ball feed, having subjects perform a specified stroke technique, aim at a target box and be provided with feedback on shot speed, it was anticipated that this would naturally reduce variation of the impact location. The only way to closely control impact location whilst maintaining a real shot would be to test using a block volley tennis stroke and fire the ball at the racket in a controlled location. It should be noted that by not fully controlling the impact location a component of analysis was gained. The factor that changes and causes injury over time may be the fact that when tired a player hits more erratically, with more shots off centre, resulting in greater loading on the body for a given number of shots. If this factor was controlled for and removed from the experimental protocol, then its effects would have been lost.

The possibility of no differences occurring in vibration or static grip measurements because of insufficient exercise stimulus was considered. However, it was felt that the players were loaded sufficiently, as evidenced by the increasing levels of muscle soreness during the day after the test session. Verbal feedback from the players confirmed them to be far more tired in the arm muscles the day after the test than they would be after normal matches. They likened it to the localised muscle disruption they would get occasionally after an intense conditioning session. It may be that the fatigue caused by a player running about the tennis court in the course of normal play also makes a significant contribution to shock loading and vibration By using a test protocol that concentrated on inducing local muscle fatigue, any other 'real play' fatigue effects were not investigated.

Another potential reason for observing no differences in vibration or static hand-grip measurements might have been that the hand-grip required to perform tennis shots requires a sub-maximal contraction. However, significant changes of the in-play grip pressure were observed to occur through the course of the test.

CHAPTER 7

GENERAL DISCUSSION

The conclusions arising from the two first studies investigating the comparative effects of playing tennis with the Type 3 oversize ball compared with the Type 2 standard ball are presented in Chapters 3 and 4. A summary of these follow:

- Ball size appears to have little effect on grip strength/fatigue or perceived muscle soreness.
- A 10 to 25% increase in the number of shots required to determine the outcome of a point occurred when playing with the oversize ball.
- No detrimental effects were identified in terms of style of play; rally composition remained independent of ball size.
- Players reported perceived differences between the ball types which were attributable to differences in the physical characteristics of the balls.
- Possible compensation (over hitting) occurred when playing with the oversize ball. This issue requires further exploration, including investigation of adaptation over time.
- Weaknesses were identified in using off-court static measuring devices for the purposes specified in the two studies. This issue formed the basis for the subsequent dynamic grip study.

The dynamic grip measurement study has investigated the application of technology to achieve a better understanding of the interaction between equipment and players. Current methods of equipment testing largely neglect performance of the equipment in combination with the player. This research has formed part of an ongoing project in conjunction with Head, a company interested in developing their techniques for evaluating equipment by taking player performance into consideration. Head wishes to correlate subjective evaluation with objective measurements.

The stated objective of this research was to develop new techniques to enable in-play measurement of player performance characteristics especially those related to fatigue. It is proposed that the provision of a new in-play technique to assess fatigue induced changes in grip activity objectively will enable investigation of the relative effects of interventions, such as equipment modification. It might also provide new insight into the causes of injury. The novelty of the approach used in this study has been the simultaneous measurement of in-play grip vibration, shock loading and grip pressure in tennis whilst in addition incorporating the component of fatigue. Previous studies that have investigated components of vibration and grip pressure have neglected the fatigue component of player performance. It is suggested that this is important in respect of determining the relative effects of equipment on fatigue and incidence of overuse injuries.

The purpose of the dynamic grip measurement study reported was to explore a range of dynamic grip pressure and vibration parameters to determine their relative sensitivity with respect to tennis induced changes and to investigate the relationship between them. The objective was that the results from this study would indicate a hierarchy of sensitivity exhibited by the measures examined, providing insight into their interrelationships. This information would then provide a foundation from which to make recommendations regarding the implementation of tennis related test protocols.

A dynamic, in-play measurement device was proposed as an improvement to the static hand-grip dynamometer test utilised in the ITF sponsored studies. In the grip study, parameters of the static hand-grip test continued to show no significant differences relating to fatigue status. However, parameters of dynamic grip pressure were shown to reduce as level of fatigue increased. In conclusion, the instrumentation developed for this study successfully achieved the aim of being more sensitive than the static hand-grip test to changes in grip performance due to fatigue or muscular overload in tennis.

The parameters of dynamic grip pressure that were identified as being the most sensitive to fatigue induced changes in grip performance were; rise rate, pre-impact peak, post-impact peak and area under the grip pressure curve between 0.05 s before impact and 0.1 s after impact. Each of these parameters significantly decreased over time as a player became increasingly fatigued. In contrast to initial expectations, the dynamic racket and grip vibration derived parameters exhibited trends, but no statistically significant changes with increasing fatigue. There were no differences due to ball type in any of the indices of measurement, probably due to the small differences between the ball types. In conclusion, it is recommended that future developments should concentrate on the grip pressure measurement aspects of the design as opposed to the vibration measuring capabilities.

The test protocol was considered to have achieved a successful balance between providing a tennis-realistic test environment whilst maintaining adequate control for the purposes of results comparison and repeatability. However, one obvious drawback was the use of signal carrying cables connecting the instrumented racket back to the data capture units. These cables certainly introduced an element of distraction to the players and although not appearing to restrict their freedom to swing the racket, did prevent free movement around the court. In this case, the test protocol was designed with player movement restricted to a small area, which presented no problem since it was fatigue of the hand-grip and arm muscles that was being investigated.

However, future studies may wish to collect in-play data using a protocol that requires whole court movement of the player.

In conclusion, a new, dynamic, in-play measurement device has been demonstrated to offer improved capabilities for measuring hand-grip fatigue status, as compared to an off court static hand-grip device. It has been shown that such an in-play measurement device can be manufactured by the application of current technology. Several parameters of grip pressure that relate to fatigue status have been identified within a test protocol that successfully achieved a balance between providing control and a realistic play environment.

CHAPTER 8

RECOMMENDATIONS FOR FURTHER WORK

A list of recommendations for further work follows and where appropriate additional discussion is provided. The recommendations may be summarised as follows and are discussed below:

1. Recommendations for further developments of instrumented racket:

- Incorporate a wireless data capture unit
- Instrument other makes and models of rackets
- Investment in a customised sensor
- Increased sensor spatial resolution
- Increased sampling rate
- Eight face (full hand) handle coverage
- Investigate shear forces

2. Recommendations for further developments of the test protocol:

- Investigation of other player populations, for example, level of ability, sex, age group, players with a history of injury
- Utilise a crossover study design
- Increase statistical power of the test
- Carry out laboratory based experiments to determine sensitivity
- Study alternative equipment with greater differences, for example larger and standard sized balls
- Consider prospective studies for investigating injury mechanisms

The equipment manufacturer Head has been in development of a wireless data capture unit designed to fit into a tennis racket handle. The incorporation of this unit into the instrumented racket would remove the limitations imposed on the test protocol by the trailing sensor cables. With a wireless test racket, the protocol could be adapted to include the player hitting alternate forehand and backhand shots whilst moving freely around the whole tennis court without interference from and becoming tangled in the signal carrying cables. This would allow investigation of whether fatigue arising from a player's movement around the court causes changes in grip force characteristics.

In view of the identified changes in some of the grip pressure parameters, it is recommended that use of a customised sensor is worthy of investigation. A customised sensor should cover all eight faces of the handle. Utilising a grip pressure sensor with greater sensor resolution (more sensor cells per unit area) may reveal more about the pressure distribution across the hand. It would be useful to study the full pressure map of the hand on the racket handle through a shot to enable muscle activity of the arm and hand to be tracked based on observed changes in hand pressure.

Ideally the Tekscan equipment would have been able to measure the dynamic grip pressure response during impact. This was not possible due to the limited sampling rate available with the system used in this study. Instead, the transient elements of the shock loading and subsequent racket vibration were investigated using the accelerometers. It would be desirable in future studies to instead use a grip pressure system with a greater sampling rate and very low hysteresis.

A system with greater sensor resolution (more sensor cells per unit area) would enable investigation of hand position more accurately during a stroke. It is possible that as a player becomes fatigued they fail to shift their grip sufficiently in preparation for different types of shots. Ideally a system would be available with increased sensor resolution and higher sampling rate. However, a balance is required since improvements in either of these would increase the amount of data generated requiring capture and storage in the data capture unit. If the data capture unit could telemetrically transmit data to a PC for storage during acquisition this would not be as big a problem, otherwise there may be limitations placed on the amount of data that can be stored per test period (before needing to download the data and free up memory space). In this scenario, an increased sample rate or resolution may reduce the capacity for testing over a prolonged time to measure fatigue. It is recommended that the optimum levels of sensor resolution and sampling rate be determined by discussion with manufacturers and further experimentation.

It might be possible to overcome the data capacity problem by periodically downloading data at convenient intervals. For practical reasons it is likely that a wireless data capture unit would operate by capturing all the data for subsequent downloading to a PC. Adding data transmission capabilities i.e. an ability to transmit captured data telemetrically to a separate base unit in real time would increase the size of the unit, especially due to the extra battery capacity required. A requirement for periodic download of data could be accommodated in the test protocol either by having periods of no data capture or by utilising multiple instrumented rackets and frequently swapping between them.

Another potential approach would be to only instrument identified key areas of activity on the hand. In this case increasing the sample rate and resolution would be possible as the overall amount of data produced would be reduced. However disadvantages of this approach would include a requirement to customise the sensor fit to individual subjects and would make comparison between subjects more difficult. An additional consideration against the approach of only instrumenting key areas of maximal activity is the possibility that areas of lower activity acting in more anatomically vulnerable areas may be of equal or greater significance in respect of fatigue and injury.

Statistical power describes the probability that the null hypothesis can be rejected. Consideration of statistical power can assist in determining the number of test subjects to be used in future studies based on this equipment and test protocol. With reference to section 5 6.2, the three factors that increase the statistical power of an experiment are (i) increasing alpha, (ii) increasing effect size, and (iii) reducing variation in the response variable (i.e. small standard deviation). Mean effect size and standard variation has been calculated for many variables measured during the grip study. This data should be used in the design of future studies which utilise an instrumented racket, to predict the number of samples to be utilised, with the aim of increasing the statistical power. The use of single subject design should also be considered as another means of reducing variability.

Whilst the testing carried out during this research was based on the concept of achieving in-play realism, it is recognised that this introduced significant variability in, for example, ball-on-racket contact position, which prevented the measurement and identification of small but consistent effects due to a lack of statistical significance. In addition to experimental tests conducted on a tennis court, it is recommended that consideration is also given to the design of additional laboratory based tests to identify potential effects by seeking to minimise variability.

In view of the demonstrated effectiveness of the instrumentation it is recommended that a range of additional studies are conducted that compare for example, larger and standard sized balls, or alternative items of equipment that have more pronounced differences. The use of a crossover study design would give greater confidence to any findings. Widening the scope of the study to include different player populations would enable the generation of a database of profile grip pressure data for different categories of players under controlled variable conditions. A database of profiles would allow correlation between variables. It would be interesting to correlate instrumented racket data with physiological measures such as MRI scans to identify areas and levels of inflammation. Furthermore, correlation of in-play grip pressure data with data generated by motion analysis of stroke technique might lead to a greater understanding of the effect of fatigue on playing technique.

It would be interesting to ask the players to perform a maximal hand-grip contraction on the hand-grip of the instrumented racket and compare the recorded pressure with the maximum grip pressure observed during tennis play. Expressing the grip pressure occurring during the shot as a percentage of the maximum could offer an appropriate means of normalising the data. Such a maximal hand-grip test could be conveniently carried out at the end of every period of CPA. However care would be required since too many hand-grip tests could also fatigue the players. Hand grip tests performed in this manner could be compared with hand-grip tests performed using the hand-grip dynamometer.

The grip study protocol utilised data capture (DC) periods that were separated by nine minutes of CPA. A future development could be to further investigate the early stages of grip fatigue onset in more detail. This would involve more frequent use of the instrumented racket. Ideally the instrumented racket could be used for all shots during the test schedule, i.e. those within the periods of CPA and DC.

Having successfully developed an instrumented racket and test protocol that can detect equipment changes or fatigue induced changes in player performance, the next logical step would be to address the issue of interpreting the exact causes of the these changes. To assist in this activity it is proposed that an additional measure would prove very useful, this being an accurate determination of ball impact location. Ball impact location would be expected to have a direct influence on a number of measures including, for example, accelerometer measurements of shock loading and racket vibration. Building up a detailed picture of the effect of off centre shots may provide insight into their relative contribution to the occurrence of tennis injuries.

In a prospective study, study subjects are divided into groups which are either exposed or not exposed to the intervention(s) of interest before the outcomes have occurred. Prospective studies should be considered as a means of investigating the effects of various interventions on injury mechanisms. It is recommended that a prospective study is set up to investigate how the use of alternative tennis equipment might affect the incidence of tennis elbow.

REFERENCES

W. M. Abraham. (1987) Factors in delayed muscle soreness. *Medicine and Science in Sports and Exercise* 9(1), 11-13.

S. Adelsberg. (1986) The Tennis Stroke: Emg Analysis of Selected Muscles with Rackets of Increasing Grip Size. *American Journal of Sports Medicine* **14**(2), 139-142.

F. L. Allman. (1975) Tennis Elbow: Etiology, prevention and treatment. *Clinical Orthop* **3**, 308-316.

R. Armstrong. (1984) Mechanisms of exercise-induced delayed onset muscular soreness: a brief review. *Medicine and Science in Sport and Exercise* **16**, 529-538.

G. Atkinson and T. Reilly. (1996) Circadian variation in sports performance. *Sports Medicine* **21**(4), 292-300.

J. A. W. Baker and C. A. Putnam. (1979) Tennis racket and ball responses during impact under clamped and freestanding conditions. *Research Quarterly* **50**(2), 164-170.

J. A. Balogun, C. Akomolafe and L. Amusa. (1991) Grip strength; effects of testing posture and elbow position. *Archives of Physical Medicine and Rehabilitation* **72**, 280.

J. Barber. (1978) Jerry Barbers unorthodox swing theories. In *Golf Digest*, Vol. 29, pp. 131-137.

BBC. (2003) Tennis history. http://news.bbc.co.uk/sportacademy/bsp/hi/tennis/rules/history/html/wimbledon.stm.

M. Beer. (1998) Light or blight. In *San Francisco Examiner Newspaper*.

D. Behm. (1988) A kinesiological analysis of the tennis serve. *NSCA Journal* **10**(5), 4-14.

A. M. Bernhang, W. Dehner and C. Fogarty. (1974) Tennis elbow: A biomechanical approach. *American Journal Sports Medicine* **2**, 235-260.

J. R. Blackwell and K. J. Cole. (1994) Wrist Kinematics Differ in Expert and Novice Tennis Players Performing the Backhand Stroke - Implications for Tennis Elbow. *Journal of Biomechanics* **27**(5), 509-516.

R. W. Bohannon. (1990) *Muscle strength testing with hand held dynamometers*. Churchill Livingstone.

R. W. Bohannon and A. W. Andrews. (1989) Accuracy of spring and strain guage hand held dynamometers. *J Orthopaed Sports Phys Ther* **10**, 323.

G. Borg. (1970) Perceived exertion: a note on History and methods. *Medicine and Science in Sport and Exercise* **5**, 90-93.

S. Bowyer, S. R. Mitchell and M. Caine. (2001) Playing with a larger tennis ball III: A study of recreational players and the effect on point play, player perception, muscle fatigue and soreness. Loughborough University.

H. Brody. (1979) Physics of the tennis racket. *American Journal Physics* **47**, 482-487.

H. Brody. (1981) Physics of the tennis racket 2. The sweet spot. *American Journal of Physics* **49**, 816-819.

H. Brody. (1988) *Tennis Science for Tennis Players*. University of Pennsylvania Press.

H. Brody. (1989) Vibration damping of tennis rackets. *International Journal Sports Biomechanics* **5**, 451-456.

H. Brody. (2001) Racket technology and tennis strokes. In *ITF Coaching And Sports Science Review*, Vol. 9, pp. 13-14.

H. Brody and R. Cross. (2000) Proposals to slow the serve in tennis. *The 1st International Congress on Tennis Science and Technology*, Blackwell Science (UK), 261-268.

H. Brody, R. Cross and C. Lindsay. (2002) The physics and technology of tennis, pp. 62-96. Racquet tech publishing.

M. Broer. (1973). In *Efficiency of human movement*, pp. 299. W.B.Saunders.

D. R. Budney. (1979) Measuring grip pressure during the golf swing. *Research Quarterly* **50**(2), 272-277.

D. R. Budney and D. G. Bellow. (1990) Evaluation of golf club control by grip pressure. *Science and golf. Proceedings of the first world Scientific Congress of Golf*, E & F N Spon, 30-35.

W. Bumgardner. (2000) Overruled. In *Tennis*, Vol. October 2000. Tennis.com.

J. W. Bunn. (1955) Scientific principles of coaching, pp. 244. Prentice Hall, Englewood Cliffs, New York.

A. K. Burton. (1984) Grip Strength in Tennis Elbow. *British Journal of Rheumatology* **23**(4), 310-311.

S. Bystrom and C. Fransson-Hall. (1994) Acceptability of intermittent handgrip contractions based on physiological response. *Human Factors* **36**, 158.

M. Caffi and F. Casolo. (1995) Ball dynamic characteristics: a fundamental factor in racket dynamic optimization. In *Science and Racket Sports* (ed. T. Reilly, M. Hughes and H. C. Lee), pp. 146-152. E&FN Spon.

B. Carroll. (1981a) Vibrational characteristics of tennis rackets and the effect on 'tennis elbow' sufferers. Manchester University unpublished report.

R. Carroll. (1981b) Tennis elbow: incidence in local league players. *British Journal of Sports Medicine* **15**, 250-256.

F. Casolo and G. Ruggieri. (1991) Dynamic analysis of the ball - racket impact in the game of tennis. *Meccanica* **26**, 67-73.

C. Chinn, J., J. D. Priest and B. E. Kent. (1974) Upper extremity range of motion, grip, strength and girth in highly skillled tennis players. *Physical Therapy* **54**, 474-482.

M. G. Ciccotti and W. P. H. Charlton. (2001) Epicondylitis in the athlete. *Clinics in Sports Medicine* **20**(1), 77-93.

A. J. Cochran. (2002) The impact of science and technology on golf equipment. In *The engineering of sport 4* (ed. S. Ujihashi and S. J. Haake). Blackwell publishing.

A. Coe. (2000) The balance between technology and tradition in tennis. *Tennis Science and Technolog', Proceedings of the 1st International Congress on Tennis Science and Technology*, S.J. Haake and A.O. Coe (Eds), Blackwell Science (Oxford), London, 3-40.

A. J. Cooke and K. Roussopoulos. (2000) Racket design and tennis elbow. 4th International Conference of the Engineering of Sport, September, 2002.

R. W. Coonrad and W. R. Hooper. (1973) Tennis elbow: its course, natural history, conservative and surgical treatment. *Journal of Bone and Joint Surgery* **55**, 1177-1182.

R. Cross. (1999) Impact of a ball with a bat or racket. *American Journal of Physics* **67**(8), 692-702.

J. S. Cundiff. (1974) Energy dissipation in human handarm exposed to random vibration. *Journal Acoust. Soc. Am* **59**, 212-214.

J. H. Cyriax. (1936) The pathology and treatment of tennis elbow. *Journal of Bone and Joint Surgery* **18**, 921-940.

P. Dabnichki. (1998) Biomechanical testing and sport equipment design. *Sports Engineering* **1**(2), 93-105.

C. B. Daish. (1972) *The physics of ball games*. The English Universities Press Ltd.

P. Davey, R. D. Thorpe and C. Williams. (2002) Fatigue decreases skilled tennis performance. *Journal of Sports Sciences* **20**, 313-315.

L. De Smet and G. Fabry. (1997) Grip force reduction in patients with tennis elbow: influence of elbow position. *Journal of Hand Therapy* **10**(3), 229-231.

J. Donnelly, W. C. Byrnes, J. T. Kearney and S. Fleck. (1991) A comparison of muscular strength and endurance measures between rock climbers and non rock climbers. *Communication to the International Congress and Exposition on Sports Medicine and Human Performance, Vancouver, BC, April.*

C. Dunkley. (1998) *Tennis nostalgia*. Open door limited.

K. E. Easterling. (1993) *Advanced materials for sports equipment: how advanced materials help optimize sporting performance and make sport much safer*. Chapman & Hall.

G. W. Eggeman and L. Noble. (1982) Measurement system for the determination of hand grip forces during a baseball bat swing. *American Society of Mechanical Engineers (ASME)* **49**.

G. W. Eggeman and L. Noble. (1985) Design and testing of a baseball bat transducer. *Experimental Techniques*, 20-23.

B. C. Elliot. (1982) Influence of tennis racket flexibility and string tension on rebound velocity following a dynamic impact. *Research Quarterly in Exercise and Sports* **53**(4), 277-281.

B. C. Elliot, B. A. Blanksby and R. Ellis. (1980) Vibration and rebound velocity characteristics of conventional and oversized rackets. *Research Quarterly in Exercise and Sports* **51**, 608-615.

B. C. Elliott. (1982) Tennis - the Influence of Grip Tightness on Reaction Impulse and Rebound Velocity. *Medicine and Science in Sports and Exercise* **14**(5), 348-352.

B. C. Elliott. (1988) Biomechanics of the Serve in Tennis a Biomedical Perspective. *Sports Medicine* **6**(5), 285-294

R. Ellis, B. C. Elliot and B. A. Blanksby. (1978) The effect of string type and tension in jumbo and regular sized rackets. *Sports Coach* **2**, 32-34.

J. Engel. (1995) Tennis: dynamics of racket-grip interaction. *Journal of Hand Surgery-American Volume* **20**(3 Pt 2), S77-81.

T. E. Fairley. (1985) Some measurements of tennis racket vibration and its transmission to the hand. *Human Response to Vibration, UK Meeting.*

Y. Fery, A. and L. Crognier. (2001) On the tactical significance of game situations in anticipating ball trajectories in tennis. *Research Quarterly for Exercise and Sport* **72**(2), 143-149.

J. Freund. (2001) A dynamic model of the forearm including fatigue. *Journal of biomechanics* **34**, 597-605.

FSA. (2003) Force sensitive applications. http://www.pressuremapping.com/products/innovation/innovation.html.

J. D. G. Furlong. (1993) The service in lawn tennis: how important is it? *First World Congress on science and racket sports*, Eds T. Reilly, M. Hughes and A.Lees, London, E & F. N. Spon. 266-271.

M. Galloway, M. DeMaio and R. Mangine. (1992) Rehabilitative techniques in the treatment of medial and lateral epicondylitis. *Orthopaedics* **15**, 1089.

S. G. Gerberich and J. D. Priest. (1985) Treatment for lateral epicondylitis: Variables related to recovery. *British Journal of Sports Medicine* **19**, 224-227.

C. E. Giangarra, B. Conroy, F. W. Jobe and M. Pink. (1993) EMG and cinematographic analysis of elbow function in tennis players using single and double handed backhand strokes. *American Journal of Sports Medicine* **21**, 394-399.

M. D. Grabiner, J. L. Groppel and K. R. Campbell. (1983) Resultant tennis ball velocity as a function of off center impact and grip firmness. *Medicine and Science in Sport and Exercise* **15**, 542-544.

S. Grant, T. Hasler, C. Davies, T. C. Aitchison, J. Wilson and A. Whittaker. (2001) A comparison of the anthropometric, strength, endurance and flexibility characteristics of female elite and recreational climbers and non-climbers. *Journal of Sports Sciences* **19**(7), 499-505.

B. Gray. (2000) A whole new ball game? In *Tennis Magazine.* www.tennis.com

M. J. Griffin. (1990) *Handbook of human vibration*. Academic press limited.

C. Griffith, M. Whyman, E. J. Bassey, B. Hopkinson and G. Makin. (1989) Delayed recovery of hand grip strength predicts postoperative morbidity following major vascular surgery. *British Journal of Surgery* **76**, 704.

J. L. Groppel. (1975) A kinematic analysis of topspin and backspin techniques in the tennis forehand. Unpublished master's thesis, University of Illinois at Urbana-Chamaign.

J. L. Groppel. (1986) The biomechanics of tennis: An overview. *International Journal of Sport Biomechanics* **2**, 141-155.

J. L. Groppel and R. P. Nirschl. (1986) A mechanical and electromyographical analysis of the effects of various counterforce braces on the tennis player. *American Journal of Sports Medicine* **14**, 195-200.

J. L. Groppel, I. S. Shin, J. G. Thomas and G. J. Welk. (1987) The effects of string type and tension on impact in midsized and oversized tennis rackets. *Journal of Sport Biomechanics* **3**, 40-46.

H. W. Grouchow and D. Pelletier. (1979) An epidemiological study of tennis elbow. *American Journal Sports Medicine* **7**, 234-238.

S. J. Haake. (1999) Modelling and analysis of oversize balls. The University of Sheffield. ITF Report

S. J. Haake, S. G. Chadwick, R. J. Dignall, S. Goodwill and P. Rose. (2000a) Engineering tennis- slowing the game down. *Sports Engineering* **3**, 131-143.

S. J. Haake, P. Rose and J. Kotze. (2000b) Reaction time testing and grand slam tie break data. *The 1st International Congress on Tennis Science and Technology*, S.J. Haake and A.O. Coe (Eds), Blackwell Science (Oxford), London. 269-276.

J. Hamill and K. Knutzen. (1995) *Biomechanical basis of human movement*. Williams and Williams, Baltimore.

Y. S. Hang and S. M. Peng. (1984) An epidemiological study of upper extremity injury in tennis players with a particular reference to tennis elbow. *J. Formosan Med Ass.* **83**, 307-315.

H. Hatze. (1976) Forces and duration of impact and grip tightness during the tennis stroke. *Medicine and Science in Sports and Exercise* **8**, 88-95.

H. Hatze. (1992a) The effectiveness of grip bands in reducing racquet vibration transfer and slipping. *Medicine and Science in Sports and Exercise* **24**(2), 226-230.

H. Hatze. (1992b) Objective biomechanical determination of tennis racket properties. *International Journal Sports Biomechanics* **8**, 275-287.

C. G. Heathcote, E. O. P. Bouverie and A. C. Ainger. (1987) *Tennis, lawn tennis, rackets and fives*. Ashford press publishing.

K. Hedrick, R. Ramnath and B. Mikic. (1979). In *World Tennis*, Vol. 27, pp. 78.

J. Henderson. (1997) Power still the glory game on grass. In *The Observer*, pp. 6.

E. M. Hennig, D. Rosenbaum and T. L. Milani. (1992) Transfer of tennis racket vibrations onto the human forearm. *Medicine and Science in Sports and Exercise* **24**(10), 1134-1140.

F. M. Hernandez and A. O. Sicilia. (1998) Analysis of a professional tennis player to determine anticipatory pre cues in the service. *Journal of Human Movement Studies* **35**(5), 219-232.

J. E. Hilbert, G. A. Sforzo and T. Swensen. (2003) The effects of amssage on delayed onset muscle soreness. *British Journal of Sports Medicine* **37**, 72-75.

A. Hocknell, R. Jones and S. J. Rothberg. (1996) Engineering 'feel' in the design of golf clubs. *1st International Conference on the Engineering of Sport*, Blackwell Science. 333-337.

M. Hughes and S. Clarke. (1993) Surface effect on elite tennis strategy. *First World Congress on science and racket sports*, (ed. T. Reilly, M. Hughes and H. C. Lee), E&FN Spon. pp. 272-278.

F. W. Ilfield. (1992) Can stroke modifications relieve tennis elbow. *Clinical Orthopaedics and Related Research* **276**, 182-186.

ITF. (1999) Tennis towards 2000 survey. International Tennis Federation.

ITF. (2003) Rules of tennis. International Tennis Federation.

M. Kamien. (1988) Tennis elbow in long time tennis players. *Austr. J. Sci. Med. Sports* **20**, 19-27.

M. Kamien. (1990) A rational management of tennis elbow. *Sports Medicine* **9**, 173-191.

Y. Kawazoe, R. Tomosue, T. Muramatsu, K. Yoshinara and H. Yanagi. (2002) Experimental study on the effects of larger tennis balls on the comfort of the wrist and the elbow. *4th International Conference of Sports Engineering*, 192-199.

Y. Kawazoe and K. Yoshinari. (2000) Prediction of the impact shock vibrations of the players wrist joint: comparisons between two super large sized rackets with different frame mass distribution. *Tennis Science and Technology*, Blackwell Science (Oxford). 91-100.

J. D. Kelley, S. J. Lombardo, M. Pink, J. Perry and C. E. Giangarra. (1994) Electromyographic and Cinematographic Analysis of Elbow Function in Tennis Players with Lateral Epicondylitis. *American Journal of Sports Medicine* **22**(3), 359-363.

J. Kirkpatrick. (1956) Evaluation of grip loss. *California Medicine* **85**, 314.

F. J. G. M. Klaassen and J. R. Magnus. (2000) How to reduce the serve dominance in tennis? Empirical results from four years at Wimbledon. *The 1st International Congress on Tennis Science and Technology*, Blackwell Science (Oxford). 277-284.

D. Knudson. (1988) An analysis of grip forces and three dimensional accelerations in the tennis forehand. PhD, University of Wisconsin.

D. Knudson and J. Blackwell. (2000) Effect of the Type 3 ball on court movement, muscle actions, and shock transmitted to the arm of the tennis player, pp. 1-17. Dept of Physical Education and Exercise Science, California State University.

D. V. Knudson. (1989a) Hand Forces and Impact Effectiveness in the Tennis Forehand. *Journal of Human Movement Studies* **17**(1), 1-7.

D. V. Knudson. (1991a) Factors Affecting Force Loading on the Hand in the Tennis Forehand. *Journal of Sports Medicine and Physical Fitness* **31**(4), 527-531.

D. V. Knudson. (1991b) Forces on the Hand in the Tennis One-Handed Backhand. *International Journal of Sport Biomechanics* 7(3), 282-292.

D. V. Knudson and S. C. White. (1989b) Forces on the Hand in the Tennis Forehand Drive - Application of Force Sensing Resistors. *International Journal of Sport Biomechanics* 5(3), 324-331.

J. Kotze., S.R Mitchell and S.J. Rothberg (2000) The role of the racket in high-speed tennis serves. Sports Engineering, Blackwell Science, Oxford UK, Vol 3, No. 2 pp. 67-84.

J. Kotze, H. Lammer, R. Cottey and W. Zirngibl (2003) The effecs of active piezo fibre rackets on tennis elbow. Tennis Science and Technology, 2, Proceedings ITF Tennis Science and Technology Congress 2003 (S. Miller Ed.), International Tennis Federation, UK, pp 55-60.

G. Kraft and P. Detels. (1972) Position of function of the wrist. *Archives of Physical Medicine and Rehabilitation* **53**, 272.

A. M. Kramer and D. V. Knudson. (1992) Grip Strength and Fatigue in Junior-College Tennis Players. *Perceptual and Motor Skills* **75**(2), 363-366.

S. Kuebler. (2001) *Book of tennis rackets: from the beginning in the 16th century until about 1990*. GmbH Germany.

U. Kuessner. (1991) Vibration dampeners: Do they work? In *Tennis Australia*, Vol. 16, pp. 57.

D. N. Kulund. (1982) *The injured athlete*. USA: Lippincott.

D. N. Kulund, F. C. McCue and D. A. Rockwell. (1979) Tennis injuries: Prevention and treatment. *American Journal of Sports Medicine* **7**, 244.

S. M. Lachmann. (1988) *Soft tissue injuries in sport.* Blackwell Scientific Publications.

P. Lantelme. (1998) White coat effect and reactivity to stress - cardiovascular and autonomic nervous system responses. *Hypertension* **31**(4), 1021-1029.

R. Laukkanen and P. Virtanen. (1998) Heart rate monitors - state of the art. *Journal of Sports Sciences* **16**(S3-S7), 39-43.

R. E. Leach and J. K. Miller. (1987) Lateral and medial epicondylitis of the elbow. *Clinics in Sports Medicine* **6**, 259.

R. C. Lehman. (1988) Shoulder Pain in the Competitive Tennis Player. *Clinics in Sports Medicine* 7(2), 309-327.

M. A. Lemay and P. E. Crago. (1996) A dynamic model for simulating movements of the elbow, forearm and wrist. *Journal of Biomechanics* **29**, 1319-1330.

D. L. MacIntyre, W. D. Reid and D. C. McKenzie. (1995) Delayed onset muscle soreness: the inflammatory response to muscle injury and its clinical implications. *Sports Medicine* **1995**(20), 24-40.

R. Marion and B. R. Niebuhr. (1992) Effect of warm up prior to maximal grip contractions. *Journal of Hand Therapy* **5**, 143.

V. Mathiowetz. (1990) Effects of three trials on grip and pinch strength measurements. *Journal of Hand Therapy* **3**, 195.

V. Mathiowetz, C. Rennells and L. Donahoe. (1985) Effect of elbow position on grip and pinch strength. *Journal of Hand Surgery-American Volume* **10A**, 694.

V. Mathiowetz, K. Weber and G. Volland. (1984) Reliability and validity of grip and pinch strength evaluations. *Journal of Hand Surgery-American Volume* **9**, 222-226.

P. R. McCarthy. (1997) Influence of fatigue and dietary manipulation strategies on skilled tennis hitting performance. PhD Thesis, Loughborough University.

T. M. McLaughlin and N. R. Miller. (1980) Techniques for the evaluation of loads on the forearm prior to impact in tennis strokes. *Journal of Mechanical Design* **102**, 701-710.

S. R. Mitchell and M. Caine. (2000) Playing with a larger tennis ball: A comparative study of the effects on point play, player perception, muscle fatigue and soreness. Loughborough University. ITF Report.

S. R. Mitchell, M. P. Caine and S. Bowyer. (2001) Playing with a larger tennis ball II: A validation study of the effects on point play, player perception, muscle fatigue and soreness. Loughborough University. ITF Report.

MittUSA. (2002) No more tennis elbow. www.mittusa.com.

M. Miyashita, T. Tsunoda, S. Sakurai, H. Nishizono and T. Mizuno. (1980) Muscular activities in the tennis serve and overhand throwing. *Scandinavian Journal of Sports Sciences* 2(2), 52-58.

M. A. Montazer and J. G. Thomas. (1991) Grip Strength as a Function of Repetitive Trials. *Perceptual and Motor Skills* 73(3), 804-806.

M. A. Montazer and J. G. Thomas. (1992) Grip Strength as a Function of 200 Repetitive Trials. *Perceptual and Motor Skills* 75(3), 1320-1322.

E. F. Moritz (2002) Innovation in sports equipment - particularities in processes and organization. In *The engineering of sport 4* (ed. S. Ujihashi and S. J. Haake). Blackwell publishing.

M. Morris, F. W. Jobe, J. Perry, M. Pink and B. S. Healy. (1989) Electromyographic Analysis of Elbow Function in Tennis Players. *American Journal of Sports Medicine* 17(2), 241-247.

M. Mundale. (1970) The relationship of intermittent isometric exercise to fatigue of hand grip. *Archives of Physical Medicine and Rehabilitation* 51, 532.

R. Murley. (1987) Tennis elbow: conservative, surgical and manipulative treatment. *British Medical Journal* 294, 839-840.

M. V. Nallakatla, J. Ari-Gur, M. Parvis and C. Howard. (1995) Design of a new tennis racket grip to reduce arm injuries. *Bioengineering Conference ASME 1995* **BED-Vol. 29**, 493-494.

R. P. Nirschl. (1973) Tennis elbow. *Orthop. Clin. North Amer.* 4, 787.

R. P. Nirschl. (1975) The etiology and treatment of tennis elbow. *Journal of Sports Medicine* 2, 308-323.

R. P. Nirschl. (1985) Muscle and tendon trauma: Tennis elbow. In *The elbow and its disorders* (ed. B. F. Morrey), pp. 537. Philadelphia, W.B.Saunders.

R. P. Nirschl and F. A. Pettrone. (1979) Tennis elbow; The surgical treatment of lateral epicondylitis. *Journal of Bone and Joint Surgery American* 61, 832-839.

C. Norkin and P. Levangie. (1992) *Joint structure and function*. F.A. Davis Company, Philadelphia.

C. M. Norris. (1994) *Sports injuries; Diagnosis and management for physiotherapists*. Butterworth Heinemann.

Novel. (2002) http://www.novel.de/nav02.htm.

V. C. Nwuga. (1975) Grip strength and grip endurance in physical therapy students. *Arch. Phys. Med* **56**, 296-299.

P. O'Donoghue and B. Ingram. (2001) A notational analysis of elite tennis strategy. *Journal of Sports Sciences* **19**(2), 107-115.

L. Pecore. (1978) A biomechanical analysis of the one handed backhand. Masters Thesis, University of Wisconsin.

T. Peters and C. L. Baker. (2001) Lateral epicondylitis. *Clinics in Sports Medicine* **20**(3), pp. 549

S. Plagenhoef. (1970) *Fundamentals of tennis*. Engelwood Cliffs, NJ: Prentice Hall.

S. Plagenhoef. (1979) *Tennis racket testing related to tennis elbow*. Champaign, IL.

K. D. Plancher, J. Halbrecht and G. M. Lourie. (1996) Medial and lateral epicondylitis in the athlete. *Clinics in Sports Medicine* **15**, 283-305.

B. M. Pluim. (2000) Rackets, strings and balls in relation to tennis elbow. *The 1st International Congress on Tennis Science and Technology*, Blackwell Science (Oxford) pp 321-332.

J. D. Priest, V. Braden and S. G. Gerberich. (1980a) The elbow and tennis, part 1: An analysis of players with and without pain. *Physician Sportsmed.* **8**, 81-91.

J. D. Priest, V. Braden and S. G. Gerberich. (1980b) The elbow and tennis, part 2: A study of players with pain. *Physician Sportsmed.* **8**, 77-84.

J. C. Pryce. (1980) The wrist position between neutral and ulnar deviation that facilitates the maximum power grip. *Journal of Biomechanics* **13**, 505.

W. Regan, L. E. Wold and R. W. Coonrad. (1992) Microscopic histopathology of chronic refractory lateral epicondylitis. *American Journal of Sports Medicine* **20**, 746-749.

P. A. F. H. Renstrom. (1993) Elbow injuries in tennis. *First World Congress on science and racket sports*, (ed. T. Reilly, M. Hughes and H. C. Lee), E&FN Spon. pp. 155-180.

D. D. Reynolds, D. E. Wasserman, R. Bassel and W. Taylor. (1982) *Energy entering the hands of operators of pneumatic tools used in chipping and grinding operations*. John Wiley and Sons, New York.

L. Richards, B. Olson and P. Palmiter-Thomas. (1996) How forearm position affects grip strength. *American Journal of Occupational Therapy* **50**, 133.

L. Richards and P. Palmiter-Thomas. (1996) Grip strength measurement: a critical review of tools, methods and clinical utility. *Critical Reviews in Physical and Rehabilitation Medicine* **8**(1&2), 145-152.

T. A. Richers. (1995) Time motion analysis of the energy systems in elite competitive singles tennis. *Journal of Human Movement Studies* **28**, 73-86.

J. Roberts, R. Jones, C. Harwood, S. R. Mitchell and S. Rothberg. (2001) Human perceptions of sports equipment under playing conditions. *Journal of Sports Sciences* **19**, 485-497.

E. P. Roetert, H. Brody, C. J. Dillman, J. L. Groppel and J. M. Schultheis. (1995) The Biomechanics of Tennis Elbow - an Integrated Approach *Clinics in Sports Medicine* **14**(1), 47-57.

P. Roetert and J. L. Groppel. (2001) World class tennis technique. Human Kinetics Europe Ltd.

K. Roussopoulos and A. J. Cooke. (2000) Correlation between racket design and arm injuries. Cambridge University.

RSScan. (2003) http //www.rsscan.com/.

F. Runge. (1873) Zur genese und behandlung des schrebekrampfes. *Klinische Wochenschrift (Berlin)* **10**, 245-248.

M. Sakamoto, T. Takano, T. Hara and Y. Tanabe. (1992) Contact pressure measurement on grips of tennis rackets on stroke motions. *International Conference on Biomedical Engineering* **7th**, 144-146.

M. Serridge and L. R. Torben. (1987) Piezoelectric accelerometers and vibration preamplifiers: Theory and application handbook. In *Bruel & Kjaer*, pp. 1-12.

L. L. Smith. (1991) Acute inflammation: the underlying mechanisms in delayed onset of muscle soreness. *Medicine and Science in Sport and Exercise* **23**, 542-551.

B. J. G. Smyth. (1953) *Lawn Tennis*. B.T.Batsford.

C. Speed. (2000) Notes on tennis injuries (ed. A. J. Cooke). Personal communication.

SPI. (2003) Sensor Products Inc. http://www.sensorprod.com/.

H. Stokes. (1983) The seriously uninjured hand-weakness of grip. *Journal of Occupational Medicine* **25**, 683.

D. A. Stone, M. Voght and M. R. Safran. (1999) Comparison of incidence of tennis elbow in first generation and graphite composite rackets. *Sportsmedicine and Science in Tennis* 4(3).

P. W. Stratford, G. R. Norman and J. M. McIntosh. (1989) Generalizability of Grip Strength Measurements in Patients with Tennis Elbow. *Physical Therapy* 69(4), 276-281.

R. A. Stretch, F. J. Buys and G. Viljoen. (1995) The kinetics of the drive off the front foot in cricket batting: Hand grip force. *S.A. Journal for Research in Sport, Physical Education and Recreation* 18(2), 83-93.

A. M. Strizak, G. W. Gleim, A. Sapega and J. A. Nicholas. (1983) Hand and forearm strength and its relation to tennis. *American Journal of Sports Medicine* 11(4), 234-239.

C. L. Stroede, L. Noble and H. S. Walker. (1999) The effect of tennis racket string vibration dampers on racket handle vibrations and discomfort following impacts. *Journal of Sports Sciences* 17, 379-385.

C. W. Suggs, J. M. Hanks and G. T. Robertson. (1977) Vibration of power tools. In *Vibration effects on the hand and arm in industry* (ed. A. J. Brammer and W. Taylor). John Wiley & Sons.

Tekscan. (2001) F-Scan pressure assessment system user manual, pp. 36-38.

Tekscan. (2003) http://www.tekscan.com/.

T. Teraoka. (1979) Studies on the peculiarity of grip strength of the hand. *Journal of Medical Sciences (Kobe)* 25, 1.

ThinkQuest. (2003) History of tennis. http://library.thinkquest.org/C0121651/history.htm.

W. Tilden. (1970) Tennis A to Z, pp. 15, 40. Victor Gollanez Ltd, London.

G. A. Tilmanis. (1975) *Advanced tennis*. Lea Febiger.

R. Tomosue, Y. Motoh, K. Yoshinari and Y. Kawazoe. (1991) Measuring the vibrations of a racket handle and the wrist joint in the tennis forehand. *Proceedings of XIIIth Int. Congress on Biomech.*, 138-139.

R. Tomosue, Y. Mutoh, K. Yoshinara and Y. Kawazoe. (1992) Vibrations of a racket handle and the wrist joint in the tennis forehand. *Journal of Biomechanics* 25(7), 719-721.

R. Tomosue, K. Sugiyama, K. Yoshinara and K. Yamamoto. (1994) The effectiveness of damping material in reducing impact shock in the tennis forehand drive. *First World Congress on science and racket sports*, (ed. T. Reilly, M. Hughes and H. C. Lee), E&FN Spon, 140-145.

B. Toski and J. Flick. (1978) How to become a complete golfer. In *Golf Digest*, Vol. 29, pp. 89-120.

L. Vergauwen, F Brouns and P. Hespel. (1998) Carbohydrate supplementation improves stroke perfromance in tennis. *Medicine and Science in Sport and Exercise* **30**(8), 1289.

T. Watanabe, Y. Ikegami and M. Miyashita. (1979) Tennis: the effect of grip firmness on ball velocity after impact. *Medicine and Science in Sports* **11**, 261-359.

P. Watts, D. T. Martin and S. Durtschi. (1993) Anthropometric profiles of elite male and female competetive sport rock climbers. *Journal of Sports Sciences* **11**, 113-117.

P. Watts, V. Newbury and J. Sulentic. (1996) Acute changes in handgrip strength, endurance, and blood lactate with sustained sport rock climbing. *Journal of Sports Medicine and Physical Fitness* **36**(4), 255-260.

J. Wilson and J. S. Davis. (1995) Tennis racket shock mitigation experiments. *Journal of Biomechanic Engineering* **117**, 479-484.

F. Yeapie. (1987) Tennis elbow avoided with fluid dynamic racket. *Design News*(June), 126-127.

APPENDICES

Appendix 1 – Muscle soreness questionnaire

Muscle Soreness Questionnaire Instructions

Name ____________________________

Test day **1** **2**

Test session **pre** **post** **post am.** **post eve.**

This questionnaire is designed to assess perceived levels of soreness in the muscles of the forearm.

To start with record your name and indicate the test day (1st or 2nd) on at least one of the sheets. Record which test this is, either: pre, post, post am (morning after test) or post eve (the evening of the day after the test).

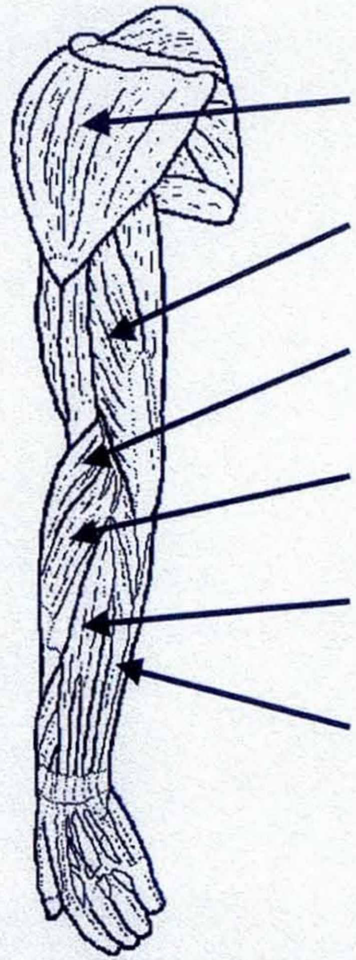
Using the picture as a guide locate the muscle indicated and press lightly on it. Indicate with a mark through the appropriate line how this muscle feels on a scale of ‘no soreness at all’ to ‘maximal soreness’.

Please note that the first 2 pages are concerned with the **left** arm. On the first of these pages you will rate the **posterior** muscles (rear of the arm), on the second page you will rate the **anterior** muscles (front of the arm).

The second 2 pages are concerned with the **right** arm. As above, the first of these pages you will rate the **posterior** muscles (rear of the arm), on the second page you will rate the **anterior** muscles (front of the arm).

Left arm (posterior): Muscle soreness ratings

Name: Day: 1 2 Test: Pre Post



no soreness at all — maximal soreness

A |————————————|

B |————————————|

C |————————————|

D |————————————|

E |————————————|

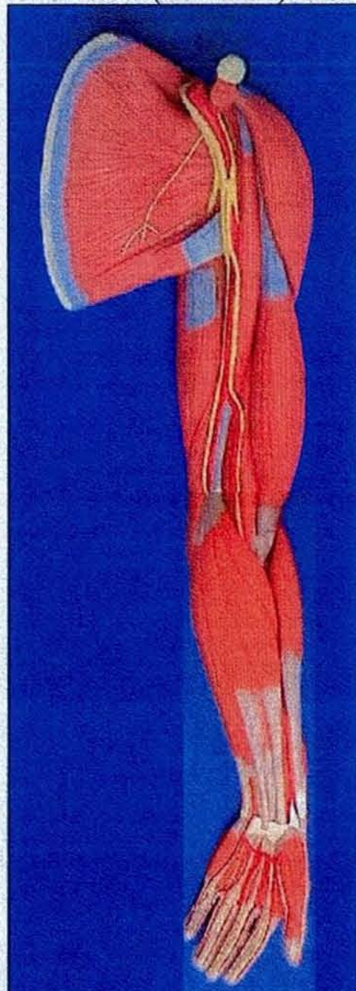
F |————————————|

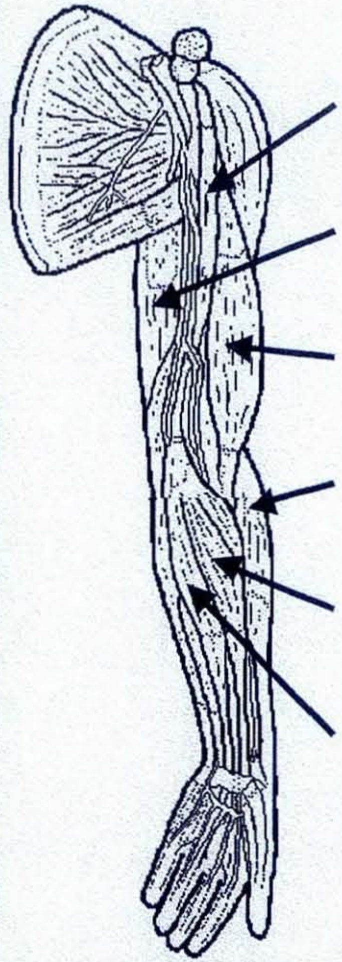
no soreness at all — maximal soreness

A - Deltoid
B - Triceps brachii, lateral head
C - Brachioradialis
D - Extensor carpi radialis longus
E - Extensor digitorum
F - Extensor carpi ulnaris

Left arm (anterior): Muscle soreness ratings

Name: Day: 1 2 Test: Pre Post



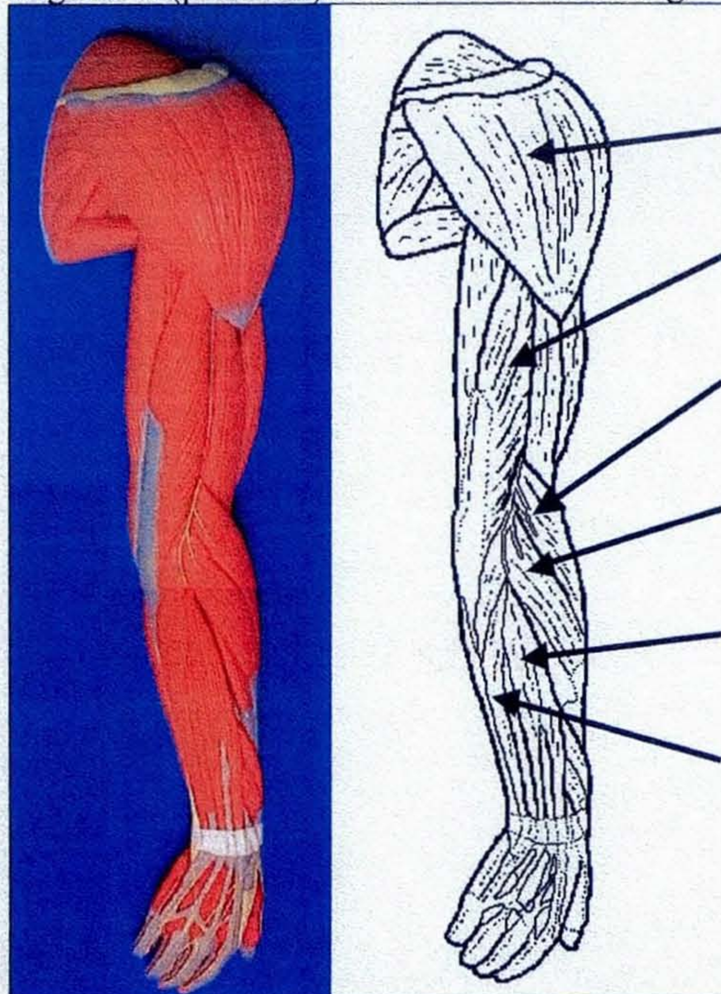


	no soreness at all		maximal soreness
A	├	────────────	┤
B	├	────────────	┤
C	├	────────────	┤
D	├	────────────	┤
E	├	────────────	┤
F	├	────────────	┤
	no soreness at all		maximal soreness

A - Coracobrachialis
B - Triceps brachii, long head
C - Biceps brachii
D - Brachioradialis
E - Flexor carpi radialis
F - Palmaris longus

Right arm (posterior): Muscle soreness ratings

Name: Day: 1 2 Test: Pre Post

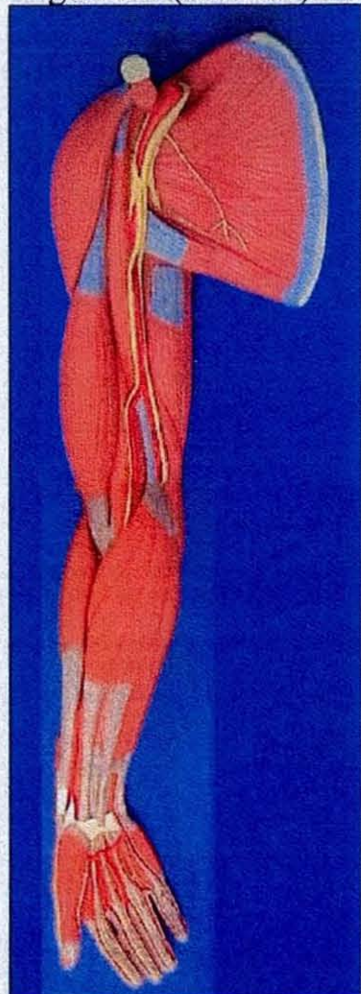


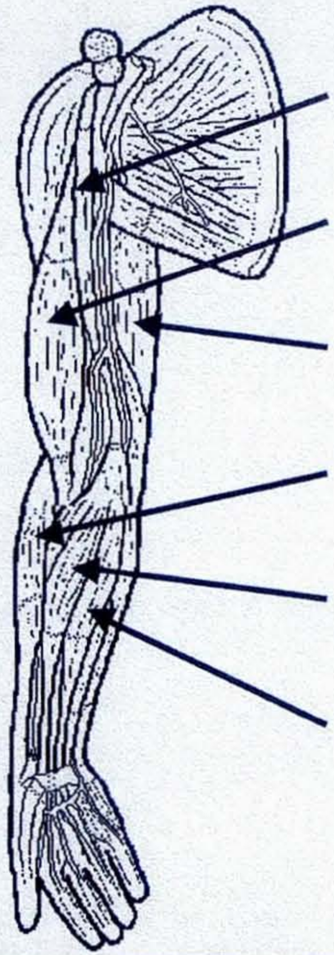
	no soreness at all		maximal soreness
A	├	───────────	┤
B	├	───────────	┤
C	├	───────────	┤
D	├	───────────	┤
E	├	───────────	┤
F	├	───────────	┤
	no soreness at all		maximal soreness

A - Deltoid
B - Triceps brachii, lateral head
C - Brachioradialis
D - Extensor carpi radialis longus
E - Extensor digitorum
F - Extensor carpi ulnaris

Right arm (anterior): Muscle soreness ratings

Name: Day: 1 2 Test: Pre Post





no soreness at all		maximal soreness
A	├──────────────┤	
B	├──────────────┤	
C	├──────────────┤	
D	├──────────────┤	
E	├──────────────┤	
F	├──────────────┤	
no soreness at all		maximal soreness

A - Coracobrachialis
B - Triceps brachii, long head
C - Biceps brachii
D - Brachioradialis
E - Flexor carpi radialis
F - Palmaris longus

Appendix 2 – Perception questionnaire

Tennis Ball Play Test Questionnaire

Player's name:	Date:
What ball do you usually play with?	

Introduction

This questionnaire has been designed to give you the opportunity to comment on your perception of the balls you have played with during the test. You will be asked in each question to compare the balls you used today, with the balls you usually play with.

Please answer all these questions to the best of your ability by marking a cross in the box below the response that most closely matches your own experience. If you feel unsure about your ability to answer any of the questions please indicate this using the box provided. We consider that each player's opinions are equally valid so please make sure that the answers you give express your own individual perception of the balls performance even if this differs from that of your team-mates.

Your answers will be treated in the strictest confidence. Thank you for your help

Tennis Ball Play Test Questionnaire

Racket/Ball Interaction:	This section deals with your perception of how the ball performed when hit by your racket.

Impact Severity	When you hit *today's* ball did the impact feel more or less jarring than with *usual* ball?	much less jarring ☐	less jarring ☐	the same ☐	more jarring ☐	much more jarring ☐	unsure ☐
Impact Vibration	When you hit *today's* ball did it feel like your racket vibrated more or less than with *usual* ball?	much less vibration ☐	less vibration ☐	the same ☐	more vibration ☐	much more vibration ☐	unsure ☐
Pace	Did you find it was easier or more difficult to put pace on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Pace Control	Did you find it was easier or more difficult to control the pace you put on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Shot Length	Did you find it was easier or more difficult to hit the ball deep with *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐

Tennis Ball Play Test Questionnaire

Topspin	Did you find it was easier or more difficult to put topspin on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Topspin Control	Did you find it was easier or more difficult to control the amount of topspin you put on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Slice	Did you find it was easier or more difficult to put slice on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Slice Control	Did you find it was easier or more difficult to control the amount of slice you put on *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐
Shot Direction	Did you find it was easier or more difficult to hit the ball in the direction you intended with *today's* ball than with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐

Tennis Ball Play Test Questionnaire

Hitting Shots In	Did you find it was easier or more difficult to keep your shots in with *today's* ball compared with *usual* ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐

Hit Sound	Did hitting *today's* ball produce a sharper or duller sound than hitting with *usual* ball?	much sharper ☐	sharper ☐	the same ☐	duller ☐	much duller ☐	unsure ☐

Hit Sound Preference	Do you prefer to play with balls that produce a sharp or dull sound when you hit them?	much prefer a sharp sound ☐	prefer a sharp sound ☐	no preference ☐	prefer a dull sound ☐	much prefer a dull sound ☐	unsure ☐

Tennis Ball Play Test Questionnaire

Ball/Surface Interaction:	This section deals with your perception of how the ball performed when bouncing on the court surface

Rebound Speed	Did *today's* ball seem to come off the court surface faster or slower than *usual* ball?	much faster ☐	faster ☐	the same ☐	slower ☐	much slower ☐	unsure ☐
Rebound Angle	Did *today's* ball seem to bounce more steeply than *usual* ball?	much more steeply ☐	more steeply ☐	the same ☐	less steeply ☐	much less steeply ☐	unsure ☐

Tennis Ball Play Test Questionnaire

General Properties	This section deals with your perception of some additional ball properties						
Ball Size	Did *today's* ball seem smaller, larger or the same size when compared to *usual* ball?	much bigger ☐	bigger ☐	same size ☐	smaller ☐	much smaller ☐	unsure ☐
Ball Size	Do you agree or disagree that *today's* ball seemed excessively different in size compared to *usual* ball?	strongly disagree ☐	disagree ☐	neither agree or disagree ☐	agree ☐	strongly agree ☐	unsure ☐
Ball Mass	Did *today's* ball feel heavier or lighter than *usual* ball?	much heavier ☐	heavier ☐	the same ☐	lighter ☐	much lighter ☐	unsure ☐
Ball Wear	Did the cloth of *today's* ball seem to wear more quickly or more slowly than the cloth of *usual* ball?	much quicker ☐	quicker ☐	the same ☐	slower ☐	much slower ☐	unsure ☐
Ball Visibility	Was *today's* ball easier or more difficult to see during play than usual ball?	much easier ☐	easier ☐	the same ☐	more difficult ☐	much more difficult ☐	unsure ☐

Tennis Ball Play Test Questionnaire

Change Over Time	Did the overall performance of *today's* ball seem to improve or get worse with use?	much improved ☐	improved ☐	the same ☐	got worse ☐	got much worse ☐	unsure ☐
Playing Confidence	Did you feel more or less confident playing with *today's* than with *usual* ball?	much more confident ☐	more confident ☐	the same ☐	less confident ☐	much less confident ☐	unsure ☐
Ball Preference	Would you prefer to play with *today's* ball or *usual* ball on this surface?	much prefer today's ball ☐	prefer today's ball ☐	no preference ☐	prefer yesterdays ball ☐	much prefer yesterdays ball ☐	unsure ☐

Appendix 3 – Game data sheet

Game Point Data Sheet

Players	Server		Date		/ /
	Receiver		Start time	[hour minute]	
Game number			End time	[hour minute]	.

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Point			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Winner		Server																
Winner		Receiver																
Number of Lets																		
Service Outcome		1st Serve Ace	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
Service Outcome		1st Return out/net	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1	M1
Service Outcome		2nd Serve Ace	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A2
Service Outcome		2nd Return out/net	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2	M2
Service Outcome		Double Fault	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF	DF
Service Outcome		Rally (№ Hits)	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )	( )
Winning / Losing Rally Shot	Stroke Type	Forehand	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Winning / Losing Rally Shot	Stroke Type	Backhand	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Winning / Losing Rally Shot	Stroke Type	Ground	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd	Grd
Winning / Losing Rally Shot	Stroke Type	Volley	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly	Vly
Winning / Losing Rally Shot	Stroke Type	Drive Volley	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV	DV
Winning / Losing Rally Shot	Stroke Type	Drop	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp	Drp
Winning / Losing Rally Shot	Stroke Type	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob	Lob
Winning / Losing Rally Shot	Stroke Type	Smash	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm	Sm
Winning / Losing Rally Shot	Stroke Type	Cross-Court	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Winning / Losing Rally Shot	Stroke Type	Pass	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Winning / Losing Rally Shot	Outcome	Winner	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win	Win
Winning / Losing Rally Shot	Outcome	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out	Out
Winning / Losing Rally Shot	Outcome	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net	Net
Winning / Losing Rally Shot	Outcome	Mishit	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss	Miss
Winning / Losing Rally Shot	Court Location																	
Time [minutes seconds]			.	.	.							.						.

Appendix 4 – Participant consent form

Participant Consent Form: Grip Fatigue Study

Principal investigator: Dr Sean Mitchell

Secondary investigators: Sonya Bowyer

I, [Print full name]

consent to participate in a research study evaluating the effects of playing tennis upon hand grip activity during the single handed backhand stroke using two different types of tennis ball I understand that the aim of the research is to compare the effect of playing with two types over time in order to quantify any differences which may exist between them in terms of hand grip pressure, grip shock severity, grip vibration severity, forearm muscle fatigue and muscle soreness.

I understand that I can withdraw at any time prior to or during the study.

As a participant in the study I agree to partake in a test session lasting approximately 1 hour on two occasions separated by a two-week period During each test session I agree to do the following:

- Maintain my normal diet 24 hours prior to testing on both occasions and where possible consume identical meals at the same time of day on both occasions
- Previous activity? Not undergo excessive training/participate in competition/consume alcohol or excessive amounts of caffeinated drink/stray from my normal sleeping patterns 48 hours prior to testing on both occasions
- Notify the investigators of any change to my health status prior to or during the testing
- Complete an initial short questionnaire reporting initial muscle soreness in the muscles of both arms
- Complete an initial set of hand grip measurements involving 3 second maximal contractions, 3 times with each hand alternating from one to the other
- Perform 15 single handed backhands with an instrumented tennis racket before, after and at 10 minute intervals during 30 minutes of controlled tennis drill activity
- During the tennis drill activity perform a single handed backhand groundstroke returning a tennis ball delivered from a tennis ball launcher at normal forehand drive speeds at a rate of 30 per minute, cross court to the far base line
- Endeavor to ensure that each shot is as close to the far baseline as possible and hit with 90-100% of my peak speed as indicated by the on-court radar gun provided
- Complete a final set of hand grip measurements involving 3 second maximal contractions, 3 times with each hand alternating from one to the other
- Complete subsequent short questionnaires reporting muscle soreness in the muscles of both arms immediately, 24 hours and 48 hours after testing and return these to Sonya Bowyer
- Fill in a short questionnaire (on completion of two sessions) about my perception of the two ball types

I have had an opportunity to ask questions and seek further clarification about the study. I understand that the study is not without risk, specifically it has been explained to me that the following activities are not risk free:

- Competitive tennis can result in injury either chronic or acute, common injuries associated with tennis include muscle / tendon damage which are typically mild with a full recovery being made in the short-term
- Intensive training can result in muscle soreness, symptoms of over-training such as lethargy and an increased susceptibility to longer term injuries such as knee and shoulder instability or elbow pain
- Repeated handgrip measurements may result in fatigue of the forearm muscles which may result in mild muscle soreness for a few days

I am aware that appropriate measures have been taken to minimise the risks to me and acknowledge that the risks associated with this study are consistent with those of other training sessions used for improving sports performance.

I agree to abide by the instructions given to me by the investigators, subject to my right to withdraw from the study at any time. I am not aware of any reason why I should not take part in this study. Furthermore I have not been advised to refrain from exercise by my doctor or other health professional.

I understand that any information obtained from the study will be treated as confidential and that where results are presented my identity will remain anonymous. I also understand that should I chose to withdraw on request all data associated with my participation will be deleted.

I understand that feedback from the study will be made available to me upon completion of the study.

Signed....................................

Date.... ... .

Appendix 5 – Health screen

HEALTH SCREEN FOR STUDY VOLUNTEERS **Name or Number** ....

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:
   - (a) on medication, prescribed or otherwise .... Yes ☐ No ☐
   - (b) attending your general practitioner ... . Yes ☐ No ☐
   - (c) on a hospital waiting list .. .. Yes ☐ No ☐
2. **In the past two years,** have you had any illness which require you to:
   - (a) consult your GP .... Yes ☐ No ☐
   - (b) attend a hospital outpatient department.......................... .... Yes ☐ No ☐
   - (c) be admitted to hospital .... Yes ☐ No ☐
3. **Have you ever had** any of the following:
   - (a) Convulsions/epilepsy .... Yes ☐ No ☐
   - (b) Asthma .... Yes ☐ No ☐
   - (c) Eczema... Yes ☐ No ☐
   - (d) Diabetes .... Yes ☐ No ☐
   - (e) A blood disorder .... Yes ☐ No ☐
   - (f) Head injury .... Yes ☐ No ☐
   - (g) Digestive problems .... Yes ☐ No ☐
   - (h) Heart problems.. Yes ☐ No ☐
   - (i) Problems with bones or joints .... Yes ☐ No ☐
   - (j) Disturbance of balance/coordination................. .... Yes ☐ No ☐
   - (k) Numbness in hands or feet. .... Yes ☐ No ☐
   - (l) Disturbance of vision .... Yes ☐ No ☐
   - (m) Ear / hearing problems .... Yes ☐ No ☐
   - (n) Thyroid problems.............................. .... Yes ☐ No ☐
   - (o) Kidney or liver problems .... Yes ☐ No ☐
   - (p) Allergy to nuts.. Yes ☐ No ☐
4. **Has any,** otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? .... Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.) ....

....

Additional questions for female participants

(a) are your periods normal/regular? .... Yes ☐ No ☐

(b) are you on "the pill"? .... Yes ☐ No ☐

(c) could you be pregnant? .... Yes ☐ No ☐

(d) are you taking hormone replacement therapy (HRT)? Yes ☐ No ☐

Thank you for your cooperation!

Loughborough University

28.5.1999/WJ Clarke

Appendix 6 – Participant information

Subject General Questionnaire

Please bring this filled out with you to the first of your test sessions

PERSONAL DETAILS

Name ______________________________

DOB ____________

Age ____________

Weight (kg) ____________

Height (cm) ____________

Tournament ID ____________ (you will be given this on the day)

Term time address ______________________________

____

____

Telephone ____________ Mobile ____________

Email ______________________________

TENNIS DETAILS

Number of years playing competitive tennis ____________

Current Standard (team/LTA ranking) ____________

How regularly do you play ____________

Which hand do you play with Left / Right

Usual racket make and model ____________

____

Grip diameter ____________

Usual string type (if known) ____________

Usual string tension (if known) ____________

Date racket last restrung ____________

INJURY HISTORY

Have you ever suffered with tennis elbow? If so provide details such as how old you were, how often had it, how bad, treatment needed etc. (continue on back of page if need to)

____

____

____

____

____

What do you think causes tennis elbow?

____

____

____

____

____

What do you think worsens the symptoms of tennis elbow?

____

____

____

____

____

____

What do you think helps alleviate the symtoms of tennis elbow?

____

____

____

____

Appendix 7 – Test day well being form

Test day well-being

Please record how you feel on the morning of your scheduled test. For example are you starting with a cold or have you felt under the weather for the last couple of days. If so in what way?

The first section corresponds to your week 1 test and the second section to your week 2 test (keep hold of this and hand it in when you attend the second week's test).

Morning of Week 1

Morning of Week 2

Appendix 8 – Subject feedback form

Player Feedback Sheet

I hope you have enjoyed participating in this research project. If not, now is your chance to tell me! For the benefit of future events I would appreciate your comments on the whole process. Are there any aspects that you think could have been done better? What have you enjoyed or thought has been done well?

Feel free to comment anonymously or fill in your name (especially if you want me to respond to any of your points!)

For all those interested, I'll also be arranging a debriefing session to present the findings of the research study. I shall inform you of when this will be via either email or John Thompson. For any questions or feedback you may like don't hesitate to contact me.

Again, a big THANK YOU to all of you for supporting this event.

Your comments:

Appendix 9 – Dietary record cover sheet

DIETARY ASSESSMENT QUESTIONNAIRE

You will need to make a note of everything you eat and drink during the day before the test session and on the day of the test session up until you complete the test.

As you can see, there are separate sections for breakfast, lunch, dinner and snacks. Anything you eat or drink between breakfast, lunch and dinner should be recorded in the snacks section.

Try to fill in your meals and snacks immediately after eating/drinking them. This way you will not miss anything out.

Fill in your diary as a tally; for example , if you eat 2 slices of bread during the afternoon write "2" in the column for that day under the snacks section. If you eat another 2 at supper, write "+2" in the same column, so bread snacks for that day reads "2+2".

Where the type of food is required, please fill this in in the appropriate column as accurate as possible, with some idea of portion size. For example, if you eat some chicken at lunchtime, on the lunch section write "chicken breast, no skin, 1 medium" in that days column.

If you have eaten a double helping of a food remember to put "2" down in the appropriate box. If you eat something that isn't listed in that section please record under "others".

I need you to within reason eat and drink as similarly as possible on the day before both test sessions and up till the test commences. So, if for example this weekend you eat a bowl of shreddies, 2 slices of toast and jam and 1 mug coffee at 9.00am on the morning of the test I would like you try and replicate that the following weekend for the test.

Thank you for your cooperation.

Appendix 10 – Accelerometer data processing spreadsheet macros

```
Function SB_THRESHOLD_PRE(single_column_array, threshold_fraction)
'Function to return time at which threshold acceleration occurs
'BEFORE the peak value.
'Searches all through the given cells to find the peak value and
'then searches backwards until the threshold value is found.
'In Excel, call function with the following papameters:
   'single_column_array - single column array of cells to be searched
   'threshold_fraction  - threshold fraction of the peak value
   'e g  SB_THRESHOLD_PRE(E7.E2054,0.2)
   Dim max_val, min_val, min_abs_val, peak_val
   Dim peak_array_pos, threshold_val, array_pos

   'Find the peak value in the single column array of input cells
   'ALLOW FOR THE POSSIBILITY OF THE PEAK VALUE BEING NEGATIVE
   max_val = WorksheetFunction Max(single_column_array)
   min_val = WorksheetFunction Min(single_column_array)
   min_abs_val = Abs(min_val)
   If max_val >= min_abs_val Then
      peak_val = max_val
   Else
      peak_val = min_val
   End If
'   SB_THRESHOLD_PRE = peak_val

   'Find the column array position of the peak value
   peak_array_pos = WorksheetFunction Match(peak_val, single_column_array, 0)
'   SB_THRESHOLD_PRE = peak_array_pos

   'Calculate the target threshold value
   threshold_val = threshold_fraction * peak_val
'   SB_THRESHOLD_POST = threshold_val

   'Starting at the peak value row check backwards one row at a time until
   'a value less than the threshold value is found
   array_pos = peak_array_pos 'initialise array position index
   If max_val >= min_abs_val Then
      Do
         array_pos = array_pos - 1
      Loop Until single_column_array(array_pos) < threshold_val
   Else
      Do
         array_pos = array_pos - 1
      Loop Until single_column_array(array_pos) > threshold_val
   End If
'   SB_THRESHOLD_POST = single_column_array(array_pos)

   'Move one row forwards again to the first row above the threshold value
   array_pos = array_pos + 1
'   SB_THRESHOLD_PRE = array_pos

   'Calculate the time corresponding to this column array position.
   'Sample frequency is 2048Hz, so 2048 samples in 1 second.
   'Subtract 1 from the current array position because the first acceleration
   'sample is at time zero and not time 1/2048.
   SB_THRESHOLD_PRE = (array_pos - 1) / 2048
End Function


Function SB_THRESHOLD_POST(single_column_array, threshold_fraction)
```

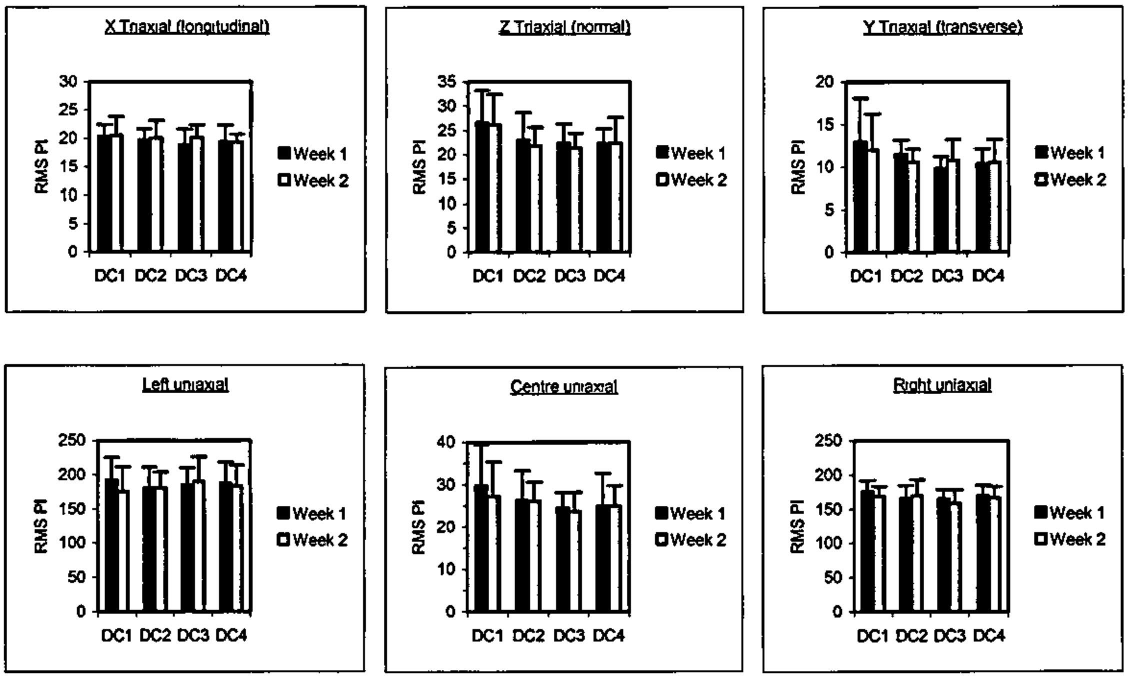
```
'Function to return time at which threshold acceleration occurs
'AFTER the peak value
'Searches all through the given cells to find the peak value and
'then searches forwards until the threshold value is found.
'In Excel, call function with the following papameters:
   'single_column_array - single column array of cells to be searched
   'threshold_fraction  - threshold fraction of the peak value
   'e g. SB_THRESHOLD_POST(E7 E2054,0 2)

   Dim max_val, min_val, min_abs_val, peak_val
   Dim peak_array_pos, threshold_val, array_pos

   'Find the peak value in the single column array of input cells
   'ALLOW FOR THE POSSIBILITY OF THE PEAK VALUE BEING NEGATIVE
   max_val = WorksheetFunction Max(single_column_array)
   min_val = WorksheetFunction Min(single_column_array)
   min_abs_val = Abs(min_val)
   If max_val >= min_abs_val Then
      peak_val = max_val
   Else
      peak_val = min_val
   End If
'   SB_THRESHOLD_POST = peak_val

   'Find the column array position of the peak value
   peak_array_pos = WorksheetFunction.Match(peak_val, single_column_array, 0)
'   SB_THRESHOLD_POST = peak_array_pos

   'Calculate the target threshold value
   threshold_val = threshold_fraction * peak_val
'   SB_THRESHOLD_POST = threshold_val

   'Starting at the peak value row check forwards one row at a time until
   'a value less than the threshold value is found
   array_pos = peak_array_pos 'initialise array position index
   If max_val >= min_abs_val Then
      Do
         array_pos = array_pos + 1
      Loop Until single_column_array(array_pos) < threshold_val
   Else
      Do
         array_pos = array_pos + 1
      Loop Until single_column_array(array_pos) > threshold_val
   End If
'   SB_THRESHOLD_POST = single_column_array(array_pos)

   'Move one row backwards again to the first row above the threshold value
   array_pos = array_pos - 1
'   SB_THRESHOLD_POST = array_pos

   'Calculate the time corresponding to this column array position.
   'Sample frequency is 2048Hz, so 2048 samples in 1 second.
   'Subtract 1 from the current array position because the first acceleration
   'sample is at time zero and not time 1/2048.
   SB_THRESHOLD_POST = (array_pos - 1) / 2048
End Function


Function SB_AREA(single_column_array)
'Function to calculate area under graph.
'In Excel, call function with the following papameters.
   'single_column_array - single column array of cells for which area is to be calculated
```

```
    'e g  SB_AREA(E7 E2054)

    Dim column_length, array_pos, area

    'Find number of data values in single_column_array, i e. array length
    column_length = WorksheetFunction Count(single_column_array)

    area = 0
    For array_pos = 1 To column_length Step 1
       area = area + Abs(single_column_array(array_pos))
    Next array_pos

    SB_AREA = Abs(area)
End Function


Function SB_FALL_TO_THRESHOLD(single_column_array, peak_value, threshold_fraction)
'Function to return first time at which acceleration falls below the given threshold.
'Searches all through the given cells to find the peak value and then searches
'forwards through the given cells until the fall below threshold value is found
'In Excel, call function with the following papameters:
    'single_column_array - single column array of cells to be searched
    'peak_value          - peak value
    'threshold_fraction  - threshold fraction of the peak value
    'e g. SB_FALL_TO_THRESHOLD(E7.E2054,E2066,0 1)
    Dim max_val, min_val, min_abs_val, local_array_peak
    Dim peak_array_pos, threshold_val, array_pos

    'Find the peak value in the single column array of input cells
    'ALLOW FOR THE POSSIBILITY OF THE PEAK VALUE BEING NEGATIVE
    max_val = WorksheetFunction Max(single_column_array)
    min_val = WorksheetFunction.Min(single_column_array)
    min_abs_val = Abs(min_val)
    If max_val >= min_abs_val Then
       local_array_peak = max_val
    Else
       local_array_peak = min_val
    End If
'   SB_FALL_TO_THRESHOLD = local_array_peak

    'Find the column array position of the peak value
    peak_array_pos = WorksheetFunction Match(local_array_peak, single_column_array, 0)
'   SB_FALL_TO_THRESHOLD = peak_array_pos

    'Calculate the target threshold value
    threshold_val = threshold_fraction * peak_value
'   SB_FALL_TO_THRESHOLD = threshold_val

    'Starting at the local peak value row check forwards one row at a time until
    'a value less than the threshold value is found
    array_pos = peak_array_pos 'initialise array position index
    If max_val >= min_abs_val Then
       Do
          array_pos = array_pos + 1
       Loop Until single_column_array(array_pos) < threshold_val
    Else
       Do
          array_pos = array_pos + 1
       Loop Until single_column_array(array_pos) > threshold_val
    End If
'   SB_FALL_TO_THRESHOLD = single_column_array(array_pos)
```

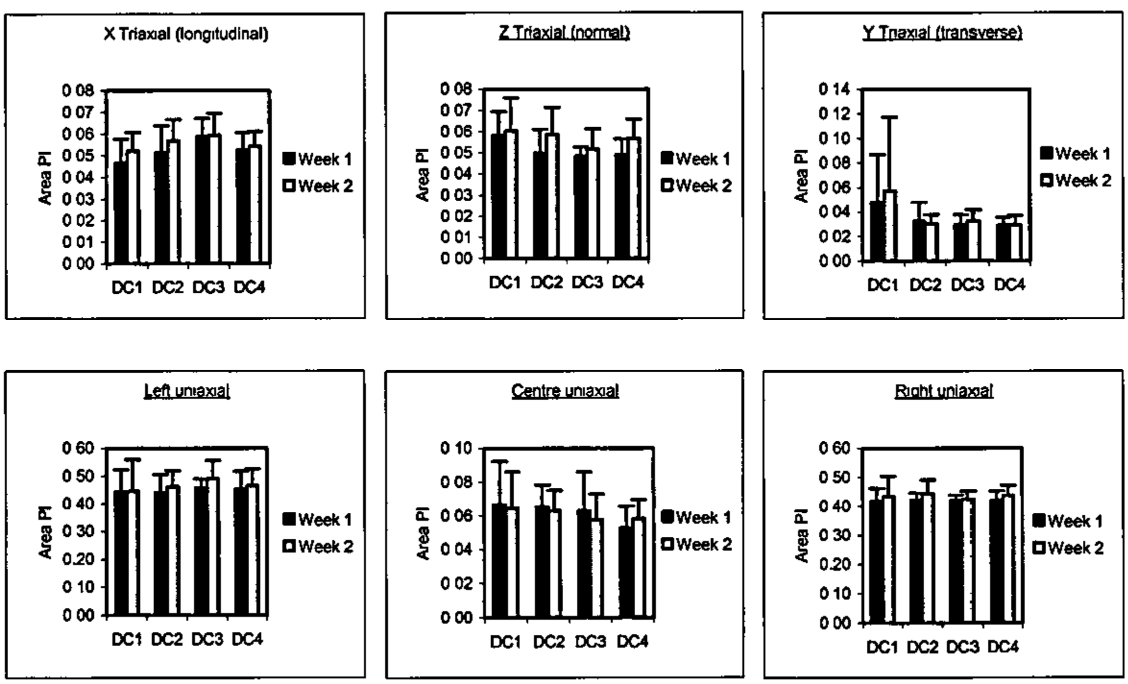
```
   'Move one row backwards again to the first row above the threshold value
   array_pos = array_pos - 1
'   SB_FALL_TO_THRESHOLD = array_pos

   'Calculate the time corresponding to this column array position
   'Sample frequency is 2048Hz, so 2048 samples in 1 second.
   'Subtract 1 from the current array position because the first acceleration
   'sample is at time zero and not time 1/2048.
   'Add 7 to the current array position to allow for the filtered column of
   'data starting 7 rows after time zero
   SB_FALL_TO_THRESHOLD = (array_pos - 1 + 7) / 2048
End Function


Function SB_LOCAL_PEAK(single_column_array, array_index)
'Function to return the value of a local peak. (The start and finish of each
'local peak are marked by the adjacent values being of the opposite sign,
'i e  +ve or -ve).
'In Excel, call function with the following papameters.
   'single_column_array - single column array of cells to be searched
   'array_index        - position in array from which to start search for local peak
   'e.g. SB_LOCAL_PEAK(E2100 E2199,row())
   Dim column_length, array_index_value_is_positive
   Dim array_fwd_pos, array_back_pos
   Dim i, local_array_peak_value

   'Find number of data values in single_column_array, i.e. array length
   column_length = WorksheetFunction Count(single_column_array)

   'check if value at given array index position is +ve or -ve
   If single_column_array(array_index) >= 0 Then
      array_index_value_is_positive = True
   Else
      array_index_value_is_positive = False
   End If
'   SB_LOCAL_PEAK = array_index_value_is_positive

   'Starting at the given array index position check backwards one row at a time
   'until a value of the opposite sign is found
   array_back_pos = array_index 'initialise array position index
   If array_index_value_is_positive = True Then
      Do While (single_column_array(array_back_pos) >= 0 And array_back_pos >= 1)
         array_back_pos = array_back_pos - 1
      Loop
   Else
      Do While (single_column_array(array_back_pos) < 0 And array_back_pos >= 1)
         array_back_pos = array_back_pos - 1
      Loop
   End If
   array_back_pos = array_back_pos + 1
'   SB_LOCAL_PEAK = array_back_pos

   'Starting at the given array index position check forwards one row at a time
   'until a value of the opposite sign is found
   array_fwd_pos = array_index 'initialise array position index
   If array_index_value_is_positive = True Then
      Do While (single_column_array(array_fwd_pos) >= 0 And array_fwd_pos <=
column_length)
         array_fwd_pos = array_fwd_pos + 1
      Loop
   Else
      Do While (single_column_array(array_fwd_pos) < 0 And array_fwd_pos <= column_length)
```

```
      array_fwd_pos = array_fwd_pos + 1
    Loop
  End If
  array_fwd_pos = array_fwd_pos - 1
'  SB_LOCAL_PEAK = array_fwd_pos

  'Search for the peak value (+ve or -ve)within the range of values bounded
  'by the backwards and forwards array positions just identified
  local_array_peak_value = 0 'initialise peak value
  If array_index_value_is_positive = True Then
    For i = array_back_pos To array_fwd_pos Step 1
      If local_array_peak_value < single_column_array(i) Then
        local_array_peak_value = single_column_array(i)
      End If
    Next i
  Else
    For i = array_back_pos To array_fwd_pos Step 1
      If local_array_peak_value > single_column_array(i) Then
        local_array_peak_value = single_column_array(i)
      End If
    Next i
  End If
  SB_LOCAL_PEAK = local_array_peak_value
End Function


Function SB_GET_VALUE(single_column_array, value_index)
'Function to search forwards through an array of values, many of which are
'set to '#N/A' and return the 'value_index'th non-'#N/A' value.
'In Excel, call function with the following papameters:
  'single_column_array - single column array of cells to be searched
  'value_index         - which non-'#N/A' value to return
  'e g. SB_GET_VALUE(E2100 E2199,row()-2100)
  Dim column_length
  Dim array_index, value_count

  'Find number of data values in single_column_array, i e. array length
  column_length = WorksheetFunction.Count(single_column_array)

  'Search forwards through the given array of values to find the value_index'th
  'non-'#N/A' value
  array_index = 1 'initialise array position index
  value_count = 0
  Do While (array_index <= column_length And value_count < value_index)
    If Abs(single_column_array(array_index)) > 0 Then
      value_count = value_count + 1
    End If
    array_index = array_index + 1
  Loop
  SB_GET_VALUE = single_column_array(array_index - 1)
End Function
```

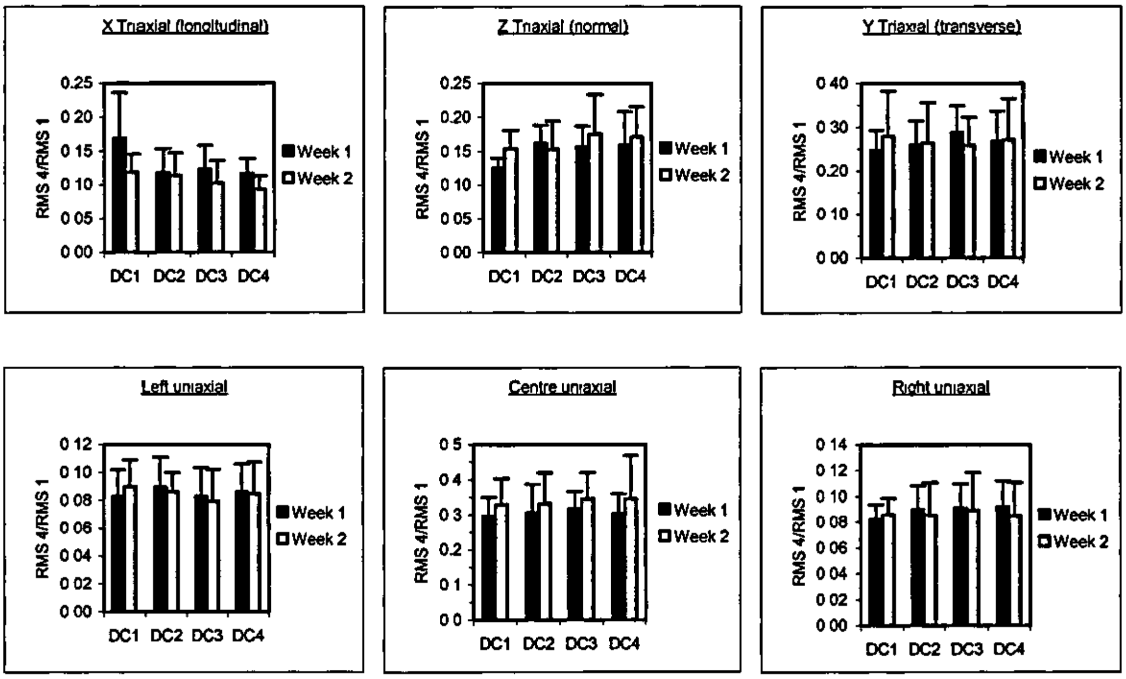
Appendix 11 – Accelerometer derived parameters group results



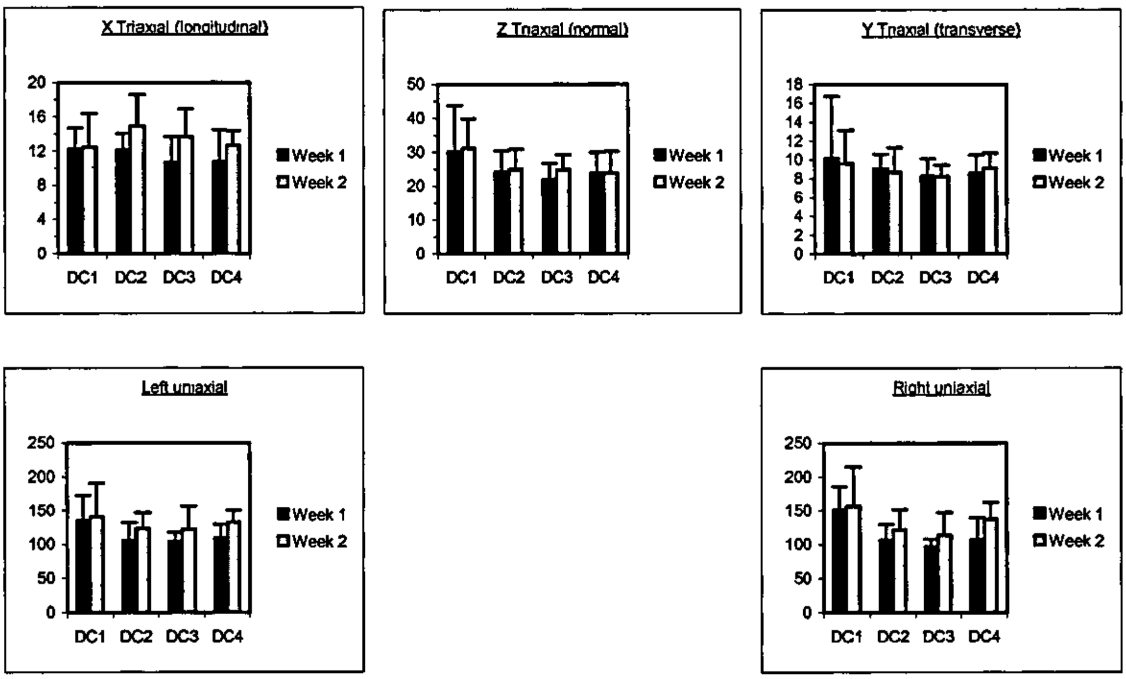
Group RMS (PI)



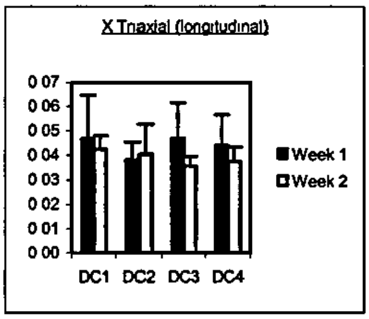
Group area (PI)

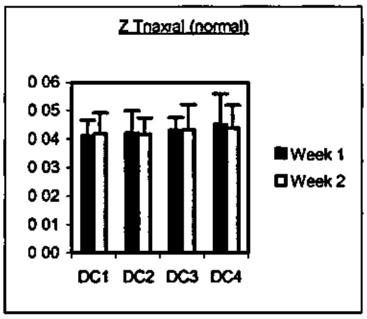


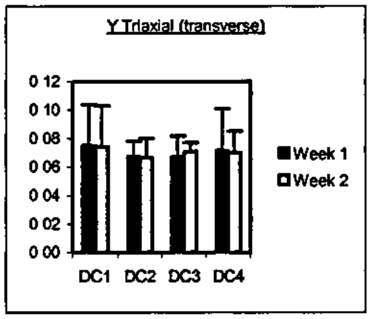
Group RMS 4/RMS1

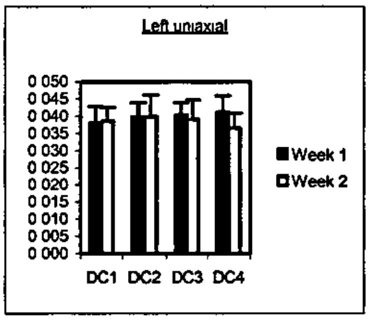


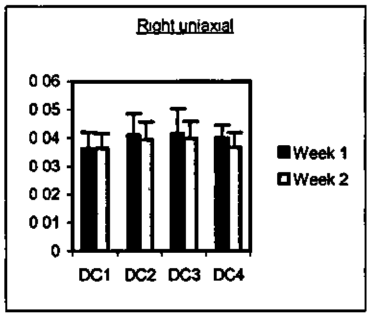
Exponential parameter 'a'



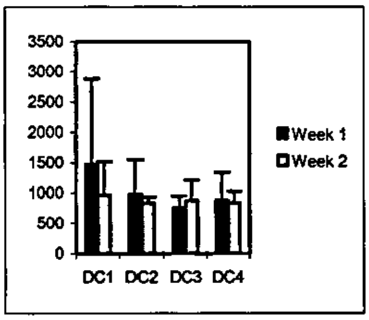


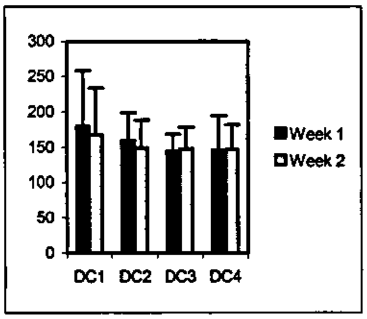


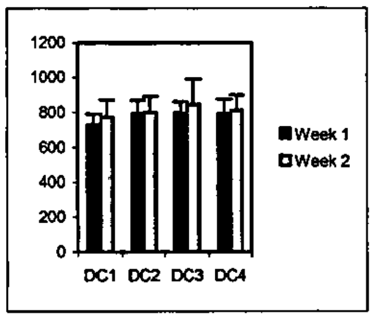




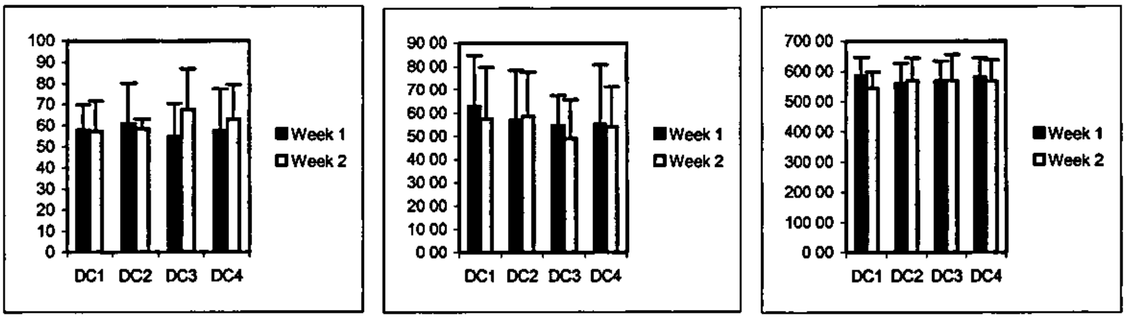
Exponential duration



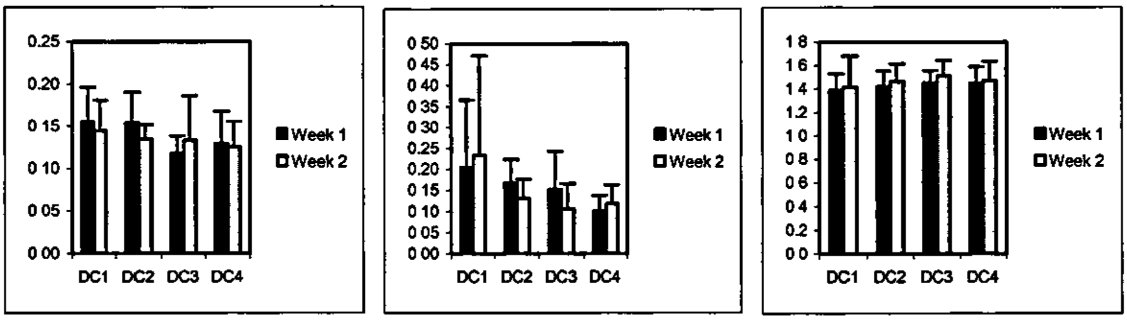




Angular acceleration – peak (radians/second^2)



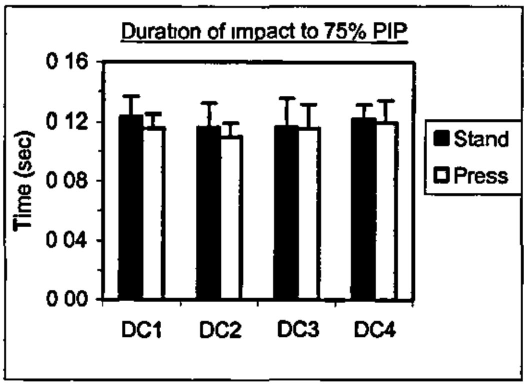
Angular acceleration – RMS (PI) (radians/second^2)

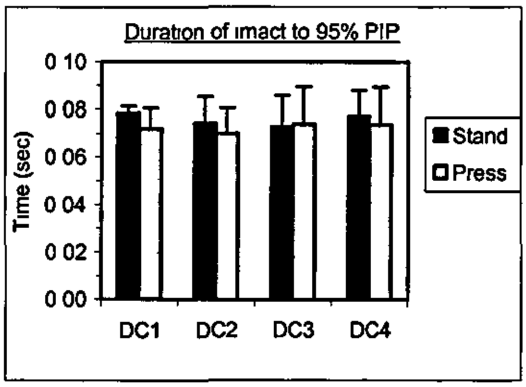


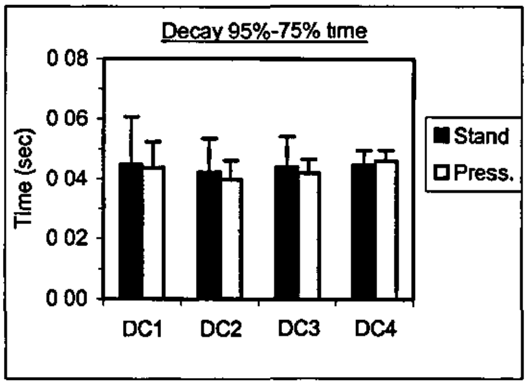
Angular acceleration – area (PI) (radians/second^2)

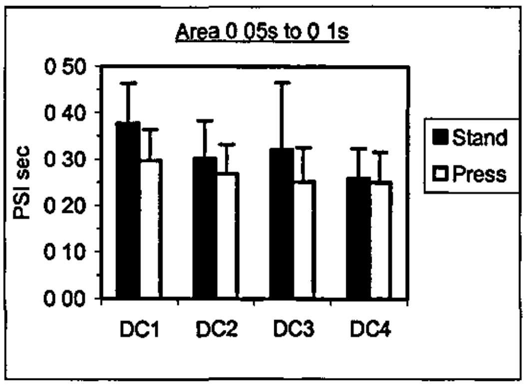
Appendix 12 – In-play grip pressure group results

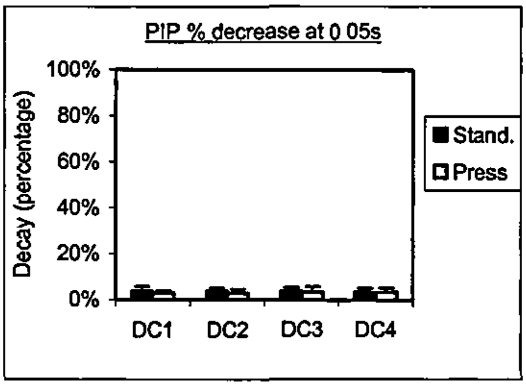
Whole sensor pressure group results

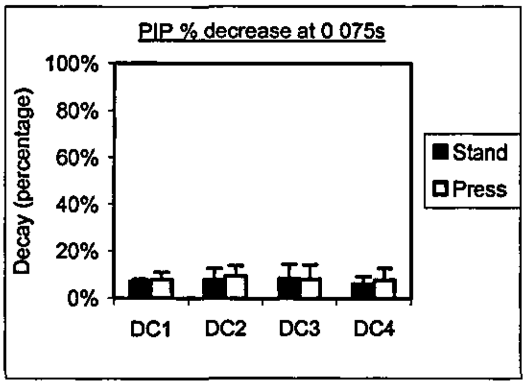


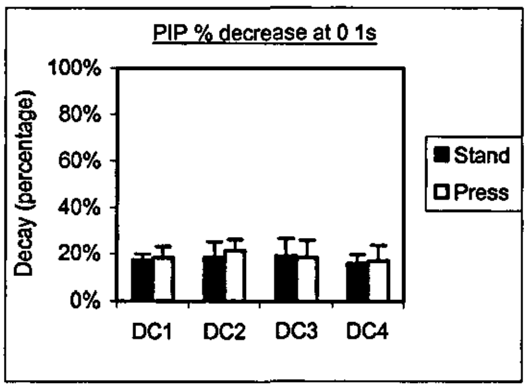


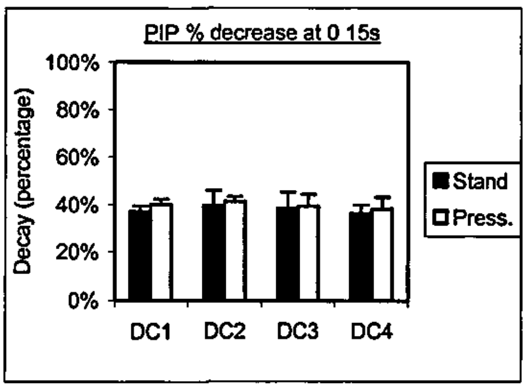


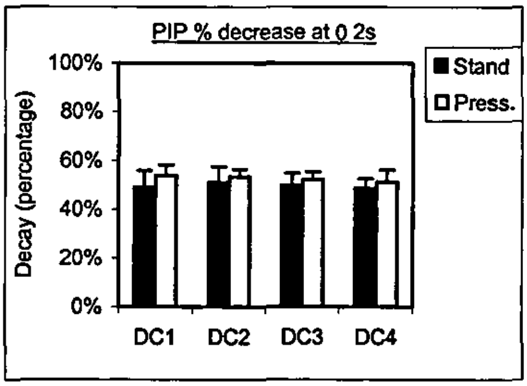








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40%
20%
0%
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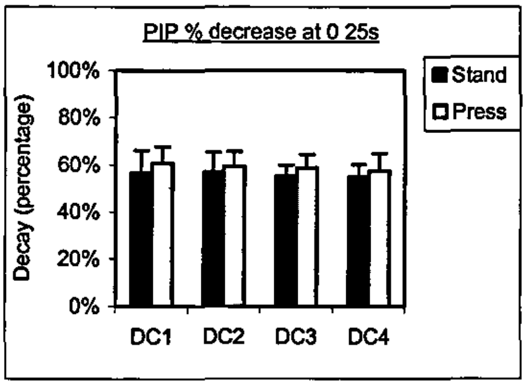
DC2
DC3
DC4
Stand
Press.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DC1
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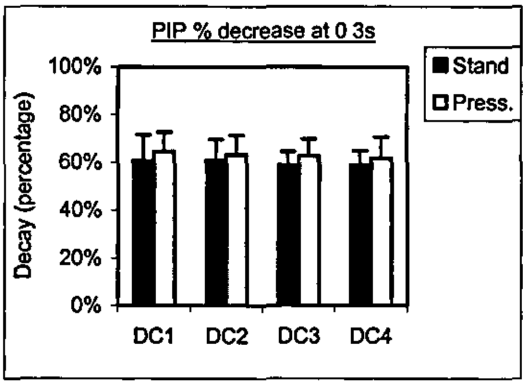
DC3
DC4
Stand
Press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DC3
DC4
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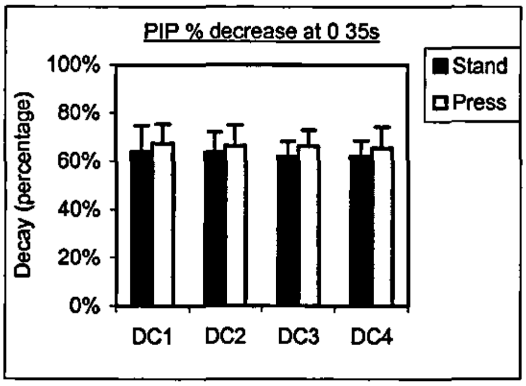
Press.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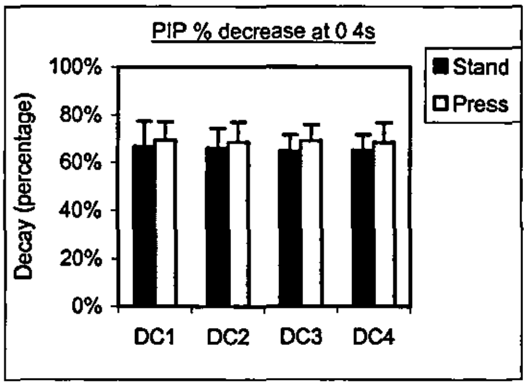
DC3
DC4
Stand
Press


PIP % decrease at 0 4s
Decay (percentage)
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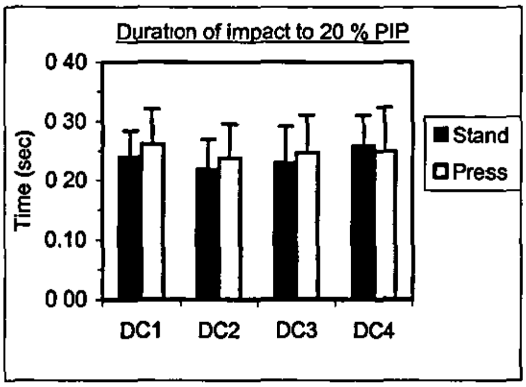
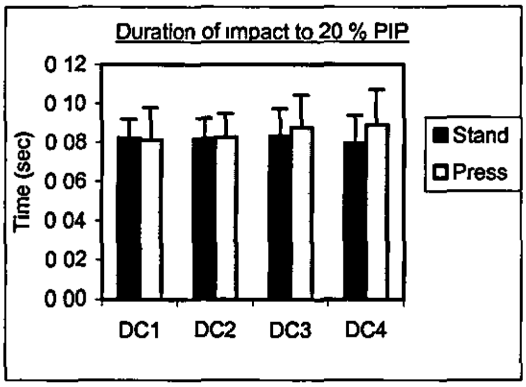
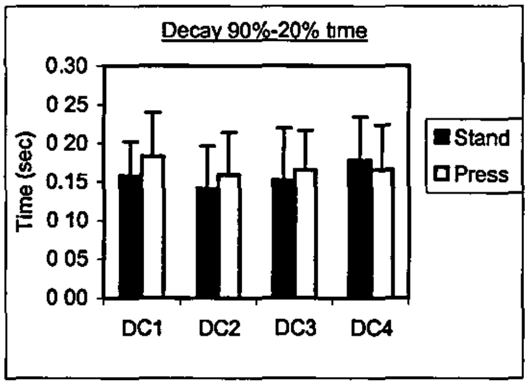
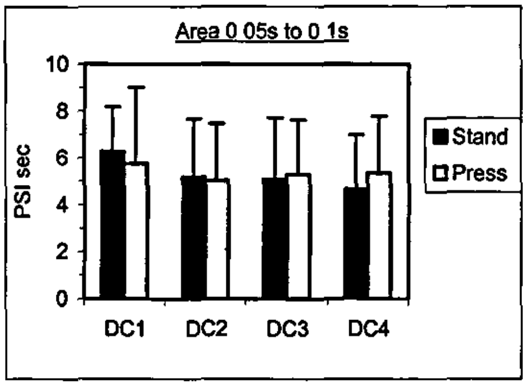
DC1
DC2
DC3
DC4
Stand
Press

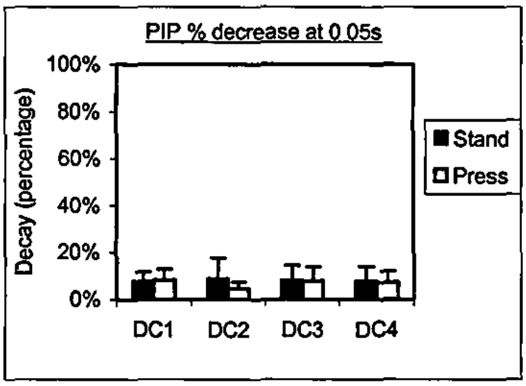
Peak pressure cell group results

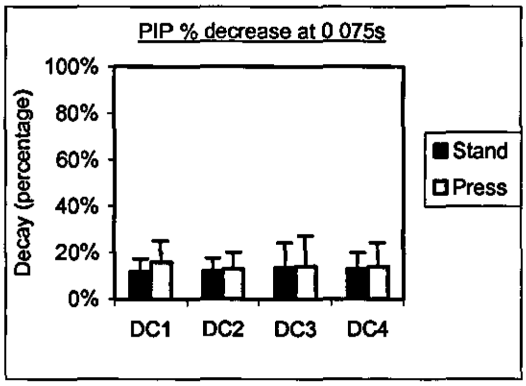


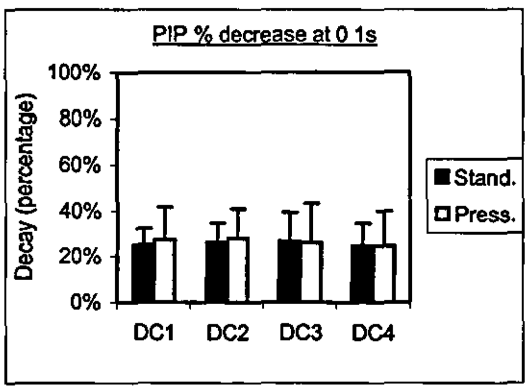


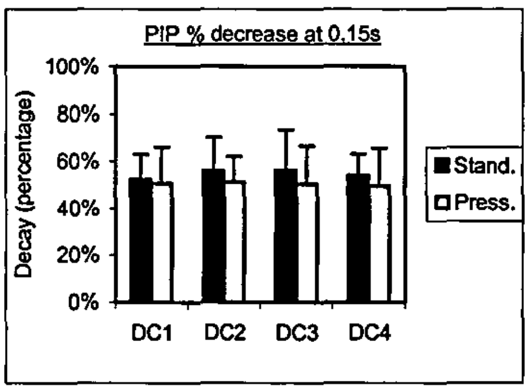


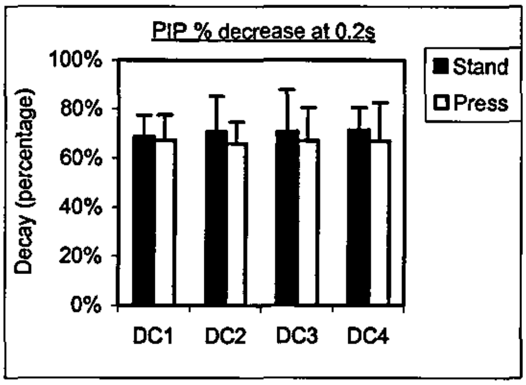








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Decay (percentage)
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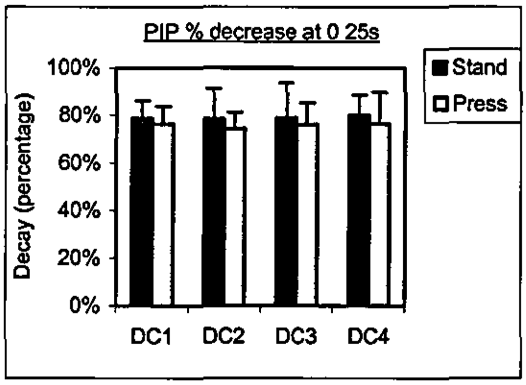
20%
0%
DC1
DC2
DC3
DC4
Stand
Press


PIP % decrease at 0 25s
Decay (percentage)
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DC3
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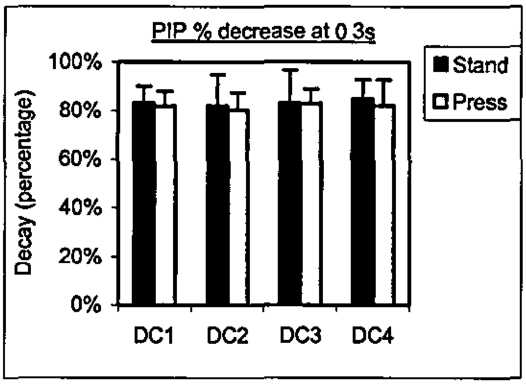
Stand
Press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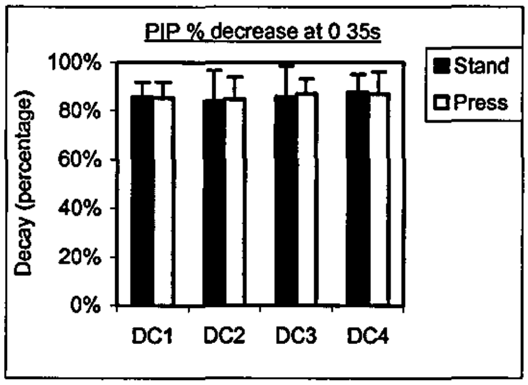
0%
DC1
DC2
DC3
DC4
Stand
Press


PIP % decrease at 0 35s
Decay (percentage)
100%
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60%
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DC1
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DC3
DC4
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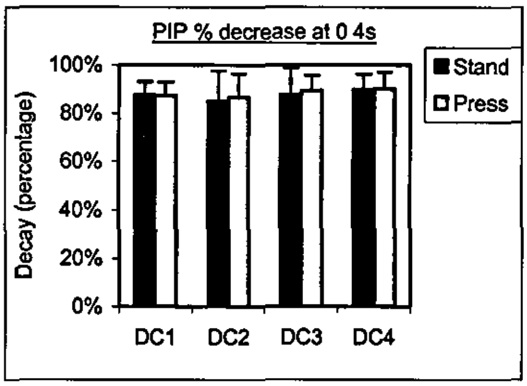
PIP % decrease at 0 4s
Decay (percentage)
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DC1
DC2
DC3
DC4
Stand
Press