Mechanical and psychological influences on the ‘feel’ of a golf shot

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MECHANICAL AND PSYCHOLOGICAL INFLUENCES ON THE 'FEEL' OF A GOLF SHOT

by

Jonathan Roberts

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Loughborough University

2002
Modern day sports players enjoy an ever-increasing range of equipment from which to choose and their selection is often based on physical and technical parameters, such as power, speed, distance and accuracy. In an attempt to increase their market share, manufacturers have applied advanced technologies to the design and development of sports equipment to increase the 'performance' of their products. These benefits may only be realised, however, if the player feels physically and psychologically comfortable using the equipment and these factors can only be investigated through the assessment of subjective human perceptions.

Focusing on a group of elite golfers, this study presents a formalised approach for eliciting and structuring players' descriptions of their perception of sports equipment in use. Qualitative methods of inquiry were used to generate perceptions from a group of professional golfers \((n = 15)\) during play testing. Ten dimensions of a golf shot of significance to the players emerged from an inductive analysis of their responses. In addition, fifteen themes emerged which suggested that there were relationships between the dimensions. A new technique, entitled structured relationship modelling, was developed to illustrate these associations. From the results, a postal questionnaire was designed to determine the feel of an 'ideal' golf shot and the relative importance of the emergent dimensions from a wider sample of golfers.

Initial testing was conducted to investigate variations in the duration of a golf impact with different equipment and the subsequent effect on the golfers' perceptions. Clubhead type, ball construction, ball compression and clubhead speed were all found to have a significant effect on impact duration but, despite the perceptions they reported, golfers were unable to accurately perceive the differences.

Characteristics of the feel of a golf shot related to the sound or vibration from impact were investigated further during a series of tests where objective data measured from impact was correlated with the perceptions of golfers, measured using rating scales. In a study of tactile sensations, the sound of the impact was masked and the measured vibration was correlated with golfers ratings of the feel of the shot. In a study of the sound of a golf shot, the sound from impact was measured at two locations and correlated with the golfers responses. In both studies, significant correlations were discovered between parameters of
the sound and vibration and the golfers' ratings, the strongest correlations being with the sound data.

This is the first study to identify all of the characteristics of a golf shot that influence a golfer's perception of the equipment and to analyse so extensively the subjective and objective data from impact.
ACKNOWLEDGEMENTS

First and foremost, I would like to thank my two main supervisors, Professor Roy Jones and Dr Steve Rothberg, for their advice, support, guidance and enthusiasm throughout the project. Meeting their relentless demands for results may have added years to my appearance and destroyed my social life but without them this thesis would not have been possible.

Thanks are due to Dr Chris Harwood, for his assistance on the psychological aspects of this work, and to Dr Neil Mansfield for his advice on human response to sound and vibration. Members of the technical staff in the department, particularly Steve Carr and Nev Carpenter, also deserve recognition for assisting with and developing instrumentation for the testing carried out as part of this study, as does Tim Roberts for his help in collecting the impact duration data. I would like to extend my gratitude to the golfers who participated in the tests and donated their time and effort and showed interest and enthusiasm often during adverse testing conditions.

I would also like to thank Callaway Golf for funding this research and providing equipment and facilities and the people there for involving themselves in the project and providing valuable advice and recommendations at the many progress review meetings. For taking responsibility for the project at Callaway's headquarters and promoting the work amongst his colleagues, I would like to extend my appreciation to Dr Alan Hocknell.

Finally, I would like to thank my family, particularly my mother, for providing encouragement and support, both emotional and financial, throughout my time in higher education and to all my friends who have kept me sane during the most trying times.
PUBLICATIONS ARISING FROM THIS WORK


"An intellectual is a man who takes more words than necessary to tell more than he knows."

Dwight D. Eisenhower
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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_p )</td>
<td>Contact approach deformation</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Mean value of a set of data</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Standard deviation of a set of data</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Impact duration</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Poisson's ratio</td>
</tr>
<tr>
<td>( a_i )</td>
<td>Magnitude of a frequency spectrum at frequency, ( f_i )</td>
</tr>
<tr>
<td>( b )</td>
<td>An arbitrary constant</td>
</tr>
<tr>
<td>( c )</td>
<td>Decay of a sound measurement</td>
</tr>
<tr>
<td>( C_{\text{ms}} )</td>
<td>Combined RMS vibration of the ( x ) and ( z )-direction measurements</td>
</tr>
<tr>
<td>( C_{\text{grip}} )</td>
<td>Combined ( x ) and ( z )-direction vibration of the grip</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of percussion</td>
</tr>
<tr>
<td>COR</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>( C_{\text{shaft}} )</td>
<td>Combined ( x ) and ( z )-direction vibration of the shaft</td>
</tr>
<tr>
<td>( d_i )</td>
<td>Difference between the value ( x_i ) and the value ( y_i ) for each pair of data ((x_i, y_i))</td>
</tr>
<tr>
<td>( D_i )</td>
<td>Difference between the rank given to ( x_i ) and the rank given to ( y_i )</td>
</tr>
<tr>
<td>( E )</td>
<td>Young's modulus</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
</tr>
<tr>
<td>( f_c )</td>
<td>Centroid of a frequency spectrum</td>
</tr>
<tr>
<td>( F )</td>
<td>Contact force</td>
</tr>
<tr>
<td>GBB</td>
<td>Callaway Great Big Bertha</td>
</tr>
<tr>
<td>( I )</td>
<td>Sound intensity</td>
</tr>
<tr>
<td>( l )</td>
<td>Deformation of a golf ball during compression testing (Thousandths of an inch)</td>
</tr>
<tr>
<td>( L )</td>
<td>Sound pressure level</td>
</tr>
<tr>
<td>( m )</td>
<td>Mass</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of data points in a set</td>
</tr>
<tr>
<td>NUD*IST</td>
<td>Non-numerical Unstructured Data Indexing Searching and Theorising</td>
</tr>
<tr>
<td>( p )</td>
<td>A measure of the significance of the result of a statistical test</td>
</tr>
<tr>
<td>PGA</td>
<td>Professional Golfers Association</td>
</tr>
<tr>
<td>( r )</td>
<td>Pearson correlation coefficient</td>
</tr>
<tr>
<td>( r_s )</td>
<td>Spearman rank-order correlation coefficient</td>
</tr>
<tr>
<td>( R )</td>
<td>Radius</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
</tbody>
</table>
SPL: Sound pressure level
\( t \): Time
\( T \): Sum of the negative ranks
\( T^+ \): Sum of the positive ranks
\( v_0 \): Clubhead speed at impact
\( x_i \): The \( i \)th data point in the set \( X \)
\( x_{\text{rms}} \): RMS vibration in the \( x \)-direction
\( x\text{-grip} \): Vibration of the grip in the \( x \)-direction (see Figure 4.4)
\( x\text{-shaft} \): Vibration of the shaft in the \( x \)-direction (see Figure 4.4)
\( y_i \): The \( i \)th data point in the set \( Y \)
\( z_i \): The \( i \)th data point in the set \( Z \)
\( z_{\text{rms}} \): RMS vibration in the \( z \)-direction
\( z\text{-grip} \): Vibration of the grip in the \( z \)-direction (see Figure 4.4)
\( z\text{-shaft} \): Vibration of the shaft in the \( z \)-direction (see Figure 4.4)
CHAPTER 1

INTRODUCTION

In today's expanding sports equipment market, performers at all ability levels enjoy an ever-increasing range of equipment from which to choose. Subjective assessment of equipment capability has been used for many years by manufacturers and players but relatively few studies have attempted to develop a systematic approach to the measurement of human perceptions (Noble and Walker, 1994; Hocknell et al., 1996; Merkel and Blough, 1999, Stroede et al., 1999). The choice of equipment may often be based on the belief that performance enhancement will result from its use, with cost sometimes a secondary consideration especially for the more able performer. These enhancements may take the form of increased power, speed, distance or accuracy. However, such benefits may not be achieved if the player feels physically or psychologically uncomfortable using the equipment. The degree of personal comfort may be a key determinant when selecting sports products, yet a systematic approach for assessing such a factor remains insufficiently developed. As the major sector in the global sports equipment market, golf has been used for this study, which aims to identify the characteristics of a golf shot of importance to the player and investigate the effect of tactile sensations and sound from impact on a golfer's perceptions.

1.1 THE 'FEEL' OF A GOLF SHOT

In golf, a player's perceptions of a shot result from the feedback received from a number of internal and external sources. Kinaesthetic perception describes the internal, proprioceptive feedback by which the golfer senses the sequence and nature of limb movements that form the swing (Sherwood, 1993). By comparing this with the memory of previous swing experiences, the golfer judges the quality of that swing. The player's perception of the shot will also be affected by external sources that either induce somesthetic sensations in the hands or provide exteroceptive information to the eyes and ears (Schmidt, 1991; Sherwood, 1993). Even before a shot has been played, the golfer will begin to receive salient feedback from observing and holding or wagglng the club. Additional feedback will then be received during the swing, from impact and from post-impact sensation (Cochran...
and Stobbs, 1968; Hedrick and Twigg, 1994; Hocknell et al., 1996). For the purposes of this study, it is the perceptions created from the external sources of feedback that are of interest because they contribute to the 'feel' of a golf shot that is associated with the equipment used.

Perception can be defined as 'our conscious interpretation of the external world as created by the brain from a pattern of nerve impulses delivered to it from sensory receptors' (Sherwood, 1993, p151). However, different people can perceive the same sensory input in a different manner. Take, for example, Figure 1.1, in which, from identical visual input, it is possible to 'see' two faces in profile or a wineglass. This much used optical illusion illustrates how the brain interprets information received according to its own rules and it is important, therefore, to consider a number of significant points when analysing players' subjective perceptions of golf equipment. Through differences in swing dynamics, sensory feedback may vary between different golfers using the same equipment. In addition, different golfers can receive the same feedback but interpret it and describe it differently.

1.2 SOUND AND VIBRATION OF SPORTS EQUIPMENT

Sound and vibration are unavoidable by-products of an impact between two objects and in golf they are two of the predominant forms of external feedback received by the player. In sports equipment research, the vibration characteristics of an implement have been investigated to a greater extent than the sound characteristics, mainly because the vibration generated at impact has been linked to both injury, such as tennis elbow (Fairley, 1985; Hatze, 1992; Hennig et al., 1992; Tomosue et al., 1994; Wilson and Davies, 1995), and a cause of discomfort or annoyance to the player, particularly when the impact is not located at the 'sweet spot'. Although, several studies have acknowledged the relevance of impact sound and its effect on the perception of the player (Hedrick and Twigg, 1994; Noble and Walker, 1994; Hedrick, 1995; Stroede et al., 1999) only four actually investigated sound characteristics of the equipment (Hocknell et al., 1996, 1998a, 1998b; Wicks et al., 1998b).

1.2.1 THE 'SWEET SPOT'

In sports involving the striking of a projectile with an implement, such as tennis, baseball and golf, it is the general aim of the player to strike the projectile at the 'sweet spot' of the implement. There are, however, several definitions of the term 'sweet spot' that relate to different physical phenomena and as a result each one identifies a different point on the implement. One definition of the 'sweet spot' is the location at which the coefficient of restitution (COR) is at its greatest. Alternatively, the 'sweet spot' has been defined as the centre of percussion (COP); when an impact is located at this point on the implement there
is no resultant force on the hand. The final definition of the 'sweet spot' is the location of a concentration of node lines; impact at this point, therefore, does not excite modes of vibration in the implement that have a node at this location (Brody, 1981; Cross, 1998a; Wicks et al., 1998a).

Two similar studies, one on tennis rackets (Cross, 1998a) and one on baseball bats (Cross, 1998b) demonstrated the reduction in vibration when an impact was located at a node and the reduction in forces on the hand when an impact was located at the COP. In golf, Hedrick and Twigg (1994) compared vibration from centre, heel and toe hits with the same club and found that the frequencies of vibration were similar regardless of impact location but the vibration amplitudes from the off-centre shots, particularly those out of the heel, were greater.

The 'sweet spot' to a player, however, is 'that point or area on the racket where it feels good when you hit the ball' (Brody, 1981, p 816); the player determines this point by learning from the feel of impacts at different locations over a number of shots (Care1lo, 1999). The 'sweet spot' can, therefore, be considered to be a subjective location, which may, or may not, correspond to the locations defined previously based on physical phenomena. It is surprising, therefore, that few studies of the 'sweet spot' of sports equipment actually obtained and analysed players' perceptions.

1.2.2 MODAL ANALYSIS AND THE EFFECT OF THE GRIP CONDITION

Numerous studies have performed modal analyses to identify the natural frequencies, mode shapes and node locations of golf clubs (Varoto and McConnell, 1995; Wicks et al., 1998a, 1998b, 1999; Barpanda et al., 1999; Merkel and Blough, 1999) and baseball bats (Tognarelli and Dunbar, 1994) for the purposes of investigating the 'sweet spot'. The node lines obtained by Varoto and McConnell (1995) for two drivers and two irons clamped at the grip are reproduced in Figure 1.2 as an example. The authors concluded that Driver A and Iron A are superior in terms of their dynamic performance because they both have node lines that all intersect in a region close to the centre of the clubface. Little vibration at these frequencies will therefore be transmitted to the golfer from a central impact and consequently the clubs will have a better feel.

The conditions in which modal analyses are conducted, however, are far removed from actual play conditions. The implement is stationary and the gripping condition is only a simulation of that occurring in play. The boundary conditions used for a modal analysis have a dramatic effect on the natural frequencies of the implement. Investigations of the effect of
different boundary conditions discovered that the natural frequency of the fundamental mode of a golf club increased from approximately 5 Hz to 40 Hz when the boundary condition was changed from fixed-free to free-free. In addition, it was found that the natural frequencies measured using a free-free condition showed good agreement with those obtained using a handheld-free condition (Thomas et al., 1995; Wicks et al., 1999). Although the most realistic condition is handheld-free, during an actual golf swing, grip force is dynamic (Budney, 1979) and therefore, according to Thomas et al. (1995), the boundary condition and the modes of the shaft may alter during the course of a swing. The large clubhead speeds generated in golf will create a large centrifugal force, which will have a stiffening effect on the golf shaft (Mather and Jowett, 1988) and also cause the shaft to deform during the swing. Only the study by Merkel and Blough (1999) obtained both vibration frequency spectra from an actual golf shot and the natural frequencies of the same club from a modal analysis. From the results reported, however, it is difficult to compare the natural frequencies of the club obtained from the modal analysis with the peaks in the frequency spectra from an actual shot. Modal analysis of golf clubs certainly has a role to play in predicting the feel of a club but, before any conclusive statements can be made, a better understanding is required of the effect of the dynamic influences during an actual swing on the natural frequencies and mode shapes of a club.

In tennis, mainly because of widespread disagreement on the effect of the grip on ‘racket power’, there have been numerous studies of the influence of the grip on impact dynamics, including in several cases racket vibration. In these studies, the tests were carried out using methods more representative of those occurring in play; typically a tennis ball impacted a stationary racket that was restricted using different grip configurations. As in golf, the grip condition has a considerable effect on the natural frequencies of a tennis racket. The fundamental mode of vibration of a hand-held tennis racket has been found to be similar to a free racket (Brody, 1987; Cross, 1998a), with the natural frequency of a hand-held racket slightly lower than a free racket (Cross, 1998a) but still approximately four times higher than a clamped racket (Brody, 1987). The hand also adds considerable damping to the system (Brody, 1989; Cross, 1998a) with the level of damping increasing with grip strength (Brody, 1989). Hatze (1976) concluded that a stronger grip increases the magnitude of vibration of the racket but the results obtained by Brody (1989) do not show this trend.

1.2.3 TRANSMISSION OF VIBRATION TO THE HAND AND ARM IN SPORT

The majority of studies of the vibration of sports equipment have only measured vibration of the implement itself. This measurement, however, is not necessarily
representative of the vibration transmitted into and perceived by the human. The vibration is usually measured at a different location to where the implement is gripped, it does not take into account the effect of the complex mechanical coupling between the hand and the implement or, in sports such as golf and tennis, the attenuation of vibration caused by rubber grips. As a result, a number of studies in tennis have investigated the transmission of vibration from the racket to the hand and arm. To measure vibration of the human body, accelerometers have been mounted with wax to the knuckle of the index finger (Fairley, 1985), attached at the wrist (Tomosue et al., 1991, 1994; Naβ et al., 1998) and pressed against the bone above the ulna head and the lateral epicondyle of the humerus (see Figure 1.3) with elastic wrist bands (Hennig et al., 1992). In the majority of these studies, vibration was measured from actual shots (Fairley, 1985; Tomosue et al., 1991, 1994; Naβ et al., 1998) except for Hennig et al. (1992) who fired balls at handheld, stationary rackets.

Measures of vibration magnitude at the wrist were found to be a tenth of the vibration of the racket handle (Tomosue et al., 1991, 1994) and at the elbow, approximately a quarter of the magnitude at the wrist (Hennig et al., 1992). In terms of frequency, Fairley (1985) discovered that all frequencies were largely transmitted to the knuckle, particularly frequencies around 100 Hz and 300 to 500 Hz, which is not wholly consistent with the findings of hand-arm vibration studies (Reynolds and Angevine, 1977), which are discussed further in Section 5.1.1. Tomosue et al. (1991), however, noted that higher frequency vibrations were only evident at the racket handle and not at the wrist. Measures of vibration magnitude of the body were also found to be dependent on impact location (Tomosue et al., 1991; Hennig et al., 1992; Naβ et al., 1998), although the locations that resulted in minimum shock and minimum vibration of the wrist did not necessarily correspond with the sweet spots hypothesized by Brody (1981) (Naβ et al., 1998). In addition, physical characteristics of the players and racket type (Hennig et al., 1992) along with grip strength (Fairley, 1985) and the presence of a string damper (Tomosue et al., 1994) were also found to influence vibration magnitude measured on the body.

1.2.4 PERCEPTION OF VIBRATION IN IMPACT SPORTS

Although there have been numerous studies of the vibration characteristics of sports equipment and the predicted effect on the feel or discomfort of the player, only a few have actually obtained the perceptions of players using the equipment. The techniques used in these studies to elicit subjective responses vary in complexity from obtaining a general consensus of players' opinions to actually quantifying the players' perceptions after each shot on either a categorical or continuous scale. The circumstances for collection of objective data
also vary from being measured from the same shots that the player is rating to being measured on a separate occasion.

A number of studies have been conducted in golf in an attempt to correlate subjective perceptions of the golfer with objective measurements from impact. Wicks et al. (1998b) investigated reasons for the general opinion amongst professional golfers that forged heads feel better than cast heads. The professional golfer used in the study, however, consistently preferred the feel of the set of cast clubs to the forged clubs, whilst modal analysis revealed that there were no significant differences in the natural frequencies or mode shapes between comparable cast and forged irons in the sets selected.

In addition to conducting a modal analysis, Merkel and Blough (1999) also measured vibration from golf shots hit with the clubs and obtained golfers' ratings of whether the shots played were either 'good' or 'bad'; 'The subjective qualifications for a 'good' [or 'bad'] hit included both feel and flight of the ball'. The vibrations of the rear of the head in the swing plane and the shaft immediately below the grip in the swing and droop planes for a representative 'good' and 'bad' shot were compared. The authors concluded that for a 'good' hit the vibration energy in the shaft is concentrated in the low frequency bending modes whereas for a 'bad' hit the majority of the energy is in the higher frequency modes, ranging from 300 to 3000 Hz. Other researchers, however, have demonstrated that a player's assessment of feel is much more complex than just 'good' or 'bad'.

Hocknell et al. (1996) constructed an average ranking of the 'hardness' of feel and the pitch of sound for combinations of two different club types and three different ball constructions from the opinions of golfers using the equipment and responses to a questionnaire. In addition, measurements were taken of the vibration from impact using an accelerometer mounted to the shaft immediately below the grip and the impact sound from shots hit by a golf robot with each of the six club-ball combinations. The authors concluded that a softer, more desirable sensation in the hands could be achieved by exciting modes of vibration in the club in the frequency range 500 to 2500 Hz more strongly than modes in the region of 100 Hz. In addition, the ball was found to be predominantly responsible for sound in the frequency range 0 to 3.5 kHz whilst in the range 5 to 11 kHz the sound was generated mainly by the vibration of the hollow metal clubhead.

Two studies have used scaled questions to quantify the players' discomfort. In baseball, Noble and Walker (1994) investigated the perceived discomfort of impacts at four locations, near the barrel end, the COP, the node of the fundamental mode of vibration and 100mm (4
In a study of the effect of string vibration dampers in tennis, Stroede et al. (1999) obtained discomfort ratings when balls were fired at stationary rackets held by the participants. Discomfort ratings were obtained for two different rackets, both undamped and damped when impacts were located at the geometric centre and 100 mm distal to the centre of each racket. A visual analogue scale, labelled ‘comfortable on impact’ and ‘uncomfortable on impact’ at each extreme, was used to quantify the perceived discomfort of the participant. Of the three variables, racket type, damping condition and impact location, only the impact location was found to have a significant effect on discomfort. Measurements of racket vibration indicated that the vibration from a central impact damped more quickly than from an off-centre impact and that the string damper was only effective at absorbing high frequency vibrations.

1.3 RESEARCH OBJECTIVES AND PROPOSED APPROACH

The few studies of sports equipment that have obtained subjective responses of players were limited to measuring perceptions of discomfort, pain or shot quality in terms of ‘good’ or ‘bad’. The characteristics ‘hardness’ of feel and pitch of impact sound studied by Hocknell et al. (1996) indicate that the feel of a golf shot is more complex. This study aims to develop a complete understanding of the characteristics that contribute to a player’s perception of a golf shot and determine the relative importance of each of the characteristics.

In order to correlate the perceptions of golfers with the feedback received from impact, a series of tests will need to be conducted. The validity of some of the test methods used in previous studies of the vibration of sports equipment is debatable and, during their analysis, only three studies, Noble and Walker (1994), Hocknell et al. (1996) and Stroede et al. (1999), considered human sensitivity to vibration, as depicted by perception curves reported, for example, by Reynolds et al. (1977). These are discussed further in Section 5.1.2. This study
aims to develop valid test procedures for quantifying subjective human perceptions and measuring objectively the feedback received by the players. It is intended that the tests will be conducted in conditions representative of actual play, measuring both subjective and objective data simultaneously from the same shots, whilst taking into account the transmission of vibration into the human hand. In addition, this study aims to develop techniques for correlating subjective and objective data, taking into account human response to both sound and vibration. As a result, the final objective is to identify properties of the sound and vibration from impact responsible for each feel characteristic.

If this can be achieved then, in future, the feel of golf equipment may be predicted from the natural frequencies and mode shapes of a club or ball, which could be obtained either from a modal analysis or a finite element model. The feel of the equipment may then be manipulated and improved earlier in the design process.

1.4 THESIS OUTLINE

This thesis is comprised of seven subsequent chapters, reporting the methods, results and findings of four main studies. A review of literature relevant to each study is included at the beginning of each appropriate chapter. The outline of the thesis is as follows:

Chapter 2 presents the results of a series of interviews with elite golfers to elicit their perceptions of a golf shot and an inductive analysis to structure their responses, allowing the dimensions of importance to the players to emerge. The results of a postal questionnaire to ascertain the relative importance of each of the dimensions are also reported.

Chapter 3 investigates the effect of clubhead type, ball construction and impact speed on the duration of impact. The results are compared with the golfers' perceptions of impact duration when using the equipment.

Chapter 4 describes the development of test methods for quantifying the golfers' perceptions and measuring sound and vibration from impact that is representative of that perceived by the player. Two separate studies are described, one investigating the tactile sensations of the golfer, the other investigating the impact sound perceived by the golfer.

Chapter 5 reviews the current literature on human response to sound and vibration and the factors that may have a significant effect on golfers' perceptions of a golf shot are identified and discussed.

8
Chapter 6 presents the analysis techniques used to correlate the subjective and objective data from the tactile sensation study and the impact sound study. The results of the analysis from each study are discussed and compared.

Chapter 7 discusses possibilities that have emerged for further work, whilst Chapter 8 presents the conclusion of this research study.
CHAPTER 2

ELICITATION OF HUMAN PERCEPTIONS OF A GOLF SHOT

2.1 INTRODUCTION

To understand the characteristics that contribute to a golfer's perception of the equipment used, suitable research techniques are required for eliciting and analysing these components. A number of previous studies in sports psychology have employed qualitative techniques to obtain and analyse rich, detailed, descriptive data. For example, Scanlan et al. (1989a, 1989b) developed a methodology that enabled acquisition and structuring of qualitative data on sources of enjoyment and stress for elite figure skaters. Open-ended questions were used during a series of in-depth interviews to collect data from a sample of skating coaches. An inductive analysis was then performed to structure the data, which allows the significant components to emerge from the data through a process of clustering together common themes. 'Clustering involves comparing and contrasting each quote with all the other quotes and emergent themes to unite quotes with similar meaning and to separate quotes with different meanings' (Scanlan et al., 1989b, p 68). The process is then repeated with the base level themes identified, being compared and contrasted in a similar manner generating higher level themes. At each level of analysis, an individual theme should be inclusive, in that it adequately captures the clustering of lower order themes that comprise it, and all themes should be mutually exclusive, with clear distinctions between them (Scanlan et al., 1989b). 'The analysis continues building upward until it is not possible to locate further underlying uniformities to create a higher theme level' (Scanlan et al., 1989b, p 68). The highest level theme is referred to as a 'general dimension'. Other studies have used similar methods to elicit information from Olympic wrestlers (Gould et al., 1992a, 1992b), junior tennis players (Harwood, 1997) and swimmers (Hanton and Jones, 1999).

To develop an understanding of the perceptions, feelings, thoughts and knowledge of a golfer, it is essential that minimal constraint be placed upon the responses of the player. It is important that the player is allowed the opportunity to express himself about matters of central significance to him rather than those presumed to be important by the interviewer.
That is, ... it uncovers what is on the subject's mind rather than his opinion of what is on the interviewer's mind' (Merton and Kendall, 1946, p 545). The use of open-ended questions during semi-structured interviews allows the participants the freedom to respond in their own terms and phrases about issues of importance to them. A subsequent inductive analysis of these responses enables the significant issues to emerge without presupposing in advance what those important dimensions will be (Patton, 1990). Thus, the template of semi-structured interviews followed by an inductive content analysis was deemed ideal for this study. However, it became apparent during the analysis procedure that although this method was invaluable in identifying the key components of a player's subjective perception, it did not enable any interactivity between dimensions to be investigated. As a result an additional analysis stage was introduced to facilitate exploration of inter-dimension relationships and to develop a more suitable method for representing the findings, and this will be discussed later.

2.2 STUDY DESIGN AND TEST METHODOLOGY

The procedure followed for the design of this study is illustrated in Figure 2.1. The flow diagram was used to aid the design of the research study by providing a logical progression through the major design issues involved in the process. The design decisions taken and the compilation of an interview guide are discussed in the following section.

2.2.1 PARTICIPANT SELECTION

The selection of a sample of people from whom to collect information is of considerable importance because it will affect the quality of the data. A technique called purposeful sampling of information-rich cases was used for this work. 'Information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the research, thus the term purposeful sampling' (Patton, 1990, p 169).

For this study, it was specified that the sample should consist of male professional golfers aged between 20 and 55 years old. Elite players were chosen because it is believed that a golfer's sensitivity to differences in equipment characteristics increases as the player improves and gains experience, whilst the age range of 20 to 55 years is thought to represent the period when a golfer will still be competing and will have gained sufficient experience. The wide age range allows any differences between different generations of golfers to be assimilated. Exclusively male golfers were chosen since elite male golfers were more readily available. However, the same procedure can easily be replicated in future studies to investigate population samples of other groups of golfers.
The size of the sample is another important consideration. 'Sample size depends on what you want to know, the purpose of the inquiry, what's at stake, what will be useful, what will have credibility and what can be done with available time and resources' (Patton, 1990, p 184). A study that has a fixed time scale and limited resources generally introduces a choice as to whether limited detail is obtained from a large number of people giving breadth of knowledge, or a greater detail is obtained from a smaller number of people giving depth of knowledge. Patton (1990, p185), however, also noted that 'the validity, meaningfulness, and insights generated from qualitative inquiry have more to do with the information-richness of the cases selected and the observational/analytical capabilities of the researcher than with sample size'. As a result Patton recommended specifying a minimum sample size and having a study design sufficiently flexible that this value could be increased if, as the fieldwork unfolds, new information continues to emerge.

For the purposes of this study, a minimum sample size of fifteen was initially selected based on experience of a number of previous research studies involving interviews with elite performers (Scanlan et al., 1989a, 1989b; Gould et al., 1992a, 1992b; Harwood, 1997; Hanton and Jones, 1999). A sample size of fifteen was also considered to provide a balance between breadth and depth of knowledge obtained.

Professional golfers satisfying the selection criteria were identified based upon their position in the 1997 UK PGA Midlands Order of Merit Table. Of those approached only two refused, one because of illness and the other due to a commercial conflict of interest. The sample of golfers had a mean age of 38, $\sigma = 10$ years, and had been playing at a professional level for a mean of 19, $\sigma = 11$ years. After interviewing fifteen players, it became apparent that a 'saturation' stage had been reached where no new information appeared to be emerging and so the interview program was terminated (Biddle et al., 2001).

2.2.2 DEVELOPMENT OF A PSYCHOMETRIC INSTRUMENT

A naturalistic style of inquiry was deemed more suitable for this study as it is a 'discovery-oriented' approach with minimal investigator manipulation of the study setting and no prior constraints placed on the outcomes of the research (Guba, 1978; Patton, 1990). By utilising this type of inquiry, the characteristics of importance to the golfer could be investigated, as little restraint would be imposed on the responses of the golfer by the study design.
2.2.2.1 Data Collection Technique

The two most common methods for acquiring data are the interview and the questionnaire and the relative advantages and disadvantages of the two techniques are summarised in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>Interview</th>
<th>Questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility to vary content, sequence and wording of questions</td>
<td>Limited to extensive (depending on structure)</td>
<td>Limited</td>
</tr>
<tr>
<td>Opportunities for probing</td>
<td>Possible</td>
<td>Difficult</td>
</tr>
<tr>
<td>Number of respondents</td>
<td>Limited</td>
<td>Extensive</td>
</tr>
<tr>
<td>Rate of return</td>
<td>Generally good</td>
<td>Generally poor</td>
</tr>
<tr>
<td>Sources of error</td>
<td>Interviewer effects, instrument, sample</td>
<td>Instrument, sample</td>
</tr>
</tbody>
</table>

Table 2.1 - Comparison of the strengths and weaknesses of two data collection techniques (Based on Cohen and Manion, 1989)

To collect data, the interview technique was considered more appropriate for this part of the study than the questionnaire. Depending on the level of structure, an interview can offer increased flexibility to vary the content, sequence and wording of questions and can provide greater opportunities for probing; follow-up questions that an interviewer can use to seek clarification or elaboration upon a previous response. As a result, the interviewer can change the content and direction of an interview to explore an unanticipated response, vary the sequence if a subject introduces a topic that was scheduled for later in the interview or rephrase any questions that cause confusion. These features allow a subject's responses to be explored in greater detail and result in the completeness of information and depth of understanding that are required to explain the full complexity of feel in a golf shot.

Interviews, however, can vary in the level of structure and the benefits of flexibility and opportunities for probing are not achieved if the structure of the interview is fixed and the interviewer merely progresses through a series of predetermined questions. In an unstructured interview, there is no predetermined content, sequence and wording of questions and the direction of the interview is based on the responses that emerge. As a result each interview can be tailored to the individual subject and the questions have more salience and relevance. The data, however, can be less comprehensive if certain questions do not arise 'naturally', may be difficult to compare if each interview covers a different subject
area and more prone to interviewer effects as there is a greater emphasis on the skills of the interviewer (Patton, 1990).

An interview guide provides a compromise and as a result was deemed the most suitable level of structure for this study. Subject areas are outlined in advance to aid comparability of data but within each area there is enough flexibility to explore and probe the subject's responses. The interview guide developed is described in detail in Section 2.2.2.3.

2.2.2.2 Qualitative Vs Quantitative Data

The final consideration when designing a research study is the type of data to be collected. The decision between quantitative and qualitative data is also related to the choice between naturalistic and scientific inquiry. 'Experimental designs predominantly aim for statistical analyses of quantitative data, while qualitative data are the primary focus in naturalistic inquiry' (Patton, 1990).

Qualitative data consists of detailed descriptions and direct quotations, whilst quantitative data is in, or can be represented in, numerical form allowing statistical analysis to be performed on the data. Obtaining the alternative types of data requires different formats of questions and responses. Qualitative data is obtained from open-ended questions, which allow respondents to reply using their own words and phrases, whilst quantitative data is obtained from fixed response or scaled response questions, where the respondents are given a choice of replies.

Open-ended questions are, therefore, ideal for this study as they place minimal restraint on the replies and a vocabulary of terms used by golfers to describe their perceptions of feel can be built up from their responses. ‘Open-ended situations can also result in unexpected or unanticipated answers which may suggest hitherto unthought-of relationships or hypotheses’ (Cohen & Manion, 1980, p 313).

2.2.2.3 Interview Guide and Schedule

The interview guide developed, which is included in Appendix 1, has a basic structure comprising several sections, with the same sequence of sections used for each interview. Within each section, an introductory question was posed with some possibilities for further questioning and discussion listed. After the initial open-ended question had been asked, the interviewer had complete freedom and flexibility to explore and probe the golfers' responses. Topics were only discussed, however, if they had been introduced into the discussion by the golfer.
The first stage of each interview was conducted outdoors, on the driving range of the golf club where the Professional was resident, thus placing him in surroundings in which he would be comfortable and familiar. The golfer was then asked to hit several shots with each driver club and ball and, once he had formulated an opinion, describe his perception of that combination. Verbal probes were then used to discuss his perceptions in more detail. Clubheads constructed from titanium, stainless steel, persimmon, laminated wood and graphite were assembled with steel and graphite shafts of different flexibilities. An assortment of grip styles was used and two different constructions of golf ball, the Precept EV, a two-piece, surlyn ball and the Titleist Tour Balata, a three-piece, wound, balata ball, were also provided. The various combinations of club construction and ball type were thought to encompass the spectrum of feel characteristics associated with golf equipment. The specification of each of the test clubs used is given in Appendix 2. The golfer was introduced to this section of the interview with the following explanation.

First of all I would like you to hit a number of golf shots with each club/ball combination. After you have played each shot I want you to describe your perception of 'feel' of that shot. If you wish to hit a number of shots to get used to the club before you respond, please do. It is important that you comment upon the 'feel' of the shot you have played and avoid allowing preconceptions of different club/ball designs to affect your responses.

Examples of specific questions posed to encourage player responses include:

How do the traditional wooden clubs 'feel' in comparison to the modern titanium clubs?

How does the 'feel' of the shot differ between the two different ball types?

Terms and phrases used by the golfer to describe his perceptions were noted whilst clarification and elaboration probes were used to obtain detailed descriptions and a more comprehensive understanding (Patton, 1990). As these types of question are specific to a particular characteristic they were only used once the golfer had introduced that characteristic into the discussion. Typical probes used include:

What do you mean by 'solid feel'?

What don't you like about the appearance of that club?

How would you describe the sound from that club?
The first stage of the interview served two purposes. It placed the golfer in an environment in which he was comfortable and at ease but, most importantly, it stimulated the player's mind, increasing the quantity and quality of responses. Golfers were more able to talk in depth about their perceptions as they used each club and ball than when they were required to recall past experiences of their perceptions.

The second stage of the interview did not require the golfer to hit shots. The remaining sections were used to ascertain the reasons why the golfer selected his current set of equipment, the characteristics of an 'ideal' golf shot and the relative importance of the characteristics discussed during the interview. In the final section the golfer was asked to provide some feedback on the interview itself and to suggest possible improvements that could be made.

Five pilot interviews were carried out to determine the suitability of the interview technique and a number of modifications were made to remove redundant sections and reword ambiguous questions.

2.2.3 RECORDING SYSTEM

Each interview was recorded to enable complete and accurate information to be logged in an efficient manner. As part of the interview took place outdoors in varying weather conditions with the golfer hitting a number of shots, a specialised recording system had to be developed that fulfilled several criteria.

i) Every spoken word by each individual must be clearly and audibly recorded on a single medium to allow complete and accurate transcriptions to be produced with a minimum of effort.

ii) Recording equipment must be unobtrusive and not impede the golfer's swing.

iii) Recording equipment must be portable, battery powered and quick to set up.

A dual, wireless, lapel microphone system feeding into a radio transmitter satisfied these requirements. In the interview situation, participant and interviewer can talk at the same time making transcription difficult, so a mini-disc stereo recording device was used which allowed information from each microphone to be recorded on separate tracks.

2.2.4 DATA ANALYSIS

The organisation of raw data into structured, meaningful themes can be approached from two perspectives. A deductive analysis involves arranging quotes into a set of pre-
determined categories while an inductive analysis allows the themes and categories to emerge from the quotes. Previous studies in sports psychology (Scanlan, et al., 1989a, 1989b; Gould et al., 1992a, 1992b; Harwood, 1997; Hanton and Jones, 1999) have argued that they followed an inductive process for structuring qualitative data. To allow those characteristics important to the golfer to emerge and to minimise restrictions imposed by the investigator, an inductive analysis was viewed to be the most suitable approach for this study.

The software package QSR NUD*IST was used during the analysis to manipulate the unstructured, qualitative data obtained. NUD*IST assists in shaping understanding of the information by enabling categories of data to be created and emergent categories to be linked. Exploration tools are also provided to form and test theories grounded in the data.

The inductive analysis procedure used, as illustrated in Figure 2.2, began with the verbatim transcription of each interview. Familiarisation with the data involved listening to the interviews, reading each transcript several times, highlighting important quotations and making notes on the subject matter discussed during each interview. The selected quotes became the basic unit of analysis.

In the next stage, the inductive analysis advocated by Scanlan et al. (1989a, 1989b) was conducted. A number of guidelines are suggested by different authors to assist in the process of structuring and making sense of large volumes of qualitative data. Patton (1990) advocates focusing the analysis by considering the purpose of the study and attempting to answer the research question formulated at the start of the study design process.

One issue that often arises during an inductive analysis is the problem of alternative classification schemes. Take for example four of the base level themes, 'Feel Club Twist from Off-Centre Shots', 'Hard Feeling Ball', 'Soft Feeling Ball' and 'Hard Feel from Off-Centre Shots' that emerged during the analysis of golfers' responses. As illustrated in Figure 2.3, there are a number of different ways of grouping the themes at a higher level. In this situation, Patton (1990) suggests developing each classification system and then establishing priorities to determine which of the category systems is more important than the others. A technique used during this study to eliminate different systems and refine the configuration was to consider each dimension in terms of redundancy. A dimension can be considered to be redundant if all the base level themes can successfully be re-coded into another dimension. If a large number of unassignable or overlapping themes still exist, this is evidence of a basic fault in the category system (Guba, 1978).
Finally the structure was tested for completeness using a number of checks.

i) The analysis should leave as few unassignable themes as possible. Any remaining unclustered themes should be either disregarded if indistinguishable or retained if important (Scanlan et al., 1989b).

ii) The structure should be reasonably inclusive of the data and information that exists. If the set of categories does not appear to be sufficient, on logical grounds, to cover the facets of the problem, the structure is probably incomplete (Guba, 1978).

The structure for each dimension was then created in NUD*IST, and a deductive process of coding the previously highlighted quotes into the composed structure was used to validate the inductive process. With the data in a more organised format more subtle themes emerged allowing the creation of refined themes from initial base level categories.

Triangular consensus validation was then used to minimise any bias from the principal investigator and this is discussed further in the following section.

2.2.5 QUALITY OF RESULTS

A number of steps were taken to obtain trustworthy results by minimising individual bias. Firstly, two investigators conducted each interview to reduce potential errors that can arise from a single person collecting all the data (Patton, 1990). Possible sources of error in the interview technique (Cohen and Manion, 1989) include:

i) The attitudes and opinions of the interviewer

ii) A tendency for the interviewer to see the respondent in his own image

iii) A tendency for the interviewer to seek answers that support preconceived notions

iv) The interviewer misinterpreting the responses

v) The respondent misunderstanding what is being asked

During the interviews, these sources of error were minimised where possible by using unambiguous questions that did not guide or force responses in a particular manner. The two interviewers received methodological guidance on interview techniques from an experienced colleague and through reading relevant texts. Five pilot interviews were conducted prior to the main interview programme to refine techniques and become familiar with the terminology used by the golfers.
Secondly, triangular consensus validation (Scanlan et al., 1989b; Patton, 1990) was conducted, during which the emergent dimensions were discussed by the two investigators present at each interview, together with a third person also experienced in qualitative data analysis, until agreement was reached at each stage of the analysis.

Upon completion of the analysis, five further interviews were conducted with a sample of elite American golfers. Similar themes were discussed, albeit using alternative, American terminology, which could easily be coded deductively into the structure created from UK golfers’ responses. For example, both groups of golfers discussed the relative stiffness of a shaft, but American golfers would use the terms ‘unstable’ or ‘stable’ as opposed to the British golfers who used the corresponding terms ‘whippy’ and ‘firm’. Although it was encouraging that no additional themes emerged, a study with a larger sample of American golfers would be required to confirm that the results of this study are applicable to a similar group of American golfers.

2.3 THE GENERAL DIMENSIONS OF FEEL

The purpose of the study was to identify the important characteristics that affect a player’s perception of the equipment used when hitting golf shots and, in so doing, to develop a methodology that could be used for the assessment of a wide range of sports equipment. Ten general dimensions emerged from the inductive analysis of the golfers’ responses.

i) Feel from Impact
ii) Impact Sound
iii) Shaft Feel
iv) Club Weight
v) Club Control
vi) Feel of Club Position During Swing
vii) Grip
viii) Ball Flight
ix) Club Appearance
x) Golfers’ Psychology

The tree-structures for these dimensions are illustrated from Figure 2.4 to Figure 2.13. Each structure illustrates how the analysis progressed from the initial quotes, examples of
which are provided in the left-hand column, through each different level of clustering to the general dimension at the right-hand side.

2.3.1 FEEL FROM IMPACT

The general dimension 'Feel from Impact', which is illustrated in Figure 2.4, contains two major sub-themes 'Feel up the Shaft' and 'Feel of Ball Behaviour'. The high order category 'Feel up the Shaft' embodies all the comments and themes that are considered to be describing the level of vibration that is being transmitted up the shaft from impact and felt in the hands of the golfer. When the ball is struck out of the centre of the club face, less vibration tends to be perceived by the golfer from the impact and the shot is described as having a 'soft' or 'sweet' feel or in some instances 'no feel'. In general, the traditional wooden headed clubs are described as having a softer feel than the modern metal headed clubs.

Quite a soft feel, when you hit these out of the middle it's quite a soft feel off the club face with these Pings.

Compared to the first club we tried, there's hardly any vibration in that at all. There was no sort of hardness or anything like that, just very much a sweet feeling. No vibration, no feeling in the hands, it was a very nice feel.

Completely reducing the vibration level perceived by the golfer is, however, not always desirable, the base level theme 'No Feel' also contains negative comments.

That's absorbing... all the vibrations. Nothing at all. Very soft feel. Again, not the sort of feel I'd be looking for because it's a little bit too soft for me. I like to feel that bit of hardness there, it's just absorbing a bit too much of the shock...

Shots producing higher levels of vibration are often described as having a 'hard feel', 'more feel' or alternatively the golfer refers directly to the vibration level itself. This harder feel is not only caused by variations between clubs but also by striking the ball away from the centre of the club face.

It feels very positive, if that's the right word. You get a real positive hit off the club face. And while it feels hard and a nice solid hit, it doesn't feel uncomfortable in the hands. So, it's very, very positive.

Certainly more feeling through the hands with that one... just more feeling through the shaft, especially if you don't get it out of the middle. Compared to a wood, you tend not to be able to feel as much with a wood as you can... with a metal head, certainly not up through your hands.
With the modern, oversize metal clubheads, however, off-centre impacts can still feel relatively good

Just hit that a bit out of the toe and, again, I felt it twist a little bit but it still felt very soft in the hands...

The type of ball can also have an influence on how 'hard' or 'soft' a shot feels; of the two ball constructions used in this study, the two-piece Precept EV tended to be perceived as feeling harder than the three piece Titleist Tour Balata, although the majority of golfers found the difference in feel to be negligible when using a driver.

I mean you can feel a little bit of difference at impact with using a harder ball in terms of using the Precept as opposed to using the Balata but... it's so slight that there isn't a great deal of difference.

The difference in balls, I mean is negligible off the driver. I think you'd probably feel it more round the greens and when you're putting.

Variations in sensitivity between golfers may explain why some golfers detected differences in feel between balls whilst others did not but a number of players that were able to differentiate between balls could not perceive the differences with every club used indicating that the influence of the ball on the feel of the shot may depend on the type of club.

Golfers' descriptions of their perception of the ball compressing and releasing off the clubface are grouped together in the high order theme 'Feel of Ball Behaviour'. Players generally describe feeling the ball compress more and be 'absorbed' by the traditional wooden headed clubs, increasing the impact duration and as a result when the ball recovers, it is perceived to leave the clubface slower, which creates a 'dead' or 'dull' feel. In contrast, typically with the modern clubheads, golfers perceive the ball to 'explode' off the clubface with greater speed creating a 'powerful' feel.

Again, it just feels dead. It feels as though the ball's not coming off the clubface. It feels as though the wood is, if you can imagine the ball going right into the wood and it's absorbing it and then it's just not coming off at any pace at all. It was very dead, heavy, no liveliness at all to it.
If I hit a wood... the flight of [the] ball's nice and soft... Now a titanium, that just flies away, just ridiculous, it pings off, and it seems to have less spin on it, I would think. So with a wood I feel that the ball and the club compress before it goes off. With metal wood, it's like, it, it shoots it off.

The final theme within the dimension 'Feel from Impact' is 'Solid Feel'. Golfers prefer the club to feel 'solid' at impact especially if the ball is not hit from the centre of the clubface.

[It] just doesn't feel as solid and certainly doesn't feel as... uniform as it would on a metal wood. Obviously with a bigger sweet spot on the metals you tend to get a more uniform feeling anyway but you can drastically tell... the difference if, you know, you don't get one out of the middle of the wooden wood. It feels a lot less solid than a... bad one off one of the metal woods.

2.3.2 Impact Sound

The general dimension 'Impact Sound', which is illustrated in Figure 2.5, contains the terms and phrases used by the golfers to describe properties of the sound from impact. The most common descriptors of the sound as a whole include 'tinny', 'dead', 'dull', 'explosive' and 'crisp', although numerous other less common terms are used.

The bigger the head the more you have this like tinny sound off it. The [traditional] woods generally sound better... for a person who's played golf for a long time.

The big down side on this is the sound, 'cause if it made the crack that the titanium head would make then I would say this would be top quality, but it's a slightly dead sound, which you'd expect from a wood.

These descriptors were used to describe the sound as a whole but it may be possible to associate terms such as 'tinny' and 'dull' with the pitch of the sound, 'explosive' with loudness and 'crisp' and 'tinging' with the perceived duration of the sound. The latter two properties, loudness and duration were referred to specifically by several of the golfers.

[Callaways are] by far the loudest, noise wise, they make a ting. Titleists are... not quite as loud, they make more of a thud...

It is also noticeable that many of the terms used to describe the sound of the impact, such as 'dead', 'dull', 'explosive', 'solid' and 'powerful' were also used to describe the feel of a shot in the dimension 'Feel from Impact'.

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Several golfers described perceiving differences in impact sound due to ball type but the quotes tend to refer to previous experiences rather than identifying differences between the two balls used in this test.

Golfers use the impact sound as a guide to the quality of the strike and, as a result, the sound can have a psychological effect on the player. Clubs that have a sound which is ‘duller’, resembling that of a miss-hit shot, can give the golfer the impression that the shot was of a lower quality.

I think that is important when somebody hits it, it makes a crack and immediately you associate it with being a good hard hit. I think the persimmon tends to sound and the graphite head tended to sound much duller, and... I immediately perceive that as a poor shot.

With the more forgiving modern clubs, however, even off-centre impacts can sound good which players find ‘encouraging’ and a ‘confidence booster’.

With my own Callaway driver it goes off with a crack... even if it's not a great hit, and certainly when you play in Pro-Ams you find that... even if you miss hit it, if it goes off with a crack they all go, “Oh, that was a good shot”... you know if it was a piece of wood it would be a horrid thing.

Other effects of impact sound on the perceptions of the golfer will be discussed further in Section 2.5.1.

2.3.3 SHAFT FEEL

Golfers' perceptions associated with shaft flexibility and shaft length are grouped together in the general dimension ‘Shaft Feel’, as shown in Figure 2.6. ‘Shaft Flexibility’ is a high-order category that contains themes covering golfers’ perceptions of the shaft flexing when a club is either waggled or swung. The quotes are grouped into categories depending on whether the shaft was perceived by the golfer to be ‘too flexible’, ‘well suited’ or ‘stiff’.

The most popular way of describing a shaft that is unsuitable for the golfer is with the term ‘whippy’, if the shaft is too flexible, or ‘stiff’, if the shaft is not flexible enough.

The shaft is totally unsuited to me I should think, it feels very whippy, not very strong at all.
Shaft flexibilities that golfers considered were appropriate for their swings were described in a variety of ways, such as ‘well suited’, ‘firm’, or ‘together’ whilst, again, the term ‘solid’ was used.

I felt the shaft was solid and there wasn’t a lot of sort of kick in the shaft and it felt quite good really...

Two separate themes were created to accommodate the specific feel of the shaft twisting. General quotes were grouped together in the category ‘Twisting Feel in the Shaft’, whereas quotes that attributed the twist to an off-centre impact were collected together in the theme ‘Feel Club Twist From Off-Centre Shots’.

A number of golfers also described feeling the shaft ‘release’ or ‘kick’ prior to impact as the shaft recovered from the loading during the downswing. However, this was only considered desirable if the shaft released in time with the golfer’s swing.

The shaft for me was probably just a little bit too stiff. I felt as though there was no release. When I released, the club wasn’t releasing with me.

‘Feel of Shaft Length’ encompasses the quotes from golfers who perceived a difference in the lengths of the shafts.

With the difference in the length as well, it makes it far, far easier to generate or to create the feeling of width, which then generates more power.

2.3.4 CLUB WEIGHT

The dimension ‘Club Weight’ encompasses the golfers’ perception of differences in both overall weight and swingweight and is therefore sub-sectioned into these two themes, as shown in Figure 2.7. Swingweight is a measure of the weight distribution of a golf club about a fulcrum point usually 14 inches from the grip end of the club and is considered as a measure of the ease with which a club can be swung. Clubs with a large proportion of their mass distributed towards the clubhead have a heavy swingweight and therefore require more effort to swing.

Three themes emerged from the quotes describing the golfers’ perceptions of different swingweight. These three categories effectively divide the swingweight scale into three sections. Clubs perceived as having a heavy swingweight were described as being ‘head heavy’ or ‘shaft heavy’. At the other end of the scale, clubs perceived as having a light swingweight
were described as being ‘head light’ or ‘shaft light’, whilst clubs in between were described as being ‘balanced’.

From the top of the back swing when you change direction, if it’s very head heavy you just feel like the head’s going to be thrown out and you’re going to hit it very early and hook the pants off it.

It feels a nice club, it just feels very well balanced, as in the head and the shaft feel matched up...

‘Overall Weight’ covers the themes of the club having an overall ‘heavy’ feel or an overall ‘light’ feel.

Oh, dear. This feels very weighty, extremely weighty. It is a... let the club work for you sort of club.

It feels overall lighter, so it feels if I wanted to really lash one I could hit it and I’d feel I’m swinging the club, much more in control of the club... the club’s not wanting to overtake me.

2.3.5 CLUB CONTROL

The dimension ‘Club Control’ brings together the contrasting themes of the golfers’ feelings of being either in control or not in control of the club and is illustrated in Figure 2.8.

It’s when you hit the golf ball, if you don’t feel the club has swung you, if you feel you have control of the club, and the ball seems to come off with a proper spin on it, you’re happy.

It’s just because it’s steel, I think, you feel as though you’ve lost a little bit of control there. It feels as if there’s going to be a little bit more variation in the flight with a steel shaft.

2.3.6 FEEL OF CLUB POSITION DURING SWING

Golfers descriptions of being able to perceive where the clubhead is during the swing are grouped together in the general dimension ‘Feel of Club Position During the Swing’, which is illustrated in Figure 2.9. In order to produce a good shot, it is important that the golfer is able to feel the position of the clubhead during the backswing and downswing and its orientation at impact.

I can feel the head and the swing with this club. It feels quite nice really.
You need to know what is happening, you need, when you swing a golf club, to know where the club is, so that's extremely important, yes.

The effect of clubhead feel during the swing on a golfer's club control will be discussed further in Section 2.5.2.

2.3.7 GRIP

The feel of the grip is an important characteristic to golfers because it is their only contact with the club; quotes relating to the feel of the grip are grouped together in the general dimension ‘Grip’, which is illustrated in Figure 2.10. The main characteristics described by the golfers are the thickness, hardness, level of adhesion and harshness of the grip. Although the choice of grip is individual to the golfer, particularly the thickness, generally, 'soft', 'tacky' grips that do not slip in the hands are preferred to 'hard', 'harsh' or 'slippery' grips.

The actual thickness of the grip again, I think, is very important. There's one there, that Titleist, one with the Titleist head, the grip is a little bit thicker on that, which for me is too thick.

The grip that I'm using at the moment is the Golf Pride Tour Velvet one, which is just perfect really. It feels... soft, it's tacky, it still gets a little bit shiny but once you've scrubbed them again it's like brand new again.

A grip that is unsuitable, particularly if it may slip, can have a detrimental effect on a golfer's game.

If it feels like it's going to slip, you tend to strangle it and it stops your swing, I think.

2.3.8 BALL FLIGHT

Golfers descriptions of the flight of the ball are grouped together in the general dimension ‘Ball Flight’, which is illustrated in Figure 2.11. The major characteristics of the flight described include, distance, in terms of overall distance as well as carry and run, accuracy, flight trajectory and shape of flight.

Professional golfers tend not to have any difficulty getting the ball airborne and as a result they generally dislike a trajectory that is 'high', 'loopy' or where the ball 'climbs' during the flight. Much more desirable is a 'penetrating' or 'boring' trajectory that does not get too high, whilst some golfers prefer it to stay 'low'.
It felt as though it wasn't a piercing flight. Whether it was the way I struck the ball, but it seemed to be an up and over flight, looks like it got a lot of top spin on it, whether it had... so wet up there we'll never know. But it didn't seem to be like a more penetrative flight on the ball.

Golfers tend to prefer a 'penetrating' trajectory because the ball flight is less affected in windy conditions. However, it is perhaps more desirable for golfers to have a club with which they feel able to control the trajectory depending on the wind direction and the softness of the course.

The important thing for me is wanting to be able to alter the flight... if I wanted to hit a driver low into the wind, I want to be able to feel I can do that, and if I want to hit it high downwind, I want to be able to feel I can do that too... With my driver I definitely can do that.

It is also important for the golfer to be able to control the lateral shape of the flight and hit a draw or fade.

I would put the Callaway or the Titleist in that category where I could hit more of a different shot with it, which is very important of course.... It's no good just standing there and hitting the ball straight all the time, you've got to be able to draw it or fade it as you want to.

2.3.9 CLUB APPEARANCE

The major themes described within the general dimension 'Club Appearance', which is illustrated in Figure 2.12, are the 'Head Appearance' and the 'Club Posture'.

Over the years, golfers have adapted to the increase in size of the clubheads and, as result, prefer an oversize driver mainly because they are more forgiving when impacts are off-centre, although for many people some of the recent models are too big. The 'traditional', 'rounded' shape, however, is still preferred by the majority of golfers.

I think when the bigger ones first came out I wasn't very keen on them at all because they looked massive, but now they look quite standard and when you pick up a head of sort of ten years ago it looks tiny.

Tidy head on it... it hasn't got any frills, it's getting quite close to the persimmon driver. It just sits there, it's a nice almost semi-circle, no frills about it, just got a little Taylor Made logo on it, doesn't have any lines or strange grooves... it just sits there and says hit me.
A number of quotes describe the way in which the golfers perceived the club to sit when the ball was addressed and these themes are grouped together within ‘Club Posture’. If the sole of the clubhead did not sit flat on the ground, the lie angle was described as either ‘flat’ or ‘upright’ depending on whether the toe or the heel of the clubhead was off the ground. Golfers also described the angle of the clubface as being ‘open’, ‘square’ or ‘closed’ as well as the appearance of clubhead loft.

The appearance of the club as the golfer is addressing the ball can have a considerable psychological effect on the player.

I think if you look down at something and feel confident with it... you've got a much better chance of playing... and hitting a good shot. If you look down at something and you're not overly keen on the look of it, I think it's harder to convince yourself that you're going to hit a good shot.

The perception of the player, if he looks at that club and likes it... you're 99% of the way there, before he's hit a shot... and really the way that the club is sat on the ground is how people get the perception...

2.3.10 Golfers' Psychology

The final dimension ‘Golfers’ Psychology’, which is illustrated in Figure 2.13, contains themes describing general feelings of the player as well as quotes describing other factors that can have a psychological effect on the golfer. Feelings such as enjoyment, confidence, comfort and usability are grouped together as being a positive response to the equipment. In contrast themes covering a lack of enjoyment, unusable equipment and feelings of discomfort and hard work are grouped together as negative responses to the equipment.

Two further factors emerge as having a psychological effect on the golfer even before a shot has been hit, the overall feel of the club and familiarity with the brand.

It feels lovely... as soon as you pick a club up, you only have to have a couple of swishes with it... you feel as though you're going to be able to hit it. You know the composition's right from gripping the grip, having a couple of swings, you can feel the shaft, you can feel the head, you feel when the shaft is going to kick in and as soon as you pick a club up it's very evident you're going to be able to use it.

The reputation of a manufacturer, previous experiences with a particular club or brand and the perceived age of the club can cause the golfer to have significant preconceptions when presented with a club.
Whether this is psychology taking over, but as soon as you pick up something like this [a Callaway] or the Titleist I automatically feel better, I feel more comfortable.

The perception that you've got something that is behind the times automatically [makes you feel]... before you even pick the club up, that you haven't got something that you really quite want.

2.4 ANALYSIS LIMITATIONS

During this initial stage of the analysis, quotes were considered on the individual characteristics of the equipment or shot that were perceived by the golfer. To maintain the meaning of the quote, descriptions were kept whole. This often resulted in quotes containing a number of themes, which had to be coded into numerous base level categories. Take, for example, the following quotation:

The shaft is so flexible, I can feel that really flexing and twisting and turning, and for me, I just could not control it...

The golfer quoted above described three different perceptions; the shaft felt flexible, the shaft felt as though it twisted and the club felt uncontrollable. Initially, the quote was coded into the base level themes 'Flexible Feeling Shafts', 'Twisting Feel in the Shaft' and 'Uncontrollable Feel'. However, the quote also suggests that there is a relationship between the flexibility of the shaft and the degree of control the golfer has over the club. Further analysis of the data revealed numerous other inter-dimension relationships and it became apparent that the complete analysis could no longer be represented by simple tree-structures.

A relationship 'map' was initially created during the analysis to represent the alternative classification schemes, as shown in Figure 2.3, which could be used to categorise the data. Using the same themes as an example, Figure 2.14 illustrates the way in which a map can be used to represent dimensions with shared themes. Each dimension was then assessed in terms of redundancy and any remaining shared themes then became inter-dimension relationships. In the example illustrated in Figure 2.14, 'Feel From Off-Centre Shots' proved to be a redundant dimension as all the base level themes were linked to other dimensions and therefore could be recoded into them. Completeness checks were performed on the structure and a diagrammatic style developed to visually distinguish between each theme level and the inter-dimension relationships.
2.5 STRUCTURED RELATIONSHIP MODELLING

The structured relationship model that was developed from the initial map is illustrated in Figure 2.15 and contains the ten dimensions discussed in the previous section and the fifteen inter-dimension relationships, which are discussed in the following section.

2.5.1 RELATIONS INVOLVING THE SOUND AND FEEL FROM IMPACT

In the general dimension ‘Feel from Impact’, a sub-theme, entitled ‘Feel of Ball Behaviour’ was created for quotes describing the golfers’ perceptions of the ball compressing and releasing off the club face at impact. Several responses indicated that this feel from impact had an effect on both the perceived distance of the shot and their ability to control the shape of the flight. Generally, a shot that has a ‘lively’, ‘explosive’ feel is perceived to go further than a shot that has a ‘dead’ or ‘dull’ feel, although in reality it is not necessarily true.

I don’t think the ball goes quite as far. I don’t think it has quite the same bounce off the club face.

Now that ball went, like the Titleist one and my one. Though it hasn’t gone very far, it hasn’t gone any further than probably anything I’ve hit, it seemed to really explode off the club face and it felt really as though I’d hit it.

However, if the shot has a ‘dead’ feel then the ball is perceived to stay on the club face longer, which the golfers believe, enables them to control the shape of the flight and hit a draw or a fade.

It should be easier to play [draw or fade] shots [with traditional woods] because the ball stays longer on the club face. My perception of it is that, because it’s a softer textured club, that when the ball makes contact, the harder the face the quicker the ball releases off the club face where the softer, it stays on. So you’ve got more time to alter the flight.

I think the ball probably stays on the club head a bit longer with a traditional wood so you feel that you can shape it a wee bit more.

The effect of sound on the perceived quality of a shot has already been discussed in Section 2.3.2 and it has already been noted that there are a number of terms, such as ‘dead’, ‘dull’, ‘explosive’, ‘solid’ and ‘powerful’ that are used by golfers to describe both the impact sound and the feel in the hands from impact. This is unlikely to be a coincidence; several golfers indicated that there is a link between the sound and feel of a shot and it may be that other golfers were unable to distinguish which form of feedback was influencing their perceptions.
You take away the sound and all of a sudden the feel is lost.

Sound, it would appear, has a particular influence on the feel of ball behaviour.

It's a duller sound, so maybe the feel of the club has a lot to do with the sound it makes as well.

It might just be the sound of the club on the ball, but it feels as if it's just on there a bit longer, it feels a bit more of a crunch... forward... It sounds as if the ball is on the clubface longer.

As sound has an effect on feel of ball behaviour, and feel of ball behaviour has been found to influence perceived distance, it follows, therefore, that sound can have a direct affect on perceived distance.

When it first came out, people didn't use it because it sounded so loud. Now they quite like that sound and the duller sound doesn't sound like it's going so far.

Sounds sort of this explosion and it's gone, where as you get the ball that still goes but it sounds duller... I think your image may think, it's come off quicker, it's going to go further.

2.5.2 FACTORS AFFECTING CLUB CONTROL

The responses of the golfers indicate that there are a number of characteristics of a club, such as the weight, the length and flexibility of the shaft, and the players' perception of the club position during the swing that affect their ability to control the club. Golfers described the effect of shaft flexibility on the feeling of control particularly when the shafts were too flexible for them to control during their swing.

It doesn't feel like I've got as much control through the swing because the shaft is bending more than I'd like it to.

Shaft-wise it didn't feel very controllable. The shaft feels quite whippy.

Only one golfer made reference to the length of the shaft and its effect on control, believing he was more able to control clubs with shorter shafts.

It feels a lot shorter, [I'm] feeling more in control of this club because it's a lot shorter in the shaft.
The effect of the weight of the club on the feel of control over the club was a connection made by a number of the golfers interviewed. In general, golfers feel less in control of heavier clubs and more in control of lighter clubs.

Because the club head's a lot lighter with that one, you can actually feel you've got more control at the end.

It certainly felt so much heavier to me that... I wouldn't like to play with it at all. I'd feel it was controlling me and not me controlling it.

It cannot be concluded, however, that the lighter a club is made the more controllable it becomes, there appears to be an optimum weight for each golfer.

That feels like I've lost the feel of swinging a weight... I don't want to feel something that's too heavy, but I've lost the feel of swinging a weight with that, that felt very light.

The final characteristics found to affect club control is the golfers' perception of the position of the clubhead during the swing. If a golfer is unable to determine the location of the clubhead as it is being swung, the player finds it much more difficult to control

I feel I've no control over that head at all. I don't know where it is.

The shaft, it's an ultra light shaft and a heavier head so you can feel it a lot more during the swing, you feel a lot more in control.

If a golfer feels in control of a club then it gives the player more confidence to be able to shape the flight of the ball.

Just the feel of control of the head... when you're trying to shape shots, if you lose control, then, especially if you're trying to move it right to left, if you get a strong hook going... [it] could be very disastrous... 'cause it's a very strong shot. Yes, just all round control and feel of the club during the swing... the feel of the head.

Three of the characteristics that have been found to influence club control also appear to be inter-related. The flexibility of the shaft can have an effect on the perceived swingweight of the club and the golfers' feel of clubhead position during the swing. When a club had a more flexible shaft, golfers described feeling the head move more during the swing and this resulted in the perception of a heavier head.
I perceive that in a persimmon block, that the tip is almost too thin, which therefore makes this move a little bit more ... and that's what, for me, makes it [feel] a little bit heavier...

If the shaft is too stiff for the golfer, however, the player can lose the feel of the club during the swing.

When I swing it I like to be able to feel what the shaft is doing without feeling it has a mind of its own, meaning that it is not too flexible. If it is too flexible, I have no confidence that when it meets the ball it's going to be where I want it to be. If it's too stiff I lose any feel at all of the head.

Not only does the flexibility of the shaft affect a golfer's ability to feel the position of the head, it also affects how the golfer perceives the club to be performing through impact.

That shaft is horrific. That is so flexible. It feels so soft. It feels the clubface is coming way open into the golf ball.

That felt very stiff in the shaft... the others felt like the head was coming in too quickly, like the head was wanting to come in before the shaft. This one felt the opposite. This felt like the head was not wanting to strike the ball at all.

Finally, golfers are more able to feel the position of the clubhead during the swing if they perceive the swingweight of the club to be heavier.

Just the shaft, it just feels so light the head and everything, I can't feel where it is through the swing.

It feels a bit more like you're swinging a steel rod with a steel shaft. The shaft feels a bit heavier. When you're swinging it you can feel it a bit more.

2.5.3 RELATIONSHIPS INVOLVING CLUB APPEARANCE

It has already been mentioned that, when a golfer addresses a ball, the appearance of a club can have a considerable psychological effect, particularly on the player's confidence.

I think [head shape is] very important. You want to stand there and feel confident and if you like the look of the club, that's half the battle. If you like the look of it nine times out of ten you're going to feel confident you can hit it.

The posture of the club also affects whether the golfer feels able to control the shape of the flight, although the preferred lie and face angle is individual to the golfer.
Callaway have produced a club here which, to me is just a bit too upright and closed... toed in, which really suits the punters... Very easy to draw it without...any effort.

I prefer to look down at the head and it sits a little bit closed, I feel a lot happier with that because I feel as though I can shape it right to left or left to right.

2.6 DISCUSSION

The purpose of this study was to elicit and understand golfers’ perceptions of the equipment used when playing golf shots as previous studies had made only limited attempts to measure these subjective perceptions. This study has shown that manufacturers of golf products need to assess aspects of their equipment other than distance or power achieved. For example, a golfer needs to feel in control of the club and the subsequent flight of the ball, which, as the structured relationship modelling has shown, has direct implications for the weight of the club and the shaft fitted. Although only a relatively small number of golfers described these relationships, they suggest that such links exist. As Krane et al. (1997, p 215) state, ‘in many cases, rare experiences are no less meaningful, useful or important than common ones.’ Many golfers may have been unable to understand or explain, in this example, the source that results in a lack of control. It is also feasible that because the sample contains elite players, many of these golfers were able to adjust to variations in the equipment and able to control the many different clubs.

The emergence of these relationships certainly warrants further investigation. However, not all the dimensions will be of equal importance and so the results of this qualitative study were used to develop a postal questionnaire to quantify the feel of an ‘ideal’ golf shot and the relative importance of each dimension. In the next section the design of the postal questionnaire is described and the results discussed.

2.7 SELECTION OF FEEL CHARACTERISTICS FOR FURTHER STUDY

The number of characteristics of a golf shot of importance to the player that emerged was too great to enable each one to be studied in sufficient detail within the scope of this project. A number of characteristics of interest were selected, therefore, for further in-depth investigation.

Prior to, during and on completion of a golf shot, a golfer receives visual feedback from the club appearance and flight of the ball, tactile sensations in the hands during the swing and from impact and also auditory feedback from the impact sound. For the purposes of this study, feel characteristics were selected that were considered to be associated with the sound and vibration of the club from impact, which are those that are grouped together within the
general dimensions 'Feel from Impact' and 'Impact Sound', illustrated in Figure 2.4 and Figure 2.5 respectively. In terms of the feel in the hands, the characteristics that are of interest include the perceived vibration level from impact, the feel of ball behaviour during impact, the feel of solidity and the feel due to the ball type. Properties of the sound that are considered to be of interest include the perceived pitch, loudness and duration of the impact sound.

2.8 THE POSTAL QUESTIONNAIRE

A psychometric instrument was required to quantify, for each of the characteristics of interest, the feel of an 'ideal' golf shot and investigate the relative importance of the selected characteristics compared to the other dimensions that emerged. Now that the features of importance to the golfer are better understood, a technique was required that could reach a larger sample of people so that the results could be considered to be representative of all elite golfers. A postal questionnaire was, therefore, deemed the most appropriate technique.

2.8.1 PARTICIPANT SELECTION

It cannot be assumed that the same dimensions would have emerged had a different group of golfers, such as ladies, seniors or amateurs, been used. Therefore, the same criteria specified in the initial study were again used for the selection of participants and the questionnaire was sent to male professional golfers aged between 20 and 55.

For the results to be representative of the wider population of male, elite golfers, it was considered that a minimum of seventy-five completed questionnaires was necessary. Working on the basis of a 25% return rate, three hundred questionnaires were sent to golfers distributed across England.

2.8.2 QUESTIONNAIRE DESIGN

The first section of the postal questionnaire, which is included in Appendix 3, was used to obtain general information about the golfer's age and experience. The golfer was also asked to complete a description of the specification of their current clubs so that a database could be built up of popular equipment. This was done to aid the selection of clubs for later tests so that they would be appropriate for the standard of golfer.

The second section of the questionnaire was designed to obtain the 'ideal' feel for each characteristic of interest and their importance relative to each other and the remaining dimensions. For each of the selected characteristics, a 1 to 9 scale was used to quantify the golfers' 'ideal' feel. A 1 to 9 scale was used as it provided a balance between having enough
points so that the golfers could accurately rate their preferences without having to force their responses into the nearest available category but not so many as to be excessive. Descriptive words were used to give the scale orientation; where possible, the descriptive words were those used by the golfers during the interviews to describe each characteristic. These descriptors often form the base level themes of the tree structures and are sub-themes of the characteristics they are describing. Take, for example, the following question, phrased to measure the 'ideal' rating of 'Feel of Ball Behaviour':

**How quickly would you feel the ball to have come off the clubface?**

<table>
<thead>
<tr>
<th>Drug</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>'dead', ball comes off slowly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'lively', ball comes off quickly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The phrases 'dead', 'ball comes off slowly' and 'ball comes off quickly' are all base level themes of the high order sub-theme 'Feel of Ball Behaviour', as illustrated in Figure 2.4c.

For each of the seven characteristics of interest, a question was also phrased to measure their relative importance; again, these questions followed the same style, utilising a 1-9 scale. Instead of using descriptors from the analysis to give the scale orientation, the phrases 'not important', 'moderately important' and 'extremely important' were used. For example, the importance of 'Feel of Ball Behaviour' was obtained using the following question:

**How important is the feel of speed at which the ball comes off the clubface?**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not at all important</td>
<td>Moderately important</td>
<td>Extremely important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar questions were phrased to obtain the relative importance of the following characteristics:

i) Shaft flexibility
ii) Club weight
iii) Grip
iv) Flight trajectory
v) Distance
vi) Accuracy
vii) Control of flight shape
2.8.3 THE FEEL OF AN 'IDEAL' GOLF SHOT

A total of eighty-one completed questionnaires were received and a summary of the results is discussed in the following two sections. Graphs showing the spread of responses for the 'ideal' value of each of the seven characteristics selected are shown in Figure 2.16.

How would the impact feel in your hands? (See Figure 2.16a) With a mean rating of 4.21, the 'ideal' feel is neither very 'hard' nor very 'soft'. The standard deviation of 2.08 suggests that this is a characteristic that is very specific to the individual player and the range of preferences can be clearly seen from the spread of data in Figure 2.16a.

How much vibration would you feel in your hands? (See Figure 2.16b) The 'ideal' perceived vibration level is very low; the mean rating is just 1.75 and over 60% of the players preferred to feel 'no vibration'. Golfers appear more united in their desire for less vibration, as the spread of results is much less, resulting in a standard deviation of 1.27. This also suggests that, for some of the golfers, an impact can feel hard even if little vibration is perceived. This may be an indication that the definition of hardness of feel varies between players and that, for some golfers, factors other than just vibration, such as sound, may have an influence.

How solid would the shot feel? (See Figure 2.16c) Again, golfers are unanimous in their desire for a very 'solid' feeling golf shot. With a mean value of 8.43, a standard deviation of just 1.06 and over 65% of golfers responding with an 'ideal' rating of nine, it can be concluded that almost all golfers seek a very 'solid' feel to a shot.

How quickly would you feel the ball to have come off the clubface? (See Figure 2.16d) Ideally, golfers desire a livelier feel from impact; almost 70% of golfers gave a rating of seven or higher resulting in a mean rating of 6.94. With a standard deviation of 1.94, however, the preference again varies between individuals. This may be due to a number of golfers still preferring the feel of the traditional style clubs.

How would the impact sound? (See Figure 2.16e) It would appear that the majority of golfers prefer an impact sound that is neither 'dull' nor 'tinny', as the most popular response was five, and the mean rating is 5.43. Responses were received across the whole range suggesting some golfers like the 'tinny' sound often associated with the modern day clubheads whilst others like the traditional, 'dull' sound of the wooden heads. The tendency for the golfers to give a rating of five may have been because 'dull' and 'tinny' are considered undesirable sound qualities rather than because the golfers preferred a sound of medium pitch. If this is
the case, 'dull' and 'tinny' may not be the most suitable terms to place at the extreme ends of a scale that is intended to measure perceived pitch and this will need to be addressed if this style of question is persevered with in future tests.

**How loud would the impact sound be? (See Figure 2.16)** Generally, golfers appear to prefer a louder, more 'explosive' impact sound as approximately 90% of the golfers responded with a rating of five or greater, resulting in a mean rating of 6.32. The majority of responses are reasonably evenly distributed between five and nine.

**How long would the impact sound last? (See Figure 2.16g)** On the whole, a shorter, crisper sound tends to be preferred to a long, ringing sound; over 60% of the 'ideal' ratings are less than or equal to three, whilst the percentage response decreases as the scale, and therefore the duration of sound, increases.

### 2.8.4 The Relative Importance of Each Characteristic

The characteristics investigated are listed in order of their importance in Table 2.2 based on the mean rating given. The characteristics are also grouped into one of three different categories. The first category encompasses outcome variables and covers all the characteristics that are a result of the impact, such as accuracy, distance, flight shape and trajectory. The second category contains variables that have a direct effect on the outcome, such as the grip, the shaft and the weight of the club. The third category encompasses those characteristics that do not have a direct effect on the result of the shot but can affect the player's perception of the quality of the shot and the equipment. This category contains the characteristics related to the feel in the hands from impact, properties of the impact sound and the club's appearance.

In general, for a driver, the outcome variables are the most important, followed by those variables that can influence the outcome and finally those that do not have a direct effect on the result of the shot but can inform the golfer of the quality of the shot and equipment. The feel of the golf shot, however, is still important. For 'solid' feel, the mean importance rating is 8.44 whilst for hardness of feel, perceived vibration level, feel of ball behaviour and pitch of impact sound the mean importance ratings of 6.93, 6.39, 6.27 and 5.98 respectively indicate that these variables can still be considered to be crucial in the evaluation of golf equipment. It is also possible that golfers are not explicitly aware of the contribution of a characteristic such as the sound and, therefore, underestimate its significance. It is clear from these results that, although the feel of a golf shot is important, any changes that can be made to improve the feel of a club must not be done at the expense of performance.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Category</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>1</td>
<td>8.95</td>
<td>0.22</td>
<td>9</td>
</tr>
<tr>
<td>Control of flight shape</td>
<td>1</td>
<td>8.59</td>
<td>0.91</td>
<td>9</td>
</tr>
<tr>
<td>Flight trajectory</td>
<td>1</td>
<td>8.52</td>
<td>0.85</td>
<td>9</td>
</tr>
<tr>
<td>The grip</td>
<td>2</td>
<td>8.44</td>
<td>0.86</td>
<td>9</td>
</tr>
<tr>
<td>Solid feel</td>
<td>3</td>
<td>8.44</td>
<td>1.00</td>
<td>9</td>
</tr>
<tr>
<td>Distance</td>
<td>1</td>
<td>8.15</td>
<td>1.13</td>
<td>9</td>
</tr>
<tr>
<td>Shaft flexibility</td>
<td>2</td>
<td>8.10</td>
<td>1.71</td>
<td>9</td>
</tr>
<tr>
<td>Club weight</td>
<td>2</td>
<td>7.92</td>
<td>1.58</td>
<td>9</td>
</tr>
<tr>
<td>Club appearance</td>
<td>3</td>
<td>7.39</td>
<td>2.17</td>
<td>9</td>
</tr>
<tr>
<td>Hardness of feel</td>
<td>3</td>
<td>6.93</td>
<td>1.82</td>
<td>9</td>
</tr>
<tr>
<td>Perceived vibration level</td>
<td>3</td>
<td>6.39</td>
<td>2.92</td>
<td>9</td>
</tr>
<tr>
<td>Feel of ball behaviour</td>
<td>3</td>
<td>6.27</td>
<td>2.04</td>
<td>5</td>
</tr>
<tr>
<td>Pitch of impact sound</td>
<td>3</td>
<td>5.98</td>
<td>2.59</td>
<td>5</td>
</tr>
<tr>
<td>Loudness of sound</td>
<td>3</td>
<td>4.98</td>
<td>2.32</td>
<td>5</td>
</tr>
<tr>
<td>Duration of sound</td>
<td>3</td>
<td>3.67</td>
<td>2.49</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.2 – Relative importance of each characteristic

2.9 SUMMARY

The purpose of this study was to identify the characteristics of a golf shot of importance to the golfer and in so doing develop a formalised, qualitative approach for the elicitation of players' perceptions of equipment during play that could be applied in other sports. Ten general dimensions emerged from an inductive analysis of golfers' responses obtained during a series of interviews, whilst further analysis suggested relationships between the dimensions. A technique named structured relationship modelling was developed to represent both the tree-structures that emerged from the inductive analysis and the inter dimension relationships. Finally, a postal questionnaire was used to ascertain the 'ideal' feel and relative importance of the emergent characteristics. The results suggest that although the feel of a golf shot is important, the performance of a club should not be sacrificed to improve feel.
CHAPTER 3

IMPACT DURATION: MEASUREMENT TECHNIQUES AND CORRELATION WITH GOLFERS’ PERCEPTIONS

3.1 INTRODUCTION

The purpose of conducting the interviews with elite golfers and the subsequent inductive analysis of their responses was to elicit the thoughts and opinions of importance to them and to structure the many different themes discussed. Having identified the important characteristics of a golf shot, the next stage in the project was to investigate a number of the emergent characteristics further by correlating the golfers’ subjective perceptions with objective data.

During the interviews, the golfers frequently described their perception of the compression and release of the ball off the clubface and their quotes were grouped together within the high-level theme ‘Feel of Ball Behaviour’, illustrated in Figure 2.4c.

My perception of it is that, because it’s a softer textured club, that when the ball makes contact... the harder the face the quicker the ball releases off the clubface where[as] the softer [the longer], it stays on.

I think the ball probably stays on the club head a bit longer with a traditional wood so you feel that you can shape it a wee bit more.

With the persimmon it’s almost as if everything becomes a lot more compressed so the actual speed of the ball off the clubface ... feels much slower, ... it just feels dead.

The ball comes off an awful lot quicker and it feels an awful lot more powerful, whereas [with] the wooden headed club it seemed to absorb the ball and it came off with hardly any power on it at all. Whereas this [titanium] club feels as though it comes off an awful lot quicker.

Generally, golfers perceive that the ball is ‘absorbed’ by traditional wooden clubs increasing the contact time between ball and clubface and decreasing the speed at which the
ball leaves the clubface. With modern titanium clubs, they believe the face to be ‘harder’ and perceive the ball to come off the clubface quickly with increased velocity and a reduced contact time. This feel from impact has a direct influence on the perceived quality of the shot played and is used as an indicator of club performance.

However, since the duration of a golf impact has been estimated in previous studies to be approximately 0.5 ms (Cochran and Stobbs, 1968; Gobush, 1990; Scheie, 1990; Ujihashi, 1994; Hocknell, 1998b), it is debatable whether a human can accurately determine small variations in such short periods of time.

The following chapter investigates whether golfers' perceptions of impact duration correlate with measured values for a range of conditions including different clubhead types, ball constructions, ball compressions and clubhead speeds. Correlation of golfers' perceptions with ball velocity will be investigated later in the thesis. Should golfers be unable to determine differences in impact duration and ball velocity then other factors such as club vibration, impact sound or ball flight may be influencing their perceptions. If the mechanism for generating these perceptions can be understood then it may be possible to design this feel into a golf club.

3.2 MEASURING IMPACT DURATION

Three different techniques, force plates, high-speed cameras and electrical circuits, have previously been used for measuring the duration of sports ball impacts. In the following section, the results from different studies are compared and the relative merits of the three techniques discussed, a summary of which is provided in Table 3.1. The selection of an appropriate method for this study is justified and the chosen measurement technique is then developed further.

3.2.1 FORCE PLATES

The projection of a ball onto a force plate is a popular method that has been used in a number of sports to investigate characteristics of ball impacts. The force profiles obtained during the collision can be of relevance particularly when studying injury potential. In a study by Cross (1999), balls from tennis, golf and baseball were dropped onto a ceramic piezo disk. With a velocity at impact of 2.95 m/s, the impact duration of the tennis ball was 5.75 ms, the velocity at impact of the baseball was 1.25 m/s and the impact duration was 2.20 ms whilst the golf ball impact velocity was 1.47 m/s and the duration of impact was 0.94 ms. The ball velocities at impact in this study, however, were considerably slower than those occurring in play. Ball velocities typical of those generated during a shot with a mid-iron were achieved in
a study by Gobush (1990) of the forces acting on golf balls during oblique impacts. Two different construction golf balls were fired by an air cannon at 29 m/s onto a three-component force plate, adjustable in angle, to obtain normal and tangential force profiles during impact. Impact durations were measured at 436 and 442 μs for the two piece and wound balls respectively when striking the plate at an angle of 20° (70° to the axis of ball flight), increasing to 468 and 476 μs respectively when the plate was adjusted to an angle of 40°. In another study of the dynamic characteristics of golf balls, Ujihashi (1994) fired a selection of balls at speeds from approximately 37 to 48 m/s at a circular steel bar, instrumented to function as a load cell. Impact durations were measured at approximately 420 μs for balls of a two-piece construction and up to approximately 480 μs for balls of a three-piece wound construction but it was unclear whether impact duration varied with ball velocity. Hendee et al. (1998) conducted a study to investigate the effect on impact characteristics of different baseball constructions at impact speeds from 13.4 to 40.2 m/s (30 to 90 mph) using a rigidly mounted force plate. The authors estimated the impact duration of a baseball travelling at 26.8 m/s (60 mph) to be approximately 650 μs. Finally, in two related studies, Armstrong et al. (1988) and Levendusky et al. (1988) investigated the effects of football characteristics on impact dynamics by dropping balls onto a force plate. With impact velocities ranging from 9.6 to 9.84 m/s, an increase in inflation pressure was found to decrease impact duration from 12.40 ms at 41 kPa (6 psi) to 11.67 ms at 83 kPa (12 psi) and the mean impact duration of 12.13 ms with stitched balls was found to be marginally longer than the 11.94 ms with moulded balls (Armstrong et al., 1988). This relationship was also shown to hold true at greater impact velocities of 17 to 18 m/s, with the mean impact duration for the stitched balls now being measured at 10.76 ms compared to 10.24 ms for the moulded balls (Levendusky et al., 1988).

3.2.2 HIGH-SPEED IMAGING

A popular method of studying impacts and measuring impact duration is to use a high-speed camera. Difficulties can arise when filming more dynamic sports such as tennis or football as, during play, both human and ball are generally in motion so the impact location is unpredictable and camera placement is problematic. In such studies the usual procedure has, therefore, been to have either the ball or surface stationary prior to impact. In an investigation of tennis impacts by Baker and Putnam (1979), a tennis ball practice machine was used to fire tennis balls at approximately 28 m/s at stationary rackets. Impacts were filmed at rates slightly in excess of 2400 frames/second (0.42 ms/frame) and the impact duration was found to be approximately 4 ms. In studies of football by Tsaousidis and Zatsiorsky (1996) and Asai and Akatsuka (1998), the ball was stationary prior to impact.
Tsaousidis and Zatsiorsky (1996) used a camera capable of 4000 frames/second (0.25 ms/frame) to measure impact durations of approximately 25 ms when a football was 'toe kicked' with maximum effort. In comparison, Asai and Akatsuka (1998) used a camera capable of 4500 frames/second (0.22 ms/frame) to measure impact durations of 8.2 and 10.5 ms when two free kick situations 25 to 30 m from goal were simulated. Conveniently, in golf, the ball is always stationary prior to impact and therefore there is no need to manipulate play conditions when using high-speed cameras to film an impact. In a study conducted by Scheie (1990), impact durations of approximately 420 μs were measured between a golf ball and a metal wood, swung at 50.3 m/s by a mechanical robot, using a camera configuration capable of filming 19,100 frames/second (52 μs/frame).

3.2.3 ELECTRICAL CIRCUITS

A third technique to measure impact duration, that has been used by Cochran and Stobbs (1968) and Hocknell (1998b) in golf and Johnson et al. (1973) in football, involves creating an electrical circuit in which the surface and ball act as a 'switch'. During impact, the circuit is complete for a period of time equal to the duration of contact between the two bodies, thus the impact duration can be obtained by measuring the width of the electrical pulse. To enable the circuit to be formed, the two surfaces of the contacting bodies must be conductive. In the study by Johnson et al. (1973), both a football and a rigid plate were covered in a layer of copper foil and the impact duration measured between the two varied from 8.3 ms for a ball striking the plate at 2.68 m/s to 7.5 ms for a ball impacting with a velocity of 7.53 m/s. Cochran and Stobbs (1968) reported the impact duration for a putt with the putter head travelling at 12 feet per second to be 600 μs. In the study by Hocknell (1998b), a metal 'wood' was used and a 100 μm thick copper strip was pressed into the cover of a ball during manufacture. The subsequent duration of impact for a club swung by a golf robot with a head speed of 35 m/s was measured at 450 μs.

3.2.4 SELECTION OF MEASUREMENT TECHNIQUE

The reasons behind the selection of an appropriate measurement technique for this study are summarised in Table 3.1 and outlined below. The force plate method for measuring impact duration was rejected because the data, although a useful indicator of impact characteristics, is only an accurate measure of impact duration between a ball and a rigid surface. During impacts between ball and implement or ball and human, significant differences in impact dynamics will occur as the impacting surface will not necessarily be flat, rigid or stationary. In addition, post impact vibration of the transducer makes it difficult to determine the instant at which separation occurs.
<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Sport</th>
<th>Investigators</th>
<th>Impact Duration Measured (ms)</th>
<th>Suitability of Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Plate</td>
<td>Golf</td>
<td>Gobush (1990)</td>
<td>0.4 - 1.0</td>
<td>Accuracy and measurement resolution excellent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ujihashi (1994)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cross (1999)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Baseball</td>
<td>Hendee et al. (1998)</td>
<td>0.6 - 2.2</td>
<td>Unrealistic testing conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cross (1999)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tennis</td>
<td>Cross (1999)</td>
<td>5.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Football</td>
<td>Armstrong et al. (1988)</td>
<td>10.2 - 12.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Levendusky et al. (1988)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-Speed Imaging</td>
<td>Golf</td>
<td>Scheie (1990)</td>
<td>0.4</td>
<td>Measurement resolution insufficient for this study</td>
</tr>
<tr>
<td></td>
<td>Tennis</td>
<td>Baker &amp; Putnam (1979)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Football</td>
<td>Tsousidis &amp; Zatsiorsky (1996)</td>
<td>8 - 25</td>
<td>More realistic testing conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Asai &amp; Akatsuka (1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Circuit</td>
<td>Golf</td>
<td>Cochran &amp; Stobbs (1968)</td>
<td>0.4 - 0.6</td>
<td>Accuracy and measurement resolution excellent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hocknell (1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Football</td>
<td>Johnson et al. (1973)</td>
<td>7.5 - 8.3</td>
<td>More realistic testing conditions</td>
</tr>
</tbody>
</table>

Table 3.1 – Comparison of techniques used for measuring impact duration in sport

The use of high-speed cameras enables measurements to be taken in more representative conditions but it is not without its limitations. The start and end points of contact are difficult to determine and the resolution of the measurement is limited by the frame-rate of the camera. For example, the camera system used in the study by Scheie (1990) resulted in a measurement resolution of 1/8 of the impact duration. A camera capable of 40,000 frames per second was available for this study but the technique was deemed unsuitable because the measurement resolution would still be too coarse to detect differences in impact duration below 25 ms.

The electrical circuit technique was, therefore, adopted for measurement of impact duration in this study because it is suitable for use with a real club and ball and it offers appropriate measurement resolution.
3.2.5 DEVELOPMENT OF MEASUREMENT TECHNIQUE

The electrical circuit technique, which has been used previously to measure the impact duration of both a full golf shot (Hocknell, 1998b) and a putt (Cochran and Stobbs, 1968), requires the two contacting surfaces to be conductive. Providing a metal clubhead is used, and any non-conducting surface finish is removed, then the only concern is applying a conductive layer to the golf ball. In the study by Hocknell (1998b), a 100 μm thick copper strip was pressed into the cover of a ball during production. However, as this procedure requires the involvement of ball manufacturers, it restricts the number of different ball types that can be compared and the process is also time consuming. For the purposes of this study, a more suitable method of applying a conductive layer quickly and easily to any golf ball was required and so alternative techniques were investigated.

Three methods of covering an area of the ball with a conductive layer were compared; embedding a copper strip during manufacture, as in the study by Hocknell (1998), attaching a 70 μm thick aluminium foil strip with an acrylic pressure sensitive adhesive and painting on a silver conductive coating, as illustrated in Figure 3.1. A long, lightweight wire was joined to each ball by soldering it to a small patch of metallic tape. The tape, with a conductive adhesive backing, was attached to the surface of the conductive covering away from the impact area, as illustrated in Figure 3.2.

To compare the three techniques, five unused balls with a copper strip pressed into them were selected. A driver was placed in a golf robot such that the impact would be located in the centre of the face and the circuit illustrated in Figure 3.3 connected. The role of the capacitor was to filter out high frequency noise from the trace. Three shots were hit with each ball, with a clubhead speed immediately prior to impact of 44.7 ± 0.45 m/s (100 ± 1 mph). The pulse width was measured at 50% of the maximum pulse amplitude and the pulse fall time measured the transition time of the falling edge from 90% to 10% of the maximum amplitude, as illustrated in Figure 3.4. The results of the fifteen shots were then averaged before the procedure was repeated with the same five balls being prepared using each of the two alternative methods. Example traces from shots using each of the three techniques on the same ball are shown in Figure 3.5. The means and standard deviations of the pulse widths and fall times from the fifteen shots using each of the three techniques are summarised in Table 3.2. In addition, the standard deviations of the three shots with each individual ball for each technique were averaged and are also included in the table.
<table>
<thead>
<tr>
<th>Method</th>
<th>Pulse Width (μs)</th>
<th>Pulse Fall Time (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Embedded Copper Strip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of 15 Shots</td>
<td>397.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Standard Deviation of 15 shots</td>
<td>8.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Mean Standard Deviation for Each Ball</td>
<td>3.6</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Aluminium Foil Strip</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of 15 Shots</td>
<td>408.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Standard Deviation of 15 shots</td>
<td>9.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Mean Standard Deviation for Each Ball</td>
<td>2.5</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Silver Conductive Paint</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average of 15 Shots</td>
<td>406.3</td>
<td>29.7</td>
</tr>
<tr>
<td>Standard Deviation of 15 shots</td>
<td>16.1</td>
<td>17.1</td>
</tr>
<tr>
<td>Mean Standard Deviation for Each Ball</td>
<td>16.0</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 3.2 – Impact duration measurements for each ball covering technique

A comparison of the results from the aluminium foil technique with the copper strip method reveals a number of notable points. The contact duration measured using the aluminium foil method is on average 10 μs longer than the copper impregnated strip technique. The mean pulse fall time measured using both techniques is approximately 3 μs and is attributable to the discharge of the capacitor. As can be seen from Figure 3.5a and Figure 3.5b, both techniques produce a pulse with a sharp, distinct endpoint. For both methods, the standard deviation of the measured contact durations for the fifteen shots with five balls is approximately 9 μs, which is larger than the mean standard deviation for the three shots with each individual ball of approximately 3 μs, about 1% of the impact duration, which is close to the variation in clubhead speed. This indicates that variability in nominally identical balls has a greater influence on deviations in measured impact duration than inconsistency in the measurement technique. Finally, the measured contact times using the copper impregnated strip became successively longer by on average 2 to 3 μs with each shot with each ball, which may have been due to the strip becoming detached from the ball surface.

There are two possible explanations for the difference of 10 μs in contact duration between the two techniques. Observation of the aluminium strip after each shot revealed that
the foil had been forced into the grooves of the clubface during impact. If the foil then became trapped as the ball released from the clubface, an increase in the measured duration of contact may have resulted. It is also possible that the copper strip was stiff enough to affect the properties of the ball cover and decrease the contact time.

The application of silver conductive paint was expected to have the least effect on the impact but in practice, a problem became apparent, as illustrated in Figure 3.5c. Towards the end of an impact, the pulses often had an inconsistent and indistinct endpoint. As a result, the standard deviations of both the pulse widths and the fall times of the measured pulses are large and a number of the contact times measured may have been shorter than in reality, rendering this method inappropriate for this study. This effect may have been a result of the coating losing integrity during the large deformation of the ball that occurs at impact.

The results from this method can still be used to support the other techniques because, having the least influence on the ball's own properties, the method is likely only to underestimate the contact duration. Therefore, it appears that the actual impact time is longer than that measured using the impregnated copper strip and is closer to the time measured using the aluminium foil. A major consideration was that the copper strip would have to be pressed into the ball during manufacture, whereas the aluminium foil could easily be attached to any ball making this the most suitable method for this investigation. The foil also proved useful for attaching to the faces of non-conducting clubheads such as the traditional wooden headed clubs.

3.3 EFFECT OF CLUBHEAD TYPE AND BALL CONSTRUCTION ON IMPACT DURATION

The first test was to investigate the effect of clubhead type and ball construction on impact duration. For this test, five different types of clubhead and two different types of ball construction, which had previously been used during the interviews, were selected. The clubheads used were:

i) Titleist 975D – a modern, oversize titanium clubhead

ii) Callaway Great Big Bertha (GBB) – a modern, oversize titanium clubhead

iii) Taylor Made Burner – a modern, stainless steel clubhead

iv) Ping Eye 2 – a traditional, laminated wood clubhead

v) Slazenger Persimmon – a traditional, persimmon wood clubhead
The balls used were:

i) Precept EV – a two piece, surlyn covered ball

ii) Titleist Tour Balata – a three piece, wound, balata covered ball

Each club, in turn, was set up in an electrically powered golf robot such that the impact would be located at the geometric centre of the clubface, with the clubhead travelling at 44.7 ± 0.45 m/s (100 ± 1 mph) immediately prior to impact. Five balls of each type were randomly selected and hit five times with each club. The mean mass of the two-piece balls was 45.9 g, standard deviation, \( \sigma = 0.1 \) g, and the mean mass of the three-piece balls was 45.5 g, \( \sigma = 0.2 \) g.

The results from this test are illustrated in Figure 3.6. It can be seen that the mean impact duration with the three-piece, wound, balata ball is approximately 16 \( \mu \)s longer than with the two-piece ball, regardless of club type. A \( p \)-value of 0.000 was obtained when a two-sample \( t \)-test was conducted on the impact durations for each ball type; the ball impact durations can therefore be considered to be significantly different. The variation in mean impact duration of 12 \( \mu \)s between the Taylor Made Burner and the Titleist 975D, the clubs with the shortest and longest impact durations, is smaller than that due to ball type. A two-sample \( t \)-test was performed on each club combination with each ball to determine the significance between the impact durations. For a golfer to be able to determine differences in impact duration, a significant difference in the mean values for each club would be required. The \( p \)-values computed from each two-sample \( t \)-test are shown in Table 3.3. Assuming a level of significance of 0.05, \( p \)-values greater than this, which are shown in italics, indicate that the mean values of impact duration for the two clubs being compared cannot be considered to be significantly different.

It can be seen from the results in Table 3.3a that with the two-piece ball only one pair of clubs, the two traditional wooden headed clubs, have statistically similar impact durations. In rank order, the longest impact duration is with the Titleist 975D followed by the Callaway GBB, which is followed by the two traditional style clubs. Finally, the shortest impact duration is with the Taylor Made Burner.

A similar pattern emerges when the results with the three-piece, wound ball in Table 3.3b are analysed. In addition, however, the differences between the Callaway GBB and the persimmon clubhead and the Ping Eye 2 and the Taylor Made Burner are not significant. This is attributable to the larger standard deviation of results from the three-piece wound balls compared to the two-piece balls. It can be seen from Figure 3.7 that in many cases the
### Table 3.3 – Computed p-values from two sample t-tests on each club combination with each ball type

<table>
<thead>
<tr>
<th>club combination</th>
<th>Titleist 975D</th>
<th>Callaway GBB</th>
<th>Persimmon</th>
<th>Ping Eye 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Precept EV – two piece ball</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>0.033</td>
</tr>
<tr>
<td>Taylor Made Burner</td>
<td>0.000</td>
<td>0.000</td>
<td>0.006</td>
<td>0.197</td>
</tr>
<tr>
<td>Ping Eye 2</td>
<td>0.000</td>
<td>0.001</td>
<td>0.282</td>
<td>0.283</td>
</tr>
<tr>
<td>Persimmon</td>
<td>0.000</td>
<td>0.015</td>
<td>0.165</td>
<td>0.165</td>
</tr>
<tr>
<td>Callaway GBB</td>
<td>0.001</td>
<td>0.000</td>
<td>0.283</td>
<td>0.283</td>
</tr>
</tbody>
</table>

variation in impact duration between balls supposedly of the same construction and compression is greater than that found between clubs, which has resulted in difficulties in identifying true differences between clubs. The variability between balls of the same construction can be attributed to the tolerances in the manufacturing process resulting in varying ball compressions, particularly with the wound balls where consistency in the winding process is more difficult to achieve.

Before comparisons of the results with the golfers’ perceptions can be made, the effect of clubhead speed on impact duration must be considered. In this first test, the clubhead speed was kept constant at 44.7 ± 0.45 m/s but golfers will attain different clubhead speeds due to variations in club weight and length. In addition, differences in the strength, flexibility and ability of individual golfers will have a large effect on the clubhead speed each is able to generate. A comparison of the weights, swingweights and lengths of the test clubs is shown in Table 3.4. Swingweight is a measure of the weight distribution of a golf club about a fulcrum point usually 14 inches from the grip end of the club. To obtain the swingweight of a club, the moment required to balance the club about the fulcrum is measured and converted to a value on an alphanumeric scale, with A0 equivalent to a moment of 161 inch-ounces and
FO equivalent to 248.5 inch-ounces (in the golf industry, imperial units are still predominantly used).

<table>
<thead>
<tr>
<th>Club</th>
<th>Weight (g)</th>
<th>Swingweight</th>
<th>Length (in.)</th>
<th>Shaft Material</th>
<th>Loft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titleist 975D</td>
<td>330</td>
<td>D8</td>
<td>45 ⅛</td>
<td>Graphite</td>
<td>10.5°</td>
</tr>
<tr>
<td>Callaway GBB</td>
<td>309</td>
<td>D0</td>
<td>45</td>
<td>Graphite</td>
<td>8.0°</td>
</tr>
<tr>
<td>Ping Eye 2</td>
<td>359</td>
<td>C8</td>
<td>43 ½</td>
<td>Steel</td>
<td>12.0°</td>
</tr>
<tr>
<td>Persimmon</td>
<td>368</td>
<td>D0</td>
<td>43 ⅛</td>
<td>Steel</td>
<td>10.0°</td>
</tr>
<tr>
<td>Taylor Made Burner</td>
<td>317</td>
<td>D5</td>
<td>44 ½</td>
<td>Graphite</td>
<td>10.5°</td>
</tr>
</tbody>
</table>

Table 3.4 — Specification of clubs used

It can be seen from these results that the traditional style clubs are significantly heavier and shorter than the modern clubs and it is likely that the golfer will generate less head speed with these clubs. In the tactile sensation test, described later in the thesis, four of the five clubs used in this study were again incorporated and the clubhead speeds generated by fifteen elite golfers, hitting five shots with each club were measured and shown to vary from 34.7 to 50.1 m/s among the group. On average, the golfers swung the Callaway GBB fastest with the two traditional wooden headed clubs 1.7 m/s slower and the Titleist 975D 0.5 m/s slower.

As a result of the findings from this test, a second stage of testing was conducted to investigate the effect of clubhead speed and ball compression on impact duration.

3.4 EFFECT OF BALL COMPRESSION AND CLUBHEAD SPEED ON IMPACT DURATION

Although many golf balls are graded as being nominally ‘90’ or ‘100’ compression, tolerances in the manufacturing process mean that, in reality, a wider range of compressions are found in each category. Sullivan and Melvin (1994) reported that 90 compression balls typically have compression values in the range 85 to 100, and 100 compression balls range from 95 to 105. Therefore, the first stage of the investigation was to identify a selection of balls of similar construction with compression values close to the standard values of 80, 90 and 100. The Titleist Tour Professional, a three piece, wound, elastomer covered ball type, was selected for these tests as it could be purchased in both 90 and 100 compression ranges and it was anticipated that, on compression testing, samples as low as 80 compression would be revealed.
To determine the compression of each golf ball, an Instron 4411 Series IX Automated Materials Testing System was used to compress the balls. There is no international standard for ball compression measurement; manufacturers follow similar methods but the formulae used generate slightly different values. For this test, the procedure used by a leading ball manufacturer was employed, which involved applying a 35.6 N (8 lbf) pre-load to the ball, followed by the application of a further 409.2 N (92 lbf). The deflection of the ball, \( \delta \), from the pre-load to the final load was measured in thousandths of an inch and the compression value of the ball calculated using equation (3.1).

\[
\text{Compression} = 188 - 2\delta 
\]  

(3.1)

Each ball was loaded in three mutually perpendicular directions using the manufacturer's logo to locate the principal axis and the results averaged to give a compression rating for each ball. In total, sixty-six nominally 90-compression balls and forty-eight nominally 100-compression balls were tested. Four balls were identified with a mean compression of 81.4, standard deviation, \( \sigma = 0.5 \), which had a mean mass of 44.4 g, \( \sigma = 0.3 \) g, and five balls were selected with a mean compression of 90.7, \( \sigma = 1.4 \), which had a mean mass of 45.0 g, \( \sigma = 0.1 \) g. A further five balls were identified with a mean compression of 100.0, \( \sigma = 0.7 \), that had a mean mass of 45.0 g, \( \sigma = 0.1 \) g.

Each of the fourteen balls was hit five times with the Callaway GBB. Again, the club was aligned so that the impact was located at the geometric centre of the clubface with a head speed of 44.7 ± 0.45 m/s (100 ± 1 mph) immediately prior to impact.

The effect of ball compression on impact duration is illustrated in Figure 3.8, which shows the mean impact time for each ball plotted against its compression rating. It can be seen that a 20-unit reduction in ball compression from 100 units results in an increase in impact duration from a mean of 446 \( \mu \)s to a mean of 490 \( \mu \)s. Figure 3.8 shows a larger difference between the 80 and 90 compression balls than between the 90 and 100 compression balls.

Finally, a single ball was selected from each compression category and struck five times at each clubhead speed ranging from 31.3 ± 0.45 to 53.6 ± 0.45 m/s (70 ± 1 to 120 ± 1 mph) in 4.47 m/s (10 mph) increments, as this was considered to represent the range of clubhead speeds attained by golfers from amateur level to tournament professional. Care was taken to ensure a centre impact location after each speed change. The 80, 90 and 100 compression balls selected had masses of 44.2 g, 45.2 g and 44.9 g respectively.
Figure 3.9 illustrates that, over this range, the average difference in impact duration between the 80 compression ball and the 90 compression ball is 26.1 μs but between the 90 and 100 compression balls this difference has reduced to 18.5 μs, consistent with the results shown in Figure 3.8. This suggests that there is a non-linear relationship between ball compression and impact duration.

Figure 3.9 also illustrates the effect of clubhead speed on impact duration within the speed range tested. Impact duration reduces as clubhead speed is increased, in this case by approximately 65 μs over the 22.3 m/s range used, regardless of ball compression. It can also be estimated that a decrease in clubhead speed of 1.7 m/s from 44.7 m/s, the clubhead speed used in the first test, will result in an increase in the duration of impact of the order of a few microseconds. Therefore, if the clubs were swung at speeds comparable with those attained by a golfer instead of at constant speed, it is predicted that the difference in impact duration between the traditional clubs and the Callaway GBB would decrease, further reducing the statistical significance between the means.

In conclusion, the impact durations achieved with the Callaway GBB and the two traditional style clubs can be considered to be similar, whilst the impact duration with the Titleist 975D is statistically significantly longer and the stainless steel club statistically significantly shorter, differences are of the order of a few microseconds.

3.4.1 Hertz Law and Impact Duration Estimation

The effects of clubhead speed and ball compression illustrated in Figure 3.9 can be compared with theoretically obtained values. Hertz law of contact, which was originally developed for static contact, relates the contact force, \( F \), to the contact approach deformation, \( \sigma_D \), (Goldsmith, 1960).

\[
F \propto \sigma_D^{3/2}
\]  
(3.2)

Hertz law of contact is also applicable to colliding bodies, providing that the contact area is small compared to the dimensions of the colliding bodies and the duration of impact long in comparison with the period of the lowest mode of vibration of the bodies. Although a golf impact does not meet these requirements, Hocknell (1998b) showed that a reasonable estimation of impact duration, \( \tau \), could still be achieved with the following formula, derived from Hertz Law (Goldsmith, 1960).
Where,

\[
\delta_a = \frac{1 - \nu_a^2}{\pi E_a} \quad \text{and} \quad \delta_b = \frac{1 - \nu_b^2}{\pi E_b}
\]

The following are typical values: for a titanium clubhead, Young’s modulus \( E_a = 110 \, \text{GN/m}^2 \) and Poisson’s ratio \( \nu_a = 0.33 \), and for a golf ball, mass \( m_b = 0.0449 \, \text{kg} \) and radius \( R_b = 0.02133 \, \text{m} \). In the study by Hocknell (1998b), the value of Young’s modulus for the core material of a golf ball was found to be strain rate dependent. From static compression tests, a Young’s modulus of 85.7 \( \text{MN/m}^2 \) was obtained at a low strain rate, increasing to 164.4 \( \text{MN/m}^2 \) when the strain rate was increased to the highest available of 10 \( \text{m/s} \). In addition, a value of 0.48 was used for Poisson’s ratio. Other studies have reported values of 50 \( \text{MN/m}^2 \) and 0.49 (Thomson et al., 1990) and 103.4 \( \text{MN/m}^2 \) and 0.49 (Chou et al., 1994) for Young’s modulus and Poisson’s ratio respectively.

Theoretical curves, obtained using values from each aforementioned study with equation (3.3), are plotted alongside the experimental data in Figure 3.10. It can be seen that the experimental results fall well within the limits of the two extreme curves and show good agreement with the curves obtained using values of Young’s modulus of 85.7 and 103.4 \( \text{MN/m}^2 \).

It is interesting to note that the curve obtained with a Young’s modulus of 164.4 \( \text{MN/m}^2 \) underestimates the impact duration. This value was obtained with the highest available strain rate of 10 \( \text{m/s} \) but this is still considerably lower than occurs at impact. Hocknell (1998b) found that the stiffness of a golf ball was strain rate dependent with the value of Young’s modulus increasing with strain rate. At impact, therefore, a ball would be expected to behave in an even stiffer manner than in the compression test conducted by Hocknell (1998b); this will, however, reduce the duration of impact even further.

It can also be seen from Figure 3.10 that the gradients of the experimental curves are marginally greater than the theoretical curves with impact durations approximately proportional to \( v_0^{-1/4} \) rather than \( v_0^{-1/5} \) as in equation (3.3).
3.5 CORRELATION BETWEEN GOLFERS' PERCEPTIONS AND IMPACT DURATION

The responses of the golfers interviewed during the study described in Chapter 2 indicated that the impact duration was generally perceived to be longer with the traditional wooden headed clubs than with the modern titanium headed drivers. The results of this investigation, however, do not correspond with the golfers' perceptions. The longest impact duration was achieved with a titanium clubhead, whilst traditional wooden heads were shown to give marginally shorter duration impacts. It is also debateable whether a human can perceive variations of a few microseconds in impact durations of less than 0.5 ms. Therefore, the golfers' perceptions appear to be influenced by other factors, indeed one of the quotes suggests that the sound of the impact may have a significant influence.

It might just be the sound of the club on the ball but it feels as if it's just on there a bit longer...

Modern, hollow, metal headed drivers tend to produce louder impact sounds that are higher pitched and last longer than the dull, quieter sounds that are produced by solid, wooden headed drivers, and these differences are discernable to the golfer.

[With the laminate head] it's a dead, ... dull sort of sound rather than the explosive sound you get from the metal.

I think the explosion is ... quite an exciting sound, ... the difference is just that incredible explosion. When you strike the ball ... it makes even the weakest of hitters feel very powerful.

The explosive sound generated by metal woods may give the golfer the impression that the ball has come off the clubface quicker, with a reduced duration of impact and an increased ball velocity and is therefore thought to travel further. In addition, golfers can have preconceived ideas about different clubs, often generated by advertising claims of substantial improvements in performance that can be achieved by using titanium clubheads. This may lead the golfer to have negative opinions of older clubs and as a result describe the performance of the clubs to be worse.

It is also interesting to note that, in the first test, the ball type had a substantially greater effect on impact duration than clubhead type and yet almost half of the golfers, when questioned during the interviews, did not feel any difference between balls.
Again, I don't think you can feel an awful lot of difference between the two balls ... either to be honest with you.

Of the remaining golfers, a number perceived a difference in the hardness of the ball but only a very few perceived a difference in the manner in which the ball came off the clubface.

[With the two-piece ball], no sooner [have] you hit it... you've lost it, you know, it's gone... it comes off the club fairly quickly... At least with the balata one, you can feel it a little bit longer... you feel as if you've got hold of the ball a bit more.
CHAPTER 4

SOUND AND VIBRATION OF A GOLF SHOT: TEST METHODOLOGY

4.1 INTRODUCTION

The sound and vibration from impact are two of the most significant forms of feedback received from a golf shot that will influence the players' perceptions but the methods used in previous studies of sound and vibration characteristics of sports equipment have been questionable. In this chapter, the development of valid test procedures for quantifying subjective human perceptions and measuring objective data that is representative of the feedback received by the players is reported. The test procedures, which are described for two separate studies, one for investigating tactile sensations, the other for investigating impact sound, are designed to represent actual play conditions, with both subjective and objective data measured simultaneously from the same shots, whilst taking into account the transmission of vibration into the hand.

4.2 MEASUREMENT OF SUBJECTIVE DATA

The use of psychometric instruments to measure players' opinions of sports equipment has been rare and, in the few cases where techniques have been reported, the methods used vary in quality. Numerous studies have investigated the vibration characteristics of golf equipment but the majority of these studies did not attempt to assess and therefore link the measurements to the perceptions of a golfer using the clubs (Hedrick and Twigg, 1994; Varoto and McConnell, 1995; Wicks et al., 1998a, 1999; Barpanda et al., 1999). Merkel and Blough (1999) obtained players' subjective ratings of whether shots played were either 'good' or 'bad'. 'The subjective qualifications for a 'good' (or bad) hit included both feel and flight of the ball' (Merkel and Blough, 1999, p 515). Although the golfers' perceptions were included in this study, the initial stage of this project demonstrated that a player's assessment of equipment is much more complex. In addition, the choice of responses was limited, preventing the golfer from indicating how 'good' or 'bad' a shot was. In a preliminary study for this work, golfers ranked a series of club-ball combinations in terms of the feel of the shot played, from 'hard' to 'soft', and the perceived pitch of the impact sound, from 'high' to
‘low’ (Hocknell et al., 1996). Alternatively scaled questions have been utilised to obtain players ratings of perceived discomfort. In a study by Noble and Walker (1994), baseball players rated the pain caused by impact at various locations on each hand using the category scale ‘none’, ‘slight’, ‘moderate’ and ‘severe’ whilst tennis players used a visual analogue scale, labelled ‘comfortable on impact’ and ‘uncomfortable on impact’ at each extreme to rate perceived discomfort in a study by Stroede et al. (1999).

In selecting a method to be used in this study to measure subjective perceptions, a number of alternatives were considered. The first option was to have the golfers rank the clubs in order for each characteristic being assessed. The advantage of this technique is that an overall comparison of clubs may be possible but it does not provide information on how much better, or worse, one club is when compared to another. If a large number of clubs and feel characteristics are to be investigated, golfers may easily forget the feel of a club used earlier in the test. As the ranking will be based on an overall impression it may not be clear whether the golfer is basing the decision on all of the shots played or on a sub-sample, such as shots hit from close to the sweet spot. For this study, it was intended to measure the vibration from each shot, so it was desirable to have subjective ratings that would correspond to each individual shot, which would also indicate the magnitude of difference in feel between the shots. As a result, the use of rankings was deemed unsuitable for this study and techniques involving the use of a scale were investigated.

The postal questionnaire used earlier in the study to ascertain the feel of an ‘ideal’ golf shot, as described in Section 2.8, contained questions that requested responses on a 1 to 9 scale, with descriptive words used to give each scale orientation. Where possible, these words were taken from golfers’ quotes obtained during the recorded interviews. An example question from the postal questionnaire is given below.

During an ‘ideal’ golf shot with a driver, how loud would the impact sound be?

| Quiet, dead sound | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Loud, explosive sound |

The assessment format of the questions appeared to have been successful and so was reconsidered for this study. The main problem when using scaled response questions is that initially golfers will not have a common reference level, and as a result each player may use a different range within the overall scale. A number of alternative techniques were considered.
in an attempt to overcome this problem. Firstly an alternative scale was considered where a shot would be rated relative to a reference level provided either by a specific golf club or by the golfers' ideal preferences. For example:

How solid did the shot feel?

<table>
<thead>
<tr>
<th>Felt less solid</th>
<th>-4</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Felt more solid</th>
</tr>
</thead>
</table>

Two alternative techniques were considered for providing a reference level '0'. A club could be selected specifically for the purpose of providing feel characteristics that the golfers could then compare the other shots to; a shot that felt more solid than a shot with the reference club would be rated with a positive value whose magnitude would depend on the degree of difference in feel. However, this technique was deemed unsuitable for a number of reasons. The reference feel would not be a consistent level for all golfers, as not only will every golfer grip and swing the club differently, generating different vibrations, but each golfer may also perceive the vibration differently. The reference club would have to be the first club used and, in a test that could last over an hour, the golfer could easily forget the reference level. Allowing the golfer to regularly reuse the reference club, as a reminder, will also cause problems. If the impact location varies with each shot with the reference club, then the reference level will vary throughout the test. From a practical point of view, constantly changing clubs would be difficult and time consuming because of the proposed accelerometer cabling arrangement and, with a limit on the number of shots that can realistically be hit in one session before fatigue becomes an issue, the more shots that are hit with the reference club, the fewer clubs that can be incorporated into the tests.

The second alternative was to use each golfer's 'ideal' feel as the reference level; a shot would then be rated as more or less solid, for example, than they would ideally like it to feel. This technique also presented a number of problems. It was found from the postal questionnaire that often golfers' ideals are at extreme ends of the spectrum and, therefore, in the example used before, a shot could not feel more 'solid' than ideal, thus restricting the golfer to using only half the scale. Ideal ratings for each characteristic will also vary between golfers and previous experience suggests that golfers will not always find it easy to define their ideal feel. Therefore, this technique was also deemed unsuitable.

As a result, the decision was made to continue with the original question format and develop techniques to overcome its limitations. It was anticipated that, although the golfers
would not have a reference level to work from initially, after a number of shots they would begin to develop their own. The biggest errors were therefore expected to occur with the first club, reducing in significance as the tests progressed. To minimise this problem, it was decided that the results from the first club would be removed from the analysis and the club order would be varied to distribute any further errors across all the clubs. Statistical techniques to overcome the variations between each golfer's reference level and the subsequent variations in their use of the scales were also investigated and are discussed further during the analysis of the results.

4.2.1 SELECTION OF FEEL CHARACTERISTICS

The feel characteristics selected for further investigation in Section 2.7 were chosen because they were generally thought to relate to either club vibration or impact sound or both. The characteristics of interest all originate from the two general dimensions 'Feel from Impact' and 'Impact Sound', illustrated in Figures 2.4 and 2.5. For each test, it was decided to limit the number of feel characteristics that could be investigated to five, one of which would be an overall rating of the pleasantness of feel of each shot played. The selection of the remaining characteristics is discussed below.

During the interviews, golfers generally described off-centre impacts as feeling 'hard' and the vibration level was perceived to be greater. In contrast, central impacts were described as 'soft' or 'sweet' and the golfers described feeling little, if any, vibration. The type of club also had an influence, with the older, wooden clubheads generally described as having a 'softer' feel than the modern, metal clubheads and the type of ball also influenced how 'hard' or 'soft' a shot felt. Therefore, club vibration from impact was thought to contribute to the hardness of feel. However, as the sound of the impact may also influence this characteristic, it was decided to measure the golfers' perceptions of hardness of feel in both studies and also obtain perceptions of vibration level separately in the tactile sensation study.

With some clubs, typically traditional wooden headed clubs, golfers described feeling the ball being 'absorbed' by the clubhead and coming off slowly resulting in a 'dead' or 'dull' feel. In contrast, a more 'powerful' feel resulted when a ball 'exploded' or 'came quickly' off the clubface. Again, this feel may be related to both the impact sound and the club vibration and so it was selected as a feel characteristic to be measured during both sets of tests.

The pitch and loudness of sound were selected as the remaining two characteristics to investigate in the impact sound study as they were considered to be the most significant properties of the sound. Popular terms used by golfers to describe the sound of an impact
were ‘tinny’, ‘dead’, ‘dull’, ‘explosive’ and ‘crisp’ and where possible these terms were used in the questionnaire.

The term ‘solid’ was used to describe both the sound and the feel of a shot and was selected as the final perception to measure in the tactile sensation study.

### 4.2.2 TACTILE SENSATION STUDY

The five questions used to measure the golfers’ perceptions of each feel characteristic in the tactile sensation study are listed below; in order to follow the analysis of the results it is of particular importance to be familiar with the orientation of each scale.

<table>
<thead>
<tr>
<th>Perception</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>How did the shot feel?</td>
<td>1 2 3 4 5 6 7 8 9 PLEASANT</td>
</tr>
<tr>
<td>How did the impact feel in your hands?</td>
<td>VERY SOFT 1 2 3 4 5 6 7 8 9 VERY HARD</td>
</tr>
<tr>
<td>How much vibration did you feel in your hands?</td>
<td>NO VIBRATION 1 2 3 4 5 6 7 8 9 LOTS OF VIBRATION</td>
</tr>
<tr>
<td>How solid did the shot feel?</td>
<td>NOT SOLID 1 2 3 4 5 6 7 8 9 VERY SOLID</td>
</tr>
<tr>
<td>How quickly did you perceive the ball to have come off the clubface?</td>
<td>DEAD, BALL CAME OFF SLOWLY 1 2 3 4 5 6 7 8 9 LIVELY, BALL CAME OFF QUICKLY</td>
</tr>
</tbody>
</table>

### 4.2.3 IMPACT SOUND STUDY

The five questions used to measure the golfers’ perceptions of each feel characteristic in the impact sound study are listed below.

<table>
<thead>
<tr>
<th>Perception</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>How did the shot feel?</td>
<td>UNPLEASANT 1 2 3 4 5 6 7 8 9 PLEASANT</td>
</tr>
<tr>
<td>How did the impact sound?</td>
<td>VERY DULL 1 2 3 4 5 6 7 8 9 VERY CRISP, SHARP</td>
</tr>
</tbody>
</table>
How loud was the impact sound?

Quiet, dead sound 
1 2 3 4 5 6 7 8 9 Loud, explosive sound

How did the impact feel in your hands?

Very soft 1 2 3 4 5 6 7 8 9 Very hard

How quickly did you perceive the ball to have come off the clubface?

Dead, ball came off slowly 1 2 3 4 5 6 7 8 9 Lively, ball came off quickly

4.2.4 QUESTIONNAIRES

The actual questionnaires developed to measure the golfers' subjective perceptions are included in Appendices 4 and 5. The front pages are identical and were used to record the individual details of the golfer and their current choice of equipment. A separate sheet for each club was then used to measure and record the golfer's perceptions of each feel characteristic after each of the five shots played with that club. In addition to the golfers' perceptions, the questionnaires enabled information about the quality of the measured data to be recorded. Finally, after completing the test, the golfer was then asked to rate the feel of an ideal shot on the same scales.

4.3 MEASUREMENT OF OBJECTIVE DATA

4.3.1 TACTILE SENSATION STUDY

In previous studies of the vibration of sports equipment induced by an impact, measurements have been taken using accelerometers, which have tended to be mounted directly on the implement. In golf, Hedick and Twigg (1994) mounted accelerometers on the hosel of the clubhead and on the shaft immediately below the grip to compare club vibrations from centre, heel and toe impacts. Hocknell et al. (1996) used a single accelerometer, mounted on the shaft below the grip, to compare club vibration with golfers' perceptions of the shot. Merkel and Blough (1999) measured vibration of the rear of the clubhead in the swing plane and of the shaft immediately below the grip in both the swing and droop planes. Clearly, in all of these studies, the vibration was measured at a different location to that where the club was gripped and the transmissibility of the golf grip was not taken into account. Several studies concerned with the transfer of vibrations from a tennis racket to a player have attempted to directly measure acceleration of the player's hand/arm bone structure. In these studies, accelerometers have been mounted on the knuckle of the index finger (Fairley, 1985), the wrist (Tornoe et al., 1991, 1994; Naš et al., 1998) and
strapped to the skin above the ulna head and the lateral epicondyle of the humerus (see Figure 1.3) (Hennig et al., 1992). Although these measurements may be invaluable for assessing injury potential, they are unlikely to correlate well with perception of vibration because human flesh attenuates vibration at higher frequencies. 'Transmissibility to the knuckle of the hand gripping a handle tends to decrease below unity above 100 Hz' (Griffin, 1990), so only low frequency vibration will be transmitted from the surface of the skin into the bone structure. The sensors in the hand that detect vibration, however, are under the surface of the skin and will respond to vibration at frequencies greater than 100 Hz (Reynolds et al., 1977). The perception of a person is, therefore, unlikely to correlate with measurements of bone vibration, which will have little frequency content above a few hundred Hertz.

For the purposes of this study, it was desirable to measure the vibration of the club at the hand-grip interface where vibrations would be perceived. A technique, developed for industry to assess the injury potential of vibration transmitted to the hands and arms of power tool users, involves the operator clamping an adaptor, on which accelerometers are mounted, between the hand and the tool grip. This method is particularly appropriate when a resilient material is present between the hand and the vibrating structure (ISO 5349:1986; BS 6842:1987), which is the case in golf. To obtain representative measurements of the vibrations transmitted into the human hand from a vibrating structure, Rasmussen (1982) specified the following requirements of an adapter.

i) The frequency response of the mount should be constant from 5 Hz to above 1200 Hz

ii) The mount should represent a minimum dynamic load to the hand

iii) It should be easily installed and measure as close as possible to the standardised reference point (the origin of the co-ordinate system for the hand) on both right and left hands

iv) It should reflect the grip strength used

v) It should never underestimate the energy transmitted to the hand from the handle

A number of additional requirements were also specified for the adapter to be suitable for measuring vibrations from a golf impact.

vi) The adapter must not cause discomfort to the player
As the grip is the golfer's only contact with the club, it must not adversely affect the player's ability to swing the club.

The adapter should be lightweight.

It must be able to measure vibration on the surface of a soft rubber grip.

An adapter was developed, on which two accelerometers were mounted perpendicularly, which could comfortably be gripped between the hand and the golf club during stroke play. The adapter, illustrated in Figure 4.1, was designed to accommodate two low profile ENDEVCO model 2222C accelerometers and to match the diameter of the grip. It was constructed from aluminium and was approximately 80 mm long and 3 mm thick and had a total weight of 17.6 g. To obtain the frequency response of the adapter, a rig was developed that could be mounted on a shaker, into which the grip section of a golf club was clamped, as illustrated in Figure 4.2. The accelerometer used to measure the input was attached with adhesive to the surface of the grip material on the opposite side of the grip to where the adapter was positioned, on which a second accelerometer measured the output. The assembly, which was held with a standard golf grip and a representative force, was shaken randomly in the frequency range 0 to 4 kHz. The response of the adapter in each measurement direction was calculated using a spectrum analyser and is illustrated in Figure 4.3. The upper graph, in both a) and b), shows the coherence of the measurement, an indicator of the influence of noise, which ideally would have a value of one across the frequency range. The lower graph in each part of Figure 4.3 shows that in each direction the frequency response of the adapter is acceptably flat up to approximately 1200 Hz.

During the tactile sensation tests, the adapter was positioned so that the accelerometers were 2 ½ inches from the butt of the grip and aligned to measure vibration in the direction of strike (x-axis) and perpendicular to that and the shaft axis (z-axis), as illustrated in Figure 4.4; these measurements will subsequently be referred to as x-grip and z-grip. In this location, the adapter fitted comfortably between the left hand and the grip and was taped lightly in place to prevent it from moving, as illustrated in Figure 4.5. Discussions with players indicated that minimum intrusion was experienced. This measurement location was chosen because, for a right-handed golfer there is a larger contact area between the left hand and the grip than the right hand and a previous study by Budney (1979) reported the greatest grip forces immediately after impact to be produced by the left hand and this may increase the transmission of vibration from the club to the hand-arm system.
A further bracket was developed, on which two Brüel and Kjer type 4375 accelerometers were mounted; it was then clamped to the shaft 14 inches from the butt end of the grip to measure shaft vibration in corresponding directions to the grip adapter, as illustrated in Figure 4.6; these measurements will subsequently be referred to as x-shaft and z-shaft. The purpose of this bracket was to examine whether measurements taken from the shaft could still be correlated successfully with golfers' responses and also to provide a reference, which could be used to identify erroneous measurements at the grip. If good correlations could be obtained with shaft measurements, this would justify discarding the less convenient grip measurements in future studies.

The cables from each accelerometer were run along the left arm, over the shoulder and down the back of each golfer and were held in place by a combination of wristbands and clips. A computer based, multi-channel, data acquisition system was used to collect the vibration data. Each signal was sampled at 5120 samples/second for 100 ms with a 2 kHz low pass filter used to prevent aliasing; vibrations in the frequency range 8 Hz to about 1000 Hz are considered to be the most significant in previous hand/arm vibration studies (BS 6842:1987; Griffin, 1990). The resolution of subsequent frequency spectra is therefore 10 Hz. All measurements taken comply with the recommendations made in BS 6842:1987.

In order to assess whether golfers could accurately perceive the speed of the ball off the clubface, both the clubhead speed immediately before impact and the ball speed immediately after impact were measured. To measure clubhead speed, two optical beams were aligned 8 inches apart behind the golf ball, so that the clubhead would pass through both beams prior to impact. A counter was then used to measure the time taken for the clubhead to travel between the two beams of light, from which the velocity could be calculated. A camcorder, three strobe lights and a computer based acquisition system were used to capture three images of the ball in flight immediately after impact. The images were then digitised and processed to obtain ball launch velocity.

Finally, impact location was measured using a powder spray. The approximate geometric centre of each clubface was marked in advance as a datum. On completion of each shot, the location of the centre of the imprint of the ball in the powder deposit was measured in relation to the datum, as illustrated in Figure 4.7.

4.3.2 IMPACT SOUND STUDY

The impact sound was measured using a Brüel and Kjer type 2231 sound level meter. The microphone was situated at a horizontal distance of 90 cm ± 10 cm from the ball and
140 cm ± 10 cm above ground level, i.e. the approximate location of the head of a left-handed golfer addressing the same golf ball, and was directed at the ball in accordance with IEC recommendations, as illustrated in Figure 4.8. During the tests conducted at the headquarters of Callaway Golf in California, the sound was also measured using a microphone attached to a baseball cap close to the left ear of the golfer, as illustrated in Figure 4.9, to assess whether sound measured closer to the golfers’ ears would correlate better with golfers’ perceptions than when measured using the free-field stationary microphone. Windshields were used on the microphones to minimise the effect of wind noise. The unweighted measurement from each microphone was collected using a computer based data acquisition system. Each signal was sampled at 51,200 samples per second for 80 ms with a 20 kHz low pass filter used to prevent aliasing; sounds with a frequency above 20 kHz cannot be heard by adults (Coren et al., 1999). The resolution of the subsequent frequency spectra is therefore 12.5 Hz.

The impact location was measured by applying pressure sensitive tape to the club face prior to each shot, as illustrated in Figure 4.10. A datum corresponding to the approximate geometric centre of the club face, which had been marked in advance, was transferred onto the face tape. After each shot, the tape was archived and, at a later date, the location of the impact relative to the datum was measured.

4.4 PARTICIPANT SELECTION

Fifteen elite golfers, with handicaps less than five, aged between 20 and 55 were targeted for each study. Where possible, golfers were only used if they had not previously participated in tests of a similar nature in case knowledge had been gained, which could influence their responses in these tests. No golfers participated in both sets of tests.

The fifteen golfers used in the tactile sensation study, assigned the Subject numbers 1 to 15, had a mean age of 29 years, standard deviation, $\sigma = 6$ years. Two of the golfers were European Tour professionals, five were club professionals, one an assistant professional and seven were amateur golfers with handicaps between plus two and two. The golfers were predominantly male; one of the European Tour professionals was female.

For the impact sound study, twenty golfers, Subjects 21 to 40, participated in the tests but the data from three golfers, Subjects 23, 29 and 32 was later discarded either because their ball striking was too inconsistent or it was considered that they were not concentrating fully during the test and therefore their results could be unreliable. The remaining seventeen golfers had a mean age of 35 years, $\sigma = 8\frac{1}{2}$ years. One of the golfers was a Tour professional,
eight were club professionals, six were assistant professionals and two were amateur golfers. Nine of the golfers were American of which eight were male and one was female, the remaining eight were British males.

4.5 EQUIPMENT SELECTION

Ten clubs were selected for use in each study, along with one ball type, the Titleist Professional 100 Compression ball, in order to cover a broad range of variations in feel. Eight clubs were used in both sets of tests; two were changed.

For the tactile sensation study, two Callaway GBB clubheads and two Callaway ERC clubheads were each assembled with a True Temper EI70 R flex shaft and a RCH 5.3 Gold shaft, enabling differences wholly due to either shaft or clubhead to be evaluated. A Titleist 975D, a Ping TiSi and a Taylor Made Firesole were also included as they represent a large share of the driver market, along with a number of older clubs, a Maxfli VHL steel clubhead, a Ping Eye 2 laminated wood clubhead and a Slazenger persimmon clubhead.

As the clubhead is predominantly responsible for the sound of an impact, it was deemed inappropriate to include two identical clubheads in the set of clubs used in the impact sound study, so the ERC and the GBB with the RCH 5.3 Gold shafts were replaced with a Callaway Steelhead and a Yonex graphite head.

The complete specification of each club is given in Appendix 6.

4.6 TEST PROCEDURE

On arrival at the test location, the procedure was outlined to each golfer. The five questions the golfers were required to answer on completion of each shot were described. They were also written up on a wallboard as a reminder to increase the rate of data collection. The golfers were asked to avoid allowing preconceptions or previous experiences of clubs or manufacturers’ equipment to affect their ratings; they were requested to rate each shot played on its own merit. Finally, the golfers were asked to answer the questionnaire before looking at the impact location.

Prior to the commencement of each test, the golfer was given the opportunity to warm up. The participants in the tactile sensation tests were given a further opportunity to take several swings once the cables from the accelerometers had been connected and secured to each golfer to enable them to become accustomed to the arrangement.
Club order was varied throughout the complete set of tests according to the Latin square illustrated in Table 4.1. In the design of the square, each club features once in each test and, over ten tests, in a different position in the order. Each club is also preceded and followed by a different club in each test. This overcomes problems with order effects; a club may be rated differently if it follows a very good club rather than a very poor club.

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
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<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.1 – Latin Square used to vary club order

For the majority of the tests, the golfers hit five shots with each of the ten clubs; four of the golfers who participated in the impact sound tests only had sufficient time available to hit three shots with each club, hence the increase in the number of participants to seventeen. All subjective and objective measurements were recorded for each shot played.

The tactile sensation tests were all conducted in the indoor player testing facility at Loughborough University. For this set of tests it was important that the golfers' perceptions were not affected by the impact sound or the flight of the ball. Therefore, to isolate vibration transmitted to the hands as the sole form of feedback received by the golfers from impact, the tests were conducted in a net and pink noise was played to the golfers through a pair of ear defenders during each shot to mask the sound of the impact. At the end of each test, a number of questions were asked to obtain feedback from the golfer on their opinion of the
procedures and whether they had encountered any problems during the test. None of the golfers reported being unduly affected by the noise.

The impact sound tests were conducted at a variety of locations. The nine tests with the American golfers were conducted on the driving range at Callaway’s headquarters in Carlsbad, California, whilst the tests with the British golfers were conducted on the driving ranges at the golf clubs where they worked. Each test was conducted outdoors and if any loud noises were present the test was paused until the noise level subsided.
CHAPTER 5

HUMAN RESPONSE TO SOUND AND VIBRATION

One of the biggest criticisms of previous sports research in this field is that only a very few studies considered human perception of sound and vibration. In the following section human response to both sound and vibration is discussed and consequences for the testing of golf equipment are emphasised.

5.1 HUMAN RESPONSE TO VIBRATION

In order to identify the significant properties of vibration measured from impact that influence a player's perception, it is important to understand the dynamic response of the human body, the transmission of vibration throughout the body and the mechanisms by which vibration is perceived. The study of human response to vibration is generally separated into two fields: whole-body vibration and hand-arm vibration. For the purposes of this study, as a golf club is held in the hands of the player, it is transmission of vibration into the body through the hands that is of interest. The majority of studies of hand-arm vibration have investigated either the potential of power tools to cause injury to the operator, particularly tools used in industry, or the development of alternative communication systems for deaf or blind people.

Vibration-induced white finger, a vascular disorder, is perhaps the most common impairment linked to over exposure to damaging vibration levels transmitted into the hand. This type of vibration has also been identified as a possible cause of disorders of the bone, joint, muscle and peripheral nervous system. In sports that require a projectile to be hit by a hand held implement, players can develop tendonitis, where the fibrous tissues of a tendon are torn and inflamed. Particularly susceptible are tennis players and golfers and the common occurrence of the injury at the elbow has led to the condition being renamed 'tennis elbow' or 'golfers elbow' (Griffin, 1990). A number of studies have investigated the contribution of vibration generated at impact, which is subsequently transferred into the hand and arm of the player, as a possible cause of tennis elbow (Fairley, 1985; Hatze, 1992; Hennig et al., 1992;
Tomosue et al., 1994; Wilson and Davies, 1995). Griffin (1990), however, suggests that tendonitis may be associated with repeated movements of a heavy tool rather than vibration.

Although studies investigating injury potential are interesting, it is human perception of vibration that is of importance to this study and the mechanisms that cause injury may be different to those that affect perception. In the following section the factors that have been found to affect the dynamic response of the hand and arm, the transmission of vibration into the hand and perception of vibration are reviewed and the guidelines provided in both British and International Standards are summarised.

5.1.1 VIBRATION TRANSMISSION TO THE HAND AND ARM

The transmission of vibration from a hand-held implement into the hand and arm is a complex process. Of all the possible contributing factors that are listed by Griffin (1990), those of relevance to this study include characteristics of the vibration, such as the magnitude, frequency and direction, and characteristics of the person, such as the dynamic response of the individual’s hand, the type of grip and grip force exerted, the method of using the implement and whether the person chooses to wear a glove.

A study by Reynolds and Angevine (1977) investigated the transmission of vibration from a tubular handle to several locations on the hand and arm of a human subject gripping the bar with two types of grip, a finger grip and a palm grip, with two grip forces, a 9 N (2 lbf) and a 36 N (8 lbf) force. Each subject was seated such that their forearm was within 20° of horizontal when they grasped a 1.905 cm diameter bar, aligned parallel to both the ground and their torso, which was attached to an electromechanical shaker. The bar was vibrated at frequencies continuously varying from 5 to 1000 Hz in each of three directions, horizontal, vertical and axial, as illustrated in Figure 5.1. Miniature piezo-resistive accelerometers were attached at the eight locations on the hand and arm illustrated in Figure 5.2 using double-sided tape and then pressed against the skin using surgeon’s tape. The average ratio of the acceleration measured at each location to the acceleration of the handle in each direction is shown in Figure 5.3. All the measurement positions are not featured on each graph, as the vibration could not be measured in all three axes at every location.

The authors concluded that below 400 Hz in the vertical direction and below 100 Hz in the horizontal and axial directions, the vibration is transmitted almost unattenuated from the surface of the hand in contact with the handle, through to the back surface of the finger (curves 1 and 2). Above these frequencies, the vibration amplitudes of the backs of the fingers decreased as the vibration frequency increased. The ratio of vibration magnitude of
the wrist to the handle (curves 4 and 5) decreased to approximately 0.1 at 100 Hz and at 1000 Hz had reduced to 0.01 in the vertical direction and 0.001 in the horizontal and axial directions. The vibration magnitude progressively reduced at the elbow (curves 6 and 7) and shoulder (curve 8) as the distance of the measurement location from the hand increased. This implies that above 100 Hz the vibration tends to be localised to the fingers.

The general amplitudes of the corresponding curves for the other grip configurations, although not reported in the paper, were stated to have been somewhat different but indicated similar overall trends.

5.1.2 Perception of Vibration

Humans detect vibration with sensors in the skin called mechanoreceptors, which respond to mechanical deformation of the tissue in which they are located, see Figure 5.4. When the tissue is deformed, the mechanoreceptors produce a generator potential that is proportional to the magnitude of the stimulus applied. When the generator potential exceeds the threshold level of a particular mechanoreceptor, an action potential is produced which is transmitted through the nervous system and processed by the brain. The amplitude of an action potential is constant for a given mechanoreceptor and so the magnitude of the stimulus is encoded in the rate at which action potentials are produced. Mechanoreceptors are divided into two groups, tonic receptors such as Merkel’s discs and Ruffini’s endings, which are primarily responsible for the detection of quasi-static stimuli, and phasic receptors such as Pacinian corpuscles and Meissner’s corpuscles, which are primarily responsible for detecting dynamic stimuli such as vibration (Reynolds et al., 1977; Sherwood, 1993). It is widely regarded that Meissner’s corpuscles detect vibration at frequencies below 20 Hz to 40 Hz, whilst Pacinian corpuscles detect vibration at frequencies greater than this (Griffin, 1990; Brisben et al., 1999).

There are a large number of variables that affect human perception of vibration transmitted into the hand and arm. These include characteristics of the vibration, such as frequency, magnitude, duration and direction, the nature of contact with the vibrating surface, including contact area, geometry, force and location as well as characteristics such as age, pathology and skin temperature of the subjects themselves (Griffin, 1990; Brisben et al., 1999). A number of studies have investigated these factors by generating threshold of perception curves and equal sensation contours for a variety of different conditions. Obtaining this data typically involves a human subject either grasping a vibrating handle or pressing either part or the whole of their hand against a vibrating plate. To obtain threshold
of perception curves, the amplitude of vibration is adjusted until the subject is just able to perceive the motion; this threshold level is then obtained across a range of discrete frequencies. To obtain an equal sensation contour, the device is vibrated at a reference frequency and level, to which the subject becomes familiar. The frequency of vibration is then switched and the subject adjusts the amplitude until the sensation feels equal to that produced by the reference vibration; again, the procedure is repeated across a range of discrete frequencies. Using the same procedure, other contours can then be produced by varying the magnitude of the reference vibration.

Miwa (1967) reported threshold of perception curves and equal sensation contours for the palm of a hand pressed onto a flat horizontal vibrating table with a force of 49 N (5 kgf). Similar results were produced when a handle was mounted on the table, when the horizontal direction was parallel or perpendicular to the fingers, when the plate was vibrated in a vertical direction and when the static force was doubled to 98 N (10 kgf). In addition, when both hands were vibrated simultaneously, one in the horizontal direction and one in the vertical direction, the sensation in each hand was found to be equal when the two tables were vibrated at the same acceleration level. The author concluded, therefore, that the curves reported represent human sensation for all of the conditions described above.

Reynolds et al. (1977) used the same set up and grip configurations that were used to investigate vibration transmission characteristics of the hand and arm (Reynolds and Angevine, 1977), described in Section 5.1.1, to obtain the threshold level and annoyance level curves. For the annoyance tests, the amplitude of vibration was adjusted until the subject determined that 'he would not want to clasp the handle for an extended period of time'. Reynolds et al. (1977) concluded that threshold and annoyance levels are a function of direction of vibration and of the grip configuration used. Although, it appears reasonable to have concluded that the subjects were more sensitive to vibration in the vertical direction than the axial direction, particularly at frequencies above 100 Hz, there seems little evidence in the published results to suggest that either grip type or grip force was a significant factor. When the variability in the results obtained from different subjects is taken into account, the effect of grip configuration would appear to be insignificant.

The threshold of perception curves for a 9 N (2 lbf) and 36 N (8 lbf) finger grip, obtained by Reynolds et al. (1977) are compared with the results obtained by Miwa (1967) in Figure 5.5. Also presented are curves obtained by Verrillo (1963), Lamoré and Keemink (1988) and Brisben et al. (1999). The perception thresholds obtained by Brisben et al. (1999)
are for a 3.2 cm diameter cylinder, gripped with a ‘light-to-moderate’ force, vibrated in an axial direction, whereas Verillo (1963) and Lamoré and Keemink (1988) investigated perception thresholds of vertical vibration at smaller sites on the hand; Verrillo, the thenar eminence (the fleshy base of the thumb), Lamoré and Keemink, the distal phalanx of the middle finger (see Figure 1.3). All of the curves shown in Figure 5.5 have a similar characteristic shape, two turning points, one between 10 and 40 Hz, the second between 100 and 250 Hz. The turning point between 10 and 40 Hz is caused by the transition from Meissner’s corpuscles to Pacinian corpuscles dominating the detection of vibration, whilst the turning point between 100 and 250 Hz is caused by the Pacinian corpuscles being most sensitive to vibration frequencies of approximately 200 to 250 Hz (Reynolds et al., 1977; Griffin, 1990; Brisben et al., 1999). The threshold of perception curves indicate that humans are particularly sensitive to frequencies of vibration acceleration that are either below 10 Hz, or in the range 50 Hz to 300 Hz. Above 50 Hz humans are capable of detecting RMS vibration displacements of less than 1 µm and at 200 Hz, the approximate peak of human sensitivity, Brisben et al. (1999) found that some of their subjects were capable of detecting RMS vibration displacements of less than 0.01 µm.

The threshold curve obtained by Miwa (1967) was summarised as following gradients of constant RMS velocity up to 15 Hz, constant RMS jerk up to 100 Hz and constant RMS displacement at frequencies above 100 Hz, and is remarkably similar to the curve obtained by Brisben et al. (1999). The two curves obtained by Reynolds et al. (1977) for a 9 N (2 lbf) and 36 N (8 lbf) finger grip are almost alike and very similar to the curve produced by Lamoré and Keemink (1988) but they suggest that humans are less sensitive to vibration acceleration below 100 Hz than Miwa (1967) and Brisben et al. (1999). The results obtained by Verrillo (1963) show the greatest disparity, with thresholds in general being considerably higher than was found in any of the other studies. Finally, all of the curves indicate that sensitivity reduces at a greater rate at higher frequencies than was suggested by Miwa (1967).

Identifying reasons for the variations in the data, particularly the disparity in Verrillo’s results, is difficult as there are a number of variables that influence perception of vibration. Verrillo himself, as part of the same study, Goble et al. (1996) and Brisben et al. (1999) found that for frequencies above 40 Hz, perception thresholds decreased as the area of contact between the hand and the vibrating surface was increased. Although Verrillo did use a small area of contact, approximately 3 cm², Lamoré and Keemink (1988) used an even smaller area of 1.5 cm² and obtained similar results to those who used a complete grip. Variation in contact force is also unlikely to explain the differences. Lamoré and Keemink (1988) did find
perception thresholds increased as the contact force was decreased but only when the force was less than 0.7 N. Brisben et al. (1999), however, concluded that a 20-fold change in contact force from 0.05 N to 1.0 N had no effect on perception threshold. The results of Lamoré and Keemink (1988) may have been influenced by the skin and vibrating surface not remaining in contact throughout the vibration motion, a problem that was raised and addressed by Verrillo (1963) and Brisben et al. (1999), which is likely to be exacerbated at low contact forces. Certainly at higher forces, perception threshold does not appear to be influenced by contact force (Miwa, 1967; Reynolds et al., 1977). Finally, stimulus location may have had an effect; Brisben et al. (1999) found the palm of the hand to be more sensitive than the fingers at 300 Hz, whilst the results obtained by Lamoré and Keemink (1988) suggest that the thenar eminence, the region stimulated by Verrillo (1963), may differ in sensitivity to the distal pad of the finger but only at frequencies below 20 Hz.

The equal sensation contours obtained by Miwa (1967) and by Reynolds et al. (1977) (for a 2 lb finger grip) using discrete frequencies of vibration are reproduced in Figure 5.6. The equal sensation contours obtained by Miwa (1967) are parallel and have gradient changes at 6 Hz and 60 Hz with sensation being equivalent along gradients of constant RMS acceleration up to 6 Hz, constant RMS velocity up to 60 Hz and constant RMS displacement at frequencies above 60 Hz. The equal sensation contours obtained by Reynolds et al. (1977), however, are not parallel; the contours become flatter as the level of the reference vibration is increased implying that sensation is a function of both frequency and level. Above 100 Hz, the contours produced by Reynolds et al. (1977), based on reference vibrations of 1 m/s² and 10 m/s² RMS acceleration at 100 Hz, have similar gradients to the curves produced by Miwa, which follow lines of constant RMS displacement. The contour based on a reference vibration of 50 m/s² at 100 Hz, however, has a flatter gradient and continues to follow a line of constant RMS velocity at higher frequencies. As with the threshold of perception curves, the results obtained by Reynolds et al. (1977) again suggest humans are less sensitive to frequencies of vibration below 100 Hz than the results obtained by Miwa.

In all of the studies described above, perception of vibration was investigated using continuous, discrete frequencies of vibration with each direction of vibration considered separately. In practice, vibration transmitted into the hand will be complex and three-dimensional and in sports impacts the vibration will be impulsive. A number of studies have attempted to address these issues.
Using the same technique that produced the equal sensation contours for discrete frequency vibration, Reynolds et al. (1977) obtained contours for one-third-octave broadband vibration, which are also shown in Figure 5.6. The contours obtained using broadband vibration, particularly those at the higher levels, approximately follow gradients of constant RMS vibration displacement across the complete frequency range tested, which is in contrast to the contours obtained with discrete frequencies that tend to level off temporarily between 40 and 100 Hz. This implies that humans are more sensitive to broadband vibration than discrete frequency vibration below 100 Hz.

Perception of vibration has been found to be dependent on stimulus duration when the duration of vibration is less than a second. Berglund et al. (1967) investigated subjective intensity of bursts of 250 Hz sinusoidal vibration ranging from 20 to 1200 ms in duration at five different actual intensities and the results are reproduced in Figure 5.7. The results indicate that perceived intensity is a logarithmic function of stimulus duration, increasing in magnitude until a peak sensation is reached, beyond which further increases in duration have no effect on subjective intensity. The stimulus duration at which maximum perceived intensity is reached has generally been found to be approximately 600 ms (Berglund et al., 1967; Verrillo and Smith, 1976) although it has been found to vary between 200 and 1200 ms depending on the subject and the intensity level (Berglund et al., 1967). The threshold of human perception has also been shown to decrease by approximately 3 dB with every doubling of vibration duration up to approximately 200 ms, independent of frequency (Verrillo, 1965).

5.1.3 Dynamic Response of the Hand and Arm

The dynamic response of the hand, although unlikely to have a significant affect on the mechanisms by which vibration is perceived, will influence the transmission of vibration to the hand and the vibrational characteristics of the implement gripped. Variations in the dynamic response of the hand between golfers' may cause the club to vibrate in a different manner even when shots are hit from the same location on the clubface and, therefore, the impacts may be perceived differently.

One approach used to investigate the response of the hand arm system is to measure the apparent mass of the hand gripping a handle mounted on a shaker. The impedance of the whole system is obtained from the ratio of the force input to the response of the system, measured in terms of vibration acceleration. Providing the handle behaves in a rigid manner (i.e. has constant apparent mass) across the frequency range of interest, a process known as
mass cancellation can be used to determine the dynamic response of just the hand and arm (Griffin, 1990). For the purposes of this study, however, it is of more interest to consider the system as a whole.

The resistance to motion of a hand-handle system will be greater if the coupling between the hand and the handle is enhanced and, as a result, the apparent mass of the system increases. The variation of apparent mass with frequency is, therefore, dependent on the type of grip and the grip force applied (Griffin, 1990). Apparent mass also varies between people, although, intra-subject variability, when a subject grips the handle repeatedly with nominally the same force, and inter-subject variability, when different subjects apply nominally the same grip force, have less effect on apparent mass than variations in grip force by a single subject (Griffin, 1990).

5.1.4 STANDARDS

In 1986, the International Standard, ISO 5349:1986, and in 1987 the equivalent British Standard, BS 6842:1987, were introduced to provide guidelines for the measurement and assessment of human exposure to hand-transmitted vibration. The International Standard provides a frequency weighting which has gradients of 0 dB per octave below 16 Hz, reducing by 6 dB per octave above 16 Hz. The frequency weighting can be applied over the eight octave bands from 8 to 1000 Hz or over the twenty-four one-third octave bands from 6.3 to 1250 Hz. The British Standard provides an alternative frequency weighting to the ISO weighting. It is again designed to assess vibration over the frequency range 8 to 1000 Hz and has band-limiting high-pass and low-pass filters at 6.3 and 1250 Hz respectively. Although the weighting is designed to assess injury potential, it is primarily derived from subjective and biodynamic studies of the hand and arm (Griffin, 1990). The equivalent American National Standard, ANSI S3.34-1986, is consistent with ISO 5349:1986 in that it specifies the same dependencies on vibration frequency (Griffin, 1990).

A comparison of the two frequency weightings is given in Figure 5.8. It can be seen from this figure that the two frequency weightings are similar with the only significant difference being below 10 Hz; here the BS weighting reduces to approximately 0 at 1 Hz, whereas the ISO weighting remains constant at 1. Above 16 Hz, both weighting factors reduce at a similar rate such that by approximately 32 Hz the gain is 0.5 and by 160 Hz it is only 0.1. The frequencies that dominate these weightings are therefore considerably lower than the frequencies that humans are most sensitive to in terms of perception.
5.1.5 CONSEQUENCES FOR THE ANALYSIS OF GOLF CLUB VIBRATION

Although all of the above studies have indicated that a number of factors affect human perception, there are variations in the relative effect of each factor and not all will have a significant influence on a golfer's perception of a shot. In summary, the most relevant factors, which have the greatest affect on perception, are frequency of vibration, which affects human sensitivity, and amplitude of vibration, which affects the magnitude of sensation and how vibrations at different frequencies are perceived relative to each other. The vibration from a golf shot is impulsive, complex and three-dimensional, as opposed to the continuous, discrete frequency, single axis vibration used in the majority of studies described in this section and it is these factors that are likely to have an unknown influence on golfers' perceptions.

A shot hit from the same location on the same clubhead by two different golfers will not necessarily be perceived in the same manner. Every golfer grips and swings the club differently and although this is unlikely to affect the mechanisms by which humans perceive vibration it may alter the way in which the club vibrates and if the vibration characteristics of a club vary between golfers then so will perception.

Older people have been found to be less sensitive to vibration than younger people, but the effect is reasonably consistent across the frequency range (Goble et al., 1996). Providing golfers are used who are aged between 20 and 55, this is only expected to have a small influence.

5.2 HUMAN RESPONSE TO SOUND

The human auditory system is a sensitive system that can detect tiny changes in pressure of the surrounding medium, which is perceived as 'sound'. Depending on the nature of the changes in pressure, the sound will have certain perceived qualities such as loudness, pitch, duration, timbre, volume, density and consonance or dissonance. These characteristics are all psychological properties of sound that can be linked to physical qualities such as sound pressure level and frequency of sound, although the relationships are often complex.

5.2.1 PERCEIVED LOUDNESS OF A SOUND

Perceived loudness is generally related to sound pressure level but the relationship is non-linear and it is also dependent on the frequency, duration and complexity of the sound and the characteristics of the listener.
The sone scale is used to measure loudness; 1 sone is arbitrarily assigned to be the loudness of a 1 kHz tone at a level of 40 dB, a tone that is perceived to be twice as loud has a loudness of 2 sones and a tone half as loud, 0.5 sones. The relationship between decibels and sones is illustrated in Figure 5.9; the straight line is obtained because sones are on a logarithmic scale and decibels are a log unit (Levine, 2000). It can be seen from this graph that to double the loudness of a tone, the sound intensity must be increased by 10 dB. The loudness, in sones, of complex sounds can be calculated using one of two techniques, developed separately by Stevens and Zwicker, which have been standardised in BS 4198:1967.

5.2.1.1 Effect of Frequency on Loudness

The equal loudness curves, standardised in ISO 226:1987 demonstrate the way in which the subjective loudness of a pure tone or a narrow band of noise is dependent on frequency. To obtain the curves, listeners were required to adjust the level of a variable frequency pure tone until it matched the subjective loudness of a reference tone at 1 kHz. The listeners, otologically normal persons in the age range 18 to 30 years inclusive, were placed in the free-field of a sound that originated directly in front of them so that it was heard binaurally. The sound pressure levels of tones at each frequency that have the same loudness as a 1 kHz tone at 10 dB are joined by the 10 phons curve; curves at each increment of 10 phons from 10 to 110 phons are shown in Figure 5.10. It can be seen from these contours that the loudness of a tone at a given sound pressure level is at a maximum when the frequency of the tone is approximately 4 kHz and is much quieter when the frequency of the tone approaches the limits of audible sound. In addition, at higher sound pressure levels, the curves get flatter indicating that tones at all frequencies have a similar loudness; tones with sound pressure levels ranging from 2 dB at 20 Hz to 77 dB at 4 kHz both have the same loudness of 10 phons but for sounds with a loudness of 100 phons, the range of sound pressure levels reduces from 75 dB to 39 dB.

Instrumentation for measuring sound, however, places equal emphasis on all frequencies of sound and so weightings have been developed to adjust the measurements taken to reflect the sensitivity of the human ear to different frequencies. Three weightings, 'A', 'B' and 'C', were initially developed because the equal loudness contours are flatter at higher sound pressure levels. The A, B and C weightings, which have been standardised by the International Electrotechnical Commission in IEC 651:1979, approximately follow the (inverted) shapes of the 40, 70 and 100 phons equal loudness curves and the original intention was that the weighting that corresponded closest to the sound pressure level of the
measured sound should be used. In recent years, however, the A weighting has been predominantly used regardless of sound pressure level and the B and C weightings have largely fallen out of use (Fahy and Walker, 1998). The A weighting gives less emphasis to frequencies below 1 kHz than the C weighting, whilst both reduce the influence of high frequency components, as illustrated in Figure 5.11. Consequently, from a practical point of view, the A weighting provides some immunity against wind noise and other low frequency noises from distant sources when taking measurements outdoors (Fahy and Walker, 1998).

The equal loudness contours on which the weightings are based were obtained from studies of the perceived loudness of pure tones. In reality, however, and in golf, sounds are complex in frequency and the auditory system will respond differently to complex combinations of tones than it will to pure tones. It has been found that when a subject is presented with a series of band-limited sounds with equal energy, the loudness of the sound is dependent on bandwidth. A narrow-band sound at moderate intensity has the same loudness as a pure tone of equal energy. When the bandwidth is increased, initially loudness does not change but, beyond a particular width, which is dependent on the centre frequency of the band, loudness starts to increase as bandwidth is increased (Gulick, 1971; Levine, 2000). This effect is illustrated in Figure 5.12a, which shows the results of a study by Zwicker and Feldtkeller (1956), reprinted by Levine (2000). The loudness levels for bands of noise centred at 1 kHz as a function of bandwidth for five different total energy levels are plotted on the graph. It can be seen from Figure 5.12a that the loudness of a band of noise centred at 1 kHz begins to increase with bandwidth once a width of 160 Hz has been exceeded, except when the sound has a loudness of 20 phons. Experiments using combinations of pure tones instead of band-limited sounds also led to the same conclusion unless the tones are very weak or below auditory threshold, in which case the tones are perceived as louder if they are similar in frequency (Levine, 2000). These considerations led to the development of the theory that two tones, which fall in the same band, will interact with each other, whilst tones in separate bands will be treated independently by the auditory system; this is referred to as critical band theory (Levine, 2000). Zwicker et al. (1957) found that the critical bands widened as the centre frequency was increased, as illustrated in Figure 5.12b.

5.2.1.2 Effect of Duration on Loudness

Another factor that affects loudness perception is the duration of a sound. Studies have found that, for impulsive sounds shorter than approximately 100 to 200 ms, the loudness reduces progressively as the duration of the sound is decreased; impulsive sounds that have a longer duration than this are perceived to be as loud as a steady tone (Gulick, 1971; Hassall
and Zaveri, 1979; Fastl, 1997; Fahy and Walker, 1998). This critical duration, however, can increase to 1 s if the sound level is close to either the threshold of hearing or the threshold level of a masking sound (Kryter, 1985). The duration of impact sounds in golf tends to vary from a few milliseconds with heavily damped clubheads to tens of milliseconds with lightly damped, hollow, metal clubheads and, therefore, this is likely to have a considerable effect on players’ perceptions of loudness of golf impacts.

Figure 5.13a (Hassall and Zaveri, 1979) includes the results of a number of studies that show the effect of impulse duration on the change in sound pressure level difference \((L_i - L_o)\) required between the level of an impulse, \(L_i\), and the level of a steady sound, \(L_o\), for the sounds to be judged equally loud. Most of the curves indicate that for impulse durations below approximately 200 ms, an increase of 3 dB in sound pressure level is necessary to maintain the same perceived loudness when the pulse duration is halved. Gulick et al. (1989) published a summary of the results of three studies of the effect of stimulus duration on the threshold of detection of a 1 kHz tone, which support the findings of Hassell and Zaveri (1979), as shown in Figure 5.13b. Fastl (1997) concluded that for a 1 kHz tone of duration less than 100 ms, loudness decreases by 10 phons per decade, again the rate in which loudness was found to reduce with decreasing duration is consistent with the results published by Gulick (1989) and Hassell and Zaveri (1979).

Alternatively, Fahy and Walker (1998) investigated the detectability of sounds that had constant overall energy but varied in duration, as this placed much less dependence on the participants. Comparative loudness is essentially subjective and for short transient sounds with different durations, the sound quality will vary in addition to the loudness, which may cause confusion between differences in quality and differences in loudness. The graph of mean detectability of a toneburst with change in duration is shown in Figure 5.13c. For toneburst durations below approximately 15 ms, detectability decreases as the energy in the toneburst becomes spread over an increasingly wider range of frequencies. Above 150 ms, detectability also decreases because the instantaneous sound level decreases, yet the increasing duration no longer contributes to loudness (Fahy and Walker, 1998).

5.2.1.3 Intensity Discrimination

Another important aspect of loudness is the smallest change in level that is perceptible to the listener, or 'just noticeable difference'. Hassall and Zaveri (1979) reported that a change in level of 3 dB was 'just perceptible', whilst a change of 5 dB was 'clearly perceptible' and that a sound would be perceived to be twice as loud if the level was increased by 10 dB. The
smallest detectable differences, however, have been found to be dependent on a number of factors, which include the sound pressure level, the frequency and duration of the tones as well as the manner in which the tones are presented (Gulick, 1971; Coren et al., 1999). A number of studies have calculated the Weber fraction to investigate the effects of frequency and sound pressure level on intensity discrimination. The Weber fraction, \( \Delta I/I \), is given by the smallest change in intensity that is perceptible, \( \Delta I \), relative to the intensity of the reference tone, \( I \), that can be detected 50% of the time. The results of a study by Riesz (1928), reprinted by Coren et al. (1999) are shown in Figure 5.14. This graph indicates that at particularly high or low frequencies, or at low sound pressure levels, differences in sound intensity are more difficult to discriminate. In the middle range of frequencies and sound pressure levels, however, the Weber fraction is fairly constant and a 10-20% change in intensity, approximately 1 dB, is detectable 50% of the time (Fahy and Walker, 1998; Coren et al., 1999). These results are from laboratory studies, in practice it is likely that there will be a larger time interval between different sounds and a change in level of approximately 3 dB would be required for most people to perceive the difference (Fahy and Walker, 1998).

5.2.2 PERCEIVED PITCH OF A SOUND

The perceived pitch of a sound is generally related to the frequency of a sound but the relationship is again non-linear and the pitch of a sound is also dependent on the intensity and duration of the sound and characteristics of the listener.

The mel scale, originally proposed by Stevens et al. (1937), is the most commonly used non-musical scale for pitch. A 1 kHz, 40 dB tone is assigned a pitch of 1000 mels; a tone perceived to be twice as high has a pitch of 2000 mels and a tone half as high, a pitch of 500 mels. Extending this across the range of audible frequencies and extrapolating the results produced the graph in Figure 5.15, which shows that pitch increases more rapidly than frequency for tones below 1 kHz and less rapidly for tones above 1 kHz (Schiffman, 2001).

5.2.2.1 Effect of Intensity on Pitch

The intensity of a pure tone also affects its pitch. When intensity is increased, the pitch of a low frequency tone decreases and a high frequency tone increases, whereas the pitch of the middle frequencies, 1-2 kHz, remains relatively stable (Gulick, 1971; Matlin and Foley, 1997; Coren et al., 1999; Schiffman, 2001). To detect a difference, however, the intensity level has to change by 20 dB or more and even then the change in pitch is relatively small (Gulick, 1971). In addition, for complex sounds, both Gulick (1971) and Matlin and Foley (1997)
stated that intensity does not influence the pitch. Therefore, this is not expected to have a significant effect on a golfer’s perception of the impact sound of a golf shot.

5.2.2.2 Effect of Duration on Pitch

In a similar manner to loudness, the ear requires a tone to be of a minimum duration to accurately detect pitch. The length of time a tone of a given frequency must last for a stable, definite pitch to be determined has been referred to as its critical duration, which can be expressed in milliseconds or in number of cycles. Tones shorter than the critical duration will be heard as a click, regardless of frequency. After analysing the results of several studies, Gulick (1971) concluded that the critical duration of tones of frequency less than 1 kHz is a fixed number of cycles, $6 \pm 3$ cycles, whereas for tones of frequency above 1 kHz, the critical duration is a fixed length of time, 10 ms. Even for tones that exceed the minimum duration, the tonal quality continues to improve as duration is increased to about 250 ms, above which further increases do not result in improved discrimination (Gulick, 1971; Coren et al., 1999). Tones of duration between 10 and 250 ms have a tonal quality described by Dougherty and Garner (1947) as ‘click-pitch’. As the duration of sound from a golf impact is less than 250 ms, this effect is likely to have a considerable influence on the ability of a golfer to determine the pitch of an impact sound.

5.2.2.3 Frequency Discrimination

The Weber fraction has again been used in a similar manner to investigate frequency discrimination. In this case the Weber fraction is given by $\Delta f/f$, where $\Delta f$ is the smallest change in frequency from the reference tone $f$ that can be perceived. Again the Weber fraction has been found to be dependent on frequency and intensity of the reference tone as illustrated by the results of a study by Shower and Biddulph (1931), reproduced by Coren et al. (1999), shown in Figure 5.16. Frequency discrimination is difficult at low frequencies and low sound pressure levels but for moderate level tones above 1 kHz the Weber fraction is fairly constant at about 0.005, therefore the pitch of a 1005 Hz tone can be discriminated from a 1000 Hz tone 50% of the time. These results are from tones presented in quick succession and the limitation of auditory memory is again likely to affect frequency discrimination when the time interval between the sounds is increased (Fahy and Walker, 1998).

5.2.3 Consequences for the Analysis of Golf Impact Sounds

It has been shown that no simple relationships exist between the measured pressure levels and frequencies of sounds and the subjective perceptions of the listener. The loudness
and pitch of a sound are both affected by the intensity, frequency, complexity and duration of the sound as well as the characteristics of the listener. Perhaps of most significance is the effect of duration; an impact sound in golf can range from a few milliseconds to tens of milliseconds in duration depending on the clubhead, which is shorter than the 250 ms required by the human auditory system to accurately detect the pitch and loudness of a sound.

People of all ages enjoy playing golf and for the tests conducted during this research study, players in the age range 20 to 55 years have generally been selected. Human sensitivity to higher frequency sounds, however, diminishes with age, which is known as presbyacusia (Gulick, 1971). Therefore, there are likely to be differences in the way that younger and older golfers perceive the same sound, which may be difficult to quantify.
CHAPTER 6

SOUND AND VIBRATION OF A GOLF SHOT: DATA ANALYSIS AND RESULTS

The subjective and objective data collected from the tactile sensation tests and the impact sound tests, the methodologies of which were outlined in Chapter 4, was analysed and the results are presented and discussed in the following chapter. A similar procedure was used to analyse the data from each study, which is summarised in Figure 6.1 and an overview is given in the next section. The results from each set of tests are presented separately before the findings from the two studies are compared.

6.1 ANALYSIS PROCEDURE

The first stage in the procedure was to gather all the subjective and objective data together in a single spreadsheet. At this stage, the results from the first club used by each golfer were removed from the analysis for the reasons argued in Section 4.2. It was also decided at this stage to remove the data from shots where the centre of the ball imprint from impact was less than 5 mm from the edge of the clubface; i.e. shots were only accepted if at least 75% of the area of the imprint was on the clubface.

Initially, just the subjective data was considered. The ratings of the five feel characteristics obtained in each study were correlated with each other, separately for each golfer, to investigate whether there were any relationships between the feel characteristics and if so whether the relationships held for all golfers. The Pearson correlation method was deemed a suitable technique, as it could be used to measure the linear relationship between the ratings of each pair of feel characteristics; the method is outlined in Appendix 7. The value of the coefficient can range from +1.000, a perfectly positive linear correlation, to -1.000, a perfectly negative linear correlation. After considering the correlations for each individual golfer, the subjective data from all the golfers was then combined and the correlations recalculated. In doing this, it became clear that, as the golfers had no reference level at the beginning of the test, there were variations between golfers in their use of the rating scales. As a result, two numerically different ratings given by two different golfers may
actually have been describing the same sensation. To overcome this problem, the data was standardised (Giuliano and Ugo, 1992). For each golfer and for each feel characteristic, the mean and standard deviation of their ratings were calculated. Each individual rating given by a golfer was then standardised by subtracting from it their mean rating and then dividing the result by the standard deviation of their ratings. Thus, for each feel characteristic, the standardised ratings for each golfer have a mean of zero and a standard deviation of one. Once the golfers' ratings had been standardised, the data was recompiled and the correlation coefficients recalculated.

The next stage in the analysis was to view samples of the sound and vibration data to become familiar with the measurements and identify variations in the data between golfers and between clubs. It also provided an opportunity to identify any problems with measurement quality.

As a result of variations in both the subjective and objective data observed between golfers, the data was initially analysed separately for each golfer. In order for the two sets of data to be correlated, numerical values were required, which represented properties of the sound and vibration measurements that could be correlated with the golfers' subjective ratings. For each study, a number of suitable parameters were selected and correlated with the subjective data. The response of humans to both sound and vibration is non-linear and dependent on frequency, as discussed in Chapter 5. Appropriate frequency weightings were therefore selected and applied to the measurements before the correlation coefficients were recalculated. With numerous measurement locations, several parameters to summarise each measurement, different frequency weightings that could be applied and five feel characteristics rated, the number of possible combinations of data to correlate was potentially too large. Therefore, combinations of data that correlated weakly were discarded and only those that improved the strength of the correlations were retained.

The data from all of the golfers was then combined and the correlation coefficients for the complete set of data computed. Again, the technique of standardising the data was investigated to overcome the variations in data between golfers. In addition, other statistical techniques were investigated to determine the strength of the correlations. The Pearson coefficient is a measure of the linear relationship between two variables and, as the subjective scales used to measure the golfers' perceptions of each feel characteristic appeared to be linear, it seemed reasonable to use this statistic. However, previous studies have shown that a subject does not necessarily interpret these scales in a linear manner (Otto et al., 1999). For
example, a much smaller change may be required for a subject to adjust their rating from say 5 to 6 than from 8 to 9 or 2 to 1. This is because ratings of one or nine represent the extreme values of the scales used in these two studies and subjects need to feel confident that the characteristic being judged justifies receiving such an extreme rating and that later in the test they will not require a rating beyond the limits of the scale. For this reason, many subjects avoid using the extreme values. This is one example of the way in which the relationships may be non-linear and so the non-parametric Spearman's rank-order correlation technique was used to analyse the data; the method is outlined in Appendix 7. A series of further correlations were also investigated using subsets of the sound and vibration data and also the ball and clubhead speed data.

Finally, the subjective ratings and objective data obtained for each club were compared. The results of the analysis of the data from each study are presented and discussed separately in the following two sections.

6.2 TACTILE SENSATION STUDY

6.2.1 ANALYSIS OF SUBJECTIVE RATINGS

The five subjective ratings of 'pleasantness', 'hardness', 'vibration level', 'solidity' and 'liveliness' were initially correlated with each other, separately for each golfer, to investigate whether there were any relationships between the feel characteristics and if so whether the relationships held for all golfers. The Pearson correlation coefficients calculated for each combination of feel characteristics for each individual golfer are listed in Appendix 8; the mean and standard deviation of the all coefficients for each combination are given in Table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Unpleasant - Pleasant Feel</th>
<th>Soft - Hard Feel</th>
<th>No Vibration - Lots of Vibration</th>
<th>Not Solid - Very Solid Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead - Lively Feel</td>
<td>0.823</td>
<td>-0.330</td>
<td>-0.653</td>
<td>0.867</td>
</tr>
<tr>
<td></td>
<td>0.130</td>
<td>0.591</td>
<td>0.178</td>
<td>0.081</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>0.889</td>
<td>-0.350</td>
<td>-0.676</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.066</td>
<td>0.595</td>
<td>0.164</td>
<td></td>
</tr>
<tr>
<td>No Vibration - Lots of Vibration</td>
<td>-0.685</td>
<td>0.511</td>
<td>0.164</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.164</td>
<td>0.547</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>-0.412</td>
<td>0.550</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1—Mean Pearson correlation coefficients for each combination of feel characteristics, standard deviations given in italics
The mean coefficients shown in Table 6.1 indicate that there are very strong, positive correlations between pleasantness, solidity and liveliness of feel. These three characteristics also correlate strongly, but in a negative manner, with perceived vibration level. For all these combinations, the magnitude of the mean coefficient is greater than 0.600 and the standard deviations are relatively small, indicating that these relationships are consistent amongst the golfers tested. However, for combinations of subjective ratings involving the hardness of feel, the mean coefficients are smaller in magnitude and the standard deviations much larger. This is because several golfers' ratings of hardness of feel contradict the general trend, as shown in Appendix 8. For example, a negative correlation exists between twelve of the golfers' ratings of pleasantness and hardness of feel, indicating that more pleasant feeling shots tend to have a soft feel. In contrast, the correlation coefficients for Subjects 5, 6 and 15 are 0.973, 0.245 and 0.410 respectively; for these subjects a more pleasant feeling shot has a harder feel. When hardness of feel is correlated with the remaining characteristics, the coefficients from the same three subjects again contradict the common trend. Further discussions with these golfers revealed that the question had been misinterpreted and so their ratings of hardness of feel were removed from the analysis.

To obtain an overall correlation coefficient for each combination of feel characteristics, all of the golfers' ratings were combined and the Pearson correlation coefficient recalculated; the results are given in Table 6.2.

<table>
<thead>
<tr>
<th></th>
<th>Unpleasant - Pleasant Feel</th>
<th>Soft - Hard Feel</th>
<th>No Vibration - Lots of Vibration</th>
<th>Not Solid - Very Solid Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead - Lively Feel</td>
<td>0.844</td>
<td>-0.511</td>
<td>-0.452</td>
<td>0.881</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>0.909</td>
<td>-0.599</td>
<td>-0.533</td>
<td></td>
</tr>
<tr>
<td>No Vibration - Lots of Vibration</td>
<td>-0.533</td>
<td>0.764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>-0.589</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2 - Pearson correlation coefficients for each combination of feel characteristics

Although the correlations found are strong, the magnitude of the coefficients would be greater if there had been less variation between golfers in their use of the rating scales. Standardisation, as described in Section 6.1 was applied to overcome these variations and
increase the strength of the correlations. Combining the standardised data and recalculating the correlation coefficients gave the values shown in Table 6.3.

<table>
<thead>
<tr>
<th></th>
<th>Unpleasant - Pleasant Feel</th>
<th>Soft - Hard Feel</th>
<th>No Vibration - Lots of Vibration</th>
<th>Not Solid - Very Solid Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead - Lively Feel</td>
<td>0.827</td>
<td>-0.592</td>
<td>-0.654</td>
<td>0.870</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>0.890</td>
<td>-0.601</td>
<td>-0.675</td>
<td></td>
</tr>
<tr>
<td>No Vibration - Lots of Vibration</td>
<td>-0.684</td>
<td>0.735</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>-0.643</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3 – Pearson correlation coefficients for each combination of standardised ratings (p-value = 0.000 for each coefficient)

Overall it can be seen that standardising the ratings has improved the correlations. Strong positive correlations are found within a group of characteristics containing pleasantness, solidity and liveliness of feel and also within a second group containing hardness of feel and perceived vibration level. Between the two groups, though, a negative correlation exists, so a shot that is rated as pleasant overall will also tend to be rated as feeling solid, lively, soft and with little vibration perceived.

6.2.2 Correlation of Subjective and Objective Data

Initial inspection of the vibration data revealed a number of notable points. Vibration levels measured at the shaft were greater than vibration levels measured using the adapter at the grip in corresponding directions. In addition, vibrations measured in the x-direction, aligned to the direction of strike, were greater than the z-direction measurements at both shaft and grip. This can be seen in the example measurements, illustrated in Figure 6.2, from a central impact with a Callaway Great Big Bertha fitted with an EI70 R flex shaft. As a result, low frequency noise, present in all traces, began to have a noticeable effect on the quality of the data measured in the z-direction at the grip, as this measurement had the lowest magnitude of vibration from impact. This occurred despite ac coupling in the data acquisition. In Figure 6.2, the z-grip measurement has a negative mean offset of 40 m/s². Therefore, to minimise the effect of the noise present in the traces, for each vibration measurement, the mean value of the complete signal was subtracted from each data point of that measurement.
It was also noticeable at this stage that there were some considerable variations in the vibration measurements between golfers, particularly in the magnitude, even when a ball was hit from a similar location on the clubface. This may have been due to the different ways in which the club was swung, the variations in clubhead speed at impact generated and differences in the manner and strength in which the club was gripped by each individual golfer. As a result, it was decided to correlate subjective and objective data individually for each golfer first before combining all the data and calculating an overall correlation. These inter-subject variations are investigated further at a later stage in the analysis.

6.2.2.1 Analysis of Unweighted Data

Initially, three numerical quantities were selected to represent the vibration measurements for correlation with the subjective ratings.

i) Peak to peak value (m/s²) – the difference between the maximum value and the minimum value over the complete trace

ii) Dynamic RMS of the first 20 ms of data (m/s²) – the standard deviation of the vibration over the 20 ms after impact about the mean of those points

iii) Dynamic RMS of the complete trace (m/s²) – the standard deviation of all the points about their mean value

Subtracting the mean value from each data point will only be successful in overcoming the influence of noise if there is a constant offset across the complete measurement. If the offset level varies, subtracting the mean will be less successful and so the dynamic RMS of the vibration was also evaluated over 20 ms, a shorter period of time over which the majority of vibration occurred, therefore increasing the likelihood of the noise being constant over the period.

For each golfer, the three parameters were calculated for each of the four measurements for each shot played. Pearson correlation coefficients were then calculated for each combination of feel ratings and vibration parameters. To evaluate the suitability of the parameters, the average coefficient for all golfers was then calculated. The mean of all the correlation coefficients for each combination of solidity ratings and vibration parameter are shown as an example in Table 6.4. Although it is not possible to calculate p-values for this data, as they are mean values of fifteen correlation coefficients, each individual coefficient would need to be greater in magnitude than approximately 0.3 for the result to be significant at the 0.05 level.
Table 6.4 - Mean Pearson correlation coefficients for each combination of solid feel and unweighted vibration parameter measured at four locations, standard deviations given in italics

<table>
<thead>
<tr>
<th>Vibration Parameter</th>
<th>X-shaft</th>
<th>Z-shaft</th>
<th>X-grip</th>
<th>Z-grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak to peak values</td>
<td>-0.263</td>
<td>-0.291</td>
<td>-0.341</td>
<td>-0.297</td>
</tr>
<tr>
<td></td>
<td>0.204</td>
<td>0.171</td>
<td>0.219</td>
<td>0.205</td>
</tr>
<tr>
<td>Dynamic RMS (20ms)</td>
<td>-0.302</td>
<td>-0.344</td>
<td>-0.364</td>
<td>-0.382</td>
</tr>
<tr>
<td></td>
<td>0.183</td>
<td>0.175</td>
<td>0.181</td>
<td>0.186</td>
</tr>
<tr>
<td>Dynamic RMS (entire trace)</td>
<td>-0.307</td>
<td>-0.353</td>
<td>-0.374</td>
<td>-0.408</td>
</tr>
<tr>
<td></td>
<td>0.183</td>
<td>0.180</td>
<td>0.176</td>
<td>0.174</td>
</tr>
</tbody>
</table>

It can be seen from these results that overall the correlations are negative indicating that a reduction in the vibration level results in a more solid feel. The solidity ratings correlate better with the dynamic RMS of the entire trace than with the other two parameters. This is also found when the other subjective ratings are correlated with these vibration parameters. Therefore, the decision was made to proceed further in the analysis using only the dynamic RMS of the entire trace. In addition, it can also be seen that the measurements taken at the grip correlate better than those taken at the shaft.

6.2.2.2 Analysis of Frequency Weighted Data

Human sensitivity to vibration transmitted to the hand is frequency dependent (Reynolds et al., 1977). Consequently, the standards ISO 5349:1986 and BS 6842:1987, which provide guidelines for assessing human exposure to hand-transmitted vibration, both recommend using frequency weighted vibration measurements. The two weightings provided, illustrated in Figure 5.8, are similar; the only significant difference is below 10 Hz, where the BS weighting reduces to approximately 0, the ISO weighting remains constant at 1. For the purposes of this study, the difference between the weightings is insignificant as the resolution of the vibration spectra is 10 Hz.

The relevance of these weightings to this study is debateable as they are designed to assess the injury potential of vibration transmitted into the hand. In addition, the threshold of perception curves from numerous studies, which are compared in Figure 5.5, all suggest that humans are most sensitive to vibrations in the range 100 to 400 Hz regardless of direction, considerably higher than the frequencies that dominate the weightings provided in both the British and International Standards. Therefore, it was decided to investigate the suitability of two frequency weightings in this study. The BS weighting was selected despite being designed for other applications because it was primarily derived from subjective and biodynamic
studies of the hand and arm (Griffin, 1990), which are of relevance. It was also decided to produce a second frequency weighting based on the threshold level curves for a 36 N (8 lb) finger grip reported by Reynolds et al. (1977). Grip forces during a golf swing of up to 40 N were reported by Budney (1979) so the 36 N (8 lb) finger grip was considered to be the most representative of a golf grip out of the four configurations tested.

To develop a frequency weighting from the curves, the RMS displacement was scaled off the published threshold level curves for each direction at each of the one-third octave band centre frequencies and an average of the three values calculated. The mean values were then converted into equivalent acceleration magnitudes before the curve was inverted and scaled such that the maximum value would be approximately one. Finally curves were fitted through the data points and values calculated at 10 Hz intervals to correspond to the data points in the frequency spectra of the vibration measurements.

Two polynomial curves, one for the frequency range 0 to 300 Hz and another for the range 300 to 1200 Hz define the Human Sensitivity (HS) frequency weighting developed; at all other points the value of the weighting is 0. The coefficients of the two polynomials are given in Table 6.5 and the HS weighting is illustrated, alongside the BS weighting in Figure 6.3. It can be seen from the figure that frequencies in the range 100 to 250 Hz dominate the HS weighting, a much wider range and at higher frequencies than the BS weighting.

<table>
<thead>
<tr>
<th>Frequency, ( f ) (Hz)</th>
<th>( f^6 )</th>
<th>( f^5 )</th>
<th>( f^4 )</th>
<th>( f^3 )</th>
<th>( f^2 )</th>
<th>( f^1 )</th>
<th>( f^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; ( f \leq 300 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0 &lt; ( f \leq 300 )</td>
<td>-2.4762e-14</td>
<td>2.6834e-11</td>
<td>-1.0222e-8</td>
<td>1.6166e-6</td>
<td>-1.2064e-4</td>
<td>1.0936e-2</td>
<td>1.2662e-2</td>
</tr>
<tr>
<td>300 &lt; ( f \leq 1200 )</td>
<td>0</td>
<td>-7.834e-16</td>
<td>4.971e-12</td>
<td>-1.2222e-8</td>
<td>1.4595e-5</td>
<td>-8.5176e-3</td>
<td>1.9665</td>
</tr>
<tr>
<td>( f &gt; 1200 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.5 - Definition of Human Sensitivity frequency weighting

The two frequency weightings were then applied to each vibration measurement taken at the four locations for every shot and the weighted RMS vibration calculated. Again, for each golfer, Pearson correlation coefficients were calculated for each combination of the five subjective ratings and the eight RMS vibration parameters before the mean value for all golfers was found. The mean correlation coefficients with the golfers' solidity ratings are again used as an example to compare the different weightings, which are given in Table 6.6.
Vibration Parameter | X-shaft | Z-shaft | X-grip | Z-grip |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweighted RMS</td>
<td>-0.307</td>
<td>-0.353</td>
<td>-0.374</td>
<td>-0.408</td>
</tr>
<tr>
<td></td>
<td>0.183</td>
<td>0.180</td>
<td>0.176</td>
<td>0.174</td>
</tr>
<tr>
<td>BS Weighted RMS</td>
<td>-0.339</td>
<td>-0.296</td>
<td>-0.320</td>
<td>-0.270</td>
</tr>
<tr>
<td></td>
<td>0.229</td>
<td>0.252</td>
<td>0.195</td>
<td>0.222</td>
</tr>
<tr>
<td>HS Weighted RMS</td>
<td>-0.201</td>
<td>-0.077</td>
<td>-0.328</td>
<td>-0.328</td>
</tr>
<tr>
<td></td>
<td>0.244</td>
<td>0.299</td>
<td>0.181</td>
<td>0.217</td>
</tr>
</tbody>
</table>

Table 6.6 – Mean Pearson correlation coefficients for each combination of solid feel and weighted vibration parameter measured at four locations, standard deviations given in italics.

From the findings of the analysis of the unweighted data, where grip measurements generally correlated better with the subjective ratings than shaft measurements, it was expected that frequency weighting the vibration data would improve the correlations whilst maintaining this trend. However, when the correlations with the BS weighted data are compared with the correlations with the unweighted data, the results suggest that the BS weighting only improves correlations with X-shaft measurements. This may be because of the contribution of low frequency noise in the vibration measurements. As noted previously, the magnitude of vibration at the grip is considerably smaller than at the shaft and therefore the signal to noise ratio is much lower. The BS weighting emphasises the low frequency content of a spectrum, the region in which noise is present, and therefore, when the BS frequency weighting is used, noise will contribute significantly to the weighted RMS vibration of the grip.

When the HS weighting is applied, the grip measurements correlate better with the subjective ratings than the shaft measurements. However, the correlations between solidity ratings and HS weighted data are weaker than with unweighted data. This is also the case when HS weighted data is correlated with liveliness of feel, although some improvements to the correlations with the ratings of pleasantness, hardness and vibration level are observed.

At this stage, it was difficult to conclude that any of the above parameters should be rejected, so a further technique was attempted to reduce the number of correlations being calculated and compared.

6.2.2.3 Combination of x and z data at shaft and grip

It is doubtful whether the golfers were able to distinguish the direction of vibration of the golf club after impact and so their subjective ratings were probably based on a perception of the overall vibration. Therefore, it was decided to combine the x and z-direction
measurements at both shaft and grip and correlate the overall RMS vibration with the subjective ratings.

The combined RMS, $C_{\text{rm}}$, of two individual measurements can be calculated from equation (6.1) where $x_i$ and $z_i$ are the $i$th points in the $x$ and $z$-direction vibration measurements from any one shot respectively and $N$ is the total number of data points in that measurement.

$$C_{\text{rm}} = \sqrt{\frac{\sum_{i=1}^{N} (x_i^2 + z_i^2)}{N}}$$  \hspace{1cm} (6.1)

Equation (6.1) simplifies to give equation (6.2), where $x_\text{rms}$ and $z_\text{rms}$ are the RMS vibrations in the $x$ and $z$-directions respectively. Equation (6.2) was used to obtain the combined RMS vibration from the $x_\text{rms}$ and $z_\text{rms}$ values previously calculated.

$$C_{\text{rms}} = \sqrt{x_\text{rms}^2 + z_\text{rms}^2}$$  \hspace{1cm} (6.2)

In a similar manner to before, Table 6.7 gives the mean Pearson correlation coefficients for all combinations of combined vibration at both shaft and grip using each weighting technique with solidity ratings. Also included for comparison are the correlation coefficients for each individual axis, as described previously in Table 6.6.

<table>
<thead>
<tr>
<th>Vibration Parameter</th>
<th>X-shaft</th>
<th>Z-Shift</th>
<th>C-shaft</th>
<th>X-Grip</th>
<th>Z-Grip</th>
<th>C-Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweighted RMS</td>
<td>-0.307</td>
<td>-0.353</td>
<td>-0.346</td>
<td>-0.374</td>
<td>-0.408</td>
<td>-0.399</td>
</tr>
<tr>
<td>0.183</td>
<td>0.180</td>
<td>0.159</td>
<td>0.176</td>
<td>0.174</td>
<td>0.171</td>
<td></td>
</tr>
<tr>
<td>BS Weighted RMS</td>
<td>-0.339</td>
<td>-0.296</td>
<td>-0.391</td>
<td>-0.320</td>
<td>-0.270</td>
<td>-0.350</td>
</tr>
<tr>
<td>0.229</td>
<td>0.252</td>
<td>0.248</td>
<td>0.195</td>
<td>0.222</td>
<td>0.191</td>
<td></td>
</tr>
<tr>
<td>HS Weighted RMS</td>
<td>-0.201</td>
<td>-0.077</td>
<td>-0.197</td>
<td>-0.328</td>
<td>-0.328</td>
<td>-0.360</td>
</tr>
<tr>
<td>0.244</td>
<td>0.299</td>
<td>0.267</td>
<td>0.181</td>
<td>0.217</td>
<td>0.189</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7 - Mean Pearson correlation coefficients for combined and single axis vibration measurements, weighted using three methods, with solidity ratings, standard deviations given in italics

In general, it is apparent that improvements have been made to the strength of the correlations by combining the vibration measurements. Only three out of the twelve individual measurements, the unweighted $z$-direction RMS vibration at both shaft and grip, and the HS weighted $x$-direction RMS vibration at the shaft correlate better than the
corresponding combined measures. To determine which combination of parameters to proceed with into the next stage of the analysis, it was decided to identify, for each of the three weightings, the shaft measurement and the grip measurement that provide the best overall correlation. Until now the correlation with each feel characteristic has been considered separately; to identify the best combination of parameters when all the feel ratings are taken into account, the procedure detailed below was followed.

For each vibration measurement, the correlation coefficients were calculated with each of the five feel ratings for each golfer. For example, for Subject 1, the Pearson coefficients for correlations between the unweighted RMS vibration at x-shaft and pleasantness, hardness, vibration level, solidity and liveliness of feel are -0.453, 0.606, 0.423, -0.425 and -0.430 respectively. The negative correlations with the feel ratings pleasantness, solidity and liveliness and the positive correlations with hardness and perceived vibration level is a trend consistent among many of the golfers. To calculate a mean correlation coefficient of all of the feel ratings, the pleasantness, solidity and liveliness correlation coefficients were inverted so that a larger value indicated a stronger correlation. The five coefficients for every other golfer for the same combination of unweighted RMS vibration at x-shaft with each feel rating were then processed in the same manner and the mean of all the coefficients, \( \mu \), was then calculated, which, in this case, was found to be 0.302. The same procedure was then followed for the other two unweighted vibration measurements at the shaft, z-shaft and c-shaft; for the measurement at z-shaft, \( \mu = 0.325 \) and c-shaft, \( \mu = 0.335 \). It appears, therefore, that when all of the feel characteristics are taken into account, for unweighted RMS vibration at the shaft, the combined measure correlates better with the subjective ratings than the individual measures.

To determine whether the difference between these mean values is statistically significant, a Wilcoxon Signed Ranks Test was performed on each pair of data; the Wilcoxon test is explained further in Appendix 7. For the combination of x-shaft and z-shaft, \( p = 0.902 \), for x-shaft and c-shaft, \( p = 0.000 \) and for z-shaft and c-shaft, \( p = 0.299 \). Therefore, it can be stated that, at the level of significance, \( \alpha = 0.05 \), the x-shaft and z-shaft measurements correlate similarly with the subjective ratings and the combined shaft measurements correlate better than x-shaft measurements but not z-shaft measurements. The same process was then performed for the grip measurements and then the whole procedure repeated for the two different weightings, BS and HS. The mean correlation coefficients are shown in Table 6.8 and the \( p \)-values for each combination of measurements are listed in Table 6.9.
<table>
<thead>
<tr>
<th>Vibration Parameter</th>
<th>X-direction</th>
<th>Z-direction</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>0.302</td>
<td>0.325</td>
<td>0.335</td>
</tr>
<tr>
<td>Grip</td>
<td>0.357</td>
<td>0.367</td>
<td>0.377</td>
</tr>
<tr>
<td>Unweighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td>0.338</td>
<td>0.270</td>
<td>0.371</td>
</tr>
<tr>
<td>Grip</td>
<td>0.271</td>
<td>0.262</td>
<td>0.312</td>
</tr>
<tr>
<td>BS Weighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td>0.199</td>
<td>0.101</td>
<td>0.199</td>
</tr>
<tr>
<td>Grip</td>
<td>0.318</td>
<td>0.324</td>
<td>0.347</td>
</tr>
<tr>
<td>HS Weighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.8 – Mean correlation coefficients for each measurement using each weighting with all subjective ratings

<table>
<thead>
<tr>
<th>Vibration Parameter</th>
<th>X-direction vs. Z-direction</th>
<th>X-direction vs. Combined</th>
<th>Z-direction vs. Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>0.902</td>
<td>0.000</td>
<td>0.299</td>
</tr>
<tr>
<td>Grip</td>
<td>0.403</td>
<td>0.000</td>
<td>0.862</td>
</tr>
<tr>
<td>Unweighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td>0.078</td>
<td>0.027</td>
<td>0.000</td>
</tr>
<tr>
<td>Grip</td>
<td>0.590</td>
<td>0.004</td>
<td>0.005</td>
</tr>
<tr>
<td>BS Weighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td>0.000</td>
<td>0.809</td>
<td>0.000</td>
</tr>
<tr>
<td>Grip</td>
<td>0.575</td>
<td>0.000</td>
<td>0.297</td>
</tr>
<tr>
<td>HS Weighted RMS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9 – P-values obtained from performing a Wilcoxon Signed Ranks test on each set of Pearson coefficients

It can be seen from Table 6.8 that, at a particular measurement location using a given frequency weighting, the mean of the coefficients obtained using the combined measures is greater than or equal to the means obtained using either the corresponding shaft or grip measurements. At a significance level of 0.05, the means of the coefficients obtained using the combined measures are significantly greater than the means obtained using the equivalent x-direction measures in five out of six cases and in three cases significantly greater than the means obtained using the z-direction measures, as illustrated in Table 6.9. On the basis of these statistics, the decision was taken to continue the analysis using only combined measurements at both shaft and grip.

6.2.3 Compilation of All Golfers' Data

The next stage in the analysis was to compile the data from all the golfers together and compute correlation coefficients for the complete set of data. With the large quantity of data...
now being correlated, between 494 and 650 values depending on the combination of vibration parameter and feel characteristic, a Pearson correlation coefficient with a magnitude of approximately 0.08 or greater is now significant at the 0.05 level; coefficients not significant at this level are shown in italics.

Initially, the Pearson coefficients were calculated for each combination of the six vibration parameters selected and the five feel characteristics, both in their original format and in their standardised format, as described in Section 6.1. The results are compared in Table 6.10.

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Unweighted RMS</th>
<th>BS Weighted RMS</th>
<th>HS Weighted RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Grip</td>
<td>Combined Shaft</td>
</tr>
<tr>
<td>Unpleasant - Pleasant Feel</td>
<td>-0.149</td>
<td>-0.110</td>
<td>-0.347</td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>0.444</td>
<td>0.372</td>
<td>0.234</td>
</tr>
<tr>
<td>No Vibration - Lots of Vibration</td>
<td>0.168</td>
<td>0.186</td>
<td>0.353</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>-0.200</td>
<td>-0.157</td>
<td>-0.298</td>
</tr>
<tr>
<td>Dead - Lively Feel</td>
<td>-0.108</td>
<td>-0.169</td>
<td>-0.281</td>
</tr>
<tr>
<td></td>
<td>Standardised</td>
<td>Unweighted RMS</td>
<td>Standardised</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unpleasant - Pleasant Feel</td>
<td>0.271</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standardised Soft - Hard Feel</td>
<td>0.333</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standardised No Vibration - Lots of Vibration</td>
<td>0.232</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standardised Not Solid - Very Solid Feel</td>
<td>-0.287</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standardised Dead - Lively Feel</td>
<td>-0.267</td>
</tr>
</tbody>
</table>

Table 6.10 – Pearson correlation coefficients for each combination of feel characteristic in original and standardised formats and vibration parameter

It can be seen from these results that when relationships between data in an original format are investigated, the correlations are weak; only five coefficients are greater in
magnitude than 0.300. When the ratings are standardised, in the majority of cases, the coefficients have increased in magnitude. Only four coefficients, interestingly the four strongest correlations with the original ratings, have decreased considerably in magnitude.

Similar trends to those seen previously can also be observed. Pleasant feel, solid feel and liveliness of feel all consistently correlate negatively with RMS vibration level whilst hardness of feel and perceived vibration level correlate positively, regardless of the frequency weighting used. Again, the BS weighting only improves correlations with the shaft measurements whereas the HS weighting rarely improves any of the correlations.

Although the majority of these correlations are significant at the 0.05 level, the correlations are not particularly strong. Variability in the vibration levels generated by each golfer may have affected the strength of the correlations. Golfers will rate the amount of vibration perceived relative to their own reference level, which may differ between golfers. To illustrate these variations, Figure 6.4 shows the mean RMS vibration levels, calculated from BS weighted measurements from the shaft and unweighted measurements at the grip, as an indicator of the way in which each golfer's reference level may vary. These two measurements are used as an example as the results given in Table 6.10 suggest they correlate strongest with the subjective ratings. Only the data from central impacts, within 10 mm of the geometric centre of the clubface, was used to calculate the mean values so the data would be comparable and not influenced by the consistency and accuracy of the golfer.

This graph indicates that there are variations in the mean vibration levels generated by each golfer from central impacts. When comparing the combined measurements taken at the grip, the mean RMS vibration values for Subjects 9 and 10 are 326 m/s² and 424 m/s² respectively, which are considerably higher than the mean RMS values of 164 m/s² and 190 m/s² for Subjects 4 and 5 respectively. Therefore, Subjects 9 and 10 would be expected to rate a vibration magnitude of 250 m/s² RMS, for example, much lower than Subjects 4 and 5. It is interesting to note however that a different trend is evident when the mean BS weighted RMS shaft vibration for each golfer is considered. Subject 5 now has one of the highest mean values and Subject 9 one of the lowest.

To overcome these variations, two methods of standardising the vibration data were investigated. For each golfer and for each vibration parameter, the mean RMS vibration value and the standard deviation were calculated. The first standardisation method involved subtracting, for each golfer, their mean value from each individual value. The second method also involved subtracting the mean value but the result was then divided by the standard
deviation. The data was then recompiled and the correlation coefficients recalculated. To illustrate the effect of the data processing on the strength of the correlations, the coefficients for each vibration parameter, standardised using the two alternative methods correlated with standardised solidity ratings are again used and are listed in Table 6.11. The coefficients for every combination of vibration parameter, original and standardised, and feel characteristic, both original and standardised, are listed in Appendix 9.

<table>
<thead>
<tr>
<th>Standardising Technique</th>
<th>Unweighted RMS</th>
<th>BS Weighted RMS</th>
<th>HS Weighted RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Shaft</td>
<td>Combined Shaft</td>
</tr>
<tr>
<td></td>
<td>Combined Grip</td>
<td>Combined Grip</td>
<td>Combined Grip</td>
</tr>
<tr>
<td>Original Data</td>
<td>-0.287</td>
<td>-0.342</td>
<td>-0.168</td>
</tr>
<tr>
<td></td>
<td>-0.306</td>
<td>-0.134</td>
<td>-0.236</td>
</tr>
<tr>
<td>Method 1 ((x_i - \mu_o))</td>
<td>-0.345</td>
<td>-0.397</td>
<td>-0.189</td>
</tr>
<tr>
<td></td>
<td>-0.398</td>
<td>-0.323</td>
<td>-0.337</td>
</tr>
<tr>
<td>Method 2 ((x_i - \mu_o)/\sigma_i)</td>
<td>-0.343</td>
<td>-0.384</td>
<td>-0.187</td>
</tr>
<tr>
<td></td>
<td>-0.400</td>
<td>-0.350</td>
<td>-0.360</td>
</tr>
</tbody>
</table>

Table 6.11 - Pearson correlation coefficients for each combination of vibration parameter, standardised using two different methods, with standardised ratings of solid feel.

The results show that standardising the vibration data by subtracting each golfer's mean value has consistently improved the strength of the correlations irrespective of which frequency weighting is used. Marginal improvements are also made to the strength of the correlations when the data is standardised by subtracting the mean and then dividing the result by the standard deviation. The Wilcoxon Signed Ranks Test can again be used to determine whether these improvements are significant. When all the data in Appendix 9 is analysed, standardising by subtracting the mean has increased the magnitude of the coefficients by on average approximately 0.1, further dividing the result by the standard deviation produced an additional increase. Although the average increase produced is less than 0.01, in some individual cases it is considerable. Both increases are significant at the 0.05 level. Further analysis found that standardising the subjective ratings improved the strength of the correlation by on average approximately 0.06, again the result was significant. When compared to the coefficients obtained using unweighted data, the BS weighting has increased the coefficients with shaft measurements by on average 0.04 but decreased them with grip measurements by 0.1. On average the use of the HS weighting has reduced the coefficients with both shaft and grip measurements by 0.11 and 0.04 respectively and again all of these results are significant.

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The final stage in the analysis was to investigate using a non-parametric correlation statistic. The Pearson Correlation used thus far is only a measure of the linear relationship between two variables and so the non-parametric Spearman's Rank correlation technique was also used to analyse the data. Again, a Wilcoxon Signed Ranks Test was performed to compare the coefficients calculated using each statistic. On this occasion, no significant differences were found between the two techniques.

In Appendix 9 the strongest correlations for each of the feel characteristics with shaft measurements are highlighted using a bold red typeface and with grip measurements using a bold blue typeface. These results are summarised in Table 6.12.

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Measurement Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shaft</td>
</tr>
<tr>
<td>Unpleasant – Pleasant Feel</td>
<td>-0.397</td>
</tr>
<tr>
<td>Soft – Hard Feel</td>
<td>0.444</td>
</tr>
<tr>
<td>No Vibration – Lots of Vibration</td>
<td>0.371</td>
</tr>
<tr>
<td>Not Solid – Very Solid Feel</td>
<td>-0.397</td>
</tr>
<tr>
<td>Dead – Lively Feel</td>
<td>-0.371</td>
</tr>
</tbody>
</table>

Table 6.12 – The strongest Pearson correlation coefficients for each feel characteristic at the two vibration measurement locations

Each of these coefficients is obtained using one of many different combinations of frequency weightings and standardising techniques. However, two vibration parameters, one for shaft measurements and one for grip measurements correlate almost as strongly with all the feel characteristics. The best overall set of correlations with shaft measurements are obtained when the subjective ratings are standardised and the vibration data from the $x$ and $z$ directions are weighted according to BS 6842, the RMS values calculated, the two directions combined using equation (6.2) and the data standardised by subtracting the mean RMS value. The best overall set of correlations with grip measurements are obtained when the subjective ratings are standardised and the vibration data is left unweighted, the RMS values for each direction again combined using equation (6.2) and the data standardised by subtracting the mean value and dividing the result by the standard deviation. These results are summarised in Table 6.13 and can be compared with the best coefficients obtained which are shown in Table 6.12.
<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Shaft</th>
<th>Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Weighting</td>
<td>BS 6842</td>
<td>None</td>
</tr>
<tr>
<td>Vibration Parameter</td>
<td>RMS (entire data)</td>
<td>RMS (entire data)</td>
</tr>
<tr>
<td>Measurement Direction</td>
<td>Combined x and y directions</td>
<td>Combined x and y directions</td>
</tr>
<tr>
<td>Standardisation Method</td>
<td>Subtract mean</td>
<td>Subtract mean and divide by the standard deviation</td>
</tr>
<tr>
<td>Correlation Statistic</td>
<td>Pearson Correlation</td>
<td>Pearson Correlation</td>
</tr>
<tr>
<td>Correlation with Standardised Unpleasant – Pleasant Feel</td>
<td>-0.397</td>
<td>-0.373</td>
</tr>
<tr>
<td>Correlation with Standardised Soft – Hard Feel</td>
<td>0.349</td>
<td>0.378</td>
</tr>
<tr>
<td>Correlation with Standardised No Vibration – Lots of Vibration</td>
<td>0.371</td>
<td>0.304</td>
</tr>
<tr>
<td>Correlation with Standardised Not Solid – Very Solid Feel</td>
<td>-0.397</td>
<td>-0.400</td>
</tr>
<tr>
<td>Correlation with Standardised Dead – Lively Feel</td>
<td>-0.371</td>
<td>-0.429</td>
</tr>
</tbody>
</table>

Table 6.13 – Summary of procedure required to obtain the set of strongest overall correlations

When these values are compared to the coefficients calculated between the unprocessed data, shown in Table 6.10, it can be seen that frequency weighting the data, in the case of the shaft measurements and standardising generally increases the magnitude of the coefficients by more than 0.200. Surprisingly though, the original ratings of hardness of feel correlate as well or better with the unprocessed vibration data, with the coefficients changing from 0.444 and 0.372 to 0.349 and 0.378 respectively when the data is processed.

To illustrate these correlations, two vibration parameters, similar to those that provided the strongest set of correlations shown in Table 6.13, are used as an example: the BS weighted RMS shaft vibration standardised by subtracting the mean and the unweighted RMS grip vibration also standardised by subtracting the mean. The correlations with vibration data standardised by only subtracting the mean are used as an example because the graphs are easier to interpret. If only the mean values are subtracted, the resultant data is the RMS vibrations in m/s² above or below the golfers’ mean levels. If this data is further
divided by the standard deviation, the values become non-dimensional and from a practical point of view are difficult to interpret.

To illustrate the correlations, the standardised ratings of solid feel from -3 to 2 were divided into ten bands of equal width. For each of the vibration parameters, the mean and standard deviation of the standardised RMS values were calculated for the data associated with each band of ratings. These results, along with a linear line of best fit through the mean values, are plotted in Figure 6.5 and Figure 6.6.

These graphs illustrate the negative correlations that exist between vibration level and solid feel. They also indicate the reason why it was difficult to improve the strength of the correlations. Although definite trends are observable, the spread of RMS values in each band of ratings is large compared to the overall range of RMS values. Therefore there is little distinction between adjacent bands and vibrations with an RMS equal to the golfers' mean level have received ratings in every single one of the bands.

**6.2.4 CORRELATION OF MEAN DATA FOR EACH CLUB**

It has to be taken into account when following this analysis that the ratings are based on subjective human perceptions. Therefore, differences are to be expected in the way each golfer perceives the feel of a club. They are also being asked to hit shots in an unfamiliar manner; their hearing is restricted and they cannot see the ball flight. For these reasons, it is possible to obtain individual data points far away from the general trend. To minimise the effect of these values on the overall correlation, mean values for each golfer were calculated for the five shots with each club. The data for all golfers was then compiled and the analysis procedure repeated to investigate relationships between the mean values.

The Pearson coefficients for each combination of standardised subjective rating and combined vibration measurement, using each of the frequency weightings, both in original format and standardised by subtracting each golfers' mean value, are included in Appendix 10. The best overall set of correlations are now obtained for both shaft and grip measurements when the subjective ratings are standardised and the vibration data is left unweighted, the RMS values for each direction combined using equation (6.2) and the data standardised by subtracting the mean value. The coefficients obtained are listed in Table 6.14.

When compared with the coefficients in Table 6.13, the results show that the strength of the correlation has been improved by calculating, for each golfer, the mean rating and the mean value of the vibration parameters for each club. However, these improvements are only
Table 6.14 – Pearson coefficients obtained when the mean rating and mean vibration parameter for each club and for each golfer are correlated

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Standardised Unweighted RMS Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
</tr>
<tr>
<td>Standardised Unpleasant – Pleasant Feel</td>
<td>-0.483</td>
</tr>
<tr>
<td>Standardised Soft – Hard Feel</td>
<td>0.426</td>
</tr>
<tr>
<td>Standardised No Vibration – Lots of Vibration</td>
<td>0.406</td>
</tr>
<tr>
<td>Standardised Not Solid – Very Solid Feel</td>
<td>-0.529</td>
</tr>
<tr>
<td>Standardised Dead – Lively Feel</td>
<td>-0.490</td>
</tr>
</tbody>
</table>

achieved with the unweighted vibration data; correlations with weighted vibration data are considerably weaker as shown in Appendix 10. To illustrate these results, the correlation between the mean values of standardised solidity ratings and the mean values of unweighted RMS of combined grip vibration, is shown in Figure 6.7. This compares with the correlation using individual values illustrated in Figure 6.6.

The considerably larger values of the Pearson coefficients obtained by correlating mean values of both subjective ratings and vibration parameters for each club and for each golfer suggest that this technique is the most suitable for analysing the data obtained in these tests. However, it is only appropriate to use this method when all the data from every golfer has been combined and the resultant sample size is large. In this case, there were approximately 135 pairs of data and consequently a coefficient greater than 0.166 in magnitude is significant at the 0.05 level.

6.2.5 Correlation of Ball Speed with Liveliness Ratings

Finally, the measured ball speed and the ratio of ball to clubhead speed were correlated with liveliness ratings to investigate whether golfers could accurately perceive the speed at which the ball came off the clubface. Using the data from each individual shot, the values of ball speed and ratio of ball speed to head speed, both in their original format and standardised by subtracting the mean, were correlated with liveliness ratings again in both original and standardised formats. The Pearson coefficients are compared in Table 6.15.

These results again suggest that standardising the data improves the correlations significantly, particularly when the ball speed and ratio of ball to head speed are standardised. This is not surprising considering the golfers’ mean clubhead speeds ranged from 80 to 108
Table 6.15 – Pearson correlation coefficients for combinations of liveliness ratings, ball speed and ratio of ball to head speed

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Ball Speed</th>
<th>Ratio of Ball to Head Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Data</td>
<td>Standardised Data</td>
</tr>
<tr>
<td>Dead – Lively Feel</td>
<td>0.294</td>
<td>0.491</td>
</tr>
<tr>
<td>Standardised Dead – Lively Feel</td>
<td>0.253</td>
<td>0.575</td>
</tr>
</tbody>
</table>

mph. It also appears that golfers have a reasonably accurate perception of the speed of the ball off the clubface. This is most likely to be a result of golfers knowing, from their perception of club vibration, how well they have hit the ball, possibly combined with preconceptions or knowledge of the performance of different types of clubhead.

The correlation between the standardised liveliness ratings and standardised ball speeds is illustrated in Figure 6.8. Again the stronger correlation is reflected in a greater distinction certainly between the two ends of the ratings scale. Analysis of the outlying points revealed an interesting finding. Relative to the other clubs, there are a number of occasions when the ball was perceived to have come off the two traditional wooden clubs faster than it actually did and perceived to have come off the two ERC clubheads slower than it did. This is illustrated in Figure 6.9, where the majority of the data points in the region below the lower dotted line are associated with the wooden headed clubs and many of the data points in the region above the upper dotted line are associated with the two ERC clubs. In Figure 6.10, the mean standardised ball velocity, ± one standard deviation, from a central impact is plotted for each club and clearly shows the greater ball velocities that are achieved with modern titanium clubheads.

6.2.6 CLUB COMPARISON

6.2.6.1 Subjective Data

In Section 6.2.1 the feel characteristics pleasantness, solidity and liveliness of feel were found to be strongly and positively interrelated, as were the two characteristics hardness of feel and perceived vibration level. Between these two groups of characteristics, however, a negative relationship was discovered suggesting that, in general, shots that were perceived to have a pleasant feel were rated as having felt solid, lively and soft with little vibration perceived. To investigate whether these relationships held for all of the clubs tested or whether it was possible that a club could feel solid but dead, or lively but hard, for example, the mean standardised rating of a central impact with each club was found. The data from
off-centre impacts was not included because it would increase the variance of the data making it more difficult to identify differences between clubs. A central impact was specified as having been within 10 mm of the geometric centre of the clubface. This distance was chosen as it provided a region large enough to include sufficient data to represent as many of the golfers' opinions as possible without the region becoming so large that the variance of the data increased; it is acknowledged, however, that the distance may be large enough for the feel to vary within the region.

The graphs in Figure 6.11 show, for each feel characteristic, a range of two standard deviations, one each side of the mean standardised rating for a central impact with each club. Feel characteristics that are positively correlated are plotted on the same graph; the ratings of pleasantness, solidity and liveliness of feel are shown in Figure 6.11a and the ratings of hardness of feel and perceived vibration level are shown in Figure 6.11b. These graphs both illustrate the strong positive correlations found within the two groups of characteristics. In general, the mean standardised ratings of pleasantness, solidity and liveliness are similar for each club, as are the mean standardised ratings of hardness of feel and perceived vibration level. In Figure 6.11a, it can be seen that central impacts with the ERC (EI70 shaft), the GBB (5.3 Gold shaft), the Titleist 975D and the Ping TiSi are all rated consistently above average in terms of their pleasantness, solidity and liveliness of feel. The range of ratings given to these clubs is also small indicating that the golfers generally agreed about the feel of these clubs. Given the overall negative correlation found between these three characteristics and hardness of feel and perceived vibration level, it would be expected that the ratings of hardness of feel and perceived vibration level for these four clubs would consistently be below average. In Figure 6.11b, it can be seen that the ratings for the GBB (5.3 Gold shaft), Titleist 975D and the Ping TiSi followed this trend but the ERC (EI70 shaft) only received average ratings indicating that it has a harder feel than expected. The ERC (5.3 Gold shaft) has also been rated harder than would be expected given the pleasantness, solidity and liveliness of feel ratings it received. It is also noticeable from Figure 6.11b that the traditional wooden headed clubs, the Ping Eye 2 and the Persimmon, which tend to be perceived as having a soft feel, have not been rated that way during this set of tests. This may be because the sound of the impact was masked and so the golfers could only base their ratings on their tactile feedback.

A novel method was developed to illustrate the distribution of golfers' standardised pleasantness ratings for shots hit across the face of each club and the results are shown in Figure 6.12. Each square, which represents an area of 5 mm x 5 mm on the clubface, is
shaded according to the mean standardised pleasantness rating for shots with centres of impact location within that region. The numerical mean value is included in each square along with the standard deviation of the ratings, given in italics.

It can be seen from these illustrations that as the impact location gets further from the geometric centre of the club face, as would be expected, the golfers' ratings decrease, indicating a more unpleasant feel. However, the rate at which the values decrease with distance from the centre varies with clubhead type. Some of the more modern heads, such as clubs 8-10, have a more consistent feel across the clubface and shots can still feel pleasant well away from the geometric centre, especially if the impact is located higher on the clubface. In contrast, the feel from older heads, such as clubs 3, 4 and 7, decreases much more quickly as the impact location moves away from the centre. This may be because the modern clubheads have a larger rotational moment of inertia and therefore the torsional vibrations are reduced.

These figures also highlight the findings of the analysis of central impacts, as illustrated in Figure 6.11a, that the Ping Eye 2, Maxfli VHL and Slazenger persimmon have a less pleasant feel as, for impacts within 10 mm of the geometric centre, the mean standardised pleasantness ratings for each club are -0.3, -0.2 and 0.04 respectively, whereas the Titleist 975D and the Ping TiSi achieved mean ratings of 0.8 and 0.7 respectively. If only impacts are considered that are even more central, such as those within the square located at the geometric centre of each clubface, then club 5, the Callaway ERC with the EI70 shaft was rated as feeling the most pleasant. Club 6 is unusual in that the region that corresponds with the most pleasant feel is not located at the geometric centre, but higher on the clubface and towards the toe. It would also appear that the golfers achieved greater consistency with club 2, the Callaway GBB with the EI70 shaft, particularly in comparison to the other oversize clubs, as the majority of the shots were hit from a much smaller region on the clubface.

With such strong correlations between pleasantness of feel and solid and lively feel, similar results are seen when solid and lively ratings are plotted across each clubface.

6.2.6.2 Vibration Data

Included in this set of test clubs were two Callaway ERC's and two Callaway GBB's, both assembled with two different shafts, a regular flex True Temper EI70 and a stiffer flex RCH 5.3 Gold. The purpose of using these clubs was to evaluate the contribution of the clubhead and the shaft to the vibration characteristics of a club and therefore its feel. For each of the four clubs, frequency spectra were produced for each of the vibration
measurements, both $x$ and $z$-direction at shaft and grip, from every shot with an impact location within 5 mm of the geometric centre of the clubface. The frequency spectra of $x$-direction measurements at both shaft and grip with the GBB fitted with a 5.3 Gold shaft are compared in Figure 6.13. The $x$-direction measurements were chosen as the spectra to evaluate as the vibration magnitudes are considerably greater than in the $z$-direction and even if combined spectra were used, the $x$-direction measurements would still be dominant.

The spectra from shaft measurements, illustrated in part a), are remarkably consistent regardless of which golfer hit the shot, especially above 800 Hz. Below this frequency some variability can be observed. The peak in most spectra at approximately 130 Hz is absent from two shots by Subjects 1 and 4 and the peak at approximately 250 Hz is absent from shots by Subjects 4, 5, 12 and 14. At the grip, however, considerably more variability is observed in the frequency spectra across the range 0 to 800 Hz, although consistency does return at the higher frequencies. Differences between golfers in the overall level of the spectra can also be seen regardless of measurement location.

The mean frequency spectrum is also plotted on each of the graphs. Equivalent mean spectra were generated in the same manner for the other three Callaway clubs, and are compared in Figure 6.14. At both shaft and grip it can be seen that the mean frequency spectra for clubs with identical shafts show greater similarity than the spectra for identical clubheads. This suggests that the shaft contributes much more to the vibration characteristics of the club in the frequency range 0 to 2000 Hz than the clubhead and therefore will have a greater effect on the feel of a club. It can also be seen that the peaks in the mean spectra for clubs fitted with the 5.3 Gold shaft are at higher frequencies than the corresponding peaks in the spectra for clubs with the EI70 R flex shaft, which is because the 5.3 Gold shaft is stiffer.

The general magnitude of each spectrum, however, is similar and therefore the RMS values would not be expected to vary considerably between each of the four clubs. If golfers are unable to perceive the differences in frequency and instead are more sensitive to variations in the overall magnitude of vibration then the clubs will have a similar feel. To compare typical vibration magnitudes for each club, the unweighted RMS of combined grip vibration, standardised by subtracting each golfer's mean value, was again selected to illustrate the differences. For each club, the mean RMS vibration, ± one standard deviation, from a central impact, within 10 mm of the geometric centre is plotted in Figure 6.15. This figure confirms that the difference between the RMS values for the Callaway clubs is small. The RMS vibration of the two wooden headed clubs appears to be consistently higher than a
golfer's average vibration level, whereas the RMS vibration of the Titleist 975D and the Ping TiSi are consistently below. The mean standardised subjective ratings for central impacts with the Callaway clubs, illustrated in Figure 6.11, are similar, which suggests that golfers are not so sensitive to frequency variation within the range 0 to 2 kHz and, therefore, their perceptions are more likely to be affected by the overall magnitude of vibration.

6.3 IMPACT SOUND STUDY

6.3.1 ANALYSIS OF SUBJECTIVE RATINGS

The analysis of the data from the impact sound tests followed a similar procedure to the tactile sensation study and again began with an investigation of the subjective data. The five subjective ratings of 'pleasantness', 'pitch', 'loudness', 'hardness' and 'liveliness' were again initially correlated with each other, separately for each golfer, to investigate whether there were any relationships between the feel characteristics and if so whether the relationships held for all golfers. The Pearson correlation coefficients calculated for each combination of feel characteristics for each golfer are listed in full in Appendix 11, the mean values of the coefficients for each combination are given in Table 6.16.

<table>
<thead>
<tr>
<th></th>
<th>Unpleasant - Pleasant Feel</th>
<th>Dull - Sharp Sound</th>
<th>Quiet - Loud Sound</th>
<th>Soft - Hard Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead - Lively Feel</td>
<td>0.785</td>
<td>0.834</td>
<td>0.830</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>0.188</td>
<td>0.150</td>
<td>0.135</td>
<td>0.673</td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>-0.107</td>
<td>0.121</td>
<td>0.181</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.681</td>
<td>0.629</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quiet - Loud Sound</td>
<td>0.628</td>
<td>0.880</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.294</td>
<td>0.147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull - Sharp Sound</td>
<td>0.696</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.239</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.16 - Mean Pearson correlation coefficients for each combination of feel characteristics, standard deviations shown in italics

Strong correlations, with Pearson coefficients greater than 0.800, are found between the characteristics pitch and loudness of sound and liveliness of feel, indicating that almost all golfers agree that these characteristics are related in a positive manner, i.e. crisper, sharper sounds are perceived to be louder and result in a livelier feel. These three characteristics also correlate strongly and in a positive manner with the overall pleasantness of feel, but the mean Pearson coefficients are smaller and the standard deviations are larger, indicating that there is greater variation between golfers. Indeed, examination of the coefficients for each individual golfer, given in Appendix 11, reveals that these relationships do not hold true for Subjects 28,
35 and 40. Finally, the mean coefficients for all relationships involving the hardness of feel are small and the standard deviations large. Again, analysis of the coefficients given in Appendix 11 reveals the cause. For some golfers there are strong positive relationships, for others strong negative correlations and yet for others there is no correlation between hardness of feel and the four other characteristics. These findings all lead to the conclusion that there are differences between golfers either in the manner in which the feedback from a golf shot is perceived or in the meaning of the questions and the descriptors.

Further analysis of the trends between the correlation coefficients revealed that fourteen of the seventeen golfers tested in this study could be grouped into three distinct categories; the remaining three showed significant individual traits. For each of the three groups, the mean and standard deviation of the coefficients for each combination of subjective ratings were calculated and the results are illustrated in Figure 6.16. Each line of each diagram represents the relationship between the two feel characteristics it connects, with the mean and the standard deviation of the correlation coefficients for that group of golfers shown at the mid-point of the line, highlighted in bold and in italics respectively. Solid blue lines represent a positive correlation, whilst dashed red lines represent a negative correlation; thick lines are used to highlight particularly strong correlations, where the mean coefficient is greater in magnitude than 0.500 and thin lines are used to indicate weak, but significant, correlations. The individual correlation coefficients for each golfer are based on a sample size of approximately forty-five, implying that coefficients greater in magnitude than approximately 0.300 are significant. Although the mean values cannot be analysed for significance, mean coefficients below 0.300 are enclosed in brackets and coloured grey to indicate that if a golfer followed the mean trend of the group, these correlations would not be significant.

Subjects 21, 22, 24, 33, 36, 38 and 39 were grouped together and formed the largest set, Group A. For this collection of golfers, all of the feel characteristics are strongly related and the correlation coefficients are all positive, indicating that a pleasant feeling shot has a crisp, loud sound and a hard, lively feel. For Subjects 25, 30, 31 and 34 in Group B, the characteristics are also strongly related but the hardness of feel for this group of golfers is negatively related to the other characteristics, so a pleasant feeling shot also has a crisp, loud sound and a lively feel but has been rated by this group as having a soft feel. The final set of golfers, Group C, was created for Subjects 26, 27 and 37. Again, for this group of golfers, the characteristics pleasantness and liveliness of feel and pitch and loudness of sound are all...
strongly related in a positive manner but hardness of feel is unrelated to any of the other characteristics, with the majority of the coefficients being insignificant.

When the diagrams a) to c) in Figure 6.16 are compared, it can be seen that the only difference between the three groups of golfers is the way in which the hardness of feel of each golf shot has been rated. For Groups A and B, the magnitude of the mean correlation coefficients for the combinations of hardness of feel and the sound characteristics are large, for Group C they are small. This may suggest that for the golfers in Groups A and B the hardness of feel is related to the impact sound, with the relationship being different for golfers in Group A than those in Group B, whereas for golfers in Group C hardness of feel could be related to another form of feedback, such as tactile sensations. Alternatively, there may have been different interpretations of the question, an issue that arose in the tactile sensation study. A solution to this problem could not be found from the available data, so the ratings of hardness of feel for all golfers were removed from the analysis, with an aim to resolve the issue during a future investigation.

The equivalent diagrams for Subjects 28, 35 and 40, who did not fit into any of the three groups, are illustrated in Figure 6.17. Subject 28 is the only golfer who participated in the tests for whom the liveliness of feel does not correlate strongly with the ratings of pitch and loudness of impact sound. For this golfer, the two characteristics pleasantness and liveliness, which are positively related, correlate negatively with hardness of feel. Liveliness of feel is again related to the characteristics of the impact sound for Subject 35, but pleasantness and hardness of feel which are strongly, but negatively related, are not. The trends for Subject 40 are less clear, although pleasantness of feel does not correlate with the characteristics of the impact sound, whilst hardness of feel correlates better with perceived loudness rather than pitch of the sound. Again, it is not clear whether the weak correlations result from a feel characteristic being unrelated to the impact sound or whether they result from different interpretation of a question. Every golfer’s opinion is of equal importance so, despite the trends for these three golfers being different from the majority, their data was retained.

The subjective data for all the golfers was then combined. Again, to overcome variations between golfers in their use of the scales, the golfers ratings were standardised as described in Section 6.1. The Pearson correlation coefficients for each combination of standardised subjective ratings are shown in Table 6.17.

The overall coefficients obtained, shown in Table 6.17, are similar to the mean coefficients shown in Table 6.16, and, therefore, the overall relationships between the feel
Table 6.17 - Pearson correlation coefficients for each combination of standardised ratings ($p$-value=0.000 for each coefficient)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Unpleasant–Pleasant Feel</th>
<th>Dull–Sharp Sound</th>
<th>Quiet–Loud Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead–Lively Feel</td>
<td>0.795</td>
<td>0.839</td>
<td>0.830</td>
</tr>
<tr>
<td>Quiet–Loud Sound</td>
<td>0.643</td>
<td>0.886</td>
<td></td>
</tr>
<tr>
<td>Dull–Sharp Sound</td>
<td></td>
<td></td>
<td>0.705</td>
</tr>
</tbody>
</table>

characteristics follow the trends described previously. Perceived pitch and loudness of sound and liveliness of feel are all strongly and positively related. Pleasantness of feel also correlates strongly with these three characteristics, although the coefficients are smaller, probably because this relationship was not true for every golfer.

### 6.3.2 Correlation of Subjective and Objective Data

When samples of the impact sound measurements were inspected a number of issues arose. The sound measurements acquired from the microphone attached to the baseball cap worn by the golfer, occasionally contained low frequency noise. This was probably due to movement of the cable during the swing. Therefore, to minimise the effect of noise, for each sound measurement from the cap-mounted microphone, the mean value of the complete signal was subtracted from each data point of that measurement.

The correlations between subjective and objective data were again calculated individually for each golfer to investigate further the differences between golfers and also to identify the sound parameters that correlate strongest with the subjective data, before all the data was combined and the overall correlations calculated.

#### 6.3.2.1 Analysis of Unweighted Data

The following parameters were initially selected to numerically represent the impact sound measurements.

i) Peak level (dB re 20 μPa) — the largest absolute value of each measurement

ii) Peak-to-peak value (dB re 20 μPa) — the difference between the maximum and the minimum value of each measurement

iii) Duration (ms) — the time taken for the mean absolute sound pressure over 1 ms to reduce to 25 dB below the peak level of each measurement

iv) Decay — the power of the exponential curve that most accurately fits the envelope of the measurement.
v) Mean sound pressure level (20 ms) (dB re 20 μPa) — the RMS sound pressure over the first 20 ms of each measurement

vi) Mean sound pressure level (50 ms) (dB re 20 μPa) — the RMS sound pressure over the first 50 ms of each measurement

The peak and peak-to-peak values were selected because they may correlate with the perceived loudness of the sound. Another parameter that may correlate well with perceived loudness is the sound pressure level. This was calculated over 20 ms and 50 ms after the start of the impact sound for a number of reasons. The acquisition of the impact sound was set up to capture 4 ms of data prior to the trigger point, to ensure that the entire event was acquired. As a result, however, noise, probably from the movement of clothing during the swing, was measured by the cap-mounted microphone shortly before impact, which was not measured by the tripod-mounted microphone. In addition, the noise of the ball hitting the net was captured by both of the microphones, which tended to be over 50 ms after impact. Therefore, only the data in the 50 ms of each measurement following the onset of the impact sound was suitable for analysis. The sound pressure level over two different periods of time was investigated, as over 20 ms there is less likelihood of the measurement being affected by noise, which is occasionally present in measurements from the cap-mounted microphone.

The duration and decay parameters were selected because they are both measures of the decline of the sound over time. The procedure used to calculate the decay is illustrated in Figure 6.18, using the example sound measurement shown in Figure 6.18a. To begin with, the absolute values of the measurement were obtained, which are shown by the green line in Figure 6.18b. For each successive millisecond of data, the maximum absolute value of the measurement in that period, highlighted by a blue cross, was then identified. An exponential curve of the form \( y(t) = be^{-t} \), plotted in red, was then fitted through these data points. The decay of a measurement is given by the value \( c \).

For each golfer, the six parameters were calculated for each sound measurement acquired during the test. Pearson correlation coefficients were then calculated for each combination of sound parameter and feel characteristic rating. To evaluate the suitability of each parameter, the mean value of the coefficients for all of the golfers for each combination was calculated. At this stage in the analysis, only the measurements from the tripod-mounted microphone will be considered as these measurements were obtained during every test. The results from the cap-mounted microphone will be compared to the results from the tripod-mounted microphone in a later section. The mean coefficients for all combinations of sound parameters and feel characteristics are listed in Table 6.18. Although it is not possible to
calculate a $p$-value for each correlation, as they are mean values of seventeen coefficients, the individual coefficients would need to be greater than approximately 0.300 for the results to be significant at the 0.05 level.

<table>
<thead>
<tr>
<th>Sound Parameter</th>
<th>Unpleasant – Pleasant Feel</th>
<th>Dull – Crisp Sound</th>
<th>Quiet – Loud Sound</th>
<th>Dead – Lively Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Level</td>
<td>0.507</td>
<td>0.648</td>
<td>0.701</td>
<td>0.632</td>
</tr>
<tr>
<td></td>
<td>0.238</td>
<td>0.193</td>
<td>0.091</td>
<td>0.143</td>
</tr>
<tr>
<td>Peak-to-Peak Level</td>
<td>0.519</td>
<td>0.692</td>
<td>0.749</td>
<td>0.675</td>
</tr>
<tr>
<td></td>
<td>0.258</td>
<td>0.196</td>
<td>0.093</td>
<td>0.145</td>
</tr>
<tr>
<td>Duration</td>
<td>0.370</td>
<td>0.674</td>
<td>0.740</td>
<td>0.601</td>
</tr>
<tr>
<td></td>
<td>0.201</td>
<td>0.155</td>
<td>0.091</td>
<td>0.118</td>
</tr>
<tr>
<td>Decay</td>
<td>0.432</td>
<td>0.724</td>
<td>0.775</td>
<td>0.670</td>
</tr>
<tr>
<td></td>
<td>0.230</td>
<td>0.161</td>
<td>0.110</td>
<td>0.137</td>
</tr>
<tr>
<td>SPL (20 ms)</td>
<td>0.515</td>
<td>0.783</td>
<td>0.848</td>
<td>0.740</td>
</tr>
<tr>
<td></td>
<td>0.251</td>
<td>0.181</td>
<td>0.083</td>
<td>0.127</td>
</tr>
<tr>
<td>SPL (50 ms)</td>
<td>0.514</td>
<td>0.784</td>
<td>0.851</td>
<td>0.740</td>
</tr>
<tr>
<td></td>
<td>0.254</td>
<td>0.180</td>
<td>0.082</td>
<td>0.126</td>
</tr>
</tbody>
</table>

Table 6.18 – Mean Pearson correlation coefficients for each combination of sound parameter and feel characteristic, standard deviations shown in italics

It can be seen from these mean values that the four feel characteristics all correlate in a positive manner with the sound parameters. The golfers' perceptions of the loudness of the impact sound correlate particularly strongly with the measurements of sound pressure level, which is encouraging, as sound pressure level is considered to be related to the loudness of a sound, it suggests that all the golfers used are sensitive to differences in impact sound and were able to report their perceptions consistently and reliably over the duration of the test. Sound pressure level also correlated better than peak-to-peak level, which is probably because the effect of duration is reflected in the sound pressure level but not in the peak-to-peak level. It is interesting to note that the parameters duration and decay also correlate strongly with perceived loudness. This may be a coincidence, with all the louder sounds having had a longer duration, or it may be that the sound duration has an effect on the golfers’ perceptions of loudness. A similar trend is also observed for correlations between the sound parameters and the perceived sound pitch. Again, it may be a coincidence that the clubs selected for this study that have a duller sound are also quieter and the clubs with a crisper sound are also louder or it may be that there is an interaction between the perceived pitch of a sound and its loudness. The strong correlation between ratings of liveliness of feel and the sound parameters supports the theory that emerged from the analysis of the subjective ratings in
Section 6.3.1 that liveliness is related to sound characteristics for sixteen out of the seventeen golfers. Ratings of pleasantness of feel, however, correlate less well. Inspection of the coefficients for each golfer reveals that for Subjects 28, 35 and 40, their ratings of pleasantness of feel do not correlate with sound parameters, which also supports earlier speculation that for these golfers the overall pleasantness of feel is not related to the sound but another form of feedback, such as vibration.

At this stage in the analysis, the decision was taken to discard the parameters peak level and sound pressure level over 20 ms. The parameter peak-to-peak level consistently correlates better with the subjective ratings than the peak level and, as there is no difference in the strength of the correlations between the two sound pressure level measurements, the 50 ms measurement was retained as it incorporates more of the data.

### 6.3.2.2 Analysis of Frequency Weighted Data

Human perception of loudness is dependent on the frequency of the sound, as discussed in Section 5.2.1.1 and illustrated in Figure 5.10. The next stage in the analysis, therefore, was to frequency weight the measurements accordingly. The A weighting was selected since it is the most commonly used weighting, along with the C weighting, which is designed for use with louder sounds because it approximates the (inverted) shape of the 100 dB equal loudness contour. The unweighted sound pressure levels of golf shots measured during the tests ranged from 90 to 110 dB. The two frequency weightings are illustrated in Figure 5.11.

<table>
<thead>
<tr>
<th>Sound Parameter</th>
<th>Unpleasant – Pleasant Feel</th>
<th>Dull – Crisp Sound</th>
<th>Quiet – Loud Sound</th>
<th>Dead – Lively Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak-to-Peak Level</td>
<td>0.524</td>
<td>0.713</td>
<td>0.767</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>0.260</td>
<td>0.195</td>
<td>0.091</td>
<td>0.142</td>
</tr>
<tr>
<td>Duration</td>
<td>0.375</td>
<td>0.674</td>
<td>0.750</td>
<td>0.609</td>
</tr>
<tr>
<td></td>
<td>0.200</td>
<td>0.166</td>
<td>0.102</td>
<td>0.130</td>
</tr>
<tr>
<td>Decay</td>
<td>0.437</td>
<td>0.713</td>
<td>0.780</td>
<td>0.669</td>
</tr>
<tr>
<td></td>
<td>0.209</td>
<td>0.157</td>
<td>0.094</td>
<td>0.131</td>
</tr>
<tr>
<td>SPL (50 ms)</td>
<td>0.513</td>
<td>0.784</td>
<td>0.852</td>
<td>0.740</td>
</tr>
<tr>
<td></td>
<td>0.248</td>
<td>0.179</td>
<td>0.076</td>
<td>0.122</td>
</tr>
<tr>
<td>Peak-to-Peak Level</td>
<td>0.525</td>
<td>0.714</td>
<td>0.769</td>
<td>0.692</td>
</tr>
<tr>
<td></td>
<td>0.260</td>
<td>0.195</td>
<td>0.089</td>
<td>0.141</td>
</tr>
<tr>
<td>SPL (50 ms)</td>
<td>0.513</td>
<td>0.783</td>
<td>0.852</td>
<td>0.740</td>
</tr>
<tr>
<td></td>
<td>0.250</td>
<td>0.180</td>
<td>0.076</td>
<td>0.122</td>
</tr>
</tbody>
</table>

*Table 6.19 – Mean Pearson correlation coefficients for each combination of frequency weighted sound parameter and feel characteristic, standard deviations shown in italics*
The peak-to-peak level, duration, decay and sound pressure level over 50 ms of each A weighted measurement were calculated, whilst only the peak-to-peak level and the sound pressure level over 50 ms of each C weighted measurement were calculated. For each golfer, these parameters were then correlated with the subjective ratings and the mean coefficient for each combination of sound parameter and feel characteristic calculated, which are shown in Table 6.19.

When the mean coefficients in Table 6.18 and in Table 6.19 are compared, it can be seen that the frequency weightings have not had any significant effect on the strength of the correlations. This is because, for a typical impact sound in golf, the majority of sound energy is in the region 1 to 10 kHz, the region in which there is little difference between a linear weighting and the A and C weightings.

The parameters used so far in the analysis have all been measures associated with the loudness or the duration of the sound. To investigate whether golfers' perceptions of pitch correlated with the frequency characteristics of a sound, a method was needed to generate a single frequency value that could be considered to represent a complex sound spectrum. A technique that has been used previously, and has been shown to correlate well with the timbre of a sound (McAdams et al., 1999), is to calculate the centroid, or first moment, of a spectrum using equation (6.3).

\[ f_c = \frac{\sum_{i=1}^{N} a_i f_i}{\sum_{i=1}^{N} a_i} \]  

(6.3)

In equation (6.3), \( a_i \) is the amplitude, at frequency \( f_i \), of a spectrum containing \( N \) data points. There are, however, a number of possibilities to consider that will all have an influence on the value of the centroid of a spectrum. If the amplitudes from a power spectrum are used, the value of \( f_c \) will be different to the value calculated from an equivalent magnitude spectrum because more emphasis will be placed on the frequencies with large amplitudes. Alternatively, the logarithm of the frequency can be used, as in equation (6.4), which gives added weight to the lower frequency components of a spectrum, again influencing the value of \( f_c \). The basis for doing this is that lower frequencies of sound stimulate a greater proportion of the basilar membrane, the part of the ear responsible for detecting sound pressure, than higher frequencies and should be weighted accordingly.
A final option considered was to use the sound pressure level in each one-third octave band of a spectrum as values of $a_i$ and the centre frequencies of the bands as values of $f_i$ in equation (6.3). The third-octave band with a centre frequency of 500 Hz was the lowest frequency band used because of a lack of resolution in the spectra and, as the frequencies below this contribute little to the impact sound of a golf shot, excluding them from the calculation was not expected to have a significant effect.

The values of $f_i$ were calculated for each A weighted sound measurement using each method and correlated with each golfer's subjective ratings. The mean correlation coefficients for each combination of pitch parameter and feel characteristic are given in Table 6.20.

<table>
<thead>
<tr>
<th>Type of Spectrum</th>
<th>Frequency Values</th>
<th>Unpleasant - Pleasant Feel</th>
<th>Dull - Crisp Sound</th>
<th>Quiet - Loud Sound</th>
<th>Dead - Lively Feel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear</td>
<td>0.216</td>
<td>0.330</td>
<td>0.331</td>
<td>0.288</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.262</td>
<td>0.230</td>
<td>0.213</td>
<td>0.217</td>
</tr>
<tr>
<td></td>
<td>Log</td>
<td>0.362</td>
<td>0.581</td>
<td>0.610</td>
<td>0.525</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.257</td>
<td>0.200</td>
<td>0.164</td>
<td>0.189</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>0.384</td>
<td>0.594</td>
<td>0.618</td>
<td>0.546</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.240</td>
<td>0.203</td>
<td>0.172</td>
<td>0.194</td>
</tr>
<tr>
<td></td>
<td>Log</td>
<td>0.419</td>
<td>0.666</td>
<td>0.702</td>
<td>0.612</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.218</td>
<td>0.185</td>
<td>0.148</td>
<td>0.174</td>
</tr>
<tr>
<td></td>
<td>Linear</td>
<td>0.378</td>
<td>0.610</td>
<td>0.640</td>
<td>0.552</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.254</td>
<td>0.197</td>
<td>0.160</td>
<td>0.185</td>
</tr>
</tbody>
</table>

Table 6.20 – Mean correlation coefficients for each combination of sound pitch parameter and feel characteristic, standard deviations shown in italics

These results suggest that the value of $f_i$ calculated using amplitudes from a power spectrum and the logarithm of the frequency values, as in equation (6.4), correlates strongest with the subjective ratings, particularly with the golfers' perceptions of liveliness of feel and loudness and pitch of impact sound. As a result, the other methods were discarded from the analysis at this stage. Interestingly, the pitch parameters correlate more strongly with loudness ratings than pitch ratings. Again, this may be because all the higher pitched sounds were also the loudest or because of a relationship between the pitch and loudness of the sound of a golf shot. Evidence that such relationships exist was presented in Section 5.2.
Having refined the parameters to consider, the next stage in the analysis was to compile the data from all the golfers and examine the correlations within the complete set of data.

6.3.3 Compilation of All Golfers' Data

Variations between golfers in the mean and standard deviation of their subjective ratings for each feel characteristic investigated in this study indicated that each golfer had used the scales differently so, again, the ratings were standardised. In the tactile sensation study, considerable variation in the magnitude of club vibration was also observed between golfers and so the vibration data was standardised as well. It was deemed unnecessary, however, to standardise the sound data as, between golfers, there was much less variation in the sound measurements than the vibration measurements.

Once all the data had been combined, Pearson correlation coefficients were again calculated for each combination of sound parameter and subjective rating, in both original and standardised forms. The complete set of coefficients is included in Appendix 12. The different frequency weightings did not improve the strength of the correlations so the coefficients obtained using the A weighted sound parameters are given in Table 6.21 as an example; this is the most commonly used weighting and it provides some immunity against low frequency noise typically encountered outdoors such as wind noise. With 675 pairs of

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>A Weighted Sound Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak-to-Peak Level</td>
</tr>
<tr>
<td>Unpleasant – pleasant feel</td>
<td>0.467</td>
</tr>
<tr>
<td>Dull – crisp sound</td>
<td>0.644</td>
</tr>
<tr>
<td>Quiet – loud sound</td>
<td>0.687</td>
</tr>
<tr>
<td>Dead – lively feel</td>
<td>0.626</td>
</tr>
<tr>
<td>Unpleasant – pleasant feel</td>
<td>0.519</td>
</tr>
<tr>
<td>Dull – crisp sound</td>
<td>0.694</td>
</tr>
<tr>
<td>Quiet – loud sound</td>
<td>0.741</td>
</tr>
<tr>
<td>Dead – lively feel</td>
<td>0.664</td>
</tr>
</tbody>
</table>

Table 6.21 – Pearson coefficients for each combination of A weighted sound parameter and feel characteristic
data contributing to each correlation, a Pearson coefficient with a magnitude of approximately 0.08 is significant at the 0.05 level.

Standardising the ratings has again improved the strength of the correlations, but, on average by only approximately 0.03, although this is significant when a Wilcoxon signed-ranks test is performed on the data; this statistical test is described further in Appendix 7. Similar conclusions to those in Section 6.3.2 are also reached when the coefficients are compared. The subjective ratings of pitch and loudness of sound and liveliness of feel correlate strongest with the sound parameters, whilst pleasantness of feel correlates less strongly, possibly because for some golfers this characteristic is related to the vibration of the club. All of the feel characteristics correlate strongest with the parameter sound pressure level calculated over the first 50 ms of the impact sound. Interestingly, the subjective ratings of sound pitch correlate better with sound pressure level than with the centroid of the spectrum. However, it would be premature to conclude that sound pressure level has more of an influence on pitch than frequency, as the measurement of the centroid of a spectrum is only a crude indicator of the pitch of a complex sound.

It is also interesting to note that perceived loudness and pitch of sound have correlated strongly with all the sound parameters but this may be because of the clubs selected. Pearson coefficients were calculated to investigate relationships between the sound parameters and the results are shown in Table 6.22.

| Centroid of a spectrum | 0.699 | 0.653 | 0.762 | 0.792 |
| SPL (50ms)             | 0.915 | 0.779 | 0.847 |
| Decay                  | 0.653 | 0.801 |
| Duration               | 0.539 |

Table 6.22 – Pearson correlation coefficients for each combination of sound parameters

It can be seen from Table 6.22 that all the sound parameters are strongly correlated, therefore the impact sounds with this set of clubs are generally either loud, higher pitched and long in duration or vice versa, which has resulted in the subjective ratings correlating with all the sound parameters. If clubs could be incorporated that are loud but low-pitched and long in duration, or less loud, high-pitched but short in duration, for example, then the influence of sound pressure level on perceived pitch could be identified more conclusively.
To illustrate the correlations, two combinations of data, the sound pressure level and perceived loudness and the centroid of a spectrum and perceived pitch, are plotted in two different styles in Figure 6.19 and Figure 6.20 respectively. Figure 6.19a and Figure 6.20a show, for each combination, a linear line of best fit through the individual data points. To obtain the graphs in Figure 6.19b and Figure 6.20b, the standardised ratings between -2 and +2 were divided into eight bands of equal width and the mean and standard deviation of the sound parameters were calculated for the data in each band. In Figure 6.19a, it is clear why a large correlation coefficient of 0.836 was obtained. There is a strong positive trend through the data and, in general, impact sounds with a pressure level greater than 100 dB were distinguished from those below 95 dB. This conclusion is also supported by the graph in part b), however, this representation of the data also enables another trend to be identified. The data only appears to have a positive linear relationship between the standardised ratings of -1 and +1, outside of this region there is no relationship. For each band of ratings from 0.5 to 2, the mean sound pressure level is between 100 and 105 dB, whilst for each band of ratings from -0.5 to -2 the mean is between 90 and 95 dB. This indicates that the majority of the golfers tested are able to distinguish larger changes in the sound pressure level of a golf shot, but they have much more difficulty discriminating between the loudness of sounds when the pressure levels are more similar.

The strong positive correlation between the centroid of a spectrum and perceived pitch is evident when Figure 6.20a is inspected. The weaker correlation coefficient of 0.664 is probably due to the increase in outlying data points, particularly the impact sounds where the centroid of each spectrum was above 5 kHz yet the pitch of the sound was still given a negative rating indicating that it was perceived as having a duller sound than an average shot. These data points are likely to have resulted from off-centre shots, where the sound may well have been duller, but the rating was disproportionately low, possibly because the golfer was annoyed at hitting a poor shot. In Figure 6.20b, however, there only appears to be a positive linear relationship between pitch and the centroid of a spectrum between the standardised ratings of -1.5 to 0.5. Again, towards each end of the ratings scale, the relationship ceases to exist. For each band of positive standardised ratings, the mean centroid of the spectra is in the region 5 to 6 kHz, suggesting that golfers had particular difficulty in discriminating between the higher pitched sounds, although again the limitations of using the centroid of a spectrum as a measure of its pitch must be taken into account.

The Pearson correlation coefficient is a measure of the linear relationship between two variables. Figure 6.19b and Figure 6.20b however, have illustrated that the correlations are
not completely linear and so the non-parametric Spearman rank-order correlation statistic, which is described in Appendix 7, was investigated. When the coefficients were calculated and compared to the Pearson coefficients, however, no increase in magnitude was found.

6.3.3.1 Comparison of Measurement Location

The sound data used so far in the analysis was measured by the tripod-mounted microphone. During the tests conducted with the American golfers, Subjects 21 to 31, measurements were also taken from a cap-mounted microphone. Data from these measurements were processed in the same manner and correlated with the subjective ratings in both original and standardised formats. The Pearson coefficients for each combination of A weighted sound parameter and standardised subjective rating are shown in Table 6.23, which compare with the coefficients in the lower half of Table 6.21.

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Peak-to-Peak Level</th>
<th>Decay</th>
<th>SPL (50ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpleasant - pleasant feel</td>
<td>0.454</td>
<td>0.504</td>
<td>0.517</td>
</tr>
<tr>
<td>Dull - crisp sound</td>
<td>0.587</td>
<td>0.708</td>
<td>0.728</td>
</tr>
<tr>
<td>Quiet - loud sound</td>
<td>0.597</td>
<td>0.792</td>
<td>0.796</td>
</tr>
<tr>
<td>Dead - lively feel</td>
<td>0.551</td>
<td>0.669</td>
<td>0.679</td>
</tr>
</tbody>
</table>

Table 6.23 – Pearson coefficients for each combination of feel characteristic and A weighted sound parameter measured above the golfers' left ear

In general, the measurements from the cap-mounted microphone do not correlate as strongly with the subjective ratings as the tripod-mounted microphone measurements. The correlations with peak-to-peak level and sound pressure level are noticeably weaker, although the correlations with the decay parameter are stronger. The weaker correlations may be because of the contribution of low frequency noise probably from cable movement during the swing or other noise such as the rustle of clothing that is not present in the measurements from the tripod-mounted microphone.

6.3.4 Club Comparison

To compare the subjective ratings given to each club and the sound measurements taken from impacts with each club, only data relating to shots where the centre of the impact mark was within 10 mm of the approximate geometric centre of the clubface were included. This was done because including off-centre impacts would increase the variance of the data and make it more difficult to identify differences between clubs.
6.3.4.1 Subjective Ratings

Figure 6.21 illustrates the subjective ratings for central impacts with each club. A range of two standard deviations, one each side of the mean value is shown for each feel characteristic for each club. The general trend in the ratings across all the clubs is similar, which illustrates the strong correlations between the subjective ratings found in Section 6.3.1, for some clubs such as the Taylor Made Firesole, the GBB, the Steelhead and the Ping TiSi, the mean ratings of all the feel characteristics are very similar. Some small deviations from the general trend, however, can be observed, especially in the ratings of pleasantness of feel. Certainly, the older clubs, such as the Ping Eye 2, the Maxfli VHL, the Slazenger Persimmon and the Yonex graphite head were given pleasantness ratings higher than would be expected given their mean ratings of pitch and loudness of sound and liveliness of feel. The Titleist 975D obtained a high mean pleasantness rating despite the fact that the impact sound was not perceived to be that loud.

6.3.4.2 Sound Parameters

To investigate whether the golfers accurately perceived the differences in loudness between the clubs, the mean sound pressure level is plotted against the mean loudness rating for a central impact with each club in Figure 6.22. At 105 dB, the mean sound pressure level of an impact with the Ping TiSi is the highest of all clubs. The Taylor Made Firesole, GBB, ERC and Steelhead all generate impact sounds with a mean sound pressure level greater than 100 dB, whilst the Titleist 975D falls between these modern clubheads and the older style clubheads such as the Ping Eye 2, Maxfli VHL, Slazenger persimmon and Yonex graphite head, for which the mean sound pressure level is below 95 dB. In general, the golfers have been able to perceive this order of loudness of impact sound but they have only been able to discriminate accurately between differences in sound pressure level of 5 dB or greater. As a result, the smaller differences between the modern clubheads and between the older clubheads have not been detected by the majority of golfers, which explains the zero gradients at the extremes of the graph in Figure 6.19b.

In Figure 6.23, the mean centroid of the spectra is plotted against the mean sound pitch rating for a central impact with each club. Again, the strong correlation is reflected by the overall positive trend through the data but, in a similar fashion to loudness perception, only the large differences in pitch between the modern clubheads and the older clubheads have been accurately discriminated. Golfers have had much greater difficulty distinguishing differences within the group of modern clubheads and within the group of older clubheads. The ERC in particular was rated as having the crispest, sharpest sound, yet the dominant
frequency in the spectrum from a central impact is at approximately 4.5 kHz, lower than the region of 5-7 kHz, which usually contains the dominant frequencies of an impact sound from a titanium clubhead, as illustrated in Figure 6.24. As a result, the mean centroid for the ERC is 4.76 kHz, which is significantly lower than for the other modern clubheads and similar to the mean centroid for the Maxfli VHL, as illustrated in Figure 6.23. Again, this lack of ability to discriminate between smaller changes in sound frequency explains the change in the trend at the extremes of the graph in Figure 6.20b, although the limitations of the centroid of a spectrum as an indicator of pitch may also be contributing to this trend.

The mean duration, ± one standard deviation, of an impact sound from a central impact with each club is shown in Figure 6.25. With a mean duration of 26 ms, the impact sound from the Steelhead is the longest, which compares to the sound durations of 2-4 ms from the older clubs. The sound from the Titleist 975D has a duration of on average 7 ms which is considerably shorter than the sounds from the other modern clubheads, which may explain why it is not perceived to be as loud.

6.4 COMPARISON OF RESULTS FROM EACH STUDY

When the results from the tactile sensation study and the impact sound study are compared, the coefficients obtained with the sound data are considerably greater in magnitude, which suggests that the impact sound contributes more significantly to the feel of a golf shot than the club vibration. However, this may only be because the differences in impact sound between clubs, particularly between the older and the more modern clubheads, are greater and therefore more discernable than the differences in vibration level between the clubs. It has been seen in this study that golfers have been able to discriminate between sound pressure levels that differ by 5 dB or more and changes of approximately 2 kHz in the centroid of a spectrum. However, they have had much more difficulty in accurately discriminating smaller differences such as the subtle differences between the modern clubheads.

To investigate whether the correlations would have been just as strong if all the clubs in the test had been modern clubheads, the Pearson coefficients were recalculated using just the data from the GBB, Steelhead, ERC, Ping TiSi, Taylor Made Firesole and the Titleist 975D and are shown in Table 6.24. With the sample size now reduced to 413, a coefficient of approximately 0.100 is required for significance at the 0.05 level; coefficients smaller in magnitude than 0.100 are shown in italics.


<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>('A) Weighted Sound Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak-to-Peak Level</td>
</tr>
<tr>
<td>Unpleasant – pleasant feel</td>
<td>0.189</td>
</tr>
<tr>
<td>Dull – crisp sound</td>
<td>0.243</td>
</tr>
<tr>
<td>Quiet – loud sound</td>
<td>0.294</td>
</tr>
<tr>
<td>Dead – lively feel</td>
<td>0.260</td>
</tr>
</tbody>
</table>

Table 6.24 – Pearson coefficients for each combination of \('A\) weighted sound parameter and feel characteristic calculated using only the data from modern clubheads.

By only analysing the data from the modern clubheads, the largest correlation coefficient has been reduced from 0.836 to just 0.405, which is of a similar magnitude to the coefficients obtained in the tactile sensation study. Therefore, if discrimination of the more subtle differences between clubs is required in future studies, the approach used may need to be reconsidered.

Golfers’ perceptions of the feel characteristics pleasantness and liveliness of feel were investigated in both studies. The mean standardised ratings for these two characteristics, obtained from each study, for central impacts with the eight common clubs are compared in Figure 6.26. The mean pleasantness ratings for each club, illustrated in Figure 6.26a are remarkably similar across the two studies, despite different golfers participating in each study and the impact sound being masked in the tactile sensation study. In Figure 6.26b, it can be seen that the mean liveliness ratings are also relatively similar across the two studies, although the mean liveliness ratings for the GBB and the ERC have arguably increased when the golfer has been able to hear the impact sound.

In the tactile sensation study, the impact sound was masked and liveliness of feel correlated reasonably strongly with the vibration data. In the impact sound study, however, when the data from all the clubs was used, liveliness of feel correlated even more strongly with the sound data. This suggests that both forms of feedback contribute to the lively feel of a shot, but given both sound and vibration, the sound makes the dominant contribution.
CHAPTER 7

RECOMMENDATIONS FOR FURTHER WORK

7.1 INVESTIGATION OF OTHER DIMENSIONS

Ten general dimensions emerged from the qualitative study of characteristics of a golf shot that are important to a player, but only two, 'Feel from Impact' and 'Impact Sound' were investigated in detail in this research programme. As a result, there are many other characteristics that could be investigated in future studies, particularly the numerous inter-dimension relationships between 'Club Weight', 'Feel of Club Position During Swing', 'Shaft Feel' and 'Club Control'. Two sets of test clubs that have either identical shafts but different head weights or identical weights but different shafts could be used to investigate the relationships between perceived club control, shaft flexibility, swingweight and feel of the clubhead during a swing, whilst objective measurements may be able to quantify the effects on performance.

The approach used in this study can also be replicated to elicit perceptions of different golf equipment such as irons or balls, equipment used in other sports, alternative groups of performers or even applied in areas outside of sport. The procedure highlights the success with which information can be gathered from performers during play, allowing experiences to be described as they arise and not in retrospect. In this study, the ability to interview the golfers whilst playing shots with a wide variety of clubs certainly increased the quantity and quality of information gathered. It can be argued that this principle should be applied to any player evaluation of equipment but this presents some difficulty with dynamic games such as tennis or squash compared with the quasi-static style of golf. The wireless recording system developed in this study could prove useful in allowing interviews to take place during the progress of a game.

7.2 FURTHER TESTING TO CORRELATE SUBJECTIVE AND OBJECTIVE DATA

A number of techniques proved successful in improving the strength of the correlations, particularly standardising both the subjective ratings and objective data, and as a result significant correlation coefficients with magnitudes between 0.4 and 0.6 in the tactile
sensation study and 0.5 and 0.8 in the impact sound study were obtained. In the sound study, however, when only the data from the modern clubs was correlated, the magnitude of the coefficients reduced considerably. As it is of more interest to a manufacturer to be able to determine differences between their current club and a competitor's current club rather than a traditional club, it is recommended that further tests are carried out to refine the methodology such that the smaller variations between modern clubs that affect the feel of a shot can be distinguished. A great deal of experience in testing humans and measuring perceptions has been gained during the tests that have been conducted as part of this project and as a result a number of possible improvements to the tests procedures have emerged. These include modifications to the process of participant selection, the design of the test procedure, the measurements taken and the analysis of the data.

7.2.1 PARTICIPANT SELECTION

Variability between test subjects has regularly been observed during the analyses of the data. The different distributions of pleasantness ratings across the clubface for two golfers, Subjects 1 and 12, in the tactile sensation study are illustrated in Figure 7.1. It is noticeable from these two graphs that the rate at which the pleasantness ratings decrease with distance from the centre varies between the two golfers. Subject 12 awarded impacts within 5mm of the centre of the clubface ratings in the range 7 to 9. As impacts shift to approximately 10mm from centre, the ratings reduce to between 4 and 6. In contrast, Subject 1 still awarded impacts up to 20mm from the centre with ratings of 7 and 8. Although modern clubs are more forgiving and have been shown to feel better than traditional clubs when impacts are further from the centre, it is also apparent that this rate of change of ratings is related to attributes of the golfers themselves. Variations between golfers were further illustrated in Figures 6.16 and 6.17, which show the different relationships between the feel characteristics, particularly hardness of feel, identified in the impact sound study.

At this stage it is difficult to conclude whether this inter-subject variability is a result of golfers misinterpreting the questions, a lack of reliability and consistency in some of the golfers ratings, variations in sensitivity to changes in stimuli between people, or genuine differences between golfers in the way in which a golf shot was perceived. It does, however, raise the issue of participant selection. Typically in this project, golfers have tended to be used who are unfamiliar with testing and are not associated with Callaway Golf, so that any effect of their preconceived ideas, knowledge and bias would be minimised and their views would represent general public opinion rather than the opinion of Callaway representatives. As a result, the golfers used were inexperienced in participating in these types of test and this has
been a disadvantage. In a summary of techniques used in the evaluation of automotive sounds, Otto et al. (1999, p1317) concluded, 'customers have greater variability in their responses than employees and tend to exhibit a higher proportion of poor performers'. It is also difficult, when subjective rating scales have been used, to assess the performance of a subject from their data, whereas with techniques such as the paired comparison method, measures of consistency and reliability can be obtained.

For future tests, building up a pool of golfers who are able to discriminate changes in feel characteristics accurately and report their perceptions consistently and reliably is recommended. If these golfers were then used regularly, their greater experience in participating in these types of test may also improve their performance in the test. The development of a short simple assessment that could be performed either well in advance of a test program or immediately prior to the commencement of a test to determine the reliability of a subject will enable suitable golfers to be identified.

7.2.2 DESIGN OF TEST PROCEDURE

The ability of humans to differentiate between external stimuli is dependent on the surrounding environment and the time delay between each stimulus. Fahy and Walker (1998) suggested that the discrimination of sounds that differ in level by 1 dB and frequency by 1% is only possible under laboratory conditions, when the sounds are heard in quick succession. In practice and in golf, the sound and vibration will be perceived in less favourable conditions and with a greater time delay between events, which, owing to limitations in perceptual memory, will reduce the golfers' ability to discriminate between stimuli. This has direct consequences for the design of future test procedures. In the tactile sensation and impact sound tests, there was approximately one minute between each shot and around three-quarters of an hour between the first and last shots, so golfers may have had difficulty in recalling their perceptions of the first clubs in the test relative to the later clubs. In future, test durations may have to be reduced or methods such as the paired comparison technique used, where golfers would only have to compare shots or clubs that have been paired together in the sequence, so that there is less reliance on the perceptual memory of the golfer. This will, however, significantly limit the number of clubs or balls that can be evaluated during a single test.

In this research, the data associated with the first club used by each golfer was removed during the analyses, which effectively allowed each golfer five shots to practice using the scales and determine their own reference level. It is debateable whether this was sufficient
time for the golfers to become comfortable with the rating scales. In addition, Otto et al. (1999) recommended that for jury tests, particularly when bounded scales are being used to rate stimuli that are presented sequentially, the subjects should be presented with all of the stimuli in the practice period to give them an idea of the range covered. Clearly, extensive practice would be of benefit but this has considerable implications for the duration of a test. With the maximum number of shots that can be hit in a single test limited to fifty and a maximum length of time of one hour, the longer the practice period, the shorter a test will have to become and in future a suitable balance will need to be achieved.

The decision to conduct the tactile sensation tests in an indoor net whilst playing pink noise to the golfer was taken to isolate vibration as the only form of feedback received by the golfer from each shot. It was thought that, by doing this, golfers would find it difficult to rate feel characteristics that were related to the sound and it would focus their attention on the vibration of the club. Instead, the subjective ratings given by the golfers for each of the feel characteristics were all strongly correlated. This suggests that either the five characteristics are vibration related, or that without the impact sound, golfers were forced to use their perception of club vibration as the only basis available on which to make their subjective ratings. The same results might not occur if the study were repeated whilst allowing the golfers to hear the impact sound. It is also difficult to quantify the effect on the golfers of the abnormal manner in which they were being asked to hit golf shots, although none of them reported being unduly affected.

In the impact sound study, vibration was not measured and as a result it was not possible to identify whether golfers' ratings that did not correlate strongly with the sound parameters would have correlated with vibration measurements or whether the golfers ratings' were unreliable. It is recommended, therefore, that for future tests, both sound and vibration are measured along with the subjective ratings. This will, however, have a significant effect on the logistics of conducting the tests; extra equipment will be required, running cables from accelerometers mounted on the club to a data acquisition system will restrict the speed at which clubs can be changed and, as the tests need to be conducted outdoors from the measurement of sound perspective, all the equipment will need to be battery powered. Clearly, there is also an opportunity for more sophisticated data transmission and acquisition methods to be developed.
7.2.3 Measurement of Subjective and Objective Data

Accurate, reliable and consistent measurement of subjective perceptions is inherently difficult and each method will have its advantages and disadvantages. The justification for using the Likert scales in this study was that feel ratings could be obtained from every shot, which would indicate the magnitude of difference in feel between shots. A number of disadvantages were discovered during the tests and these, along with techniques used to overcome them, are summarised in Table 7.1. For the majority of problems identified, solutions were found but the final two issues will need addressing if more accurate ratings are to be obtained from scaled response questions in the future.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution Implemented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects use different parts of a scale — the same rating by two different golfers may not be describing the same sensation</td>
<td>Standardise ratings</td>
</tr>
<tr>
<td>Some subjects will avoid using the extreme values of a scale</td>
<td>Standardise ratings</td>
</tr>
<tr>
<td>Scales are not necessarily interpreted in a linear manner</td>
<td>Use non-parametric statistics</td>
</tr>
<tr>
<td>Number of shots hit before subjects develop their own reference levels and are comfortable with the scales</td>
<td>Remove data from first club used, vary club order</td>
</tr>
<tr>
<td>Order effects</td>
<td></td>
</tr>
<tr>
<td>1) A club may be rated differently if it is preceded by a very good club or by a very poor club</td>
<td>Vary club order</td>
</tr>
<tr>
<td>2) A shot may be rated differently if it is preceded by several good shots or by several bad shots</td>
<td></td>
</tr>
<tr>
<td>A rating of one is given to a bad shot and nine to a good shot regardless of the descriptors on each end of the scale</td>
<td>Explain questions clearly at the beginning of the test</td>
</tr>
<tr>
<td>Misinterpretation of the question</td>
<td>Phrase question carefully and pilot test questionnaire</td>
</tr>
<tr>
<td>For an individual subject, do two shots with different clubs that are both given the same rating feel the same?</td>
<td></td>
</tr>
<tr>
<td>Are there enough points on the scale to distinguish between differences in feel?</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1 — Disadvantages of using Likert scales and some of the solutions used to overcome them

The use of other types of scale such as a continuous scale or a semantic difference scale, in which the scale is divided by a sequence of words, such as ‘extremely’, ‘very’, ‘somewhat’, ‘neither’, ‘somewhat’, ‘very’, ‘extremely’, instead of by a sequence of numbers may offer some improvements but neither is likely to provide a complete solution. In the tactile sensation
study, the strongest correlations were obtained when the mean data for each club and for each golfer was used. A similar result may be achieved by having the golfers rate a club based on an impression obtained from several shots rather than rate each individual shot, as this could overcome the problem of ratings from off-centre shots being disproportionate. A final option is to use a technique such as the paired comparison method where the feel of two clubs would be compared, which should be easier for a golfer to accomplish than placing an absolute value on the feel of a club.

Improvements can also be made to the manner in which objective data is measured. In the tactile sensation study, the vibration measurements from the adapter were remarkably consistent despite the problems with noise and the possibility that the adapter could move. However, the ability to correlate shaft measurements with the feel characteristics should be the long-term goal, as they are more reliable measurements and do not interfere with the golfer's grip. It may, therefore, be worth developing transfer functions for different golf grips to predict the vibration at the hand-grip interface from the measurements of shaft vibration. Torsional vibrations have also been neglected in this study but they are likely to contribute to the feel of a shot, as any off-centre impact will induce this type of vibration. It is recommended, therefore, that torsional vibrations are measured in any future tests.

7.2.4 ANALYSIS PROCEDURE

During the analyses, a number of different techniques were developed and applied to the data to identify and improve the strength of the correlations between the subjective and objective data. Standardising the golfers' ratings and, in the tactile sensation study, the vibration data was a particularly useful technique, whilst perhaps the least successful stage in the analysis was the application of the frequency weightings.

In the tactile sensation study, the BS weighting did improve the coefficients when the subjective ratings were correlated with the combined weighted shaft data from every shot, but the increase was small. It was also interesting to note that neither of the two weightings improved the correlations with both shaft and grip measurements. The BS weighted shaft measurements correlated better than the corresponding grip measurements. As mentioned previously, this may have been due to the level of noise in the measurements, probably due to the movement of the cables during each shot. As the magnitude of the grip vibration was considerably less than that of the shaft, the contribution of noise was more significant. The BS weighting exacerbates this problem as it places more emphasis on the low frequency content of a spectrum (5 to 35 Hz), the region of the spectrum most susceptible to the
influence of any noise present in the measurement. In addition, for an impulsive vibration of duration less than 100 ms, the resolution of the subsequent spectra will be greater than 10 Hz and therefore only a very few points will be of any significance once the BS weighting has been applied. Therefore, the BS weighting is not particularly suitable for use with vibration data from a golf impact particularly when it is affected by noise. The HS weighting did not improve the correlations with either shaft or grip measurements.

In the impact sound study, the A and C frequency weightings used also had little effect mainly because, for a typical golf impact sound, the majority of energy is in the frequency range 1 to 10 kHz, the region in which there is little difference between a linear weighting and the A and C weightings.

All of the frequency weightings used are based on equal sensation contours or perception threshold curves obtained using subjects' perceptions of discrete frequency, continuous stimuli. In golf, however, the sound and vibration from impact are short in duration, complex in frequency content and the vibration is three-dimensional. It is recommended, therefore, that in future more suitable frequency weightings be developed, possibly from threshold of perception curves or equal sensation contours for impulsive, complex stimuli.

In the impact sound study, the centroid of a spectrum that was used as a measure of pitch has its limitations but it does at least give some indication as to the region in a spectrum where energy is concentrated. There are, however, many different shapes of frequency spectra that have the same centroid and it is unlikely that they will sound the same in terms of pitch. In future, the analysis of sound data will benefit from a greater understanding of the manner in which humans perceive complex sounds, which will require an investigation into more detailed models of pitch perception.

7.3 PREDICTION OF FEEL

If the frequencies of sound and vibration that improve the feel of a shot can be identified, the next stage in the process is to predict how a club will feel earlier in the design procedure. To achieve this, relationships between the natural frequencies, damping and mode shapes of a club and the feel associated with that club will need to be investigated. One technique for identifying the natural frequencies, damping and mode shapes of a club is modal analysis. A number of studies have conducted modal analyses of golf clubs, which were reviewed in Section 1.2.2 but the natural frequencies measured in these studies may be different when the club is swung because of variations in the grip condition between golfers.
and the centrifugal stiffening and deformation of the shaft during a swing. To be able to predict the feel of a golf club from the results of a modal analysis, the effects of the dynamic influences during a swing will need to be investigated. Preliminary work in this area has been carried out as part of this study to demonstrate the suitability of the modal analysis technique and to develop test methods that will improve the quality of the data collected. A Callaway GBB driver, with a steel shaft and Tour Velvet grip was freely suspended from a gantry and a shaker was used to excite the club, as illustrated in Figure 7.2. The input force, which was measured using a force transducer, was applied approximately perpendicular to the clubface towards the toe of the clubhead. The club was excited with random vibration in the frequency range 1 to 2000 Hz and the response of the club was measured at 34 locations on the clubhead and 96 locations on the shaft.

To obtain good quality mode shapes, it is desirable to measure the response of the structure in three perpendicular directions at each location. In practice, however, this is not always possible so a number of techniques were used to maximise the number of measurements that could be taken at each point. Separate local co-ordinate axes were used for the clubhead and the shaft and the response of the club was measured using a laser vibrometer. There are several advantages to using a vibrometer to measure the vibration response of a golf club. The measurement direction can be more accurately controlled with a laser vibrometer so that on a complex curved surface, such as a golf club, it is possible to measure the vibration in more than one direction at each location on the club, whereas with a single axis accelerometer, typically only the vibration in a direction perpendicular to the surface can be measured. In addition, it is a non-contacting method so the vibrational characteristics of the club are not affected by the mass of a measuring device such as an accelerometer.

Two example mode shapes are shown in Figure 7.3, which illustrate the quality of the results produced. The method developed can now be used to determine the natural frequencies of test clubs and techniques, such as mass modification, investigated to alter the vibrational characteristics of clubs in an appropriate manner to simulate the effect of the hands. Similarly for sound, Hocknell (1998a) demonstrated that the natural frequencies of a clubhead obtained from a modal analysis correlated with the dominant frequencies of the impact sound and this technique could be used to identify the source of each frequency component. If the feel of a club can be predicted from the natural frequencies and mode shapes of a club, then, as this information is available from a finite element model, a desirable feel can be designed into a club earlier in the process.
CHAPTER 8

CONCLUSIONS

The purpose of this research was to develop suitable techniques for the elicitation of human perceptions of golf equipment during play so that the characteristics of importance to the golfer would emerge from the analysis of their responses. Once this had been achieved, the aim was to develop test procedures so that the golfers’ perceptions could be quantified and correlated with objective measurements representative of the feedback received by the player from impact. It was anticipated that, as a result, the sound and vibration parameters responsible for different feel characteristics could be identified.

Ten dimensions of a golf shot of importance to the player emerged from the qualitative study of the perceptions of elite golfers. During the analysis of the golfers' responses, however, it became apparent that, although these dimensions could be represented using traditional tree-structures, other themes suggested that there were relationships between the dimensions and a new technique was required. A structured relationship model was, therefore, developed to represent both the sub-themes of each dimension and the fifteen inter-dimension relationships identified. The dimensions ‘Feel from Impact’ and ‘Impact Sound’ were selected for further detailed study.

The impact duration of a golf shot was investigated to determine whether golfers’ perceptions of contact time correlated with measured values. A technique was developed to measure the impact duration of a golf shot using an electrical circuit in which the ball and clubface formed a switch, completing the circuit whilst contact was maintained between the two bodies. The ball construction was found to have a more significant effect on contact time than clubhead type; the impact duration, which was 16 \mu s longer for three-piece balls than two-piece balls, was found to decrease by 44 \mu s when the ball compression was increased from 80 to 100. In contrast, the difference between the Titleist 975D that produced the longest impact duration and the Taylor Made Burner that produced the shortest was 12 \mu s. Clubhead speed at impact was also found to affect contact time with the duration of impact decreasing by approximately 65 \mu s as the clubhead speed was increased 31.3 to 53.6
m/s. Golfers generally perceive impact durations with the traditional clubheads to be longer than with the modern metal clubheads; this trend, however, was not evident in the experimental data. Golfers' perceptions of the feel of ball behaviour at impact are, therefore, likely to have been influenced by other factors such as the sound and vibration from impact.

Two separate studies were conducted to investigate correlations between the golfers' subjective perceptions of a shot and the sound and vibration measured from the impact. Tests, representative of actual play conditions, were designed such that both subjective and objective data were measured simultaneously from the same shots and, in the tactile sensation study, the transmission of vibration into the hand was taken into account.

In the tactile sensation study, analysis of the subjective ratings revealed that the five feel characteristics investigated, pleasantness, hardness, solidity and liveliness of feel and perceived vibration level, were strongly correlated. In general, shots that were given a high pleasantness rating were also rated as having felt solid, lively, soft and with little vibration perceived. When relationships between the subjective and objective data in their original formats were investigated, the correlations were weak, so techniques were developed to overcome some of the factors responsible. Standardising both the subjective ratings and the objective data was particularly successful in improving the strength of the correlations. Combining vibration measurements at both shaft and grip achieved smaller enhancements but the application of frequency weightings was largely unsuccessful. The strongest relationships were obtained when the mean data for each club for each golfer was correlated. These relationships suggest that a shot with a reduced RMS vibration level has a pleasant, very solid, lively and softer feel. In general, however, the correlations were not particularly strong and varied considerably between golfers suggesting that, between players, there are either differences in sensitivity to changes in vibration level or variations in their ability to consistently and reliably rate their perceptions.

In the impact sound study, analysis of the subjective ratings revealed greater inter-subject variability than in the tactile sensation study, particularly between the golfers' ratings of hardness of feel. As a result this characteristic was removed from the analysis because it was difficult to conclude whether the variations in the ratings were because the hardness of feel related to the vibration of the club for some subjects and impact sound for others, or whether the subjects misinterpreted the question or gave inconsistent responses. The remaining feel characteristics investigated correlated strongly and positively with each other; in general, a shot was rated as having a pleasant feel if it had a loud, explosive, crisp, sharp
sound and a lively feel. Strong correlations were also obtained between the subjective ratings and measures of the objective data such as peak-to-peak level, duration, decay and the centroid of a spectrum, whilst the strongest correlations achieved were with sound pressure level measured over 50 ms. Standardising the ratings again improved the strength of the correlations but not to the same extent as in the tactile sensation study, whilst the A and C frequency weightings used had little effect.

It became evident from graphical inspection of the correlations, however, that golfers were only able to detect the larger differences between the older clubheads and the modern clubheads. As a result, when the correlations were recalculated using just the data from the modern clubheads, the magnitude of the coefficients reduced considerably. As future tests are likely to include only modern clubheads, recommendations for improving the test methodology have been proposed. These include identifying 'good' test subjects, reducing the period of time over which clubs are compared, either by shortening the tests or using techniques such as the paired comparison method, modifying the question format and rating clubs rather than individual shots.

This study has been the first attempt to address the deficiencies in many of the previous studies of the feel of sports equipment. A greater understanding of the characteristics of a golf shot that influence a player's perceptions has been achieved. Test procedures have been developed to quantify golfers' perceptions and to measure objective data representative of the feedback received by the player from impact during actual play conditions. In addition, the suitability of several frequency weightings have been investigated during the analysis of the data to take into consideration the response of humans to sound and vibration.

*Nunc est bibendum!*
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Scanlan, T.K., Ravizza, K. and Stein, G.L. (1989a). An In-Depth Study of Former Elite Figure Skaters: I. Introduction to the Project. *Journal of Sport and Exercise Psychology, 11*, pp. 54-64.


FIGURES
Figure 1.1 – Variable perceptions from the same visual input

Figure 1.2 – Node lines for two drivers and two irons (Varoto and McConnell, 1995)
Figure 1.3a – Anatomy of the right hand and arm (Tortora, 1995)
Figure 1.3b – Anatomy of the right hand and wrist (Tortora, 1995)
Identify area of interest and determine research question

Determine sample size and selection criteria

Are there any constraints on the outcome?

Pursue naturalistic inquiry.

Pursue scientific inquiry.

Is a questionnaire appropriate?

Adopt interview method. Select level of structure.

Adopt structured questionnaire approach.

Is qualitative data required?

Prepare open-ended questions.

Is quantitative data required?

Prepare fixed/scaled response questions.

Compile Instrument

Pilot test instrument & analyse responses

Collect data

Does instrument need refining?

Figure 2.1 - Study design process
Verbatim transcripts produced for each interview.

Audio recordings of each interview listened to in conjunction with reading interview transcripts.

Interview transcripts re-read and emergent data themes noted. Quotes highlighted for later coding in NUD*IST.

Inductive content analysis conducted on emergent data clustering together common themes. Grouping of related themes at each higher level continued until further categorisation was no longer possible.

Tree structure constructed in NUD*IST. Interview transcript documents prepared and imported into NUD*IST.

Validity of inductive process ensured by deductively coding selected quotes into tree structure in NUD*IST.

Broad categories in tree structure refined as more subtle themes emerged. Further manipulation of tree structure until satisfactory result achieved.

Triangular consensus validation process conducted.

**Figure 2.2 - Data analysis procedure**

![Diagram](image.png)

**Figure 2.3 - Alternative classification schemes**
Example Quotes

It was the Titleist I bit first. It felt softer than the Precept.

The Balata ball was softer, much softer than the Precept ball.

But you could definitely feel, even though I knew it was a Balata against the EV, it was definitely a softer feel off the club face.

The Precept ball felt very hard.

The Precept felt a lot harder than the balata. A lot harder.

You can definitely feel a slight difference in the ball with this one as well... the Precept's a little bit harder than the Titleist.

I can't tell any difference between a balata and a two piece.

Again, the difference between the two balls was nothing. No difference between the two balls at all.

Again, I don't think you can feel an awful lot of difference between the two balls on that one either to be honest with you.

It felt actually quite solid. Not as solid as the Titleist (9752) but it felt quite solid.

That feels so much better and that's why I use the Titleist driver myself, because it feels more solid.

I just think [wood] feels more solid than a lot of the metal woods nowadays.

Base Themes

- Soft Feeling Ball
- Hard Feeling Ball
- Similar Feel From Both Ball Types

High Order Sub-Themes

- Ball Feel
- Solid Feel

Feel from Impact

(For Sub-tree See Figure 2.4 b) Feel Up The Shaft
(For Sub-tree See Figure 2.4 c) Feel Of Ball Behaviour

Figure 2.4a - General dimension 'Feel from Impact'
Example Quotes

It feels harder on my hands.
Also, feels very hard when you hit it...
... certainly much harder feel.
I hit the first off centre. It felt a lot harder...
That felt quite hard, but I didn't hit it in the middle.
A little bit harder because it came out of the toe, not as good as the first one (shot).
It just feels like when you hit it you can really feel it in your hands.
Definitely more feeling up the shaft on that one.
If anything with the steel [shaft], certainly in the Maxfi... you could feel it up through your hands more than you can with a graphite [shaft].
Certainly more feeling through the hands with that one... just more feeling through the shaft, especially if you don't get it out of the middle.
It always tends to be the bad shots that you feel more... than the good ones.
... certainly feel the vibrations through that one, compared to the other wooden driver I hit [Slazenger Persimmon].
The vibrations through the shaft are not very good.
If you don't get these quite right, you still get the vibration through the shaft, you know.
You can feel from the vibration of the club whether it's the toe, the heel...
... more of a jar really because it was hit so badly.
It feels very soft.
Right out of the middle, very soft, hardly any feedback at all, hardly any feel.
That felt soft at impact...
... hit it in the middle and it's sweeter.
That felt quite sweet.
It feels sweet. Sweeter than the Steelhead.
... there's no sort of feeling as such in the hands but it was very, very pleasant.
... you can't feel the ball on the face at all at impact. Just seems to be nothing there.
... you get the sensation of no hit, where you've made a swing and the ball's gone, without you feeling it go.
I think you get less vibration with a graphite shaft than you do with a steel shaft.
... the vibrations are dampened and if you can create less feel in the hands I think therefore you know you'll create better feel.
It's very difficult to tell if you've struck it badly.
A little bit out of the toe, but again it felt very good, it felt together.
Even if you've miss hit it slightly, it still feels good.

<table>
<thead>
<tr>
<th>Base Themes</th>
<th>Low Order Sub-Themes</th>
<th>High Order Sub-Themes</th>
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<tbody>
<tr>
<td>Hard Feel in the Hands</td>
<td>Hard Feel</td>
<td>More Feel From Off-Centre Shots</td>
</tr>
<tr>
<td>More Feel</td>
<td>More Feel</td>
<td>Increased Vibration From Off-Centre Shots</td>
</tr>
<tr>
<td>Feel Vibration in the Hands</td>
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<td>Soft Feel</td>
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<tr>
<td>Forgiving Feel From Off-Centre Shots</td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 2.4b - High order sub-theme 'Feel Up the Shaft'
The ball comes off an awful lot quicker and it feels an awful lot more powerful...

I don't know whether I'm actually hitting it bang out of the middle... that'd explain it. It feels like the ball's firing off the face very, very quickly.

If you get it off the middle of the club you get more of a springy feeling from it.

It was very lively off the club face. The ball felt as though it sprung off the club face well.

The ball feels as though it springs off the club face well...

It feels like the balls are firing off the face very, very quickly.

If you get it off the middle of the club you get more of a springy feeling from it.

That feeling I said about it being alive. The ball's coming off the club face a lot faster...

Now that feels that the ball has come off an awful lot faster ...

It feels as if it's bounced off the face.

It seemed a little bit more zip off the club face. ...

... it seemed to really explode off the club face and it felt really as though I'd hit it.

Completely dead feel off the face, there's no strike there at all.

Very dead, doesn't come off, doesn't seem to whizz off the face, just feels very dead.

It feels very, very heavy in my hands. That's not the weight of the club but as you've hit it, it's a very, very dull feeling in the hands.

... the actual feeling of the ball on the club face is very heavy, it's like a lump hammer heavy.

Strike-wise with the balls, it doesn't seem to explode off the face. A lot softer face, the strike doesn't seem quite as crisp.

... the head, as it's Persimmon, is very soft and the strike is not explosive in any way, more of a thud.

I think the ball probably stays on the club head a bit longer with a traditional wood...

... it feels as if it's just on there a bit longer...

I think again... it's on the club head a bit longer...

With the Persimmon it's almost as if everything becomes a lot more compressed so the actual speed of the ball off the club face... feels much slower.

... with a wood I feel that the ball and the club compress before it goes off.

The first impression, two shots, the ball is absorbed into the head.

It feels very much like the wooden headed club, it feels as though the club is absorbing the ball... it doesn't come off the club face as fast.

... the actual speed of the ball off the club face... feels much slower.

... it didn't feel so lively and yet that felt as though it came from the middle of the club face, there was no twist and no turn but it felt heavy and dead as opposed to a fizzle off the face. It didn't feel as though it came off the face so quickly.

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**Figure 2.4c - High order sub-theme 'Feel of Ball Behaviour'**
Example Quotes

It's just that they sound so tinny... puts me off.

It's quite a tinny sound off the club face.

You can hear with this, it's quite a dead sound...

Starting with the persimmon, it's a lot deader sound, more of a thud due to the material.

I think the persimmon tends to sound and the graphite head tended to sound much duller...

This was a little bit more of a duller sound although it's not... it doesn't sound anywhere near as dull as any of the wooden clubs.

The titanium Great Big... has got that incredible, explosion, it even sparks when you hit the ground.

Sounds sort of this explosion and it's gone...

It's got that crisp sound, it sounds like it was a good shot. It's clean...

Sound off the face is a bit crisper...

I prefer it when it doesn't make a tinging sound.

The Callaway makes a fairer ting when you hit it, which for most people would be quite encouraging I should think...

I can hear it, it's almost like a clunk as you hit it.

It's sort of a, a clunky sound.

It feels more solid and sounds more solid, you know, there's no thinness in it.

I think the Callaway gives... not quite as solid a sound as the Titleist.

...it sounds a lot more powerful.

...it makes less harsher noise really.

Certainly the Callaway I tried earlier on, the sound... it's very sharp.

This has got quite a lively sound at impact...

The Steelbead sounded harder...

[Callaways are] by far the loudest, noise wise, they make a ting. The Titleist are... not quite as loud, they make more of a thud...

It's a quieter deader sound.

I've hit a few balls with a Ping [Ti][i] wood but I don't like the ring out of it...

I often wonder whether you could really tell a difference between a two piece and a balata with a driver... in the actual hit and whether it's more of a sound, you associate it with the sound.

[The Proconcept] felt slightly harder [than the Titleist Tour Balata]. More of a click.

The couple... at the end that I didn't hit at all well sounded bloody awful.

I think the metal one sounds better... as soon as it goes off, you immediately associate a good shot...

Strike was great, you can tell by the noise when you get it.

It's sort of a, a clunky sound... it sounds, like you've miscued it...

Figure 2.5 - General dimension 'Impact Sound'
Example Quotes

Shaft's whippy for me, there's a lot more flex there.
The shaft feels quite whippy.
Shafts a bit whippy... which means you can't really hit it if you just have to wait for it...
You can almost feel that the shaft is almost too flexible.
The shaft feels very flexible.
That shaft is horrific. That is so flexible, it feels so soft.
I feel the shaft really twist and turn.
A lot of twist and turn in the shaft, you feel the head trying to twist. I mean I've hit that pretty much out of the middle and still the head was almost trying to twist and turn.
... again I felt the shaft giving too much, very flexible shaft.
... there's a lot more flex and give in the shaft.
I felt there was a bit of give in the shaft.
The shaft felt better in that one though, it felt a little bit more together, a bit firmer, it didn't feel as though it was twisting quite so much.
It feels like the whole thing is together.
That's the first one I've hit where the shaft flex feels the right flex for my swing.
Better shaft in this one, it's a lot more solid.
... the shaft felt great in that it felt... solid.
I think this one [Great Big Bertha] and the Titleist, the shafts have felt the best in these two. You know, they feel as if they're really solid to be honest with you.
It felt too stiff that did.
The shaft was probably just a little bit too stiff, I felt as though there was no release. When I released, the club wasn't releasing with me.
That felt very stiff in the shaft...
... you can feel the shaft want to kick a lot more at the bottom.
Some of those steel shafted clubs I could feel a real kick through the shot so that they felt a lot more solid throughout the swing.
I could feel the kick there, which I quite like.
... that was out of the heel, that one. When you mis-strike it you can really feel the club flex twisting and turning.
I can feel when I hit it out of the toe that the club tries to twist open. And you can certainly feel when you hit it out of the heel that the club tries to twist closed.
... it did feel a bit longer than the Callaway.
Length of shaft has... a big part in my feel, and because I think it's the height of me, the longer the shaft, I don't get a good feel from... I don't feel comfortable.

Figure 2.6 - General dimension 'Shaft Feel'
... it feels quite cumbersome... it feels very heavy in the head.
The Titleist one definitely feels more head heavy.
The shaft certainly feels a bit heavier.
It feels the best balanced of the lot this one, so shaft weight and head weight for me is about spot on there.
You want the whole thing balanced together so that when you hit it, it feels it's all part of you.
You want the club to feel part of yourself really.
The balance of the club feels better.
A massive lighter swingweight initially, just through feel of swing.
... if I use the RCH 36 shaft, the head feels too light.
Now, this shaft feels very light.
... gone back to the Titleist now. Feels quite a bit heavier than the Callaway.
First impressions... when I put it down was that it was far too heavy. It felt really heavy and felt really heavy when I was swinging it as well...
That feels more clumsy as in overall weight is heavier than the persimmon.
... the club just feels a little bit light overall. A little bit feathery.
This one probably felt a little bit light.
Instantly feels quite a lot lighter.

Figure 2.7 - General dimension 'Club Weight'

The ordinary wood... has the ultimate feel, it feels like it's a golf club that you're very much in control of, rather than it's in control of you.
The whole club swung very well, it felt nice. You felt as if you were in control.
...just feel as though I'm in control of the club head right throughout the shot.
I feel I've no control over that head at all. I don't know where it is.
This feels much more difficult to control...
... but I could not control it because of the length and the flex of the shaft.

Figure 2.8 - General dimension 'Club Control'

I can feel the head and the swing with this club, it feels quite nice really.
You need to know what is happening, you need, when you swing a golf club, to know where the club is...
... the last thing I want to feel is the head wanting to race in to hit it.
I thought I lost the shaft, didn't know where it was, no idea. I felt I lost the head.
I lost that one. Lost the feel of the head there.
I couldn't feel the head on my Callaway.

Figure 2.9 - General dimension 'Feel of Club Position During Swing'
Example Quotes

It's more comfortable as it's a thinner grip.

I prefer a thicker grip personally.

It's too thick for me, I've only got very little hands.

I prefer markings on grips, for instance on this Callaway here there are one or two markings that you could actually use to line up.

I don't like a hard feel in a grip.

I don't like cord grips because I've got very dry hands and they're inclined to get a bit hard.

The Chamois grip is just too soft... too soft really.

I tend to find those... sort of wrap grips go slippery very quickly and again with Ping's own grip, I tend to find that it goes... slippery very quickly...

I feel that's a little bit slippery...

I don't like a full cord.... I always feel it's going to slip in my hand.

I don't like the softness of the grip without the cord does feel as though you've got a bit more grip.

A lot of mine now have got the Tour Velvet job on it which again is a soft feel.

The Chamois grip is just too soft... too soft really.

I feel that because it just feels a bit tackier, it's quite soft.

I think the grip wants to be as tacky as possible. I mean, my thought is if you start having to grip the club then that's bad news.

...as long as they're tacky...

...the cord grip, I immediately take the grips off, because I don't like that grip...

The Tour Wrap... the slot cords are good grips. It has to be corded.

The grip that I'm using at the moment is the Golf Pride Tour Velvet one which is just perfect really. It feels... it's soft, it's tacky...

...but I find cord grips just shred my hands... I feel like I haven't got hold of them...

...not overly keen on cord grips anyway because they tend to rip my hands to bits.

I find [cord grips] a bit harsh.

I think if you've got a grip that feels like it's gonna slip, you start holding it too tight.

I feel that with cord grips I have to grip the club tightly. The tighter you grip it the less feel you have, really, you know.

I must feel that it is not going to slip. So without me gripping tightly I feel that that club is going to adhere.

---

Figure 2.10 - General dimension 'Grip'
Example Quotes

That's a much longer ball you see that is. That's gone through the air quite a bit longer than the others.

Distance is impressive though. That's very impressive.

Distance wise it didn't seem to be going too far.

I want to be able to carry the ball through the air so I can carry fairway bunkers.

You certainly get a lot more air time with these. The ball's in the air for, far longer.

... it's gone 20 yards further through the air.

...it flights fantastic but it doesn't run, so when the ball lands that's pretty much where it's going to finish.

You feel as though once it's hit the fairway it's going to run quite a long way.

Hopefully it runs a bit, getting a few extra yards.

It's certainly getting the balance right between... getting the right amount of distance and then maintaining the control.

[Ideally I want] something that allows me the freedom to release the club without the fear of...inaccuracy.

That's with that Precept ball, that's gone a bit further [than the balata].

The two balatas... flew a lot lower than the... the two piece.

That was good and that was with a balata and I've just about hit it as far as I would hit that other EV ball.

I know that I hit two of those three out of the heel. So, that's always going to produce quite a low trajectory on it.

I have to say with the big balls, many a time I've thought at impact where it's felt uncomfortable... I've felt I've hit a poor shot and as I've come up the balls gone OK.

You certainly feel as though it would be a little bit easier to work the ball either way, whichever way you wanted without too much trouble.

This is the type of club that you could maneuver the ball with.

I think it's very difficult to... control a draw with a metal wood. It's much easier if you accept it, hit it straight or fade it slightly.

...this feels as though it would be... quite difficult to actually shape.

Not too high and just a little touch of draw on it... is the way I like to hit it.

The shot I would be looking for is just that... penetrating flight... and just trying to hit it with a little bit of fade, trying to hit it a little bit left to right, and just land in the middle of the fairway...

... the perfect shot would be five yards of draw.

Base Themes

Overall Distance

Carry

Run

Distance

Accuracy

Flight Due To Ball Type

Flight From Off-Centre Shots

Ball Flight

Feel Able To Shape Shots

Feels Difficult To Shape Shots

Shape of Flight

Ideal Flight Shape

(For Sub-tree See Figure 2.11b)
Example Quotes

It's certainly a lot higher than I'd hit it normally. It's not my shape.

...I'd sooner go for a higher trajectory than a lower one.

With the bigger heads, the titanium, it's certainly easier to get a higher flight.

...not too high, not too low, it's just an average sort of flight.

The flight was good, good trajectory. It didn't climb up or whatever, it just flew at a good height.

Nice trajectory without being too high.

Like that. A lot lower trajectory than some of the ones I've tried.

That was a little bit too low, but I'd rather... have it probably a little bit lower than most people would. I tend to find it just... works a bit better for me because I tend to have not that much problem with the carry.

...a penetrating flight, not too low, not too high.

The flight of the ball is much better off a titanium club, it comes off all parts of it with quite a penetrating flight.

Yes, it's a lot more of a boring flight...

It felt weak on the flight, very dead.

It wasn't that high dolly I hit with that Titleist driver, which just looped up in the air.

It was more of a loopy flight than a penetrating one that we're looking for.

I feel as though I can control the height of the shot, and the distance is a lot more...

I like to be able to feel if I want to I can give it some air to carry... and into the wind if necessary sort of keep it down.

I like to be able to hit it the way that I want to hit it and if I want to hit it higher I'll see it higher and if I want to hit it lower, I'll see it lower.

I like to send my ball with very little spin, quite flat so that way the less spin you've got the less chance the wind's going to move it.

We spend 7 or 8 months of the year trying to get the ball in the air in this country, we get three, four months where it's going to actually go along the ground aren't we, so it's got to spend most of it's time up there.

Into a wind you know, you'd want to hit the ball lower or if it was a strong wind behind you, you might even want to hit it higher.

Figure 2.11b - High order sub-theme 'Flight Trajectory'
Example Quotes

But having been used to the big headed clubs, that looks again more like a fairway wood.

Small to mid, more mid, more just sort of favouring that nice mid stuff, especially with a driver.

[I like] something that just looks like a traditional wooden headed golf club

I like a prominent leading edge really, something you can feel confident that you've lined it up right.

Inviting, shallow face, tempted to hit it off the fairway.

Looks very, very shallow though. Obviously, bit of illusion perhaps but it does look very, very shallow.

Aesthetically it looks like a very, very tidy golf club.

Don't like the look of it at all. I think it's awful. I think it's ugly looking.

I don't like the look of the shaft but that's again personal.

It's not the most beautiful looking colour for a driver head.

...looking down at that the toe appears as though it's going away from me, the club appears as though it's sitting far too flat.

It's probably slightly upright...

I would rather it was sat wide open, at least then I can release it ... and then I can hit it hard.

If the club sits open I'm lost because I feel I have to release early to square the blade up to it and when I release the club early I generally play particularly badly.

It sits good as well, it sits pretty square.

This club is a little bit toed in. Now for a good player if it's toed in, I would automatically hold this off.

I like to be able to see a bit of the club face, I like when I look down at a club face that it sits a little bit closed...

I don't like a straight faced club that looks, this is personal, I think, that looks as if I'm going to struggle to get it airborne.

Yes, it is very, very lofted. It gives the impression it's very lofted as well.

It's got to look like a golf club that you can use and you can hit the shots you want to hit.

I think it's not too small, it's not too big and it is inviting to hit.

First of all it must look as if I can hit it, so I think the cosmetics of the club are quite important from that point of view.

I put this down and I'm thinking I'm going to struggle to get this in the air, which I have done.

I feel I might cut this driver, so I feel, because it's quite straight faced it also seems to me as if it sits a bit open.

Flipping back, you see straight away the old barrier goes up, you don't like the look of it.

Figure 2.12 - General dimension 'Club Appearance'
Example Quotes

Well, if God strikes me down now, I'm going to die a happy man. Yes, I enjoyed that one.

I feel, with a bit of use, I could get to like this club...

...playability-wise it's just so much easier. So much easier. I mean that was good.

Lovely, dead easy to hit.

The Taylor made is the easiest to use, closely followed by the Callaway...

I want to be able to feel confident of a reasonable strike. So the big head gives me that.

You've got confidence... you know roughly what your club is going to behave like.

The shape of the head... confidence booster, I like the shape of the head.

I could play with that, that's OK.

I could use this driver because I feel I could work it.

I feel quite comfortable with this, it's a nice feel off the face.

I feel comfortable with the driver.

I felt very comfy with the Callaway one...

It feels lovely... as soon as you pick a club up... you only have to have a couple of touches with it... you feel as though you're going to be able to hit it.

But again it might be the old grey matter thinking oh, this feels good, I'm going to enjoy this.

It doesn't feel like a golf club I would enjoy getting out of the bag all the time.

I thought I'd enjoy hitting that Persimmon driver, but I didn't, no.

It feels hard work to swing this. So, I don't feel I can swing it with any freedom. I feel I'm having to apply some effort to swing this club.

That feels like hard work that one does.

I won't be seen with that on the first tee.

... I wouldn't want to play golf with that. It's just not a good feeling golf club.

I certainly wouldn't go back to it [persimmon], let's put it that way.

... overall weight of that club is so, so heavy, I could never, ever play golf with that.

I don't think I could use this. (Shot played) No.

Titleist always feel very head heavy. Although that went quite nicely, I would feel uncomfortable playing with that.

I couldn't use this driver, I feel very uncomfortable with it.

I have used these but, whether it's psychological that you pick the club up and you automatically think oh here we go here's a better golf club, I'll hit this better.

Now straight away, I've never been a fan of these, so... The old barrier comes up, negative views.

High Order Sub-Themes

Enjoy Using

Easy To Use

Feel Confident Using

Could Use

Feel Comfortable Using

Positive Thoughts from Club Feel

Wouldn't Enjoy Using

Hard Work To Use

Wouldn't Want To Use

Couldn't Use

Feel Uncomfortable Using

Effect of Brand Name

Golfers' Psychology

Figure 2.13 - General dimension 'Golfers' Psychology'
Figure 2.14 – Relationship map
Figure 2.15 - Model of 'feel' characteristics in a golf shot
Figure 2.16 – Postal questionnaire results: the feel of an ideal golf shot
g) How long would the impact sound last?

Figure 2.16 (cont.) – Postal questionnaire results: the feel of an ideal golf shot
Figure 3.1 – Three different techniques for applying a conductive layer to a golf ball: from left to right, embedded copper strip, aluminium foil and silver conductive paint.

Figure 3.2 – Wire soldered to a small patch of tape, with a conductive adhesive backing, attached to the surface of the conductive layer.
Figure 3.3 – Electrical circuit used to measure impact duration

Figure 3.4 – Method for obtaining pulse width (impact duration) and fall time from measured electrical pulses
Figure 3.5 Example impact duration pulses obtained using three different methods of applying a conductive coating to the ball
Figure 3.6 – Mean impact duration, ± one standard deviation, for each combination of club head and ball.
a) Five nominally identical Precept EV two piece balls

![Graph showing impact duration for five Precept EV two piece balls with different clubhead types.]

b) Five nominally identical Titleist Tour Balata three piece balls

![Graph showing impact duration for five Titleist Tour Balata three piece balls with different clubhead types.]

Figure 3.7 – Effect of ball variability and clubhead type on mean impact duration using two ball types (columns are in the same order as the legend)
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Figure 3.9 – Mean impact durations, ± one standard deviation, for three different compression balls hit with a range of clubhead speeds.
Figure 3.10 – Comparison of experimental impact durations with theoretically obtained values of impact duration, calculated from Hertz Law using values of Young's modulus published in four different studies.
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Figure 4.2 – Rig developed for measuring the frequency response of the adaptor
Figure 4.3 – Frequency response of the adapter in each measurement direction
Figure 4.4 – Vibration measurement directions

Note: x-axis is out of the page

Figure 4.5 – Adaptor positioned under the upper hand of the golfer's grip
Figure 4.6 – Accelerometer mounting bracket for measurement of shaft vibration

Figure 4.7 – Impact location measurement using a powder deposit spray
Figure 4.8 – Tripod mounted microphone location

Figure 4.9 – Microphones mounted on a baseball cap
Figure 4.10 – Impact location measurement using a pressure sensitive face tape
Figure 5.1 – Vibration measurement directions (Reynolds and Keith, 1977)

Figure 5.2 – Location of accelerometers for transmissibility tests. 1. Middle phalanx; 2. proximal phalanx; 3. third metacarpal; 4. triquestrum carpal; 5. styloid process of ulna; 6. olecranon; 7. medial epicondyle; 8. acromion (Reynolds and Angevine, 1977)
Figure 5.3 – Average value transmissibility curves for vibration in the a) vertical direction, b) horizontal direction and c) axial direction for a 9 N (2 lbf) finger grip. Curves 1-8 represent locations indicated in Figure 4.2 (Reynolds and Angevine, 1977)

Figure 5.4 – Cross-section of skin showing the dermis and epidermis (Griffin, 1990)
Figure 5.5 – Comparison of threshold of perception curves obtained from different studies

Figure 5.6 – Comparison of equal sensation contours obtained from different studies, markers indicate the reference vibration used for each contour
Figure 5.7 – Effect of duration of a 250 Hz sinusoidal vibration at different magnitudes on perceived intensity (Berglund et al., 1967)

Figure 5.8 – Frequency weightings given in ISO 5349:1986 and BS 6842:1987
Figure 5.9 – Relationship between perceived loudness in sones and the intensity level of a sound (Levine, 2000)

Figure 5.10 – Equal loudness contours for pure tones (Hassall and Zaveri, 1979)
Figure 5.11 – A and C frequency weightings

Figure 5.12 – Development of critical band theory (Levine, 2000)
Figure 5.13 – Effect of sound duration on loudness: the results of three studies
Figure 5.14 – Sound pressure discrimination measured in terms of the Weber fraction for various SPLs and frequencies of sound (Coren et al., 1999)

Figure 5.15 – The relationship between perceived pitch, measured in mels, and frequency (Coren et al., 1999)

Figure 5.16 – Frequency discrimination measured in terms of the Weber fraction for various SPLs and frequencies of sound (Coren et al., 1999)
1. ASSEMBLE ALL DATA IN A SPREADSHEET

2. REMOVE SURPLUS DATA

3. CORRELATE SUBJECTIVE RATINGS
   - 3a. Identify relationships between feel characteristics
   - 3b. Investigate variations in the use of the scales between golfers

4. VIEW DATA

5. CORRELATE SUBJECTIVE AND OBJECTIVE DATA INDIVIDUALLY FOR EACH GOLFER
   - 5a. Select suitable measurement parameters
   - 5b. Apply appropriate frequency weightings
   - 5c. Identify most suitable parameters
   - 5d. Investigate variations in correlations between golfers

6. COMPILE DATA FROM ALL GOLFERS AND RECALCULATE CORRELATIONS
   - 6a. Standardise data to overcome variations between golfers
   - 6b. Use non-parametric statistics
   - 6c. Investigate the effect of measurement location on correlations
   - 6d. Correlate alternative sets of data

7. COMPARE DATA FOR EACH CLUB
   - 7a. Compare subjective perceptions of each club
   - 7b. Compare objective data obtained from each club

Figure 6.1 Analysis procedure
Figure 6.2 – Example vibration measurements at both shaft and grip in x and z-directions

Figure 6.3 – BS and HS frequency weightings
Figure 6.4 – Mean RMS vibration level, ± one standard deviation, of central impacts for each golfer

Figure 6.5 – Correlation between BS weighted combined shaft vibration and solid feel
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Figure 6.8 – Correlation between ball velocity and liveliness of feel

Figure 6.9 – Contribution of the data from four clubs to the correlation between ball velocity and liveliness of feel
Figure 6.10 – Mean standardised ball velocity of a central impact with each club
a) Ratings of pleasantness, solidity and liveliness of feel

b) Ratings of hardness of feel and perceived vibration level

Figure 6.11 – Mean standardised ratings, ± one standard deviation, for a central impact with each club
Figure 6.12 - Effect of impact location on standardised pleasantness ratings for clubs 1 - 4
Figure 6.12 (cont.) - Effect of impact location on standardised pleasantness ratings for clubs 5 - 8
Figure 6.12 (cont.) - Effect of impact location on standardised pleasantness ratings for clubs 9 & 10
Figure 6.13 – Power spectra of x-direction shaft and grip vibration for central impacts with a Callaway GBB (5.3 Gold shaft)
Figure 6.14 – Mean power spectra of x-direction shaft and grip vibration for central impacts with two ERC's and two GBB's
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Figure 6.16 - Mean Pearson correlation coefficients for each combination of feel characteristics for three different groups of golfers.
Figure 6.17 - Pearson correlation coefficients for each combination of feel characteristics for Subjects 28, 35 and 40
Figure 6.18 – Procedure for fitting an exponential curve to the decay of a sound measurement
a) SPL of each impact sound plotted against the subsequent loudness rating given

![Graph](image1)

b) Mean SPL ± one standard deviation of impact sounds in each band of loudness ratings

![Graph](image2)

Figure 6.19 – Correlation between perceived loudness and sound pressure level
a) Centroid of each impact sound plotted against the subsequent pitch rating given

![Graph showing the correlation between perceived sound pitch and the centroid of a spectrum.](figure_6.20a)

b) Mean centroid ± one standard deviation of impact sounds in each band of pitch ratings

![Graph showing the standardised sound pitch rating and frequency for each band of pitch ratings.](figure_6.20b)

Figure 6.20 – Correlation between perceived sound pitch and the centroid of a spectrum
Figure 6.21 – Mean standardised ratings, ± one standard deviation, for a central impact with each club
Figure 6.22 – Mean sound pressure level, ± one standard deviation, for a central impact plotted against the mean loudness rating given, ± one standard deviation.

Figure 6.23 – Mean centroid, ± one standard deviation, for a central impact plotted against the mean pitch rating given, ± one standard deviation.
a) Callaway ERC

b) Callaway Great Big Bertha

c) Titleist 975D

Figure 6.24 Typical sound spectra for a central impact with three different clubs
Figure 6.25 – Mean duration of sound, ± one standard deviation, for a central impact with each club
Figure 6.26 – Mean standardised ratings, ± one standard deviation, for a central impact with each club obtained from each study.
Figure 7.1 – Variation of golfers’ pleasantness ratings with impact location for all clubs tested
Figure 7.2 – Modal analysis set up

Figure 7.3 – Example mode shapes of a Callaway Great Big Bertha
APPENDIX 1 - INTERVIEW GUIDE

Subject Number _______________________ Date _______________________

Name __________________________________________________________ Age ______

Golf Club ___________________________________________________________________

SECTION 1

I would like to begin by thanking you for agreeing to participate in this interview study. As part of the project we are talking to category 1 golfers about their perceptions of 'feel' in a golf shot.

I am going to use a tape recorder to get complete and accurate information, and to make the interview process more efficient. The tape recorder is also necessary so that I will be able to make a typed transcript for later scrutiny and reference. Please can you speak clearly and in the direction of the tape recorder when responding?

I would like to draw your attention to a number of points from the interview summary you received earlier. It is the ‘feel’ associated with different clubs that is of interest for this study. We want you to describe in your own words your perception of ‘feel’ associated with a particular club/ball combination. It is important that you try and explain as clearly as you can the nature of feedback you are receiving during, and upon completion of each golf shot.

Do you have any questions so far?

SECTION 2

First of all I want you to hit a number of golf shots with each club/ball combination. After you have played each shot I want you to describe your perception of ‘feel’ of that shot. If you wish to hit a number of shots to get used to the club before you respond, please do. It is important that you comment upon the ‘feel’ of the shot you have played and avoid allowing preconceptions of different club/ball designs to affect your responses.

Compare:
- Metal / wood / graphite heads
- Steel / graphite shafts
- Grips
- Balls

Discuss differences in:
- Sound
  - Pitch
  - Volume
  - Duration
  - Perception of distance
- Feel in hands
- Flight
  - Distance
  - Trajectory
  - Accuracy / ability to shape shot

Can you rank the clubs in order of preference from the club with the best ‘feel’ characteristics to the club with the worst?
Descriptors Used:
Before we go any further, I would like to give you some more details about the interview. The information from this study will be used in two ways: firstly, the information will be used for my own Ph.D. research thesis. Secondly, the results will be published in scientific journals so that other sports equipment designers can benefit from them. I would like to emphasise that your information will remain completely confidential. I may want to use selected quotes from the interview in order to illustrate important ideas, but these will remain strictly anonymous.

As a participant in this study you have several very definite rights. Your participation in this interview is entirely voluntary, and you are free to decline to answer any questions or to stop the interview at any time. There are no right or wrong answers to the questions that I will be asking. We wish to learn from your experience and expertise so that we can better understand how golfers perceive ‘feel’ in a golf shot. We want you to think deeply and take your time to express your thoughts and ‘feelings’ as clearly as you can.

If you have any questions as we go along, please ask them and please ask for clarification if at any time you don’t understand what I am saying.

I'd like to proceed by asking you what clubs and ball you chose to use.

Driver ___________________________  Loft __________
Shaft ___________________________  Stiffness _________
Swingweight _________  Grip ___________________________
Irons _______________________  Shaft ______________________
Ball _______________________________________________________________________

Why do you use these clubs?

What do you like about the ‘feel’ of these clubs?

What ‘feel’ characteristics do these clubs have that other clubs don’t?

How could the ‘feel’ of these clubs be improved further?

When you are considering changing your driver what characteristics do you look for in the new club?

Descriptors Used:
I want you now to picture yourself standing on a tee. You have just hit the ‘perfect’ golf shot. The club and ball you used are not necessarily available, but they have your ideal ‘feel’ characteristics. I want you to describe to me the complete experience from setting yourself up to play the shot, through performing the shot to seeing the ball land in the desired place.

Discuss:
- Appearance
- Weight / balance
- Confidence
- Feel in hands
  - Grip
  - Shaft
- Sound of impact
- Flight
  - Distance
  - Shape
  - Trajectory

Descriptors Used:
SECTION 6

I want to establish now the relative importance of different sources of 'feel' to you. You have talked about ____________. I want you to consider each of these aspects of 'feel' and tell me whether that characteristic is very important, important or desirable, but you could live without or not important.

• Appearance
• Flight
  - Distance
  - Trajectory
  - Ability to shape the ball
• Sound
• Vibration / feel in hands
• Grip
• Others

SECTION 7

Finally I would like to ask you some questions about your background.

How old are you?

At what age did you take up golf?

How long have you been a category 1 golfer?

SECTION 8

To conclude the interview I would like to ask you about the interview itself.

Are there any important factors that we failed to discuss?

Did I lead or influence your responses in any way?

Did the recording equipment inhibit or affect you in any way?

Have you any comments or suggestions about the interview itself?

Are there any ways in which we could improve the interview structure?

Thank you for helping out with this interview.
## APPENDIX 2 - SPECIFICATION OF CLUBS USED DURING THE INTERVIEWS

<table>
<thead>
<tr>
<th>Club</th>
<th>Shaft</th>
<th>Grip</th>
<th>Loft (°)</th>
<th>Length (in.)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Callaway Great Big Bertha</td>
<td>RCH Pro-Series 3.1</td>
<td>Callaway Grip</td>
<td>8</td>
<td>45</td>
<td>309</td>
</tr>
<tr>
<td>Callaway Hawkeye</td>
<td>Hawkeye UL Firm Flex</td>
<td>Callaway Grip</td>
<td>9</td>
<td>45</td>
<td>310</td>
</tr>
<tr>
<td>Titleist 975D</td>
<td>Aldila Velocitor 400 S-Flex</td>
<td>Tour Wrap Full Cord</td>
<td>10.5</td>
<td>45 1/4</td>
<td>330</td>
</tr>
<tr>
<td>Callaway Steelhead</td>
<td>RCH 99 Firm Shaft</td>
<td>Callaway Grip</td>
<td>9</td>
<td>44 1/4</td>
<td>331</td>
</tr>
<tr>
<td>Taylor Made Burner</td>
<td>Taylor Made Bubble 2 S-90</td>
<td>Taylor Made Wrap</td>
<td>10.5</td>
<td>44 1/2</td>
<td>317</td>
</tr>
<tr>
<td>M23 Forged Titanium Head</td>
<td>True Temper Rocket Sensicore S-Flex</td>
<td>Tour Velvet</td>
<td>12</td>
<td>45 1/4</td>
<td>367</td>
</tr>
<tr>
<td>Ping Eye 2 Laminate Head</td>
<td>Ping ZZ-Lite</td>
<td>Ping Grip</td>
<td>12</td>
<td>43 1/2</td>
<td>359</td>
</tr>
<tr>
<td>Maxfli VHL</td>
<td>True Temper Gold Plus Sensicore 500</td>
<td>Tour Velvet</td>
<td>10.5</td>
<td>45</td>
<td>365</td>
</tr>
<tr>
<td>Slazenger Persimmon Head</td>
<td>Dynamic Gold S400</td>
<td>Avon Chamois</td>
<td>10</td>
<td>43 3/4</td>
<td>368</td>
</tr>
<tr>
<td>Prototype Club</td>
<td>Maxfli TLS0 Stiff</td>
<td>Tour Wrap Full Cord</td>
<td>10.5</td>
<td>43 1/2</td>
<td>345</td>
</tr>
<tr>
<td>Maxfli Colossus Graphite Head</td>
<td>Dynamic Gold Sensicore S-Flex</td>
<td>Tour Wrap</td>
<td>9</td>
<td>45</td>
<td>376</td>
</tr>
</tbody>
</table>
### APPENDIX 3 - POSTAL QUESTIONNAIRE

#### Demographic Questions

<table>
<thead>
<tr>
<th>Name</th>
<th>(Subject Number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf Club</td>
<td>Date</td>
</tr>
<tr>
<td>Age</td>
<td>Number of Years as a Professional</td>
</tr>
</tbody>
</table>

#### Club Choice

<table>
<thead>
<tr>
<th>Driver</th>
<th>Loft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>Stiffness</td>
</tr>
<tr>
<td>Swingweight</td>
<td>Grip</td>
</tr>
<tr>
<td>Irons</td>
<td>Shaft</td>
</tr>
<tr>
<td>Ball</td>
<td></td>
</tr>
</tbody>
</table>
During an 'ideal' golf shot with a driver,...

<table>
<thead>
<tr>
<th>Question</th>
<th>Scale</th>
<th>Very Soft</th>
<th>Moderately Important</th>
<th>Extremely Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>How would the impact feel in your hands?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Very</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the soft/hard feel in your hands from impact?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How much vibration would you feel in your hands?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the vibration level in your hands from impact?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How solid would the shot feel?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the solid feel to a shot?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How quickly would you feel the ball to have come off the clubface?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Dead, Ball</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the feel of speed at which the ball comes off the clubface?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How would the impact sound?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Very</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the impact sound?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Very</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How loud would the impact sound be?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Quiet, Dead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the volume of the impact sound?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How long would the impact sound last?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Short, Crisp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How important is the duration of the impact sound?</td>
<td>1 2 3 4 5 6 7 8 9</td>
<td>Not at all</td>
<td></td>
<td></td>
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</tbody>
</table>
In relation to the previous answers, how important are the following characteristics of a club's shot?

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Not at all Important</th>
<th>Moderately Important</th>
<th>Extremely Important</th>
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<tbody>
<tr>
<td>The feel of shaft flexibility?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The weight of the club?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The grip on the club?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The appearance of the club?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The trajectory of the ball flight?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The distance of the shot?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The accuracy you can achieve?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The ability to control the shape of the ball flight?</td>
<td></td>
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# Tactile Sensation Questionnaire

## Personal Details

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<table>
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<table>
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<th>Subject No.</th>
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<table>
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<th>No. of Years as a Professional</th>
<th>Age</th>
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## Equipment Choice

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<tbody>
<tr>
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<table>
<thead>
<tr>
<th>Driver Shaft</th>
<th>Steel / Graphite</th>
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<table>
<thead>
<tr>
<th>Loft</th>
<th>Swingweight</th>
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<table>
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<table>
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<tr>
<th>Iron Shafts</th>
<th>Steel / Graphite</th>
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<table>
<thead>
<tr>
<th>Ball</th>
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</tr>
</tbody>
</table>

Loughborough University
**1. Taylor Made Firesole**

<table>
<thead>
<tr>
<th>Data Quality</th>
<th>How much vibration did you feel in your hands?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Vibration</td>
</tr>
<tr>
<td>Ch. 1 (5 - 50 km/s²)</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Ch. 2 (2 - 20 km/s²)</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Ch. 3 (1.5 - 15 km/s²)</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Ch. 4 (0.5 - 8 km/s²)</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How did the shot feel?</th>
<th>How solid did the shot feel?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpleasant</td>
<td>Pleasant</td>
</tr>
<tr>
<td>1.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>2.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>3.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>4.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>5.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How did the impact feel in your hands?</th>
<th>How quickly did you perceive the ball to have come off the clubface?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felt Soft</td>
<td>Felt Hard</td>
</tr>
<tr>
<td>1.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>2.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>3.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>4.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>5.</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>
## Ideal Values

During an 'ideal' golf shot with a driver...

<table>
<thead>
<tr>
<th>How would the impact feel in your hands?</th>
<th>How solid would the shot feel?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Soft</td>
<td>Not</td>
</tr>
<tr>
<td>Feel</td>
<td>Very</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How much vibration would you feel in your hands?</th>
<th>How quickly would you perceive the ball to have come off the clubface?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>No Vibration</td>
<td>Dead, Ball</td>
</tr>
<tr>
<td>Lots of Vibration</td>
<td>Lively, Ball</td>
</tr>
<tr>
<td>Slowly</td>
<td>Comes off</td>
</tr>
<tr>
<td>Quickly</td>
<td>Comes off</td>
</tr>
</tbody>
</table>
# Audio Sensation Questionnaire

## Personal Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Golf Club</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of Years as a Professional</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Equipment Choice

### Driver

<table>
<thead>
<tr>
<th>Driver Shaft</th>
<th>Steel / Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loft</th>
<th>Swingweight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Iron Shafts</th>
<th>Steel / Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>
# 5. Callaway E.R.C.
## (EI 70 R Shaft)

## Data Quality & Impact Location

<table>
<thead>
<tr>
<th>Data</th>
<th>(h, v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>(h = , v = )</td>
</tr>
<tr>
<td>2.</td>
<td>(h = , v = )</td>
</tr>
<tr>
<td>3.</td>
<td>(h = , v = )</td>
</tr>
<tr>
<td>4.</td>
<td>(h = , v = )</td>
</tr>
<tr>
<td>5.</td>
<td>(h = , v = )</td>
</tr>
</tbody>
</table>

## How loud was the impact sound?

<table>
<thead>
<tr>
<th>Quiet, dead sound</th>
<th>Loud, Explosive Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

## How did the shot feel?

<table>
<thead>
<tr>
<th>Very Unpleasant</th>
<th>Very Pleasant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

## How did the impact feel in your hands?

<table>
<thead>
<tr>
<th>Very Soft</th>
<th>Very Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

## How did the Impact sound?

<table>
<thead>
<tr>
<th>Very Dull</th>
<th>Very Crisp, Sharp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

## How quickly did you perceive the ball to have come off the clubface?

<table>
<thead>
<tr>
<th>Dead, Ball Came off Slowly</th>
<th>Lively, Ball Came off Quickly</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>
## Ideal Values

During an 'ideal' golf shot with a driver...

<table>
<thead>
<tr>
<th>How would the impact sound?</th>
<th>How would the impact feel in your hands?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Very</td>
<td>Very</td>
</tr>
<tr>
<td>Dull</td>
<td>Crisp, Soft</td>
</tr>
<tr>
<td></td>
<td>Very</td>
</tr>
<tr>
<td></td>
<td>Sharp</td>
</tr>
<tr>
<td></td>
<td>Hard</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How loud would the impact sound be?</th>
<th>How quickly would you perceive the ball to have come off the clubface?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
<tr>
<td>Quiet, Dead Sound</td>
<td>Dead, Ball</td>
</tr>
<tr>
<td>Loud, Explosive Sound</td>
<td>Comes off</td>
</tr>
<tr>
<td>Slowly</td>
<td>Quickly</td>
</tr>
<tr>
<td>Lively, Ball</td>
<td>Comes off</td>
</tr>
</tbody>
</table>

APPENDIX 6 – SPECIFICATION OF CLUBS USED IN THE TACTILE SENSATION AND IMPACT SOUND STUDIES

<table>
<thead>
<tr>
<th>Club No.</th>
<th>Clubhead</th>
<th>Shaft</th>
<th>Flex (cpm)</th>
<th>Length (in.)</th>
<th>Weight (g)</th>
<th>Swingweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Taylor Made Firesole</td>
<td>TS100 (graphite)</td>
<td>268</td>
<td>45</td>
<td>321</td>
<td>D7</td>
</tr>
<tr>
<td>2</td>
<td>Callaway Great Big Bertha</td>
<td>True Temper EI70 R (graphite)</td>
<td>252</td>
<td>45</td>
<td>322</td>
<td>D0</td>
</tr>
<tr>
<td>3</td>
<td>Ping Eye 2</td>
<td>ZZ Lite (steel)</td>
<td>276</td>
<td>43 ½</td>
<td>363</td>
<td>C8</td>
</tr>
<tr>
<td>4</td>
<td>Maxfli VHL</td>
<td>True Temper Gold Plus S300 (steel)</td>
<td>239</td>
<td>45</td>
<td>365</td>
<td>D9</td>
</tr>
<tr>
<td>5</td>
<td>Callaway ERC</td>
<td>True Temper EI70 R (graphite)</td>
<td>249</td>
<td>45</td>
<td>328</td>
<td>D2</td>
</tr>
<tr>
<td>6a</td>
<td>Callaway Great Big Bertha</td>
<td>RCH Pro Series 5.3 Gold (graphite)</td>
<td>281</td>
<td>45</td>
<td>310</td>
<td>D0</td>
</tr>
<tr>
<td>6b</td>
<td>Callaway Steelhead</td>
<td>RCH 99 Firm (graphite)</td>
<td>256</td>
<td>44 ¼</td>
<td>331</td>
<td>C9</td>
</tr>
<tr>
<td>7</td>
<td>Slazenger Persimmon</td>
<td>Dynamic Gold S400 (steel)</td>
<td>252</td>
<td>43 ¾</td>
<td>373</td>
<td>D0</td>
</tr>
<tr>
<td>8a</td>
<td>Callaway ERC</td>
<td>RCH Pro Series 5.3 Gold (graphite)</td>
<td>292</td>
<td>45</td>
<td>313</td>
<td>D0</td>
</tr>
<tr>
<td>8b</td>
<td>Yonex Graphite</td>
<td>BR520 R Flex (graphite)</td>
<td>258</td>
<td>45 ¼</td>
<td>317</td>
<td>C9</td>
</tr>
<tr>
<td>9</td>
<td>Titleist 975D</td>
<td>Ultralite X Flex (graphite)</td>
<td>250</td>
<td>45</td>
<td>322</td>
<td>D3</td>
</tr>
<tr>
<td>10</td>
<td>Ping TiSi</td>
<td>350 Series Stiff (graphite)</td>
<td>243</td>
<td>45 ½</td>
<td>333</td>
<td>D6</td>
</tr>
</tbody>
</table>

a Clubs specific to tactile sensation study

b Clubs specific to impact sound study
APPENDIX 7 – OVERVIEW OF STATISTICAL TECHNIQUES

MEASUREMENT SCALES

A scale that is used to indicate that one observation was greater than (or less than) another observation is referred to as an ordinal or ranking scale. A scale that has all the characteristics of an ordinal scale but on which the difference between any two values on the scale has meaning is referred to as an interval scale.

THE PEARSON CORRELATION

The Pearson product-moment correlation coefficient $r$ is a measure of the linear relationship between two variables. “This statistic requires variables which represent measurement in at least an equal-interval scale for proper interpretation of the statistic” (Siegel and Castellan, 1988, p225). Further, to test the significance it has to be assumed that the observations are sampled from a bivariate normal distribution.

The Pearson correlation coefficient $r$ between two random variables $X$ and $Y$ is calculated by dividing the covariance between $X$ and $Y$ by the standard deviations of the two variables, as shown in equation (A7.1).

$$r = \frac{\text{cov}(X,Y)}{\sigma_x \sigma_y} = \frac{E[(X - \mu_x)(Y - \mu_y)]}{\sigma_x \sigma_y} \quad (A7.1)$$

If the points $(x_i, y_i)$ lie along a line of positive slope then $x_i$ tends to be greater than $\mu_x$ when $y_i$ is greater than $\mu_y$ and vice versa. Therefore the product of the two terms $(x_i - \mu_x)$ and $(y_i - \mu_y)$ is expected to be positive and therefore $r$ will be positive. However, if the points lie along a negative slope $(x_i - \mu_x)$ will tend to be positive when $(y_i - \mu_y)$ is negative, and vice versa, and therefore $r$ will also tend to be negative. Dividing the result by the standard deviation of each variable scales the covariance to a value that is between $+1$ and $-1$, which is dimensionless and can therefore be used to compare the linear relationships between pairs of variables in different units (Montgomery and Runger, 1994). If $r$ is equal to $+1$ or $-1$ the points lie along an exact straight line.

To test the significance of a coefficient, the probability $p$ that random samples from a population in which there is no association between the variables would yield a correlation as large, or larger than, the one obtained can be calculated. A coefficient can be considered to be significant if the $p$-value is smaller than the level of significance selected. For the purposes of this study, a 5% risk of error was deemed acceptable and so the level of significance was set at 0.05.

THE SPEARMAN RANK-ORDER CORRELATION

The Spearman rank-order correlation coefficient $r_s$ is a measure of association between two variables that must be measured in at least an ordinal scale so that each variable may be ranked in an ordered series.
To compute the Spearman correlation coefficient, the N values $x_i$ and the N values $y_i$ of the variables $X$ and $Y$ are ranked in order of size. If a perfect positive correlation exists between the two variables, the rank given to $x_i$ would be equal to the rank given to $y_i$ and the difference between the ranks would be zero. Therefore the sum of the squares of each difference $D_i$ can be used as an indicator of the disparity between two sets of rankings. The Spearman rank-order correlation coefficient $r_s$ can be calculated from equation (A7.2).

$$r_s = 1 - \frac{6 \sum D_i^2}{N(N^2 - N)}$$  \hspace{1cm} (A7.2)

If a perfect positive correlation exists, $\sum D_i^2 = 0$ and the Spearman correlation coefficient, $r_s = 1$, if a perfect negative correlation exists, $\sum D_i^2 = (N^2 - N)/3$ and $r_s = -1$. If two or more values of each variable are identical, each of them is assigned the average of the ranks that would have been assigned had no ties occurred and the formula for $r_s$ is adjusted (Siegel and Castellan, 1988).

**THE WILCOXON SIGNED RANKS TEST**

The Wilcoxon signed ranks test is the non-parametric equivalent of a paired $t$-test and evaluates both the magnitude as well as the direction of the difference between pairs of data. To perform the test, the magnitudes of the differences $|d_i|$ between each pair of data $(x_i, y_i)$ are ranked in order of size with the smallest magnitude of difference receiving a rank of 1. If any pair of values is equal, they are dropped from the analysis and the sample size reduced accordingly. Then, to indicate whether the ranks arose from a positive or a negative $d_i$, the sign of the difference is affixed to each rank. If there is no difference between the variables $X$ and $Y$ some of the ranks with a large magnitude would come from positive values of $d_i$ when $x_i$ is considerably bigger than $y_i$, and others would come from negative values of $d_i$ when $y_i$ is considerably greater than $x_i$, and therefore the sum of the positive ranks $T^+$ would be expected to be approximately the same as the sum of the negative ranks $T^-$. If $T^+$ is very much different from $T$ then it would indicate that there is a difference between the two variables. The probability $p$ of the value of $T^+$ occurring when there is no difference between the variables can be calculated and if it falls below the chosen level of significance then the variables can be considered to be different at that level of significance (Siegel and Castellan, 1988).
## APPENDIX 8 – PEARSON CORRELATION COEFFICIENTS FOR EACH COMBINATION OF SUBJECTIVE RATINGS FOR EACH SUBJECT

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.838</td>
<td>-0.794</td>
<td>0.890</td>
<td>0.815</td>
<td>0.868</td>
</tr>
<tr>
<td>2</td>
<td>-0.844</td>
<td>-0.816</td>
<td>0.894</td>
<td>0.936</td>
<td>0.902</td>
</tr>
<tr>
<td>3</td>
<td>-0.262</td>
<td>-0.423</td>
<td>0.870</td>
<td>0.660</td>
<td>0.217</td>
</tr>
<tr>
<td>4</td>
<td>-0.700</td>
<td>-0.437</td>
<td>0.949</td>
<td>0.948</td>
<td>0.772</td>
</tr>
<tr>
<td>5</td>
<td>0.973</td>
<td>-0.860</td>
<td>0.963</td>
<td>0.947</td>
<td>-0.885</td>
</tr>
<tr>
<td>6</td>
<td>0.245</td>
<td>-0.494</td>
<td>0.885</td>
<td>0.892</td>
<td>0.291</td>
</tr>
<tr>
<td>7</td>
<td>-0.798</td>
<td>-0.789</td>
<td>0.966</td>
<td>0.912</td>
<td>0.799</td>
</tr>
<tr>
<td>8</td>
<td>-0.624</td>
<td>-0.652</td>
<td>0.782</td>
<td>0.699</td>
<td>0.868</td>
</tr>
<tr>
<td>9</td>
<td>-0.302</td>
<td>-0.511</td>
<td>0.842</td>
<td>0.821</td>
<td>0.663</td>
</tr>
<tr>
<td>10</td>
<td>-0.387</td>
<td>-0.600</td>
<td>0.961</td>
<td>0.890</td>
<td>0.578</td>
</tr>
<tr>
<td>11</td>
<td>-0.899</td>
<td>-0.868</td>
<td>0.914</td>
<td>0.898</td>
<td>0.904</td>
</tr>
<tr>
<td>12</td>
<td>-0.736</td>
<td>-0.654</td>
<td>0.930</td>
<td>0.868</td>
<td>0.663</td>
</tr>
<tr>
<td>13</td>
<td>-0.613</td>
<td>-0.892</td>
<td>0.906</td>
<td>0.894</td>
<td>0.696</td>
</tr>
<tr>
<td>14</td>
<td>-0.804</td>
<td>-0.830</td>
<td>0.832</td>
<td>0.617</td>
<td>0.895</td>
</tr>
<tr>
<td>15</td>
<td>0.410</td>
<td>-0.659</td>
<td>0.745</td>
<td>0.545</td>
<td>-0.568</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.651</td>
<td>-0.685</td>
<td>0.889</td>
<td>0.823</td>
<td>0.511</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.866</td>
<td>-0.809</td>
<td>-0.843</td>
<td>-0.775</td>
<td>0.868</td>
</tr>
<tr>
<td>2</td>
<td>-0.790</td>
<td>-0.848</td>
<td>-0.762</td>
<td>-0.843</td>
<td>0.849</td>
</tr>
<tr>
<td>3</td>
<td>-0.082</td>
<td>-0.304</td>
<td>-0.486</td>
<td>-0.585</td>
<td>0.705</td>
</tr>
<tr>
<td>4</td>
<td>-0.706</td>
<td>-0.669</td>
<td>-0.485</td>
<td>-0.432</td>
<td>0.978</td>
</tr>
<tr>
<td>5</td>
<td>0.958</td>
<td>0.956</td>
<td>-0.889</td>
<td>-0.908</td>
<td>0.948</td>
</tr>
<tr>
<td>6</td>
<td>0.335</td>
<td>0.390</td>
<td>-0.430</td>
<td>-0.429</td>
<td>0.962</td>
</tr>
<tr>
<td>7</td>
<td>-0.806</td>
<td>-0.713</td>
<td>-0.765</td>
<td>-0.810</td>
<td>0.863</td>
</tr>
<tr>
<td>8</td>
<td>-0.638</td>
<td>-0.412</td>
<td>-0.711</td>
<td>-0.470</td>
<td>0.734</td>
</tr>
<tr>
<td>9</td>
<td>-0.174</td>
<td>-0.343</td>
<td>-0.417</td>
<td>-0.418</td>
<td>0.828</td>
</tr>
<tr>
<td>10</td>
<td>-0.414</td>
<td>-0.335</td>
<td>-0.597</td>
<td>-0.490</td>
<td>0.856</td>
</tr>
<tr>
<td>11</td>
<td>-0.807</td>
<td>-0.767</td>
<td>-0.822</td>
<td>-0.767</td>
<td>0.935</td>
</tr>
<tr>
<td>12</td>
<td>-0.612</td>
<td>-0.630</td>
<td>-0.568</td>
<td>-0.523</td>
<td>0.917</td>
</tr>
<tr>
<td>13</td>
<td>-0.554</td>
<td>-0.478</td>
<td>-0.852</td>
<td>-0.827</td>
<td>0.928</td>
</tr>
<tr>
<td>14</td>
<td>-0.849</td>
<td>-0.842</td>
<td>-0.796</td>
<td>-0.748</td>
<td>0.783</td>
</tr>
<tr>
<td>15</td>
<td>0.760</td>
<td>0.847</td>
<td>-0.721</td>
<td>-0.771</td>
<td>0.858</td>
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<tr>
<td>Mean</td>
<td>-0.350</td>
<td>-0.330</td>
<td>-0.676</td>
<td>-0.653</td>
<td>0.867</td>
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</table>

Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
## APPENDIX 9 – PEARSON CORRELATION COEFFICIENTS FOR EACH COMBINATION OF VIBRATION PARAMETER AND SUBJECTIVE RATING

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Original Data</th>
<th>Standardised $(\bar{x} - \mu_x)$</th>
<th>Standardised $(\bar{x} - \mu_x)/\sigma_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Grip</td>
<td>Combined Shaft</td>
</tr>
</tbody>
</table>

### Unweighted RMS Vibration Values

| Unpleasant – Pleasant Feel | -0.149 | -0.110 | -0.274 | -0.299 | -0.265 | -0.309 |
| Soft - Hard Feel | 0.444 | 0.372 | 0.313 | 0.258 | 0.308 | 0.291 |
| No Vibration – Lots of Vibration | 0.168 | 0.186 | 0.210 | 0.215 | 0.207 | 0.223 |
| Not Solid - Very Solid Feel | -0.200 | -0.157 | -0.304 | -0.337 | -0.298 | -0.347 |
| Dead - Lively Feel | -0.108 | -0.169 | -0.270 | -0.354 | -0.273 | -0.364 |

| Unpleasant – Pleasant Feel | -0.271 | -0.288 | -0.321 | -0.373 | -0.317 | -0.373 |
| Soft - Hard Feel | 0.333 | 0.266 | 0.405 | 0.346 | 0.404 | 0.378 |
| No Vibration – Lots of Vibration | 0.232 | 0.232 | 0.290 | 0.306 | 0.289 | 0.304 |
| Not Solid - Very Solid Feel | -0.287 | -0.306 | -0.345 | -0.398 | -0.343 | -0.400 |
| Dead - Lively Feel | -0.267 | -0.324 | -0.323 | -0.423 | -0.324 | -0.429 |

### BS Weighted RMS Vibration Values

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Original Data</th>
<th>Standardised $(\bar{x} - \mu_x)$</th>
<th>Standardised $(\bar{x} - \mu_x)/\sigma_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Grip</td>
<td>Combined Shaft</td>
</tr>
</tbody>
</table>

| Unpleasant – Pleasant Feel | -0.347 | -0.110 | -0.350 | -0.300 | -0.341 | -0.334 |
| Soft - Hard Feel | 0.234 | -0.078 | 0.260 | 0.152 | 0.264 | 0.152 |
| No Vibration – Lots of Vibration | 0.353 | -0.054 | 0.254 | 0.215 | 0.247 | 0.224 |
| Not Solid - Very Solid Feel | -0.298 | -0.063 | -0.347 | -0.277 | -0.334 | -0.304 |
| Dead - Lively Feel | -0.281 | -0.111 | -0.316 | -0.222 | -0.294 | -0.255 |

| Unpleasant – Pleasant Feel | -0.344 | -0.145 | -0.397 | -0.342 | -0.388 | -0.379 |
| Soft - Hard Feel | 0.302 | 0.096 | 0.349 | 0.212 | 0.341 | 0.210 |
| No Vibration – Lots of Vibration | 0.314 | 0.130 | 0.371 | 0.296 | 0.354 | 0.309 |
| Not Solid - Very Solid Feel | -0.342 | -0.134 | -0.397 | -0.323 | -0.384 | -0.350 |
| Dead - Lively Feel | -0.322 | -0.108 | -0.371 | -0.257 | -0.358 | -0.297 |

Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
### HS Weighted RMS Vibration Values

<table>
<thead>
<tr>
<th>Subjective Rating</th>
<th>Original Data</th>
<th>Standardised $(\bar{x} - \mu_x)$</th>
<th>Standardised $(\bar{x} - \mu_x)/\sigma_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Grip</td>
<td>Combined Shaft</td>
</tr>
<tr>
<td>Unpleasant – Pleasant Feel</td>
<td>-0.127</td>
<td>-0.212</td>
<td>-0.190</td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>0.359</td>
<td>0.232</td>
<td>0.249</td>
</tr>
<tr>
<td>No Vibration – Lots of Vibration</td>
<td>0.106</td>
<td>-0.017</td>
<td>0.146</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>-0.120</td>
<td>-0.203</td>
<td>-0.181</td>
</tr>
<tr>
<td>Dead - Lively Feel</td>
<td>0.019</td>
<td>-0.094</td>
<td>-0.082</td>
</tr>
<tr>
<td>Unpleasant – Pleasant Feel</td>
<td>-0.184</td>
<td>-0.257</td>
<td>-0.205</td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>0.254</td>
<td>0.248</td>
<td>0.291</td>
</tr>
<tr>
<td>No Vibration – Lots of Vibration</td>
<td>0.161</td>
<td>0.202</td>
<td>0.189</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>-0.168</td>
<td>-0.236</td>
<td>-0.189</td>
</tr>
<tr>
<td>Dead - Lively Feel</td>
<td>-0.076</td>
<td>-0.176</td>
<td>-0.084</td>
</tr>
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</table>

Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
APPENDIX 10 – PEARSON CORRELATION COEFFICIENTS FOR EACH COMBINATION OF VIBRATION PARAMETER AND SUBJECTIVE RATING AVERAGED BY CLUB FOR EACH GOLFER

<table>
<thead>
<tr>
<th>Standardised Subjective Rating</th>
<th>Unweighted RMS Vibration Values</th>
<th>BS Weighted RMS Vibration Values</th>
<th>HS Weighted RMS Vibration Values</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Original Data</td>
<td>Standardised ($\bar{x} - \mu_x$)</td>
<td>Original Data</td>
</tr>
<tr>
<td></td>
<td>Combined Shaft</td>
<td>Combined Grip</td>
<td>Combined Shaft</td>
</tr>
<tr>
<td>Unpleasant – Pleasant Feel</td>
<td>-0.351</td>
<td>-0.388</td>
<td>-0.483</td>
</tr>
<tr>
<td>Soft - Hard Feel</td>
<td>0.303</td>
<td>0.206</td>
<td>0.426</td>
</tr>
<tr>
<td>No Vibration – Lots of Vibration</td>
<td>0.283</td>
<td>0.273</td>
<td>0.406</td>
</tr>
<tr>
<td>Not Solid - Very Solid Feel</td>
<td>-0.382</td>
<td>-0.406</td>
<td>-0.529</td>
</tr>
<tr>
<td>Dead - Lively Feel</td>
<td>-0.354</td>
<td>-0.424</td>
<td>-0.490</td>
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Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
## APPENDIX 11 – PEARSON CORRELATION COEFFICIENTS FOR EACH COMBINATION OF SUBJECTIVE RATINGS FOR EACH SUBJECT

<table>
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<th></th>
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<th></th>
<th></th>
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<td>21</td>
<td>A</td>
<td>0.752</td>
<td>0.558</td>
<td>0.031</td>
<td>0.833</td>
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</tr>
<tr>
<td>22</td>
<td>A</td>
<td>0.753</td>
<td>0.731</td>
<td>0.703</td>
<td>0.830</td>
<td>0.987</td>
</tr>
<tr>
<td>24</td>
<td>A</td>
<td>0.624</td>
<td>0.565</td>
<td>0.913</td>
<td>0.895</td>
<td>0.874</td>
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<td>33</td>
<td>A</td>
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<td>0.372</td>
<td>0.806</td>
<td>0.931</td>
</tr>
<tr>
<td>36</td>
<td>A</td>
<td>0.836</td>
<td>0.800</td>
<td>0.863</td>
<td>0.894</td>
<td>0.900</td>
</tr>
<tr>
<td>38</td>
<td>A</td>
<td>0.875</td>
<td>0.823</td>
<td>0.602</td>
<td>0.921</td>
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<td>0.735</td>
<td>0.797</td>
<td>0.966</td>
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<td>B</td>
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<td>0.807</td>
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<td>0.757</td>
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<tr>
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<tr>
<td>31</td>
<td>B</td>
<td>0.819</td>
<td>0.774</td>
<td>-0.717</td>
<td>0.810</td>
<td>0.888</td>
</tr>
<tr>
<td>34</td>
<td>B</td>
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<td>0.879</td>
<td>-0.925</td>
<td>0.904</td>
<td>0.948</td>
</tr>
<tr>
<td>26</td>
<td>C</td>
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<td>0.950</td>
</tr>
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<td>0.072</td>
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<td>0.879</td>
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<td>-0.735</td>
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<td>35</td>
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<tr>
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<tr>
<td>Mean</td>
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<td>Standard Deviation</td>
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<td>0.239</td>
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<td>0.188</td>
<td>0.147</td>
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</table>

Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
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<th></th>
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</thead>
<tbody>
<tr>
<td>21 A</td>
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<td>0.913</td>
<td>0.636</td>
<td>0.810</td>
<td>0.362</td>
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<td>22 A</td>
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<td>0.953</td>
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<td>0.913</td>
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<td>0.672</td>
<td>0.511</td>
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<td>0.918</td>
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<td>33 A</td>
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<td>0.663</td>
<td>0.838</td>
<td>0.625</td>
<td>0.848</td>
<td>0.432</td>
</tr>
<tr>
<td>36 A</td>
<td></td>
<td>0.798</td>
<td>0.891</td>
<td>0.775</td>
<td>0.874</td>
<td>0.856</td>
</tr>
<tr>
<td>38 A</td>
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<td>0.727</td>
<td>0.946</td>
<td>0.864</td>
<td>0.916</td>
<td>0.717</td>
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<td>0.797</td>
<td>0.789</td>
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<td>0.886</td>
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<tr>
<td>25 B</td>
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<td>-0.880</td>
<td>0.813</td>
<td>-0.849</td>
<td>0.852</td>
<td>-0.857</td>
</tr>
<tr>
<td>30 B</td>
<td></td>
<td>-0.546</td>
<td>0.946</td>
<td>-0.465</td>
<td>0.937</td>
<td>-0.569</td>
</tr>
<tr>
<td>31 B</td>
<td></td>
<td>-0.568</td>
<td>0.918</td>
<td>-0.462</td>
<td>0.931</td>
<td>-0.562</td>
</tr>
<tr>
<td>34 B</td>
<td></td>
<td>-0.945</td>
<td>0.957</td>
<td>-0.932</td>
<td>0.929</td>
<td>-0.903</td>
</tr>
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<td>26 C</td>
<td></td>
<td>-0.316</td>
<td>0.940</td>
<td>-0.228</td>
<td>0.893</td>
<td>-0.384</td>
</tr>
<tr>
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<td>0.875</td>
<td>0.228</td>
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<td>37 C</td>
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<td>-0.057</td>
<td>0.899</td>
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<td>0.849</td>
<td>-0.441</td>
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<td>0.384</td>
<td>0.543</td>
<td>0.678</td>
<td>0.797</td>
<td>0.453</td>
</tr>
</tbody>
</table>

| Mean       |       | 0.121                      | 0.834                       | 0.181                     | 0.830                       | 0.064                       |
| Standard Deviation |     | 0.629                      | 0.150                       | 0.621                     | 0.135                       | 0.673                       |

Note: Coefficients that are not statistically significant at the 0.05 level are shown in italics.
APPENDIX 12 – PEARSON CORRELATION COEFFICIENTS FOR EACH COMBINATION OF SOUND PARAMETER AND SUBJECTIVE RATING IN ORIGINAL AND STANDARDISED FORMATS

<table>
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<tr>
<th>Frequency Weighting</th>
<th>Sound Parameter</th>
<th>Original Ratings</th>
<th>Standardised Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unpleasant – Pleasant Feel</td>
<td>Dull – Crisp Sound</td>
</tr>
<tr>
<td></td>
<td>Peak-to-peak level</td>
<td>0.461</td>
<td>0.622</td>
</tr>
<tr>
<td></td>
<td>Duration</td>
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<td>Decay</td>
<td>0.407</td>
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<tr>
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<td>SPL (50 ms)</td>
<td>0.467</td>
<td>0.739</td>
</tr>
<tr>
<td>Linear (unweighted)</td>
<td>Peak-to-peak level</td>
<td>0.467</td>
<td>0.644</td>
</tr>
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<td>Duration</td>
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<td></td>
<td>Decay</td>
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<tr>
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<td>SPL (50 ms)</td>
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<td>0.736</td>
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<td>A weighted</td>
<td>Peak-to-peak level</td>
<td>0.467</td>
<td>0.643</td>
</tr>
<tr>
<td></td>
<td>SPL (50 ms)</td>
<td>0.459</td>
<td>0.734</td>
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<td>C weighted</td>
<td>Peak-to-peak level</td>
<td>0.512</td>
<td>0.671</td>
</tr>
<tr>
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<td>Duration</td>
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<td>0.654</td>
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<tr>
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<td>Decay</td>
<td>0.434</td>
<td>0.718</td>
</tr>
<tr>
<td></td>
<td>SPL (50 ms)</td>
<td>0.518</td>
<td>0.776</td>
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<td>Peak-to-peak level</td>
<td>0.519</td>
<td>0.694</td>
</tr>
<tr>
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<td>Duration</td>
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<td>0.650</td>
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<td>Decay</td>
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<td>SPL (50 ms)</td>
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<td>Peak-to-peak level</td>
<td>0.520</td>
<td>0.693</td>
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<tr>
<td></td>
<td>SPL (50 ms)</td>
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<td>0.773</td>
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