# The Effect of Differing Shaft Dynamics on the Biomechanics of the Golf Swing

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# Abstract

The role of the shaft in the golf swing has been the subject of scientific debate for many years but there is little consensus regarding the effects of altering shaft bending stiffness. The aim of this thesis was to determine and explain the effects of changes in shaft stiffness on body kinematics, shaft strain and key performance indicators including club head speed, impact location on the club face and launch conditions. For this purpose, three clubs matched in all properties but shaft bending stiffness (l-flex (217 cpm), r-flex (245 cpm) and x-flex (272 cpm)) were instrumented with strain gauges. In an initial study, seventeen male golfers (handicap 1.8 ±1.9) tested these clubs, but no shaft effects on body kinematics, club head speed and ball launch conditions were identified. A follow-up study involved twenty skilled players (handicap 0.3 ±1.7), testing only the l- and x-flex clubs. Two optical motion capture systems were used to determine wrist angular kinematics, club head presentation and the ball's impact location on the club face. There was an effect of shaft stiffness on ball and club head speed, both of which increased by 0.7 % for the l-flex club ($p$ = 0.008 and < 0.001, respectively). Two factors contributed to these increases: (i) a faster recovery of the l-flex shaft from lag to lead bending just before impact ($p < 0.001$); (ii) an increase of 0.5 % in angular velocity of the grip of the l-flex club at impact ($p = 0.005$). A difference in angular wrist kinematics between the two clubs was identified for two swing events and may have contributed to the increase in angular velocity. The face angle ($p = 0.176$) and the ball's impact location ($p = 0.907$ and $p = 0.774$) were unaffected by changes in shaft stiffness. Decreases in shaft stiffness were associated with significantly more shaft bending at the transition from backswing to downswing ($p < 0.001$), but the amount of lead bending at impact was found to be largely unaffected by shaft stiffness. The test protocol from the follow-up study was repeated using a golf robot, confirming the results for ball speed and wrist kinematics if the impact speed was set to replicate the mean club head speed achieved by the human players. Results from this thesis contradict the conventional view that reducing shaft stiffness leads to an increase in lead bending at impact and, consequently, to an increase in ball launch angle. Overall, these results suggest that it is unlikely that changes in overall shaft stiffness in themselves have a marked effect on driving performance.

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# Nomenclature

| | |
|---|---|
| ANN | Artificial neural network |
| ANOVA | Analysis of variance |
| BASES | British Association of Sport and Exercise Sciences |
| CFRP | Carbon fibre reinforced polymer |
| COG | Centre of gravity |
| COV | Coefficient of variation |
| cpm | Cycles per minute |
| FE | Finite element |
| ISB | International Society of Biomechanics |
| MANOVA | Multivariate analysis of variance |
| MOI | Moment of inertia |
| RMS | Root mean square |
| SD | Standard deviation |
| TA | Take-away event |
| TOB | Top of backswing event |
| WR | Wrist release event |

# Research communications

## Journal paper

Betzler, N., Monk, S., Wallace, E., Otto, S. R., & Shan, G. (2008). From the double pendulum model to full-body simulation: evolution of golf swing modeling. *Sports Technology, 1*(4-5), 175-188.

## Conference papers

Betzler, N., Brown, S., Wallace, E. S., Otto, S. R., & Shan, G. (2008). Effect of 6-iron club properties on thorax and pelvis rotation at key events of the golf swing. In D. J. Crews & R. Lutz (Eds.), *Science and Golf V* (pp. 455-461). Mesa, Arizona: Energy in Motion Inc.

Betzler, N., Slater, C., Strangwood, M., Wallace, E. S., & Otto, S. R. (2009). *The static and dynamic behaviour of carbon fibre composites used in golf club shafts.* Paper presented at the International Conference on Composite Materials, 27th-31th July 2009, Edinburgh.

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# 1 Introduction

## 1.0 Research background

> "There has been much modelling and computer simulation of the golf swing, recording of data from instrumented clubs, attempts to quantify or categorize subjective impressions and other studies of components of the swing, yet understanding of the golfer's interaction with the club is still too crude to fit clubs to people properly." (Farrally et al., 2003, p. 756)

This quotation, taken from a review of scientific golf literature, highlights a problem that is not uncommon in research disciplines other than biomechanics: sophisticated analyses and simulations help understanding and optimising the technical aspect of equipment, but often human factors cannot be included in this process. This leaves the question of whether possible reactions of the human to changes in the equipment may invalidate the boundary conditions that were assumed in the isolated analysis and optimisation of the equipment. In case of the golf swing, various equipment factors have been subject to scientific analysis and debate. Examples include the golf ball (e.g. Smits & Ogg, 2004a), the face of the club head (e.g. Winfield & Tan, 1996) and the shaft (e.g. Milne & Davis, 1992). Yet, knowledge of how changes in any of these equipment properties affect the reaction of the player is often limited (Farrally et al., 2003), and it has been suggested that golf research should take a more holistic approach (Dillman & Lange, 1994). Based on this, the general scope of this thesis is an evaluation of equipment effects that considers human factors as well as mechanical behaviour. As humans interact with implements in many other situations in sport and in daily life, the opportunity exists to contribute to knowledge outside golf research through an improvement in the understanding of the interaction between human and golf club.

Most relevant for the majority of golfers may be the question of whether a particular piece of equipment has the potential to help them perform better. This thesis therefore focuses on the reaction of human players to changes in golf shaft stiffness. When a golf swing is performed, the player accelerates and attempts to control the club head that impacts the ball and determines the ball's initial launch conditions thus playing the major role in its trajectory. The player and the club head are linked by the golf shaft, which is a relatively flexible structure. The shaft's role in the golf swing and its effect on performance have been debated by a number of previous authors, often with conflicting results. On the subject of whether shafts need to be tested dynamically, for example, conclusions range from "the principal effect of flexibility ... could be estimated from static considerations" (Milne & Davis, 1992, p. 979) to "dynamic testing appears to be necessary, perhaps even essential" (Mather, Smith, Jowett, Gibson, & Moynihan, 2000, p. 46).

Modern shaft materials and construction provide manufacturers with almost limitless control over many of the shaft properties. Yet, it is only possible to make use of this potential if the effect of changes in mechanical parameters and the reaction of human players are known. It is the purpose of this thesis to enhance understanding of the golf shaft both in terms of performance and the underlying mechanisms that may lead to performance effects.

### *1.1 Thesis outline*

The thesis is organised in eight chapters consisting of a literature review (Chapter 2), a statement of the aims and objectives (Chapter 3), a discussion of methodological issues (Chapter 4), three experimental studies (Chapters 5 – 7) and conclusions (Chapter 8).

Chapter 2 aims to present a summary of the current state of shaft research in order to identify areas in which further research is needed. It describes the main mechanical properties of the golf shaft and discusses methods to characterise and simulate their effect. This is followed by a summary of the current state of research into the relationship of these mechanical properties with performance variables. The chapter concludes with the identification of key areas where more research is required and is followed by a definition of more specific aims for this thesis (Chapter 3).

Chapter 4 discusses the methodological aspects of this thesis in more detail, beginning with study design considerations. This is followed by a description of how the components of the golf clubs that were custom-assembled for the experimental studies were selected, and how these clubs were instrumented. Conducting the experimental studies required the development and validation of a number of non-standard methods for data collection and processing. These are described in the remaining sections of Chapter 4 to avoid repetition of details in later chapters.

The main part of this thesis reports three experimental studies, presented in chronological order. The first study is presented in Chapter 5 and will be referred to as Study 1 throughout this thesis. It had the more general aim of determining whether there were any effects related to shaft stiffness on body movement, shaft loading and ball launch conditions. Results of Study 1 allowed the formulation of more specific hypotheses, which are tested in Study 2 (Chapter 6). Rather than looking at the angular displacement of various body joints, Study 2 focused on wrist kinematics. Furthermore, shaft loading was studied in more detail, including an analysis of the shaft behaviour during the last milliseconds before impact and its effects on club head velocity at impact. Study 2 also applied a novel approach for determining the impact location of the ball on the club face. Following this, a golf robot was used in the third experimental study (Chapter 7) to analyse shaft effects in isolation from a human player, thereby removing any potential active adaptations that may be performed by human players to adjust their swing to changes in shaft stiffness.

Finally, Chapter 8 summarises the conclusions from the three research studies, draws general conclusions and provides suggestions for future research emerging from the work presented in this thesis.

# 2 Literature review

### 2.0 Introduction

The purpose of this chapter is to define all relevant mechanical shaft properties and critically review published scientific studies that have examined the effect of shaft properties on swing performance. No attempt is made to summarise the vast amount of information available concerning the body motion of the golfer, as this aspect has been recently reviewed elsewhere (Hume, Keogh, & Reid, 2005). Instead, limitations imposed on human tests of shaft performance will be reviewed along with the roles and contributions of biomechanical modelling techniques. Whilst the club head is not part of the golf shaft, it is commonly accepted that its properties have a significant influence on shaft behaviour (Mather & Jowett, 2000). Therefore, Appendix A (p. 193) outlines the most important mechanical properties of driver club heads for reference.

### 2.1 Scope and structure

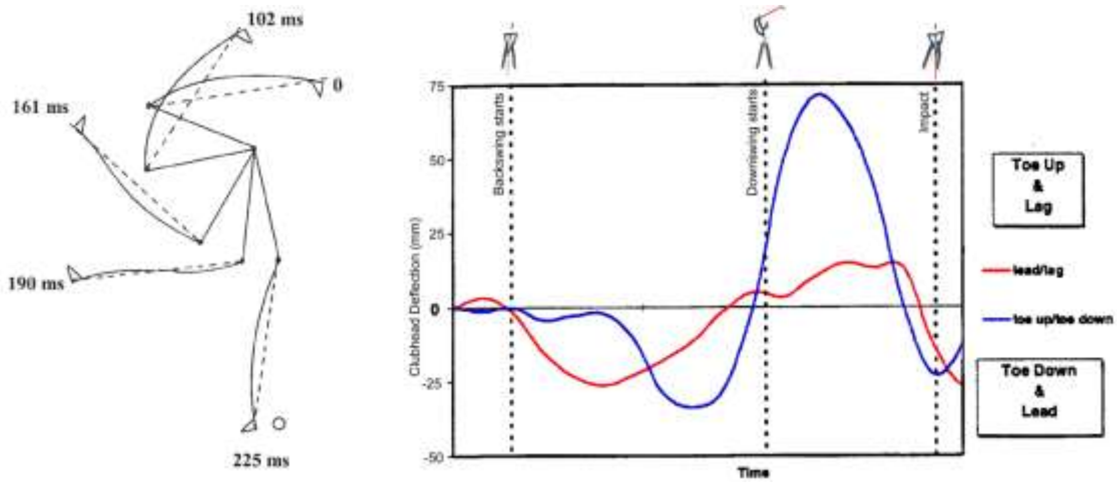
The literature review begins with descriptive information characterising typical shaft deflection patterns for human swings with a view to providing a basic understanding of the factors involved. Following on from this, mechanical shaft properties and shaft tests are described in detail, with a focus on the strength and weaknesses of the methods currently used in practice. A full understanding of the mechanical structures involved is deemed an important basis for biomechanical analysis. Following the discussion of experimental techniques used in shaft research, modelling and simulation methods are covered, in order to show potential methods that may be used in the course of this thesis. The final section of the literature review highlights the limitations of the current understanding of relationships between mechanical shaft properties and golf performance. At the end of this section, the case is made for shaft stiffness forming the main study of this thesis.

During the search for literature, all relevant international, peer-reviewed journals in English language that are indexed in the SportDiscus, ISI Web of Knowledge, Engineering Village and PubMed databases were included. The databases were searched using keywords such as ‘golf’ and ‘shaft’. Additionally, citations were followed up when they appeared to be relevant to the topic of golf biomechanics and shaft mechanics. It was found that there were also a number of monographs that provided valuable information on the topic (Cochran & Stobbs, 1968; Jørgensen, 1999; Maltby, 1995; Werner & Greig, 2000). Additional sources of information were the ‘Science and Golf’ and ‘Engineering of Sports’ conference proceedings (Cochran, 1990; Cochran & Farrally, 1994; Crews & Lutz, 2008; Farrally & Cochran, 1999; Haake, 1996, 1998; Hubbard, Mehta, & Pallis, 2004; Moritz & Haake, 2006; Subic & Haake, 2000; Thain, 2002; Ujihashi & Haake, 2002). A number of relevant PhD theses (Harper, 2006; Huntley, 2007; Lucas, 1999; MacKenzie, 2005) and one relevant M.Sc. thesis (Braunwart, 1998) were also identified and reviewed.

### *2.2 Behaviour of the shaft during a typical golf swing*

When handling a golf club it is easy to feel that the rigidity of the shaft is ‘relatively low’, permitting bending of the shaft through application of a small load (for example by using one’s hands). Combined with the high mass of the club head and the dynamic swing motion, it can be expected that the shaft undergoes a significant amount of deformation during a swing. Consequently, it has been found that there is a constant exchange of kinetic energy and strain energy (Newman, Clay, & Strickland, 1997). Strain gauge measurements and optical observation with high-speed cameras allowed researchers to analyse the typical sequence of shaft bending that occurs throughout the swing. The pre-impact sequence is illustrated in Figure 1, and the deflection pattern occurring during the downswing can be summarised as follows:

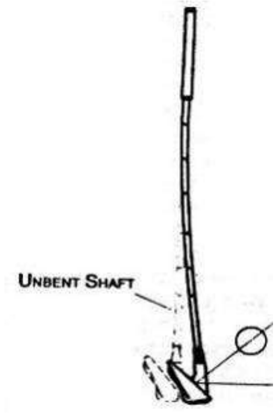
> “At the initiation of the downswing the shaft is bent backwards as a result of the inertia of the club head and the torque exerted by the golfer. As the downswing proceeds the shaft gradually straightens out and then bends forward during the final moments before impact.” (Penner, 2003, p. 157)



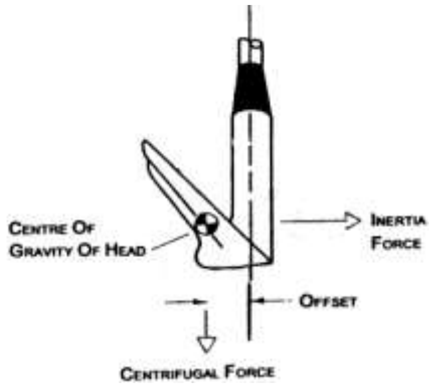

(a) (b)

**Figure 1: Shaft behaviour during a typical golf swing: (a) simulation of shaft bending according to Milne & Davis' (1992) measurements (bending exaggerated by a factor of 5) (adapted from Penner, 2003, p. 158); (b) bending of the shaft during a typical golf swing (adapted from Newman, Clay, & Strickland, 1997, p. 369).**

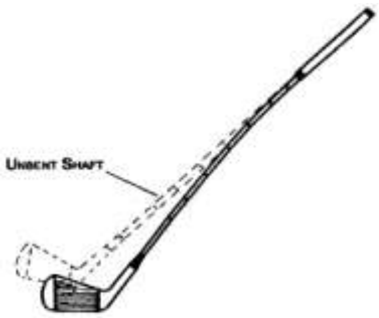
Whilst the shaft may influence the path and orientation of the club head just before impact, the shaft's effect during impact is generally considered to be negligible because of the short impact duration of ~500 μs (Hocknell, Jones, & Rothberg, 1996; Roberts, Jones, & Rothberg, 2001). Mather and Jowett reported that the change in the amount of shaft deflection during impact was minimal - "only a few millimetres" (Mather & Jowett, 2000, p. 79). After impact, however, the shaft bent considerably backwards (up to 200 mm), but this had no effect on the trajectory of the ball (Mather & Jowett, 2000). Newman *et al.* (1997) reported smaller maximum deflections (up to 75mm), probably because they did not include post-impact vibrations in their analysis (see Figure 2(b)).



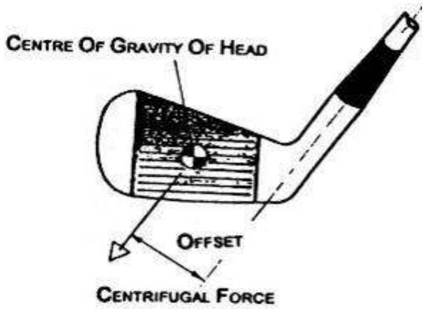

**(a) Bending in plane of swing (lead/lag)**




**(b) Assumed reason for in plane bending**




**(c) Bending perpendicular to plane of swing (toe-up/down)**




**(d) Assumed reason for toe-down bending**

**Figure 2: Definition of bending planes and suggested reasons for bending (adapted from Horwood, 1994, p. 249 and 251).**

In terms of deflection shape, measurements with multiple strain gauges along the shaft have shown that first mode vibrations dominate the downswing (Butler & Winfield, 1994). At and just after impact, however, stress waves travel up the shaft (Horwood, 1994; Masuda & Kojima, 1994), which will lead to a more complex shaft shape during this phase of the swing and the follow-through. For an observer, the forward and downward bending just before impact may be unexpected. Horwood (1994) and Mather and Jowett (2000) argue that the reason for this behaviour is the off-centre position of the centre of gravity (COG) of the club head relative to the shaft centre line (see Figure 2). The off-centre position causes a bending moment because centrifugal force is acting on the COG of the club head but centripetal force is being applied via the shaft.

It appears that Milne and Davis (1992) were the first to publish a scientific study focusing on shaft deformation and have been cited in many subsequent studies. Whilst their study laid the foundation for much of the shaft research that followed, it is important to note that there were some limitations in the data collection methods used by the authors. Strain gauge signals were sampled at a relatively low sample rate (200 Hz) and could not be sampled from all strain gauges simultaneously. Hence, the full swing data set was obtained by combining data from successive swings, which might have an effect on the accuracy of the data depending on the consistency of the players. Furthermore, the authors reported difficulties with transferring their strain data from the local shaft coordinate system to a global coordinate system because they used a single camera to determine the club orientation throughout the swing. It is not clear how they derived their three-dimensional model from data collected with a single camera. Nevertheless, the deflection patterns reported by Milne and Davis are generally in line with later studies although they are lacking an appropriate separation of the bending patterns in their lead/lag and toe-up/down components (Butler & Winfield, 1994; Horwood, 1994; N. Lee, Erickson, & Cherveny, 2002).

Based on the existing literature, it is difficult to determine the range of variation that exists for different golfers. Whilst some of the studies reporting typical patterns of shaft deflection refer to “hundreds of trials” (Butler & Winfield, 1994) or “various swings” (Newman, Clay, & Strickland, 1997), Table 1 shows that none of the studies reported shaft deflection patterns for more than 5 subjects. Furthermore, it is important to note the relatively low strain gauge sample rate that was used in some of the studies. At a sample rate of 500 Hz, as was used for example by Ozawa *et al.* (2002), it is only possible to record 100-150 samples in the duration of a typical downswing (0.2-0.3 s, Burden, Grimshaw, & Wallace, 1998; Egret, Vincent, Weber, Dujardin, & Chollet, 2003). It is evident from Figure 1 that a typical golf swing includes dynamic changes in shaft deflection, and it is likely that these cannot be adequately characterised with a small number of samples.

**Table 1: Summary of previous research into shaft deflection patterns.**

| Reference | Method used | Sample rate | Number of subjects |
|---|---|---|---|
| Milne & Davis (1992) | Strain gauges | 200 Hz | 3 |
| Horwood (1994) | Strain gauges | unspecified | 1 |
| Butler & Winfield (1994) | 2 longitudinal, 1 torsional gauge | 50,000 Hz | "hundreds of trials" |
| Kojima & Horii (1995) | 3 longitudinal, 3 torsional | unspecified | 1 robot |
| Newman, Clay & Strickland (1997) | 8 longitudinal, 1 torsional strain gauge | 500 Hz | "various", present only results for one professional |
| Mather & Cooper (1994) | Multiple exposures with two cameras (exposure time 300 ns, see Smith, Mather, Gibson, & Jowett, 1998, for details) | N/A | 2 |
| Mather &Jowett (2000) | | N/A | 3 |
| Mather *et al.* (2000) | | N/A | 1 |
| Iwatsubo *et al.* (2002) | 4 torsional strain gauges | unspecified | 1 robot |
| Lee, Erickson & Cherveny (2002) | 6 strain gauges | 500 Hz | 5 |
| Ozawa, Namiki & Horikawa (2002) | 3 strain gauges | 500 Hz | 2 |
| Tsujiuchi, Koizumi & Tomii (2002) | 6x2 strain gauges | unspecified | 3 |
| Tsunoda, Bours & Hasegawa (2004) | 8 strain gauges | unspecified | 1 |
| Shinozaki et al. (2005) | 6 longitudinal, 3 torsional strain gauges | 10,000 Hz | 3 |
| Harper, Jones & Roberts (2005) | Strain gauges ('Shaftlab') | ~500 Hz | 1 + 2 robots |

### *2.3 Mechanical properties of the golf shaft*

This section of the literature review focuses on the mechanical properties of the shaft. The purpose of this section is to put the subsequent sections of the literature review into context and to provide background information. It is deemed necessary to fully understand the mechanical characteristics of the club in order to correctly interpret its dynamic behaviour.

#### 2.3.1 Manufacturing process

Material selection and processing routes will each have a strong effect on the properties of a finished golf shaft. The section that follows summarises the manufacturing process for steel and graphite shafts.

##### *2.3.1.1 Steel shafts*

From the 1920s until the introduction of graphite shafts in the 1970s, the majority of golf shafts were manufactured from steel. A detailed description of the manufacturing process of steel shafts can be found in Maltby (1995, pp. 550-556). Briefly, Maltby describes the manufacturing process as follows: the process begins with the forming of high-alloy steel strips into tubes. High frequency welding is then used to close each tube. The diameter of this tube is bigger than the diameter of the finished shaft, so diameter and wall thickness are reduced on a draw bench. This process is repeated six to eight times until the butt diameter of the finished shaft is reached. A series of dies then produces the stepped tapering of the shaft. Next, a heat treatment improves the hardness and the strength of the shaft. After it is straightened (if necessary), the shaft is cleaned and plated with nickel and chrome for corrosion protection.

##### *2.3.1.2 Graphite shafts*

Despite their name, graphite shafts are typically made from Carbon Fibre Reinforced Polymers (CFRPs). Graphite shafts can be either sheet-wrapped or filament-wound. Maltby (1995, pp. 634-341) and Cheong *et al.* (2006) describe the sheet wrapping manufacturing route as follows. It begins with the production of crystalline carbon fibres from Polyacrylonitrile (more flexible) or pitch (highest carbon content, less flexible). These fibres are pre-impregnated with epoxy resin and woven to form pre-pregs. These pre-pregs are cut into sections (flags) with different fibre angles. These pieces of pre-preg material are rolled around tapered steel mandrels to form the shaft, resulting in a total number of approximately seven layers (see Figure 3). Usually, each flag is rolled around the mandrel more than once. The ends of the pre-pregs form seams, which have been found to result in inconsistencies in the mechanical properties of the shaft (Huntley, Davis, & Strangwood, 2004). Furthermore, micro-structural analysis (Huntley, 2007) has shown that manufacturers usually roll some of these layers simultaneously and other layers consecutively. When two layers are rolled simultaneously, this will result in an alternating order of pre-pregs (see inner layer 1 and 2 in Figure 4(b)). When two layers are rolled consecutively, this will result in a different sequence of layers (outer layer 1 and 2 in Figure 4(b)). In terms of fibre orientation[1] and order of plies, Cheong *et al.* (2006) presented a model of a shaft with ±45° fibres as inner layers and 0° fibres as outer layers. This is in agreement with the majority of shafts sectioned by Huntley (2007) as well as shafts described by Sabo (1995) and Zako *et al.* (2004), so it will be assumed here that this is the typical construction of sheet-laminated shafts.

[1] Fibre orientations are described relative to the longitudinal axis of the shaft, with 0° meaning that the fibres are parallel to the longitudinal axis of the shaft.

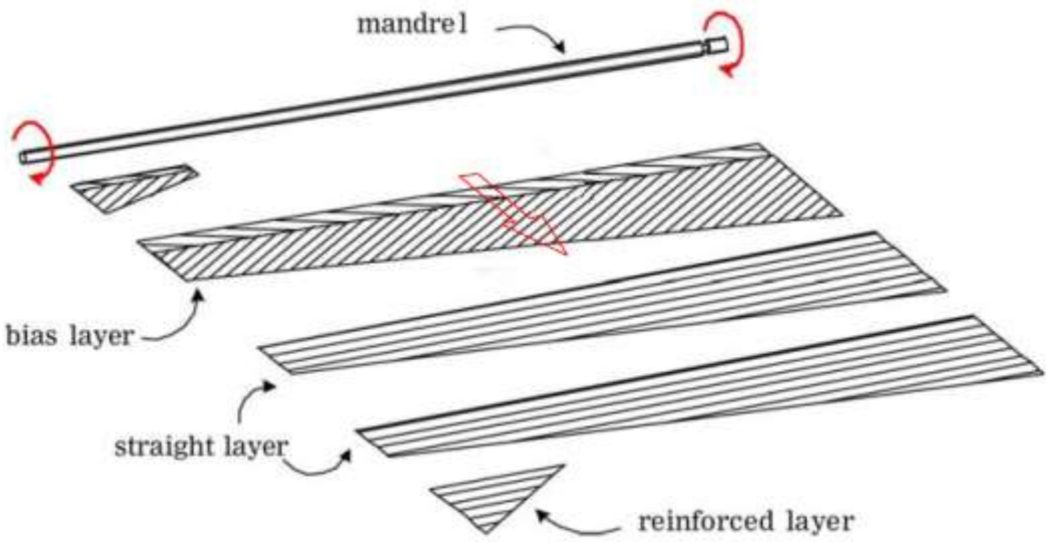



**Figure 3: Lay-up process for sheet-laminated shafts (adapted from Cheong, Kang, & Jeong, 2006, p. 465).**

When all pre-pregs are in place on the mandrel, it is covered with tape providing the necessary pressure during the curing process. After the curing process, the mandrel is removed, and the outer surface of the shafts is sanded and polished to finish. This manufacturing route leaves four options for deliberately altering the mechanical characteristics of the shaft: (1) the number and order of pre-preg layers, (2) the fibre orientation of each layer, (3) the fibre type of each layer and (4) the geometry of the mandrel. Through the work of Huntley (2007) it is evident that changes in other aspects of shaft manufacture can also lead to changes in the mechanical characteristics of the shafts, for instance the amount of interfacial material between plies.

For filament-wound shafts, the only difference is in the method used to place fibres on the mandrel. Rather than rolling plies on a mandrel, a machine wraps two layers of pre-preg tape around it. After this, a filament winding machine weaves carbon fibres around this mandrel (Maltby, 1995, p. 626). In the case of filament winding, the angle of the fibres is configured by varying “the distance the winding head travels down the length of the mandrel per mandrel revolution” (Howell, 1992, p. 1397). Furthermore, it is possible to change the number of circuits in a layer, which is the number of times the winding head travels up and down the shaft before finishing one layer. In contrast to the lay-up process, filament winding allows the manufacturer to vary the amount of tension on the fibres while they are wound on the mandrel (Howell, 1992).

The differences in the manufacturing process of filament-wound and sheet-laminated shafts manifest themselves in the mechanical shaft properties. Whilst filament winding involves less manual labour, creates more flexibility in the design of the lay-up and avoids seam effects at the end of pre-pregs sheets (Howell, 1992), it is also more expensive and leads to a decreased fibre content (Huntley, Davis, Strangwood, & Otto, 2006).

(a)

(b)

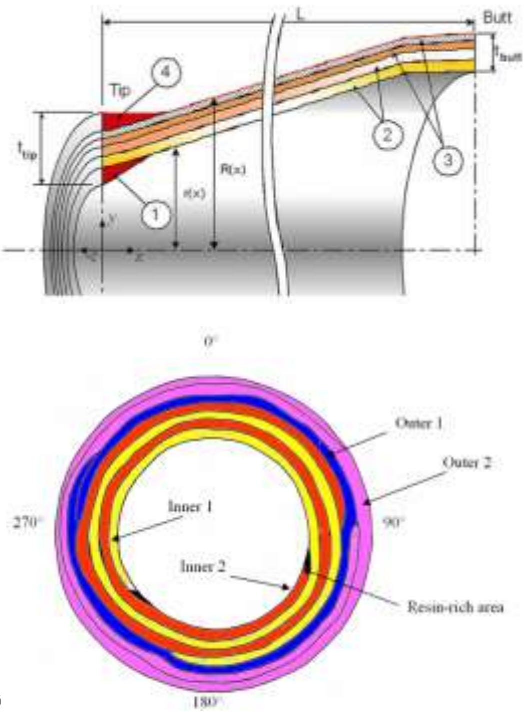


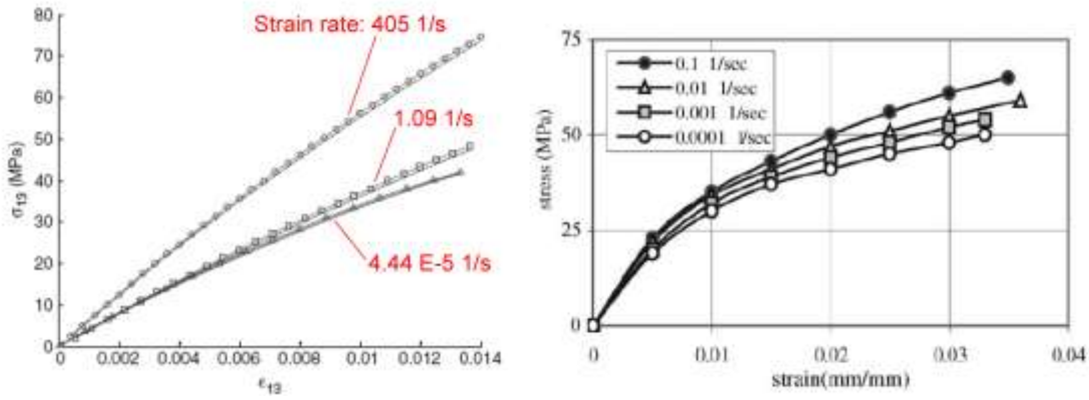

**Figure 4: (a) Typical composition of a sheet-laminated shaft from a number of layers[2] of carbon/epoxy pre-pregs (adapted from Cheong, Kang, & Jeong, 2006, p. 469). (b) Resulting lay-up of carbon/epoxy layers. Fibres of the inner layer are typically oriented at ±45°, fibres of the outer layer at 0° (adapted from Huntley, 2007, p. 140).**

[2] Fibre orientation of layers: ① and ② ±45°; ③ and ④ 0°.

### 2.3.2 Material properties of graphite shafts

For steel shafts, it is viable to assume isotropic material properties, so the shaft properties will only be governed by the choice of material and the geometry of the shaft. Composite shafts, however, consist of several layers of carbon fibres (see previous section). Therefore, they will have anisotropic properties that heavily depend on the angle between load direction and fibre orientation. Depending on load orientation, the modulus of each layer will vary between upper and lower bounds, with the properties of the fibres defining the upper bounds (longitudinal load) and the properties of the matrix materials defining the lower bounds (transverse load) (Ashby, 2005). For example, in the case of one layer of unidirectional composite material the upper bound (longitudinal load) can be 120 GPa, whereas the lower bound (transverse load) is as low as 10 GPa (Zako, Matsumoto, Nakanishi, & Matsumoto, 2004).

CFRPs have been shown to have strain rate dependent material properties under certain conditions (Gilat, Goldberg, & Roberts, 2002; Vinson & Woldesenbet, 2001; Weeks & Sun, 1998). This is illustrated in Figure 5, which shows stress-strain curves for composite materials at different strain rates. If the material properties were not strain rate dependent, each of the two graphs would show identical lines for all loading rates. Only at low strains do some of the curves overlap, in particular at low strain rates. This indicates that strain rate dependency has only a minor effect when strain and strain rates are below a material-specific limit.




**(a)** **(b)**

**Figure 5: Stress(σ)-strain(ε) graphs for composites loaded at different strain rates: (a) based on micromechanical modelling (Zhu, Chattopadhyay, & Goldberg, 2006, p. 1810); (b) based on experimental results (Fereshteh-Saniee, Majzoobi, & Bahrami, 2005, p. 46).**

### 2.3.3 Geometry

The geometry of a golf shaft can be described by the variables shown in Figure 6 and, additionally, by its wall thickness. However, there is little information in the scientific literature describing the typical characteristics of the geometry of shafts.

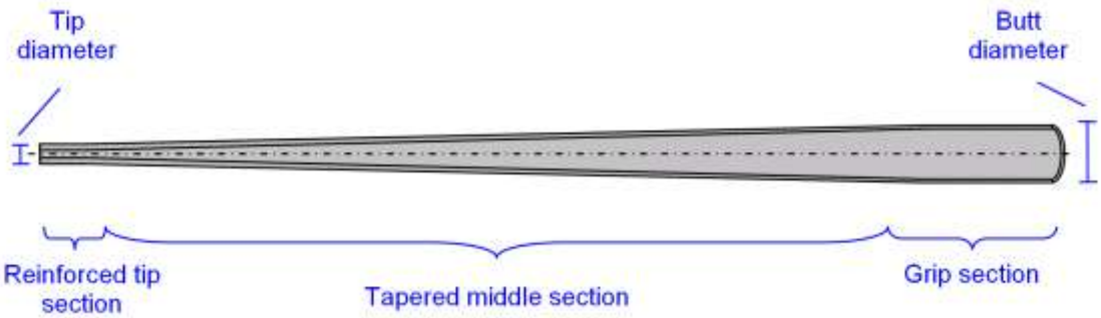



**Figure 6: Typical shaft geometry (cross section). Shaft diameter is exaggerated relative to length for clarity (based on data presented in Huntley, 2007).**

Maltby (1995) listed typical lengths and tip/butt diameters for a variety of shafts that were on the market in 1995, but no information is given regarding typical taper or wall thicknesses. Maltby only collated information that is of practical relevance to club makers when assembling a club. Huntley (2007) sectioned 33 graphite driver shafts and analysed their geometry in detail. It was found that the mean wall thickness of shafts was between 0.7 and 1.1 mm. Some of the shaft batches analysed were designed to have a constant wall thickness (with the exception of reinforced areas in the tip sections); for other shaft batches the wall thickness decreased continuously from the tip end to the butt end. The range of tip diameters was between 8.2 and 8.9 mm, and the range of butt diameters between 14.8 and 15.7 mm. The diameter increased continuously from the tip end to the grip section and remained constant in the grip section for the majority of shafts. These results are in agreement with typical shaft dimensions given by Howell (1992). Huntley (2007) noted that there were wall thickness variations around the circumference of the shaft, which resulted in standard deviations in wall thickness of between 10 and 96 µm for given shaft positions. It was found that these were related to the manufacturing process and the resulting seams (see Section 2.3.1).

### 2.3.4 Mass and Density

As for the geometry of the golf shaft, published data describing typical mass properties of shafts is limited and, in most cases, anecdotal and not based on scientific study. Lee and Kim (2004) mention a number of categories of mass ranges, which are summarised in Table 2. The overall mass range stated by Lee and Kim is similar to values presented by Howell (1992), who stated the minimum and maximum mass of composite shafts as 59g and 110g, respectively. Penner (2003) mentioned that the typical weight is 90g for a graphite shaft and 120g for steel shafts, which is within the range given by the other authors.

**Table 2: Mass ranges of golf shafts (adapted from Lee and Kim, 2004).**

| Mass | Category |
|---|---|
| < 60 g | light carbon shafts |
| 60-80g | general user carbon shafts |
| 80-100g | professional carbon shafts |
| >100g | steel shafts<br>(predominantly used by skilful players in irons) |

The mass ranges presented by Lee and Kim (2004) indicate that there is a trend for weaker players to prefer lighter shafts, presumably to reduce the inertia of the club.

In terms of density, Huntley (2007) found that it was consistent for the 33 shafts he sectioned (1.5 g $cm^{-3}$). This is close to a value of 1.55 g $cm^{-3}$ identified in a material database as a typical density of carbon/epoxy composite material (Matweb, 2007).

### 2.3.5 Length

For an assembled golf club, rather than measuring the length of the shaft in isolation, it is common to use the overall club length as a measure. This is due to the fact that the effective club length (as perceived by the player) can be different for two clubs even if they have identical shaft lengths, depending on the construction of their club heads (depth of hosel bore). Therefore, Maltby (1995, p. 426) defines club length as the distance from the cap of the grip to the intersection of the shaft centre line with the ground with the club sole resting on the ground. This definition is similar to the definition of club length in the Rules of Golf as displayed in Figure 7 (The R&A, 2008, Appendix II, Rule 1 (c)). The Rules of Golf limit the club length for all clubs except putters to a maximum of 48” (1.219 m). The only club of a typical set with a length close to this limit is the driver. The length of the other clubs decreases gradually as the loft angle of the clubs increases, with the possible exception of the putter.

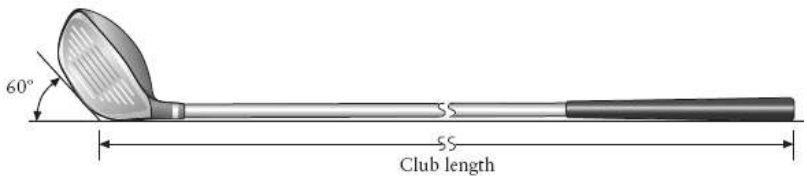



**Figure 7: Definition of club length (adapted from The R&A, 2008)**

### 2.3.6 Bend point position

To define the bend point of a golf shaft, the shaft is considered to be clamped at the butt end with a load applied to the tip end. The bend point is then defined as the position on the shaft where the radius of bending curvature is smallest (Howell, 1992). Golf shafts do not bend in a perfect arc because of changes in their cross section along their longitudinal axis, as illustrated by the equation for the second moment of the area of a hollow object with a cylindrical cross section (assuming isotropic material properties):

$$I(x) = \frac{\pi}{4}\left(R(x)^4 - r(x)^4\right) \qquad (1),$$

where:

| | | |
|---|---|---|
| where: | $x$ | is the position along the longitudinal axis of the shaft, |
| | $I(x)$ | is the second moment of area at position $x$, |
| | $R(x)$ | is the outer radius of the shaft at position $x$, |
| | $r(x)$ | is the inner radius of the shaft at position $x$. |

By multiplying equation (1) with the modulus of elasticity of the material ($E$), the rigidity ($EI$) of the object is obtained.

From butt to tip end, the shaft diameter typically decreases and the wall thickness increases (see Section 2.3.3), usually resulting in the rigidity gradually decreasing towards the tip because the effect of the decrease in diameter is not fully compensated by the increase in wall thickness. In golfing terms, a distinction is made between a high, mid and low bend point, depending on the bend point position relative to the tip end (Maltby, 1995). The position of the bend point can also be expressed as a percentage of the total club length relative to the tip end of a shaft. This position varies typically between 48 % and 56 % (Huntley, 2007).

### 2.3.7 Bending stiffness / Flexural rigidity

The bending stiffness or flexural rigidity[3] of a golf shaft characterises its resistance to flexural deformation. It depends both on the material properties of a shaft (modulus of elasticity, *E*) and on its geometry (second moment of area of its cross section, *I*). This was demonstrated experimentally by Huntley (2007), who showed that shaft wall thickness and outside diameter variations correlated with shaft stiffness variations along golf shafts. However, these variables could not explain the full range of stiffness variations, so the material's modulus must also vary along the shaft. Some researchers (Brouillette, 2002; Mase, 2004) performed repeated bending tests along the shaft to characterise their stiffness profile (see Figure 8). The stiffness of a shaft is regarded as an important parameter due to the way it affects dynamic loft (see Section 2.6.4 ).

Huntley (2007) noted wall thickness variations and inconsistencies in the number of layers around the circumference of the shaft. It was found that areas with a reduced number of layers resulted in lower static stiffness. This caused shaft stiffness variations of up to 3% when the shaft orientation was varied at a given position (Huntley, 2007).

In golfing, it is common to use simple abbreviations to characterise the flexibility of the whole shaft: l-flex (ladies), a-flex (senior), r-flex (regular), s-flex (stiff), x-flex (extra stiff). This provides a simple reference for golfers to compare shafts from one manufacturer, but can create some confusion and makes it difficult to compare shafts from different manufacturers as the stiffness ranges for the letter codes are not standardised (Summitt, 2000). Huntley *et al.* (2006) found that, at a cantilever length of 1.067 m, a 'ladies', 'regular' and 'x-stiff' flex ranking corresponded to a bending stiffness of 135-140 N/m, 154-162 N/m and 168 N/m, respectively.

---

[3]In many cases, the terms stiffness and rigidity are used interchangeably in golf literature. However, they differ in their definitions. In the case of bending tests, stiffness is defined as load divided by deflection (units: N/m). Therefore, a comparison of stiffness values is only possible if tests are performed under identical conditions (lever length, position of deflection measurement). In contrast, rigidity (units: $Nm^2$) includes the length of the lever and represents the combined characteristics of a structure's modulus (*E*) and geometry (*I*). Throughout this thesis both terms are used interchangeably in the general discussion and the literature review, but the appropriate term will be used when reporting test methods and results.

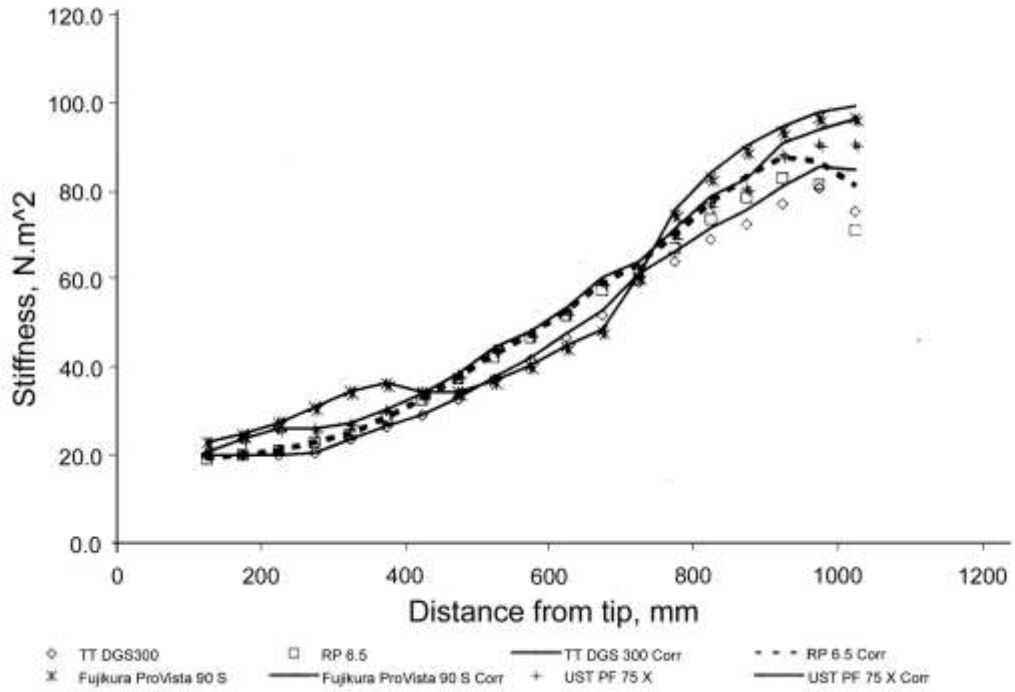



**Figure 8: Stiffness profiles for four different golf shafts before and after applying a correction for measurement errors. It can be seen that each shaft has characteristic stiffness variations between tip and butt end (adapted from Mase, 2004, p. 520).**

### 2.3.8 Fundamental Bending Frequency

The natural frequency of a structure describes its response to dynamic excitation. In the case of golf shafts, the fundamental frequency is commonly used to characterise the stiffness of a given shaft design (Cheong, Kang, & Jeong, 2006). The advantage of this approach over static bending tests is that it summarises the bending properties of the shaft as a whole, whereas typical static deflection tests, where the butt end is clamped, may overemphasise the bending stiffness of the shaft towards its butt end, because bending moments in this area will be greatest. However, shaft mass affects a shaft's fundamental frequency, so two shafts with identical stiffness characteristics could have different fundamental frequencies due to mass differences (Howell, 1992). If the oscillating shaft is regarded as a simple "spring mass" system, this is illustrated by the following equation (Horwood, 1994, p. 105):

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (2),$$

where: $\omega_n$ is the natural frequency of the shaft (Hz),

$k$ is the stiffness of the system (N/m),

$m$ is the mass of the system (kg).

The same conclusion can be drawn from the following alternative equation, which relates shaft frequency to rigidity (Howell, 1992, p. 1396):

$$\omega_n = \frac{30}{\pi}\sqrt{\frac{3\ EI\ g}{(m+0.23\ M)\ \ell^3}} \qquad (3),$$

where: $\omega_n$ is the natural frequency of the shaft (cpm),

$g$ is gravity ($m/s^2$),

$E$ is the average shaft elastic modulus ($N/m^2$),

$I$ is the average second moment of area ($m^4$),

$m$ is the mass attached to the tip end of the shaft (kg),

$M$ is the shaft mass (kg),

$\ell$ is the shaft free span (m).

In both equations, the shaft mass forms part of the equation, hence influencing the calculated frequency.

It has been noted that the fundamental frequencies of sheet-laminated shafts vary depending on shaft orientation (Horwood, 1994; Howell, 1992; Maltby, 1995). Micro-structural analysis (Huntley, Davis, & Strangwood, 2004) provided an explanation for these inconsistencies as it showed structural discontinuities due to the manufacturing process ("seams", see Section 2.3.1). However, stiffness variations observed in static tests did not affect the results of dynamic shaft tests (Huntley, Davis, Strangwood, & Otto, 2006). It remains to be clarified by future studies whether seams and the resulting variations in fundamental bending frequencies have any significant effect when a player swings a club.

### 2.3.9 Torsional stiffness

The torsional stiffness[4] of a golf shaft characterises its resistance to twisting when the shaft is clamped at the butt end and torque is applied at the tip (Horwood, 1994; Howell, 1992; Wishon, 1995). During the downswing, this form of load mainly occurs because of the offset between the COG of the club head and the centreline of the shaft (see Figure 2, p. 7). Inertial and centrifugal forces acting on the COG of the club head create a torque as they are counter-acted by the hands of the player. This causes the shaft to twist (Horwood, 1994), particularly when the player rotates the club around the longitudinal shaft axis. Twisting of the club head typically causes the face to close at impact compared to its neutral (unloaded) position (Newman, Clay, & Strickland, 1997).

In terms of shaft construction, torsional stiffness of graphite shafts mainly depends on the magnitude and diameter of fibres oriented at an angle close to ±45° relative to the longitudinal axis of the shaft. Theoretically, it is possible to design golf shafts with asymmetric torsional stiffness properties by varying fibre orientation, for example, to create higher torsional rigidity in the anti-clockwise direction compared to the clockwise direction. However, a shaft constructed like this would be non-conforming under the Rules of Golf (The R&A, 2008, Appendix II, Rule 2(b)). Conformance can be verified by repeating twist tests in two different directions. Huntley (2007) demonstrated that there was a linear relationship between load and twist angle with identical results for both load orientations.

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[4] In golf terminology, torsional stiffness is often quantified by a 'torque' value in degrees. This value specifies how much the shaft twists when the butt end is clamped and the tip end is subjected to a load of 1.34 Nm (1 lb-ft). Therefore, a low 'torque' value will be associated with a shaft with high torsional stiffness and vice versa.

## 2.4 Characterising shaft properties – shaft tests

In the previous section, all relevant shaft variables were defined. The objective of this section is to provide a brief overview of tests used to determine the magnitude of these variables. First, standardised mechanical tests are summarised; second, more complex robot tests are reviewed; finally, human tests are discussed.

### 2.4.1 Mechanical Tests

Only very basic measurement methods are needed for most mechanical shaft properties. The mass can be determined using a scale, density requires weighing and a volume measurement (Archimedes principle), and shaft length can be determined using a ruler or the Rules of Golf procedure (The R&A, 2007). The outer geometry of a golf shaft can be determined by using callipers. Inner diameters and wall thickness can be measured after sectioning shafts (Huntley, 2007). More complex, non-destructive techniques can be used to characterise carbon/epoxy composite shafts and could potentially be used to determine the inner diameter of golf shafts without sectioning them (Gao & Kim, 1998). These methods typically involve x-raying the specimen, but it is likely that it is not feasible to use these relatively expensive techniques to characterise the relatively simple geometry of golf shafts if it is possible to section the shaft instead.

A number of different methods to determine the static stiffness of golf shafts have been presented in the literature including simple bending tests (Howell, 1992; Maltby, 1995), repeated bending tests (Brouillette, 2002) and 3-point bending tests (Mase, 2004). The method that is most widely used appears to be the simple test presented by Howell (1992) as well as Maltby (1995), where the butt end is held by a fixture and a mass is attached to the tip end of the club (see Figure 9 (a)). This simple bending test set-up is commercially available as a 'deflection board' (Maltby Design, USA; see Figure 10 (a)). A second type of commercial device allows characterising shaft stiffness by fundamental frequency (Golfsmith, Inc. USA; see Figure 9 (b) and Figure 10 (b)). A mass, typically 205 g, is attached to the tip end and the shaft is clamped at its butt end. The shaft is excited and strain gauges, load cells or photo sensors measure the frequency of oscillation of the shaft. After processing the measured data, the device displays the fundamental frequency of the shaft in cycles per minute (cpm). Unfortunately, there appears to be no standard for the clamp position relative to the tip end, making it difficult to compare frequency values measured by different researchers.

Torsional stiffness is typically measured using a device consisting of a butt clamp, a lever with a mass attached to it and a fulcrum to prevent any shaft bending during the test (see Figure 9 (d) and Figure 10 (c)). The resulting twist of the shaft is measured using a dial.

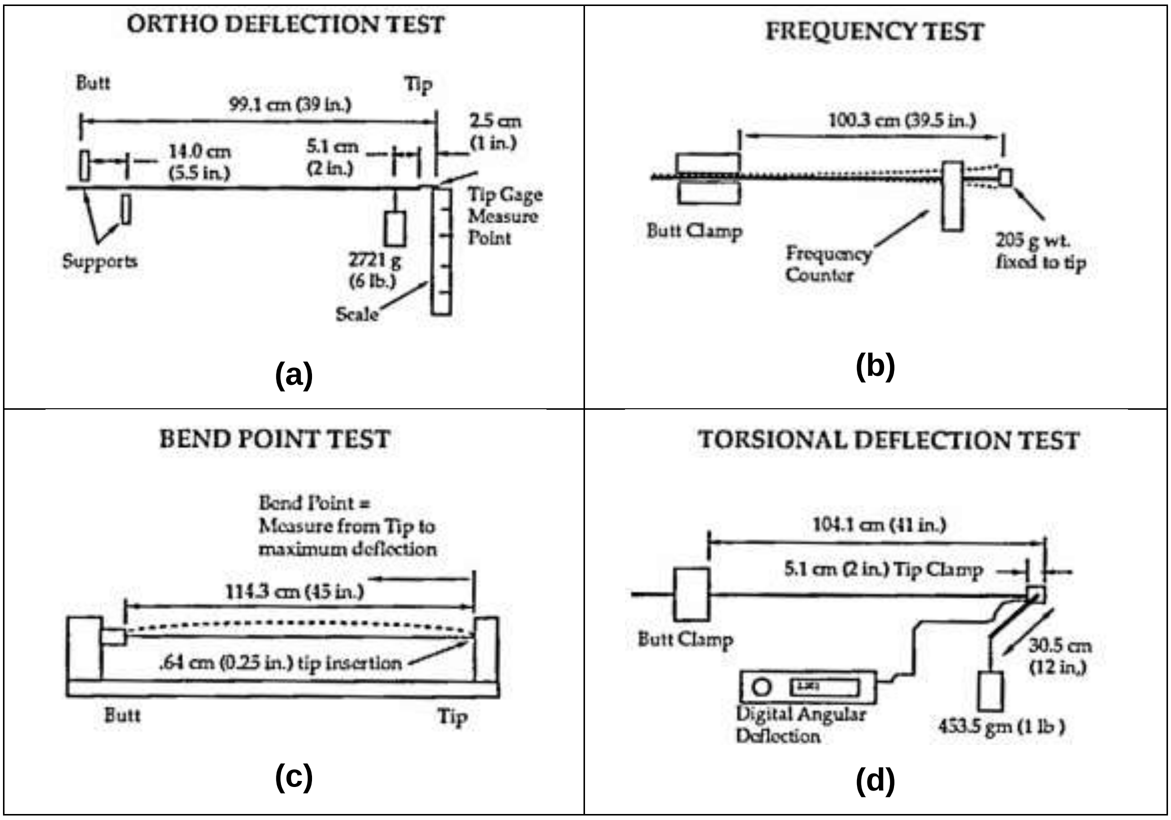
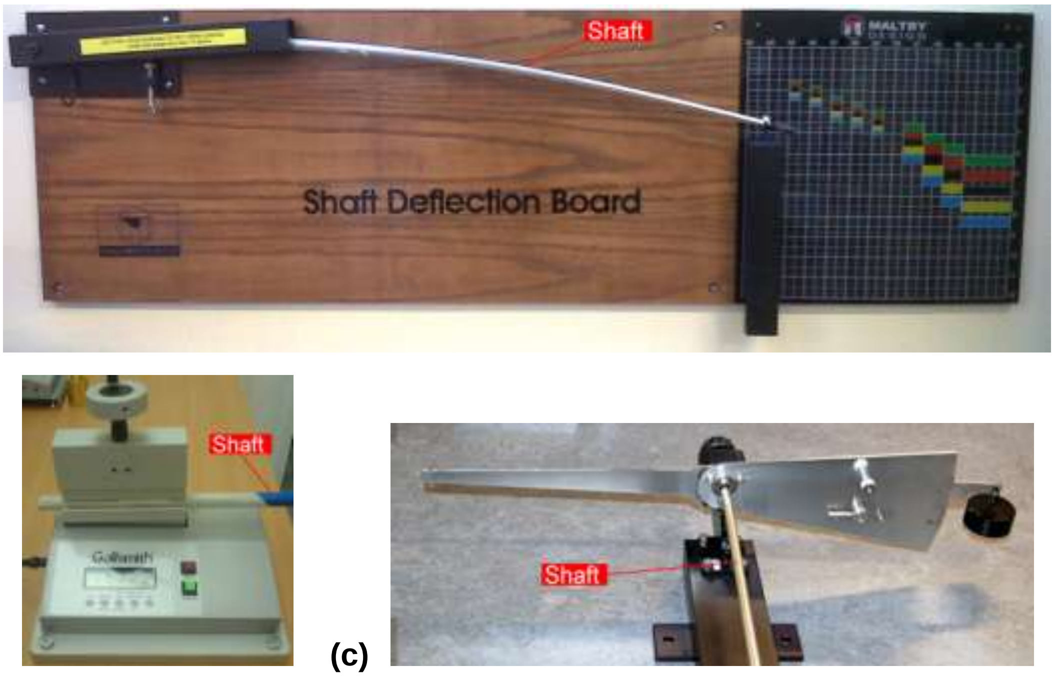



**Figure 9: Four static shaft tests (adapted from Howell, 1992, p. 1395).**




(a) (b) (c)

**Figure 10: Commercial shaft test equipment. (a) Deflection board (Maltby Design, USA), (b) Frequency analyser (Golfsmith, USA), (c) Torsion test (Golfmechanix, Taiwan ROC).**

A number of different tests have been presented in the literature to measure bend point positions. The first approach involves a simple bending test and determination of the point on the shaft with the smallest radius of curvature. This can be achieved by measuring the distance between the shaft and points on a straight line connecting the clamped end of the shaft with the butt end (Chou & Roberts, 1994; Huntley, 2007). The second approach is to test the shaft in compression, causing the shaft to buckle (see Figure 9 (c)), where the bend point is once again defined as the point with maximum distance to a line connecting the butt end and the tip end of the shaft (Cheong, Kang, & Jeong, 2006; Howell, 1992). It appears from the literature that both definitions are in use, and it is reasonable to assume that they produce similar, albeit not necessarily identical, results. Horwood (1995) mentions that, in a set-up similar to the compression test, it is also possible to apply a torque to the tip end of the shaft acting perpendicular to the shaft axis. Another alternative is to perform two bending tests, one with the tip end loaded and the butt end clamped and another one with the shaft oriented the other way around. Deflection of the free end of the shaft is measured under both conditions, and the ratio between these two values is used to characterise the stiffness distribution along the shaft (Horwood, 1995). Finally, it is also possible to determine the bend point dynamically during the swing by using high-speed imaging (Mather, 2000). However, the dynamic approach does not appear to be commonly used in the industry or by clubmakers.

### 2.4.2 Robot Tests

Whilst the previous section presented common methods to measure mechanical shaft characteristics in an isolated way, the overall performance of a particular combination of club head and shaft is often tested using standardised robot tests. Tests can be repeated for a variety of impact positions ("face mapping", Olsavsky, 1994). Combined with a launch monitor, robot testing allows the investigator to determine the launch conditions (launch angle, backspin) and the landing position (distance, dispersion), for example, in order to compare two shaft designs.

The construction of one of the first golf robots was triggered by the need for objective shaft tests (True Temper, 2004). This lead to the construction of a robot called the “Golf Club Testing Device”, but later the term “Iron Byron” emerged (Figure 11(a)). Other manufacturers of golf robots are Miyamae (Japan) and Golflabs (USA) (Figure 11(b) and Figure 11(c), respectively). As illustrated by Figure 11, the majority of current robot models are based on variations of the double pendulum model of the swing[5], which consists of two links (Cochran & Stobbs, 1968). The ‘arm’ link connects a stationary ‘shoulder’ hub with the ‘wrists’. Attached to the artificial wrist is the club, thereby representing the second part of the double pendulum. The golf robots are controlled by compressed air (Iron Byron) or a servo-motor that drives the ‘shoulder joint’. The wrist is passive (e.g. Golflabs) or driven by additional motors (e.g. Miyamae 5). It is generally accepted that the swing motion of robots is much less complex than a human swing. However, it is common to

[5] Alternative designs with two arms have been proposed in order to make the robot motion more similar to the human swing (Wiens & Hunt, 2003), but these robots do not appear to be commercially available.

validate the robot-generated launch conditions against launch conditions recorded from human swings in order to ensure the validity of a robot test. The assumption is that, due to the short impact duration, the robot results are transferable to humans as long as the robot presents the club head to the ball in the same way a human player does (identical club head velocity and path). When it comes to observations of shaft deflection for the full swing, this assumption is no longer possible as the shaft deformation will be affected by factors like the clamping of the grip in the robot and the torque curve the robot uses to drive the club. Little published data are available comparing human and robotic shaft loading patterns, with the exception of one paper (Harper, Jones, & Roberts, 2005) and sections from a PhD thesis (Harper, 2006). Harper, Jones and Roberts successfully adjusted the robot kinematics to match certain aspects of the swing of selected human players, yet there were still distinct differences between the robotic and human shaft loading curves, and not all of the characteristic deflection parameters matched, including lead deflection at impact (Harper, 2006, pp. 139-140).

(a) (b) (c)

**Figure 11: Commercial golf robots: (a) Iron Byron (True Temper, 2004), (b) Miyamae 5 (Miyamae, 2007), (c) Golflabs robot (Golflabs, 2007).**

Several researchers presented methods to determine torque patterns to control robots. The difficulty is that most robots are under-actuated because one motor (‘shoulder’) controls two joints (the ‘shoulder’ and, indirectly, the ‘wrist’). This makes it a complex task to design a torque pattern to achieve the desired joint trajectories and impact conditions. One approach that has been presented in a series of papers by Ming and colleagues will be summarised in the following. It involves the use of a relatively simple mechanical model (ignoring shaft flexibility and friction) to determine a basic torque pattern. This is combined with an artificial neural network (ANN), which automatically adjusts the torque pattern over a number of learning cycles until the robot swings the club following the target trajectory. This approach has been successfully used to control a prototype robot by using a simple ANN (Ming & Kajitani, 2003; Ming, Teshima, Takayama, Kajitani, & Shimojo, 2002) and a recurrent ANN (Ming, Furukawa, Teshima, Shimojo, & Kajitani, 2006).

An alternative approach using a more complex dynamic model (including shaft flexibility) based upon Hamilton's principle has been presented by Suzuki *et al*. in a series of papers. Their initial model (Suzuki & Inooka, 1998) included a 'brake' at the wrist joint, in order to simulate the effect of varying the time in the swing when the club was allowed to rotate around the wrist joint ('wrist release'). Later, the wrist brake was replaced by a passive stopper. This was because using a two-step torque pattern rather than a trapezoidal torque curve allowed control of the release point indirectly via the shoulder torque (Suzuki, Haake, & Heller, 2005; Suzuki, Haake, & Heller, 2006; Suzuki & Ozaki, 2002). Whilst the robot model presented in these papers provided analytical explanations of the effects of changes in some swing variables, unfortunately none of these papers includes an experimental verification using an actual golf robot and direct shaft deflection measurements. Furthermore, it is not clear how the authors determined values for the parameters of their model for performing their simulations; it appears that the parameters are found by repeating their simulation iteratively until the desired model configuration is reached. This, however, does not help to make tests with an actual robot more efficient as it still involves a 'trial and error' process.

An alternative approach for robot control is to collect kinematic data from real swings and to use this data as input for the robot (Harper, Jones, & Roberts, 2005). This approach has been applied using a Miyamae 5 robot, which was equipped with advanced control software and independent actuators for all three robot joints. Harper *et al.* (2005) presented two pairs of shaft loading profiles to demonstrate the ability of this robot to replicate different shaft loading profiles as defined by joint angle histories of a human and a traditional golf robot. However, their results only allow a qualitative comparison as they did not perform any statistical analysis, for example by comparing shaft strain at key points of the swing.

In summary, it appears that robot tests are a common tool to validate new club head designs, and the validity of results for club head tests can easily be confirmed by comparing the launch conditions produced by the robot to launch conditions achieved by human players. However, little work has been published to verify that the shaft loading profiles of humans and robots are comparable, with the work by Harper *et al.* (2005) summarised above being the only exception. Therefore, it appears to be necessary to compare robotic and human shaft loading patterns before it is possible to use a robot as a valid tool to simulate human shaft loading.

### 2.4.3 Human Tests

In terms of human tests and mechanical shaft properties, limited research has focused on the measurement of shaft deflection during human swings (see Section 2.2, p. 5). Relatively few studies used methods that would allow a judgement as to how mechanical shaft properties affect golf performance. General shaft fitting recommendations, given by, for example, Maltby (1995), appear to be based on experience and anecdotal evidence.

One general difficulty with testing golf shafts with human players is that pooling subjects' results in groups before performing statistical analysis may mask shaft effects experienced by individual golfers in a study. This was noted in previous studies (Stanbridge, Jones, & Mitchell, 2004), and, consequently, shaft effects have recently been studied on an individual rather than pooled basis (Worobets & Stefanyshyn, 2007, 2008). Another alternative is to examine correlations of variables instead of averaged data (for example club head speed at impact and club length, see Wallace, Otto, & Nevill, 2007). When plotting mechanical characteristics of different clubs and outcome variables against each other for multiple players, subject specific responses would become visible as clusters if the number of subjects was sufficiently high.

Only selected aspects of the golf swing have been studied comprehensively by including a high number of subjects. This prevented the use of statistical techniques such as cluster analysis (Ball & Best, 2007a) to define groups before moving on to the actual skill analysis within these groups (Ball & Best, 2007b). No such study could be found dealing with any aspect of shaft deflection, indicating that there is a need for more comprehensive studies on the effect of shaft properties on human golf swings. One pre-requisite for this type of analysis is that simple and relevant measures for the investigated effects have been identified successfully.

### 2.4.4 Boundary conditions in shaft tests

It is important to consider the effect different boundary conditions, such as the type of clamping, the amount of load applied and the loading rate, will have on the outcome of these tests. Theoretically, it could be expected that the ideal shaft test resembles all conditions of a real golf swing (dynamic loading, rotation of the club, club is held by a human). However, undertaking a test like this would be complicated due to dynamic loading, and it would be difficult to achieve repeatability when the club was held by a human as the hand pressure might vary between tests. Therefore, a number of quasi-standardised tests are in use instead. As these tests are static, they are relatively simple to conduct. Repeatability is assured by clamping the shaft rather than allowing any flexibility or movement, and the shaft is subject to known loads (see Section 2.4.1). Whilst this permits reliable and objective results, it is still necessary to ensure that the results are valid and actually relevant when a golfer performs a swing. If this was not the case, two shafts could appear to be different based on a static test but could perform exactly the same under dynamic conditions or vice versa.

#### *2.4.4.1 Static vs. dynamic loading*

Whilst static tests have the advantage of being easier to set up and to control, there are two problems associated with these tests in terms of validity. First, the shaft is under tension as well as flexural loading during a real golf swing, whereas static club tests use flexural loading only, for example by attaching a mass to the tip of the clubs. Additionally, the majority of golf shafts are made of carbon/epoxy composite material, which is known to have strain rate dependent material properties (see Section 2.3.2). This could potentially cause deviations between static test results and the actual behaviour of the shaft during the swing. Research comparing shaft tests under static and dynamic loading is limited, and in most cases is focused on the effect of tensile loading due to centrifugal forces rather than strain rate dependency. Loads along the shaft axis due to centrifugal loading have been found to be up to 400 to 500 N for skilled players (Mather & Immohr, 1996; Werner & Greig, 2000). Without presenting all the data that led to this conclusion, Milne and Davis (1992, p. 975) stated that conventional static tests are “peculiarly inappropriate to the swing dynamics” and suggested alternative tests. They found that bending stiffness appeared to double due to tensile loading of the shaft (Milne & Davis, 1992). This is similar to a finding by Butler and Winfield (1994), who used a finite element (FE) model to predict that centrifugal load could change the fundamental bending frequency of a shaft from 4.3 Hz (static) to 10 Hz (under tension). In a comparison of the results of static and dynamic tests using a whirling machine, it was not possible to deduct the dynamic performance from static results, and fundamental frequencies of the shafts increased by 40-50% under dynamic load (Mather & Jowett, 1998). It was also found that dynamic measurements of bend profiles using high-speed imaging did not correlate well with the results from static tests (Mather, Smith, Jowett, Gibson, & Moynihan, 2000). This is in line with findings from Chou and Roberts (1994), who determined the bend point positions of different shafts statically before performing player tests. There was no correlation between results from static bend point and dynamic player tests. However, player inconsistency may have obscured the results.

In summary, it appears that there is little evidence supporting an assumption that the commonly used practice of testing shaft properties statically produces valid results.

#### *2.4.4.2 Influence of shaft fixation*

In addition to the nature of the loading (see previous section), a secondary component of shaft test set-ups is the method of shaft fixation. Common shaft fixations reach from a ‘free’ condition in modal analysis (the shaft is suspended using a chord, Braunwart, 1998) to clamped conditions (the shaft is fixed in a vice, Brouillette, 2002). Few studies compared results obtained for identical shafts using different methods of fixation. Braunwart (1998) and Wicks *et al.* (1999) compared shaft frequencies measured and modelled under ‘free’, ‘hand-held’ and ‘clamped’ conditions and found that the lowest measurable frequencies were similar under a ‘free’ and a ‘hand-held’ boundary condition. In contrast to this, there was an almost tenfold difference between the lowest modes they could measure under ‘clamped’ and ‘hand-held’ conditions (see Table 3). Wicks *et al.* (1999) concluded that “the contribution of the hands may add some moment constraint but in general (…) the hands add little constraint” (Wicks, Knight, Braunwart, & Neighbors, 1999, p. 507). This indicates that obtaining shaft properties from tests where the shaft is clamped rigidly, and then using these shaft properties when simulating human swings, might be problematic.

**Table 3: Comparison of shaft frequency of a graphite shaft measured under different boundary conditions (adapted from Wicks, Knight, Braunwart, & Neighbors, 1999).**

| Mode | Hands (Hz) | Free (Hz) | Clamped (Hz) | % discrepancy (Free-Hands) | % discrepancy (Clamped-hands) |
|---|---|---|---|---|---|
| low | 54.01 | 50.99 | 5.84 | -5.92 | -824.83 |
| ↓ | 158.02 | 156.04 | 94.66 | -1.27 | -66.93 |
| high | 302.65 | 313.22 | 262.00 | 3.37 | -15.52 |

Based on the findings presented in the previous paragraph, it appears that the best representation for the link between the golfer and the club is a flexible connection with properties somewhere between a ‘free’ and ‘clamped’ condition, most likely with the magnitude of hand pressure being a factor. In theory, this flexible link could be modelled using a specific vice that would only apply limited pressure to the shaft or included dampening material. However, the difficulty in designing such a device is that research using pressure sensors to measure grip pressure during actual golf swings showed that hand pressure varies throughout the swing (E. Schmidt, Roberts, & Rothberg, 2006). Peak values typically occurred just before and after impact and pressure patterns varied significantly among subjects. Intra-subject variability was very high, indicating that each player had an individual “grip force signature” (E. Schmidt, Roberts, & Rothberg, 2006, p. 57). Furthermore, there could potentially be an active muscle response to shaft oscillations during the downswing (biodynamic response). Responses like this have been found to affect the legs during running (Boyer & Nigg, 2004) and, theoretically, may also be present in the arms when swinging a golf club. However, a recent review of studies applying electromyograms (EMG) in golf (McHardy & Pollard, 2005) found that muscle activity in the hand and wrist area has not yet been studied in detail for golf swings.

### *2.5 Modelling the golf swing*[6]

An alternative to testing shafts in the laboratory with human players or with robots is to use modelling and simulation techniques, for example in order to determine shaft effects on performance. To do so, the system under observation has to be reduced to its essential elements in order to simplify it and to solve a research problem associated with it. Obviously, the amount of simplifications and assumptions will depend on the aims and objectives of each individual project; but in all cases care needs to be taken to create appropriate models which adequately describe the underlying physics. Over-simplifications as well as too high a degree of detail can make it impossible to use a model to solve a research problem. The process of defining a representative alternative system is commonly referred to as modelling, whereas the application of a model (for example to run virtual experiments) is associated with the term simulation (Nigg & Herzog, 2007). Numerous researchers have presented models and simulations of the golf swing. In these studies, various degrees of sophistication were used to represent the system (see Table 4 and Table 5 on pp 37 and 39).

The following section summarises models that have been used successfully to improve the understanding of different aspects of the golf swing, with particular

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[6] This section consists of extracts from a review performed and published as part of this PhD project (Betzler, Monk, Wallace, Otto, & Shan, 2008).

focus on models and simulations applied in shaft research. The majority of these swing models follow one of the modelling routes shown in Figure 12 by either using an inverse or forward dynamic approach.

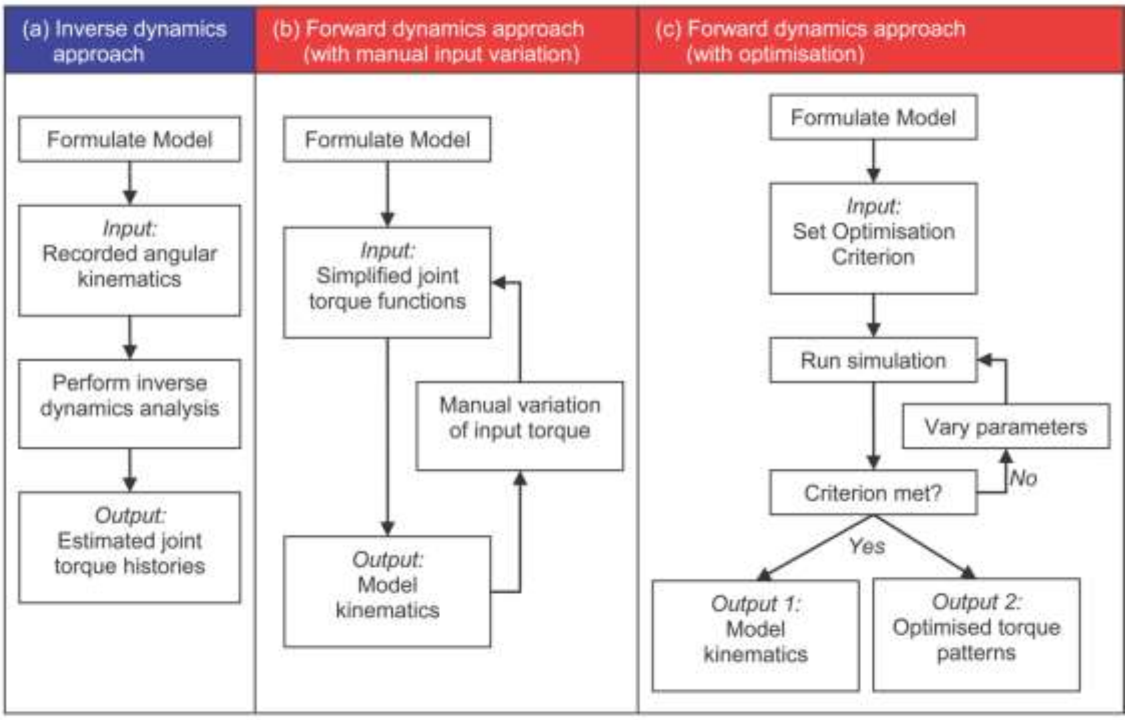



**Figure 12: Approaches commonly used in golf swing modelling and simulation (adapted from Betzler, Monk, Wallace, Otto, & Shan, 2008).**

### 2.5.1 Two-dimensional models of the swing

In order to gain insight into the basic mechanics involved in the golf swing, Cochran and Stobbs (1968) proposed a simple model of the downswing consisting of a double pendulum (see Figure 13).

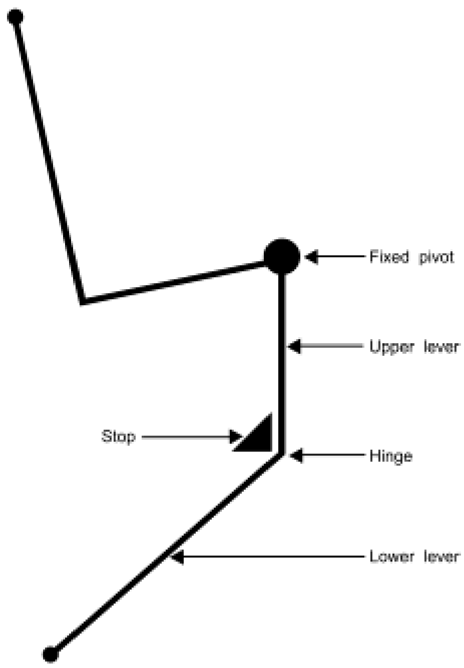



**Figure 13: Double-pendulum model of the golf swing (adapted from Cochran & Stobbs, 1968).**

Cochran and Stobbs assumed that the two most relevant pivot points of the moving body segments were the wrist and a point “roughly corresponding to the middle of the golfer’s upper chest” (Cochran & Stobbs, 1968, p. 10). This imaginary point was taken to be fixed in space and connected to an upper lever that is representative of the arms of the golfer. Another segment, representing the club, was connected to the upper lever via a hinge joint. This ‘wrist’ hinge was assumed to behave passively, restricted only by a stop that prevented the club segment from moving too far back at the initiation of the downswing. Cochran and Stobbs used this model to explain the basic mechanics of the swing and showed that the combined effect of inertia and centrifugal force acting on the lower lever can create a well coordinated downswing if the upper lever is accelerated using the correct force. In this case, no wrist torque is required to coordinate the rotation about the lower hinge (‘wrists’) other than the passive torque provided by the stopper in the wrist joint. Based on this observation, the concept of natural wrist release emerged. This concept describes a swing pattern in which no active muscular wrist torque is applied to accelerate the club during the downswing. Instead, the motion of the arm is coordinated in a way that allows the club to accelerate ‘naturally’, driven by the arm and the centrifugal force acting on its COG.

Cochran and Stobbs (1968) presented their model as a simplified mechanical representation of the golf swing to explain its underlying principles, whereas others successfully used their approach for inverse dynamics analyses (Budney & Bellow, 1982) and forward dynamics swing simulations. Of these forward dynamics simulations, some applied simplified torque profiles at the fixed pivot and the ‘wrist’ hinge (Chen, Inoue, & Shibara, 2007; Jørgensen, 1970; Milne & Davis, 1992; Miura, 2001), thereby keeping the number of input parameters manageable for manual manipulation, whilst others used optimisation algorithms to define more complex input torque profiles for multiple torque generators (Pickering, 1998; Pickering & Vickers, 1999). Table 4 provides an overview of studies that applied the double pendulum model or variations of it.

The two-segment, double pendulum model of the golf swing cannot account for rotations of the arms about the shoulder joint and rotations of the torso as there is only a single body segment representing the arms. Therefore, some researchers have introduced another hinge in the model representing a simplified shoulder joint. These three-segment models have been utilised for inverse dynamics analyses of joint torques (Tsujiuchi, Koizumi, & Tomii, 2002) as well as forward dynamics swing simulations (Turner & Hills, 1998). Furthermore, three-segment swing models have formed the basis for a number of studies using optimisation schemes to determine joint torque patterns (Aicardi, 2007; Campbell & Reid, 1985; Kaneko & Sato, 2000; Sprigings & MacKenzie, 2002; Sprigings & Neal, 2000).

**Table 4: Summary of two-dimensional golf models (adapted from Betzler, Monk, Wallace, Otto, & Shan, 2008)**

| Reference | Focus | Players | Segments | Hub | Shaft | Plane | Gravity |
|---|---|---|---|---|---|---|---|
| Cochran & Stobbs (1968) | Illustrative model | NA | 2 | yes | rigid | fixed | NA |
| Jørgensen (1970) | Wrist release, backswing length | NA | 2 | yes | rigid | fixed | no |
| Jørgensen (1999) | Parametric study | 1 | 2 | no | rigid | fixed | yes |
| Budney & Bellow (1982) | Club matching | 4 | 2 | yes | rigid | fixed | no |
| Milne & Davis (1992) | Role of shaft | 3 | 2 | yes | flexible | fixed | yes |
| Reyes & Mittendorf (1998) | Club length/mass, backswing range | 1 | 2 | yes | rigid | fixed | no |
| Pickering (1998) | Ball position (iron) | NA | 2 | yes | rigid | fixed | no |
| Pickering & Vickers (1999) | Ball position (driver), energy flow | NA | 2 | yes | rigid | fixed | no |
| Miura (2001) | Effect of inward pull | NA | 2 | no | rigid | fixed | yes |
| White (2006) | Swing efficiency | NA | 2 | yes | rigid | fixed | no |
| Suzuki, Haake & Heller (2006) | Robot simulation | NA | 2 | yes | flexible | fixed | yes |
| Chen, Inoue & Shibara (2007) | Wrist release, ball position | NA | 2 | yes | rigid | fixed | yes |
| Campbell & Reid (1985) | Optimum control | NA | 3 | yes | rigid | fixed | no |
| Turner & Hills (1998) | Parametric study | NA | 3 | yes | rigid | fixed | yes |
| Kaneko & Sato (2000) | Optimum control | 1 | 3 | yes | rigid | fixed | yes |
| Sprigings & Neal (2000)<br>Sprigings & MacKenzie (2002) | Wrist release, sequencing | NA | 3 | yes | rigid | fixed | yes |
| Tsujiuchi, Koizumi & Tomii (2002) | Club fitting, shaft stiffness | 3 | 3 | yes | flexible | fixed | no |
| Aicardi (2007) | Parametric study | NA | 3 | yes | rigid | vertical | yes |
| Iwatsubo *et al.* (2004) | Comparison 2- and 4-link model | 4 | 2/4 | yes | flexible | fixed | yes |

### 2.5.2 Three-dimensional models of the swing

A drawback of the double pendulum model is that the downswing is assumed to occur in a single, static plane. It is not clear whether this simplification influences the results of the studies presented in the previous section because it has been found that, in reality, the paths of the left arm (Coleman & Rankin, 2005) as well as the club (Coleman & Anderson, 2007) do not stay in one static plane throughout the downswing for the majority of golfers. For this reason, potentially more realistic, yet also more complex models have been developed that considered the movement of up to 15 body segments in three-dimensional space (see Table 5).

#### *2.5.2.1 Models including club and upper body only*

Two of the inverse dynamics analyses only considered the forces and moments acting on the club during the swing (Neal & Wilson, 1985; Vaughan, 1981), whereas the authors of another study of this type chose a more complex approach by including also two arm segments (Tsunoda, Bours, & Hasegawa, 2004). For the model presented by Tsunoda *et al.*, full golf swings, including backswing, were recorded using a motion capture system. All relevant joint angles of the left arm were then calculated, and the recorded joint angle histories were imposed upon the model. The disadvantage of the increased complexity was that parameters could not be modified as easily and that the mathematical model behind the simulation could only be solved by specific multi-body dynamics software (MADYMO, Mathematical Dynamic Models, TASS, The Netherlands). The model was validated by comparing shaft strain measurements to model outputs. This validation showed that the model outputs correlated with the measurements from the real swing, but that the model over-predicted shaft strain in the critical phase just before impact and some of the model outputs included distinct oscillations not occurring in reality. One possible explanation for these differences could be that the rigid connection of grip and arm segment in the model neglected any dampening that, in reality, may be provided by the hands of the player (as discussed in Section 2.4.4)

**Table 5: Summary of three-dimensional models of the golf swing (adapted from Betzler, Monk, Wallace, Otto, & Shan, 2008)**

| Reference | Focus | Players | Type | Fixed hub | Shaft | Plane | Gravity[b] |
|---|---|---|---|---|---|---|---|
| Vaughan (1981) | Inverse dynamics | 4 | club only | no | rigid | free | yes |
| Neal & Wilson (1985) | Inverse dynamics | 6 | club only | no | rigid | free | - |
| Jones (2002) | Parametric study | NA | partial | yes | rigid | restricted | no |
| Tsunoda, Bours & Hasegawa (2004) | Inverse dynamics | 1 | partial | no | flexible | free | - |
| Suzuki, Haake & Heller (2005) | Robot simulation | NA | partial | yes | flexible | one plane | - |
| MacKenzie (2005) | Shaft stiffness effects | 4 | partial | yes | flexible | 2 planes[a] | yes |
| Nesbit *et al.* (1994) | Modelling framework | NA | full-body | no | flexible | free | yes |
| McGuan (1996) | Shaft stiffness effects | 1 | full-body | no | flexible | free | yes |
| Nesbit (2005)<br>Nesbit & Serrano (2005)<br>Nesbit (2007) | Full kinetic analysis | 84 | full-body | no | flexible | free | yes |
| Kenny *et al.* (2006) | Club length effects | 1 | full-body | no | flexible | free | yes |
| Betzler, Shan & Witte (2007) | Club shaft and length effects | 1 | full-body | no | flexible | free | yes |

[a]Torso and arm/club segments moved in different planes.

[b]Where dashes are present, article does not mention whether gravity is included or not.

Rather than following the inverse dynamics approach, a number of other authors decided to use simplified torque functions to drive their three-dimensional swing models, using either manually identified torque functions (Jones, 2002; Suzuki, Haake, & Heller, 2005) or optimisation schemes to determine the input torque patterns (MacKenzie, 2005). As discussed in more detail in Section 2.4.2, Suzuki, Haake and Heller (2005) found that, keeping the maximum shoulder torque constant, the kinetic energy of the club head at impact could be maximised if the wrist release coincided with the point in time at which the deflection of the oscillating shaft became zero for the second time. Once the optimum release point had been identified, they hypothesised that additional energy could be transmitted to the club if the players applied a ramp-like torque profile. They proved that these torque profiles could in fact increase club head velocity and suggested that highly skilled players may facilitate their full-body motion to generate these profiles. However, multiple shaft oscillations as seen in their simulations are not typical for human downswings (see Section 2.2). Once again, the reason for these oscillations could be a lack of dampening provided by the model, both in terms of the material characteristics of the simulated shaft and the missing elasticity of the simulated hand-grip connection.

#### *2.5.2.2 Full-body models*

A final group of golf swing models consists of full-body swing simulations. Including a high number of body segments makes these models very complex and necessitates the use of multi-body dynamics simulation tools to obtain and integrate the underlying mathematical models. The earliest example of a full-body swing model appears to be a model presented by McGuan (1996), who utilised the software package ADAMS (Automatic Dynamic Analysis of Mechanical Systems, MSC Software Corporation, USA). The body segment trajectories of their simulation were based upon data obtained from a human golf swing. McGuan (1996) pointed out that there are two intrinsic problems when driving complex rigid-body models with motion capture data obtained from real movements: in most cases the equations of motion of the model will be mathematically over-determined when the trajectories of multiple markers are constraining the system, and the motion capture markers will change their position relative to the corresponding body segments due to skin movement or instrumental errors. McGuan (1996) overcame these problems by introducing weightless spring elements connecting each motion capture marker with the corresponding virtual marker on the rigid body model of the golfer, thereby in effect fitting the rigid body movement to the recorded marker trajectories. McGuan then performed the simulation process in two steps. During the first step, the body segments were moved by the marker trajectories as described above and angular kinematics were recorded at each joint. During the second step, the marker trajectories from motion capture were ignored and the model was set into motion by joint torques. McGuan (1996) demonstrated that this model could be used to show the effects of shaft stiffness variations on club head velocity and dynamic loft angle at impact. It is interesting to note that the simulated swings were relatively ineffective in terms of club head speed and loft angle when the shaft stiffness was changed unless the torque curves of the model were adapted. Unfortunately, McGuan did not provide any information on further results obtained from this model and how the model was validated.

Nesbit *et al*. (1994) simulated the downswing of a golfer by means of a body model (15 segments) and an FE model of the club. Again, the model was created using the software package ADAMS. However, only five out of the 15 body segments were actually driven by motion capture data from a real golfer, and Nesbit *et al.* gave no detailed information regarding the validation of their model.

More recently, Nesbit presented the results of another simulation study using a more complex model (Nesbit, 2005), consequently applied this model for a work and power analysis of the swing (Nesbit & Serrano, 2005) and published a detailed description of the model (Nesbit, 2007). Nesbit's objective was to characterise the complete three-dimensional kinetics and kinematics of golf swings performed by several subjects. After doing so, the aim was to highlight similarities and differences among golfers. He analysed one swing of each of 84 subjects. All players used the same driver for their swings. The angular displacement histories of each joint were used to define the movement of a full-body model of the golfer, which included sub-models of a rigid android, a flexible club, an impact model and a ground surface model. It was assumed that the load between both hands was distributed equally, all joints were either ideal ball and socket or hinge joints, and the model did not include any representation of muscles or tendons, so no strain energy could be stored (for example at the top of the backswing). Validation was performed by comparing manually calculated joint torques, results from other studies and ground reaction force data, and showed reasonable agreement. However, it was not possible to use the derived joint torque profiles to drive all the degrees of freedom of the model's joints in a forward dynamics way because this resulted in unpredictable results and simulation failure (Nesbit, 2007). Nesbit's earlier results (2005) support the concept that each golfer has a unique kinematic and kinetic swing 'signature'. The overall coordination was found to be an important factor for maximising club head velocities: subjects did not use hindrance torques to block their wrists as proposed by earlier simulation studies but rather coordinated the full-body motion in a way to delay wrist release and, hence, to achieve peak club velocity at impact. These findings highlight the importance of including the full-body motion of the player in golf simulation studies. If the full-body motion is not included and only two-dimensional data are considered then body segment coordination may be missed.

Another study looking at the full-body kinetics of a golfer was presented by Kenny *et al.* (2006). Their objective was to validate a full-body computer simulation of a golfer swinging three clubs with different lengths (46", 48", 50", or 1.17 m, 1.22 m and 1.27 m). One subject performed eight swings under each club condition, which were recorded using a five camera motion capture system. A full-body model was scaled to the anthropometrics of the subject based on 54 measurements taken from the players body, and both inverse and forward dynamics simulations were performed using the LifeMOD plug-in (The LifeModeler Inc., USA) of the ADAMS software. As the authors' primary objective was to validate the model, they compared the marker trajectories and club head velocities of the model and the real player data and found good agreement (Pearson coefficient > .99), although it should be noted that Pearson correlations have been found to be unsuitable for validation studies (Atkinson & Nevill, 1998). The only available data set to validate the kinetic output of the model by Kenny *et al.* were grip force measurements from previous studies, which also showed reasonable agreement. Using the validated model, Kenny *et al.* were able to demonstrate that selected muscles were required to produce significantly higher force magnitudes when swinging longer clubs to maintain the same club head speed.

Using a similar approach, yet without performing a detailed analysis of muscle forces, swings performed by one golfer with four different club models have also been simulated (Betzler, Shan, & Witte, 2007). Once again, the software ADAMS and its LifeMOD plug-in were used, but in this case the shaft model was more detailed and the club head properties were based on a CAD model derived from stereoscopic images. In agreement with the findings of Tsunoda *et al.* (2004), shaft deflection patterns were overlaid by unrealistic oscillations that were probably caused by the rigid modelling of the grip-hand interface or an incorrect dampening factor. Nevertheless, after filtering the estimated shoulder joint torque curve, the resulting pattern was similar to the ramp-like pattern that was suggested by Suzuki *et al.* (2005).

It is interesting to note that so far only two studies of the full-body kinetics of the golf swing (Betzler, Shan, & Witte, 2007; Kenny, Wallace, Brown, & Otto, 2006) included a comparison of the effects of different golf clubs on the kinetics of the swing. There is potential in this area for researchers to increase the understanding of the effects of equipment changes on golfers.

## *2.6 Shaft properties and swing performance*

After defining shaft variables and ways to test them, the objective of the following section is to relate these variables to club performance.

### 2.6.1 Shaft mass and club head velocity at impact

A number of authors state, in most cases without presenting the underlying rationale, that decreasing shaft mass enables players to reach an increased impact velocity (Penner, 2003). More specifically, it has been suggested that a reduction of shaft mass from 120 g to 50 g (Maltby, 1995) or from 120 g to 60 g (Butler & Winfield, 1995) would result in an increase in club head speed at impact by 3 mph. None of these authors provide details as to how they came to this conclusion and whether they were valid regardless of skill level. Yet, these reports are in line with findings from swing models showing that decreasing shaft mass relative to the arm mass can enhance impact velocity (Chen, Inoue, & Shibata, 2005). Another simulation study predicted that a ten yard increase in distance could be achieved when changing from a 120 g to a 40 g shaft, assuming an optimum launch angle can be achieved for both shafts and an optimised club head is used in both cases (Werner & Greig, 2000).

Based on these results, it could be assumed that the optimum golf shaft is weightless or, more realistically, as light as structurally possible. However, other authors claim that shaft mass helps maintain a consistent swing (Butler & Winfield, 1995; Jackson, 1995). Unfortunately, the authors of these studies do not provide any experimental results to support this statement, but it appears sensible that the golfer requires a certain amount of proprioceptive feedback during the swing produced from overcoming the inertia of the club to perform a successful swing.

In summary, reducing shaft mass appears to provide a means of achieving small increases in impact velocity, but potentially at the cost of reduced consistency. This could be the reason why strong players who are less concerned about maximising their club head speed further tend to prefer heavier shafts (M. Lee & Kim, 2004).

### 2.6.2 Shaft length and club head velocity at impact

Based on the mathematical relationship between angular velocity and linear (tangential) velocity, the linear velocity of a club head attached to a longer shaft will be faster than the linear club head velocity of a shorter club head at a given angular velocity. However, it is also likely that accuracy decreases when shaft length is increased. Furthermore, the inertia the player has to overcome increases with shaft length, so players may be unable to swing longer clubs at the same angular velocity as standard clubs. Nevertheless, swing models have shown that increased shaft length can lead to a faster impact velocity. This effect has been demonstrated by modelling golf swings with different shaft lengths (Chen, Inoue, & Shibata, 2005; Reyes & Mittendorf, 1998). To do so, Chen *et al.* (2005) varied the club length relative to the arm length in their model. Club were 1.5 - 2 times as long as the arm. They found that, with increasing club length relative to the arm length, more club head speed was generated. Ryes and Mittendorf (1998), in contrast, set shaft lengths to 47” and 51” and did not express them relative to the arm length of their model, but came to a similar conclusion. Werner and Greig (2000) used their swing model to calculate that a shaft with a length of 50.3” (1.28 m) could present an optimum trade-off. The effect of increased length shafts has also been examined in experimental studies with golfers of varying ability. It was found that increasing the length of drivers from 45” to 48” resulted in increased club head velocity at impact (Mizoguchi, Hashiba, & Yoneyama, 2002), and increased ball velocities were recorded when increasing club length from 46” to 52” (Wallace, Otto, & Nevill, 2007). In terms of swing adjustments to drivers with increased length, players appear to have a tendency to adjust their stance rather than changing their swing motion or timing (Wallace, Hubbell, & Rogers, 2004). Whilst there was a trend towards reduced foot torques and reduced EMG activity for some muscles when shaft length was increased from 45” to 48” (Mizoguchi, Hashiba, & Yoneyama, 2002), a full-body model of a golfer swinging clubs with lengths ranging from 46” to 50” predicted that the required muscle force would increase as club length increased (Kenny, Wallace, Otto, & Brown, 2006).

Whilst all of the studies mentioned above suggest that increasing shaft length leads to increased club head velocities and hence increased driving distance, a quantification of the effects of increased shaft length on accuracy was attempted in none of the studies. Only one study was found (Kenny, 2006) that included measurement of dispersion for drivers with different lengths. It was shown that increasing driver shaft length to more than 47” resulted in reductions in accuracy that could not be explained solely by the increased overall distance.

To summarise, increasing shaft length may help players to achieve extra distance through an increase in club head velocity. Due to the detrimental effect that this appears to have on accuracy for numerous players, only certain players with consistent swings may consider increasing their shaft length to increase club head velocity and so distance.

### 2.6.3 Bending stiffness and club head velocity at impact

Several researchers have investigated the possibility that the golf shaft behaves like a spring in a spring-mass system; in other words, the shaft stores energy during the first part of the downswing and releases it just before impact. The extra velocity that this unloading may add to overall club head velocity has been termed 'kick velocity' and "is defined as the derivative of lead/lag deflection with respect to time" (MacKenzie, 2005, p. 89). Based on the spring-mass system analogy, the oscillating shaft should be on its way from a bent backwards position to a bent forward position and be straight at impact. At this point, strain energy would be at its minimum and kinetic energy at its maximum, thus adding the maximum 'kick velocity' component to the overall club head velocity: "The optimum condition is where the shaft is straight at impact so that kinetic energy is maximised and stored potential energy is minimized" (Butler & Winfield, 1994, p. 261). With shaft frequencies of approximately 4 Hz under static conditions (Huntley, Davis, Strangwood, & Otto, 2006) and an assumed downswing duration of 0.25 s (Egret, Vincent, Weber, Dujardin, & Chollet, 2003) this appears to be a reasonable assumption (4 Hz · 0.25 s = 1 cycle during downswing). However, the natural frequency of shafts has been shown to increase significantly during the swing due to centrifugal forces acting on the club head, so, in theory, more than one oscillation would occur during the downswing (Jørgensen, 1999, p. 112; Mather & Jowett, 1998). Furthermore, it has been reported that the frequency response of a hand-held golf club may be more similar to a free-free condition than to a clamped-free condition (Wicks, Knight, Braunwart, & Neighbors, 1999), which would make multiple bending mode oscillations unlikely to occur during the downswing. In fact, multiple oscillations have only been observed in swing models where a flexible shaft was rigidly connected to the wrists (Tsunoda, Bours, & Hasegawa, 2004), and these vibrations have also been predicted for robot swings (Suzuki, Haake, & Heller, 2006). However, multiple oscillations during the downswing are not evident from any of the shaft deflection patterns published in the literature (Butler & Winfield, 1994; Horwood, 1994; N. Lee, Erickson, & Cherveny, 2002; Mather & Jowett, 2000; Newman, Clay, & Strickland, 1997). Most likely, the dampening provided by the hands prevents the shaft from vibrating more than once, and the main cause for the forward bending of the shaft just before impact is the torque created by the off-centre position of the club head's COG; see Section 2.2. As the COG position of the club head depends on club head design, Mather and Jowett (1998) concluded that correct design of the club head is essential and that "the forces/accelerations generated by the movement of the [club]head totally control the shape of the shaft" (Mather & Jowett, 1998, p. 521).

MacKenzie (2005) performed a comprehensive simulation study to determine the effect of shaft stiffness on impact velocity. Simulations were based on a model consisting of three body segments (torso, arm and hand) and three club segments connected with flexible links designed to account for the flexibility of the shaft and for the dampening provided by the hands. Body segments were driven with torque generators with the torque curves being derived using evolutionary optimisation algorithms. MacKenzie's conclusion was that "no particular level of shaft stiffness had a superior ability to increase club head speed" (MacKenzie, 2005, p. 122), which is in line with literature previously discussed here. Yet, he found that the flexible shafts produced kick velocities of up to 9.65 m/s, but due to the dynamic interaction of the model segments and the optimisation approach chosen, the model was able to reach almost the same absolute club head velocities with a rigid shaft and with identical maximum joint torque levels in place. This highlights that the ability of MacKenzie's model to adjust to changes in shaft stiffness may have a disadvantage – the swing motion under each shaft condition was optimised using 2000 iterations in order to achieve maximum performance with each shaft that was simulated. It is not known whether human players can adapt their body motion to changes in shaft stiffness in the same way as MacKenzie's optimised model did, so it seems sensible to compare impact velocities achieved by individual golfers swinging clubs with a variety of different shaft stiffnesses.

The review of literature shows that few studies reported club head velocities achieved by golfers using clubs with varying shaft stiffness properties. Some authors analysed golfer's swings using shafts of different stiffness but did not report the club head velocities achieved by the players (Tsujiuchi, Koizumi, &

Tomii, 2002) or present any statistical analysis (Miao, Watari, Kawaguchi, & Ikeda, 1998). Wallace and Hubbell (2001) analysed the launch data of 84 golfers swinging #5 irons with three different shaft stiffness ratings, but found stiffness effects on club head velocity to be negligible. They concluded that shaft stiffness might affect the 'feel' of the swing in terms of feedback the player perceives during the swing. Stanbridge, Jones and Mitchell (2004) measured impact position, distance and dispersion for 30 junior golfer (7-10 years) performing swings with #7 irons with three different shaft stiffness ratings. For the group of golfers as a whole, there was no significant difference between distances achieved with any of the clubs. However, they did provide examples showing that individual golfers performed best with different shaft stiffnesses – this was the case for 21 of the 30 golfers tested. This is in line with a recent study comparing impact velocities achieved by 40 golfers using clubs with five different shaft stiffnesses and an identical club head (Worobets & Stefanyshyn, 2008). They found significant variations in impact velocities for each of the golfers analysed. Interestingly, different golfers achieved their maximum impact velocities with different clubs, indicating that these effects were based on some shafts being particularly suited to particular golfers.

In summary, there appears to be no conclusive answer on the question of whether shaft stiffness can be used to optimise impact velocity for a given player. Simulation studies with optimised swings (MacKenzie, 2005) provide information that will help to answer this question, but it is necessary to validate these results against human swings as humans will probably not be able to adapt their swings as quickly to shaft stiffness alterations as a model. It seems shaft flexibility does not enhance ball velocity *per se*, instead it is the matching of player and shaft that could potentially be used to optimise club head speed and, hence, distance (Stanbridge, Jones, & Mitchell, 2004; Worobets & Stefanyshyn, 2008). Therefore, the two sub-sections that follow will discuss the influence of shaft stiffness on dynamic loft and the effects of body motion on shaft deformation.

### 2.6.4 Bending stiffness and dynamic loft

When driving the ball the primary objective is to achieve maximum distance with acceptable accuracy. The distance a golf ball travels depends on launch angle, ball velocity, spin rate, atmospheric conditions and the construction of the ball (Smits & Ogg, 2004b). Of these factors, launch angle, ball velocity and spin rate are directly connected to club head design and the way the player delivers the club head to the ball. The optimum launch angle changes with ball velocity and back spin, which makes it necessary to find a club that suits an individual's swing (Tuxen, 2008).

Shaft manufacturers will often claim that shafts can also be used for the customisation of launch conditions based on their stiffness and stiffness distribution, avoiding the necessity of making changes to the club head. The primary reason for this is that the shaft bends forward just before impact (see Section 2.2), thereby increasing the effective loft angle. Shaft construction may affect the dynamic loft of a club in two ways. Firstly, the stiffness distribution may have an effect on the amount of forward bending that occurs at the tip of the shaft (see Figure 14). Secondly, the overall stiffness of a shaft has an influence on the overall amount of forward bending at impact, thereby also affecting the dynamic loft angle. Both these factors are further described in the proceeding section.

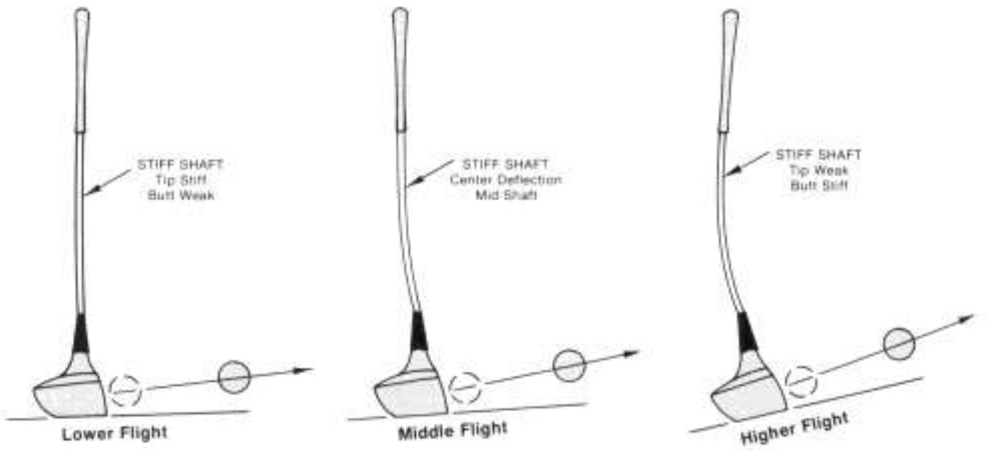



**Figure 14: Expected effect of shaft stiffness distribution on launch angle (adapted from Maltby, 1995, p. 416).**

In terms of stiffness distribution, it is usually recommended that beginners should use clubs with a lower bend point (or 'tip-flexible'), because club head speed is generally slower, which would result in less forward bending of the shaft at impact when using the same shaft as players with a faster swing. Furthermore, the optimum launch angle increases as impact velocity decreases, so weaker players benefit from an increased loft angle at impact (Chou, 2004). Whilst this seems to be a very common guideline when fitting golf clubs to individuals, no scientific study that supports these claims could be found. In fact, Chou and Roberts (1994) found no significant differences in the launch conditions achieved by players using shafts with different bend point positions.

The second factor that is commonly expected to influence dynamic loft at impact is the overall stiffness of the shaft (Maltby, 1995). This is based on the assumption that a less stiff shaft will be subject to more forward bending just before impact, resulting in an increased dynamic loft angle (Figure 15). Maltby (1995, p. 415) reports that if players hit balls with a ladies or flexible shafted club, "the results are always a higher trajectory with the more flexible shafts". However, once again, only few scientific studies have verified this assumption. In a three-subject study, differences in launch angles were negligible when subjects used shafts with different stiffness values (Tsujiuchi, Koizumi, & Tomii, 2002).

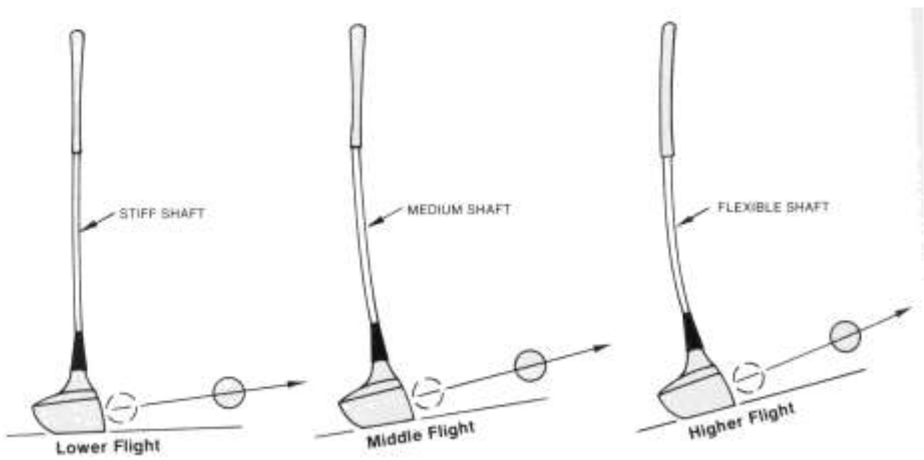



**Figure 15: Expected effect of shaft stiffness on launch angle (adapted from Maltby, 1995, p. 414).**

In conclusion, the concept of optimising club head presentation for a given player by choosing the correct shaft stiffness appears to be sensible, but little scientific research has been published proving the effectiveness of this concept. Often shaft fitting seems to be based on the experience of the club fitter and a ‘trial and error’ approach, and little is known about the precise relationship of shaft stiffness and launch conditions (for example in the form of ‘reducing shaft stiffness by x percent increases the launch angle by approximately y percent’).

### 2.6.5 Torsional stiffness and dynamic face angle

It is not only the loft angle of a club head at impact that differs from the loft angle under static conditions (see previous section). The face angle at impact can also be affected by the dynamic movement of the club head. This effect is caused by the off-centre position of the COG of the club head relative to the longitudinal axis of the shaft (Horwood, 1994; Newman, Clay, & Strickland, 1997). Torque acting at the hosel will be created by club rotation around the longitudinal axis of the club, for example when the player squares the club head just before impact, with the moment arm being the distance between the longitudinal axis of the shaft and the COG of the club head. For shaft bending, the moment arm is much longer because the closest hub for rotation is the wrist axis with the full shaft length being the moment arm.

The effect of torsional stiffness on club head presentation has received less attention in the literature than dynamic loft, but Chou (2004, p. 36) points out that “too much or too little flex can cause the club head to over- or under-rotate during the downswing, resulting in a closed (pointing to the left) or open (pointing to the right) club face at impact”. Obviously, the amount of dynamic change in face angle depends on the torsional stiffness of a shaft. Butler and Winfield (1995) stated that shafts producing a reading of 5° in a torque test (see Footnote 4 on page 22) are sufficient to allow the player to square the face at impact. Kojima and Horii (1995) performed a comparison of two shafts to determine the effect of torsional stiffness on ball velocity and direction. Using robot tests, they found that the shaft with higher torsional stiffness in their study produced higher ball velocities and more consistent ball direction. They found that this was caused by high amplitude torsional oscillations in the shaft with lower torsional stiffness, as expected. However, as they presented very few results for human swings to validate their findings, it is not clear whether these results can be transferred to humans who do not hold the shaft as rigidly clamped as a robot. An interesting finding from MacKenzie's (2005) simulated swings is that the effects of shaft bending stiffness on dynamic face angle were observed, even though his model did not allow any torsional deflection of the shaft. This was caused by the combination of lead/lag and toe-up/down bending and indicates how interrelated mechanical shaft variables are. Comments by Butler and Winfield (1994) confirm this observation, as they found that for every inch of forward bending the club face closed by 0.33°. Different methods to include torsional stiffness in swing models have been presented, however, the resulting models are yet to be validated successfully (Iwatsubo, Kawamura, Kawase, & Ohnuki, 2002).

In summary, it appears from the literature that torsional stiffness needs to be considered when analysing shaft performance, and that a certain minimum torsional stiffness is necessary to allow an effective golf swing, This is because a lack of torsional stiffness will make it more difficult for the player to consistently square up the club face before impact. The precise minimum torsional stiffness that is necessary most likely depends on the swing of the individual golfer.

### 2.6.6 Influence of body motion on shaft deflection

It has been noted by researchers that there can be marked differences in shaft deflection patterns when comparing different players (Butler & Winfield, 1994; N. Lee, Erickson, & Cherveny, 2002). Looking for a way to characterise the toe strain component, Butler and Winfield (1994) state that, "after hundreds of test trials, it has been found that most swing profiles fit into one of three categories" (p. 261). These categories are (see Figure 16):

- one peak
- double peak
- ramp-like

They hypothesise that these profiles are related to the body motion of players. The presence of these different loading profiles also leads to the conclusion that it is not sufficient to base shaft recommendations on club head velocity only, because two players can reach identical club head velocities even if their shaft loading patterns fall into different categories (Butler & Winfield, 1995). These findings were also supported by other researchers: “each player demonstrates their own shaft loading profiles, or kinetic fingerprints, for their swing sequence” (N. Lee, Erickson, & Cherveny, 2002, p. 375). Lee and colleagues found, for example, that the time between maximum toe-up strain and maximum lag strain gives an indication of the timing of “wrist roll” of the player.

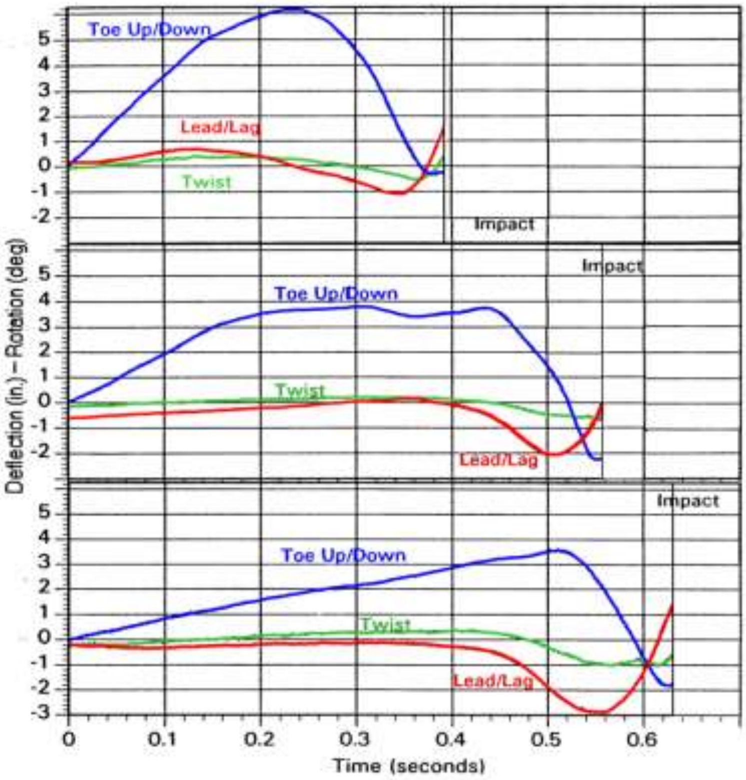



**Figure 16: Three different shaft deflection profiles. ‘One-peak’ (top), ‘double-peak’ (middle) and ‘ramp-like’ (bottom) (mod. from Butler & Winfield, 1994, pp. 261-262). Positive values correspond to toe-up, lead and face-close deflection, negative values to toe-down, lag and face-open deflection[7].**

[7] Butler and Winfield (1994) chose the start point of their graphs (t = 0) to coincide with the zero-crossing of the toe up/down strain.

No further studies relating body motion characteristics to shaft deflection patterns could be found, but it is reasonable to assume that differences in body motion patterns will result in changes in the torque pattern applied to the shaft. This assumption is supported by Mather and Cooper (1994), who concluded that not only the club head velocity at impact but also the time history of input torques influences the shape of the shaft at impact. Jorgensen (1999) performed simulations of golf swings that included flexible shafts and found that a small torque supporting the wrist “uncocking” process (‘wrist release’) could explain the way that the shaft bends during the downswing. Both Suzuki *et al.* (2006) and Nesbit (2005) claim that highly skilled players have the ability to use joint torque profiles that influence shaft deflection in a way that allows an efficient utilisation of energy stored in the shaft. Nesbit (2005) stated that the deflection pattern of the shaft follows the wrist torque pattern with a temporal delay of about 0.015 to 0.020 s. However, some of Nesbit’s simulated shaft deflection patterns seem to be contrary to previous results obtained from direct, experimental measurements. For example, for the majority of the deflection patterns presented, it appears that the shaft is still bent backward at ball contact, which is not the case for the swings analysed by other researchers using direct measurements. Another study linking shaft deflection profiles to swing characteristics has been performed by Tsujiuchi *et al.* (2002). They determined wrist torques using an inverse dynamics approach and found that all three golfers analysed in their study had a negative torque acting in their wrist joints directed against the ‘uncocking’ of their wrists just before impact. There was a correlation between the magnitude of this negative torque and shaft deflection, indicating that the forward bending of the shaft at impact might not only be caused by the off-centre position of the COG of the club head, but also by the torque pattern applied by the player. However, Tsujiuchi’s swing model was based on a two-dimensional approach, and neither the off-centre position of the club head’s COG nor the wrist action that golfers use to square the face before impact was included. Nevertheless, negative wrist torque contribution just before impact can also be seen in wrist torques calculated by Nesbit (2005) for a scratch golfer. In terms of wrist torque, all the previous findings were based on simulated swings involving simplified wrist joints and club models. In contrast to this, Koike *et al.* (2006) measured a golfer’s torque and force inputs to the shaft directly by using an instrumented grip. They only presented preliminary results for one scratch golfer, but the trend for the wrist torque to drop towards a zero or negative torque within the last 0.05 s of the downswing can also be observed in their results. This drop was from approximately 18 Nm to -15 Nm for the left hand, whereas the torque in Nesbit's (2005) simulations dropped from 40 to -18 Nm. The discrepancy may be explained by differences in the swing characteristics of the subjects used by Nesbit and Koike *et al.* All of the above findings support the theory that shaft deflection will be influenced by the torque pattern applied by players. However, it is yet unknown to what degree and whether it is possible to take advantage of this effect by selecting appropriate shafts for individual players.

Up until this point, this section suggests that choosing the correct shaft for an individual player might not only be important to optimise launch conditions (see Section 2.6.4) but also to match the shaft characteristics to the input torque pattern of the player to enhance the interaction of the player with the club. This is probably why Mather (1995) states that "if the swing pattern is poor and, as a consequence, the vibrations of the shaft are out of phase with the correct pattern, then the golfer should use the stiffest shaft possible, and minimise the vibrations and their effect". This is in direct contrast to conventional recommendations for weak players to use less stiff shafts and for strong players to use stiff shafts, and, in the same book where Mather's advice was published, Wishon (1995) stated that 450 out of 500 golfers tested by his research group were using a shaft that was – in their opinion – too stiff for their swing speed.

In summary, there is evidence that shaft deflection patterns are influenced by the torque patterns applied by individual golfers, as expected. Different swing styles appear to be used by players, resulting in different categories of shaft loading profiles. However, it is not known to what extent the torque pattern a player applies influences shaft deflection and to what extent the resulting centrifugal forces control shaft deflection. Furthermore, the relationship between body motion and shaft deflection is not well understood, and there is little research that combines analysis of the body motion of the golfer with shaft deflection measurements.

### 2.6.7 Adaptations of players to shaft stiffness variations

The previous sections of the literature review related shaft deflection to mechanical parameters, performance and body motion of the player. It is, however, also expected that experienced golfers have the ability to adjust their swing depending on the shaft used. The need for adaptations was demonstrated by McGuan (1996), who created a forward dynamics model of the golf swing of one subject. Leaving the torque patterns applied by each joint to be the same, he increased the shaft stiffness of the model by 30 %. This created an imperfect swing with decreased launch velocity and a negative launch angle. Only after using an optimisation routine to adapt the torque pattern applied by the model was the launch angle back to an acceptable value. It should be expected that humans are able to adapt their swings in a similar manner, but there has been little research on this subject. Wallace and Hubbell (2001) studied the effect of shaft stiffness on golf performance, but, as they were focusing on launch conditions achieved by the players, no quantitative analysis of the effects of shaft stiffness on body motion was included in their study. They did, however, note that there was "little variation imposed on the shoulder angular kinematics as a consequence of shaft flex" (Wallace & Hubbell, 2001, p. 33).

In conclusion, surprisingly little is known about the way golfers adapt their body motion to different golf shafts, and more in-depth research in this area is necessary to understand the effect of shaft stiffness on golf performance. This is particularly important in the light of simulation studies that use optimisation routines in order to adapt models to different shafts (MacKenzie, 2005; McGuan, 1996), because the results of these studies can only be validated when human golfers show the capability to adapt their swings in a similar manner to the models.

## *2.7 Summary of literature review and conclusions*

As outlined in the introduction, the motivation for this work is an attempt to rectify the lack of scientific understanding of the interaction between player and shaft and its implications for golf performance. There seems to be consensus in the literature regarding the basic characteristics of the deflection patterns the shaft experiences when a human swings a golf club (Section 2.2). A number of mechanical shaft characteristics and test methods, including shaft modelling and simulation, have also been identified, described and discussed (Sections 2.3, 2.4, 2.5). It was possible to describe the effects of mechanical shaft properties on swing performance for shaft mass (Section 2.6.1) and shaft length (Section 2.6.2), but difficulties arose when describing the role of shaft stiffness. Therefore, shaft stiffness effects on impact velocity (Section 2.6.3) and club head presentation at impact (Sections 2.6.4 and 2.6.5) were considered in more detail, but it was not possible to draw clear conclusions regarding the effect of shaft stiffness on these variables. It became clear that it is not possible to explain shaft stiffness effects on performance in isolation from the player, so the effect of body motion on shaft deflection was considered (Section 2.6.6) and an attempt was made to summarise the literature describing how players adapt to different golf clubs (Section 2.6.7). However, it was found that there is little consensus in the literature regarding the effect of shaft stiffness on golf performance.

The following conclusions were drawn based on the literature review:

(1) The shaft deflection pattern is mainly affected by

a. Mechanical shaft properties,

b. Club head properties,

c. Body motion and individual swing characteristics.

(2) Of the factors listed in (1), (c) (the relationship of body motion and shaft deflection) appears to be least well understood, but it is likely to be the most important aspect when analysing the interaction between player and club. Some models have been created in the past in an attempt to better understand this relationship (Tsujiuchi, Koizumi & Tomii, 2002; Nesbit, 2005; Suzuki, Haake & Heller, 2006), but there were some distinct discrepancies between shaft deflection patterns found using these models and those measured directly from human

swings. It appears that shaft models need to be improved and validated more thoroughly before holistic models including body motion and shaft deflection can be used successfully.

(3) One difficulty in understanding the relationship between shaft properties and performance is that there are many different “swing styles” rather than one model swing. This makes the use of optimised models to analyse the effect of shaft stiffness questionable because humans might not be able to optimise their swing to fit a particular shaft stiffness in the same way that an optimised model does. It appears that it is rather the fitting of the correct shaft to a player’s swing that matters instead of optimising the swing to fit a particular shaft.

(4) Robots could be used for repeatable, dynamic tests, but there is little research on how robotic shaft loading compares to human shaft loading.

(5) There is little evidence supporting the conventional view that decreases in shaft stiffness can be associated with increases in club head speed and dynamic loft. No previous study was found that compared shaft loading patterns for clubs that only differed in shaft stiffness.

# 3 Aim and objectives

The review of literature led to the following main research question:

(1) How does varying the stiffness of a golf shaft affect golf performance in terms of club delivery for a given swing?

Given the nature of the problem, this question could potentially be answered by analysing human swings performed with shafts of differing stiffness properties. This would allow mechanical variables, such as shaft stiffness, to be correlated with performance variables, such as impact velocity. The analysis of human swings could also be used to analyse the effect of shaft stiffness alterations on body motion and overall performance.

Additionally, a thorough understanding of the effects of shaft stiffness may enable us to understand the mechanism of these shaft stiffness effects in more detail, in particular:

(2) How are shaft loading patterns affected by changes in shaft stiffness?

(3) Do players adapt their swing movement depending on the shaft used?

Improving the understanding of the interaction of the human with an implement such as a golf club would be likely to present a wider contribution to research, with some of the results being potentially transferable to other research areas such as the interaction of humans with sports or other hand-held equipment. It is also expected that research into golf swing biomechanics may complement findings from disciplines like motor learning.

The literature review has shown that there are no standard methods available to characterise the dynamic behaviour of the golf shaft and the golfer. Therefore, the next chapter is dedicated to a summary of the work that led to the research methods used in this thesis. This is followed by a presentation of three separate studies with their own, more specific aims that were undertaken to address the research questions presented above.

# 4 Methodological issues

### 4.0 Introduction

It was found during the literature review that there are few standard methods available that could be used in shaft research. For example, measurement approaches for quantifying shaft deformation throughout the swing varied widely and included optical (e. g. Smith, Mather, Gibson, & Jowett, 1998), strain gauge (e.g. N. Lee, Erickson, & Cherveny, 2002) and simulation (e.g. MacKenzie, 2005) methods. The purpose of this chapter is to discuss the methodology utilised for measurements performed for this thesis. Furthermore, the results of the validation studies performed will be presented. This will avoid repetition of these details in later chapters.

### 4.1 Study design considerations

A number of decisions have to be made when designing a research study. For example, whether experiments are to be carried out on humans or whether computer models are used. When human subjects are used, boundary conditions (indoor or outdoor testing, lab or field testing) have to be defined, ensuring that a sufficient level of ecological validity is maintained (Atkinson & Nevill, 2001). It is also necessary to decide whether multiple trials from a single subject are analysed in depth (Bates, 1996) or multiple participants are included. In both cases, the researcher has a choice as to how the target population is defined, what the sampling frame is and which sampling techniques are used (Mullineaux, 2008). When using multiple subjects, a decision has to be made whether a within-group or between-group design is chosen. In a within-group design, each participant is subject to all experimental conditions, whereas in a between-group design, participants are divided into different 'treatment' groups and are only subject to one experimental condition. The researcher also has a choice as to whether multiple trials are included for each subject and condition or just one 'representative' trial per subject is used in the statistical analysis.

Study design is further complicated by the fact that many of the factors discussed in the previous paragraphs are interlinked. The aim of the section that follows is to discuss these in more detail, summarise approaches used in previous golf studies and to present the rationale behind decisions that were made when designing the studies presented in this thesis.

### 4.1.1 Experimental vs. simulation studies

Previous researchers have used both experimental and simulation methods to investigate the effects of shaft stiffness on swing performance. The advantage of simulation methods is that the researcher is in full control of boundary conditions. For instance, shaft properties may be difficult to control in experimental studies because of manufacturing tolerances, or changes in one variable inevitably affecting other variables that are not focus of the study. Difficulties that have to be solved when performing a simulation study are, however, the choice of simplifications made when creating the model and the method used to set the model into motion in simulated experiments (Betzler, Monk, Wallace, Otto, & Shan, 2008). As discussed in Section 2.5, this can either be done by recording kinematic data from human swings (inverse dynamics approach) or by selecting torque curves for each joint (forward dynamics approach). The advantage of the inverse dynamics approach is that it ensures the validity of the model's kinematic behaviour (i.e., the model will perform movements that a human golfer would perform as well), but the disadvantage is that it may be impossible to generalise the results as they may be subject-specific. Furthermore, this type of model will not be able to adapt its behaviour when the mechanical properties of the equipment change; McGuan (1996), for example, has presented an example where adaptations were necessary when properties of the shaft were modified.

Another modelling approach is to create a forward dynamics model driven by torque functions. This type of model has been used successfully to examine the effects of changes in shaft properties on club head presentation and speed at impact (MacKenzie, 2005). In MacKenzie's study, the torque patterns for each joint were determined from repeated simulations, using a genetic algorithm to optimise joint torque parameters. Whilst this approach provides the model with the capacity to adjust its behaviour to changes in boundary conditions, it may not always be possible to transfer the results to humans. It is not clear whether humans would react to changes in equipment properties in the same way as the optimising algorithm. Some studies suggest that there may be more than one 'typical' pattern for some golf variables (Ball & Best, 2007a; Komi, Roberts, & Rothberg, 2008).

Given the disadvantages of simulation models and the added difficulty of validating model outputs when data for comparisons are difficult to obtain, for example for joint torques, it was decided to use experimental methods to collect data from human players in the first and second studies. The third study will then apply swings that are simulated using a golf robot. Study design considerations for these experimental studies will be discussed in the sub-sections that follow.

### 4.1.2 General study design

Previous experimental studies in golf biomechanics research used different designs and statistical methods, some of which are summarised in Figure 17. One option is to apply single subject analysis (Bates, 1996), as used by Teu *et al.* (2006) and Kenny *et al.* (2006). This approach may be preferential when multiple performance strategies are likely to be used by different subjects. These strategies would potentially result in misleading results when looking at group means or inferential statistics based on trials performed by multiple subjects. However, generalising results from single-subject studies may be an issue, and it has been suggested that single-subject designs may be more appropriate in the early stages of an investigation when hypotheses have not yet been generated (Reboussin & Morgan, 1996).

When using multiple subjects, it is necessary to decide whether a within-group design or a between-group design is used. As can be seen in Figure 17, both approaches have been used in previous golf studies. As an increase in statistical power has been associated with within-group designs (Nevill, Holder, & Cooper, 2007), it was decided to use this type of design throughout this body of work.

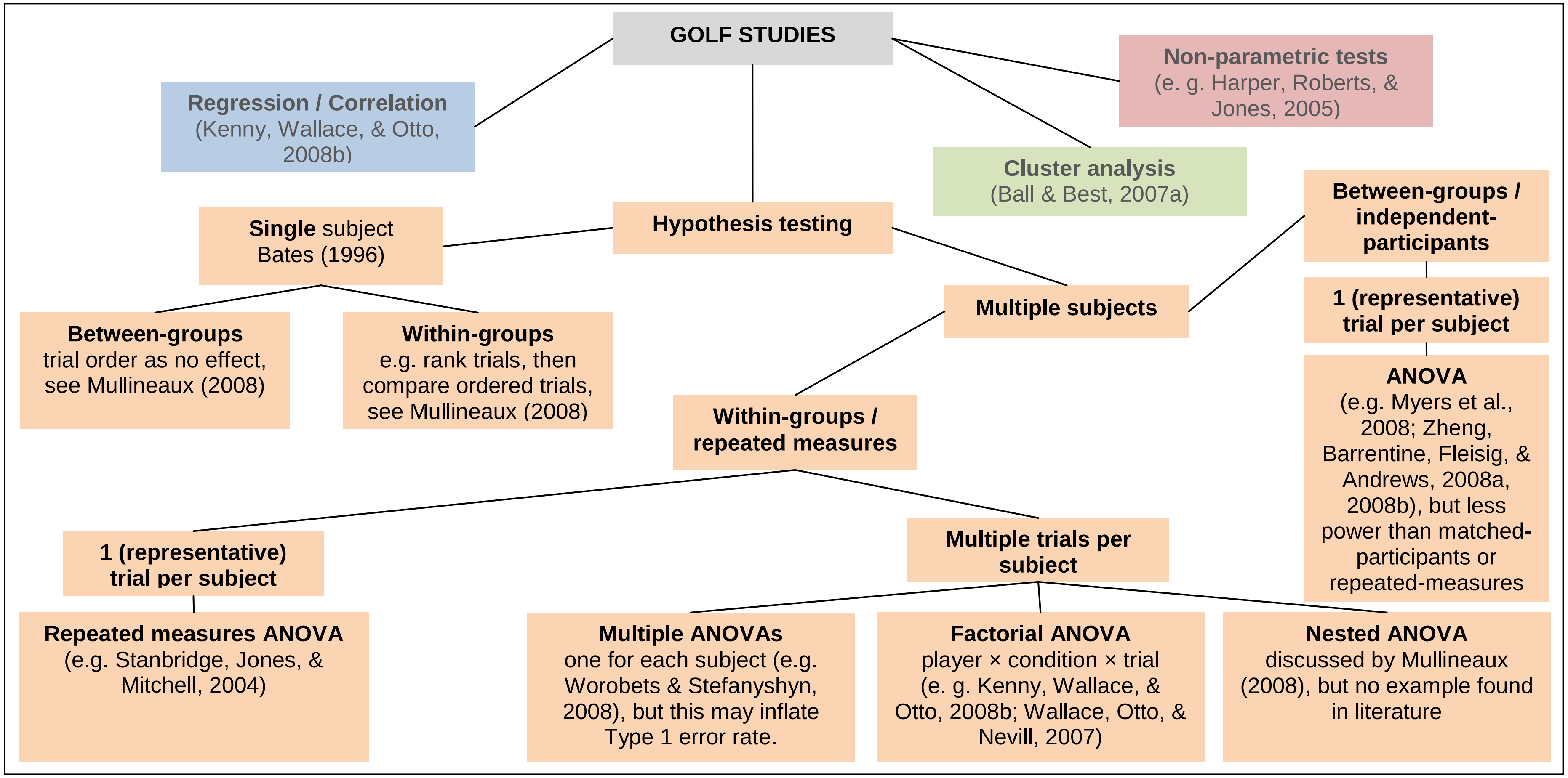



**Figure 17: Overview of study designs and statistical methods employed in previous studies.**

It is likely that each player has to perform a high number of repeated swings in a within-group design if multiple trials per condition are recorded. This is because each participant has to be subject to all experimental conditions. Therefore, it is necessary to consider what the maximum number of swings per subject is before fatigue effects occur. Table 6 summarises study designs of previous golf studies in terms of subject number, number of conditions and number of trials. It can be seen that the number of subjects and repeated trials varied broadly, which may be partly due to the different objectives of each study. The majority of studies, however, did record multiple trials for each condition per subject, which is in line with recommendations given in the literature (Mullineaux, Bartlett, & Bennett, 2001). Table 6 also shows that a number of researchers regarded a total number of trials of between 30 and 45 swings as adequate (Harper, Roberts, & Jones, 2005; Kenny, 2006; Stanbridge, Jones, & Mitchell, 2004; Wallace, Hubbell, & Rogers, 2004; Wallace, Otto, & Nevill, 2007). Qualitative observations in pilot studies suggested that subjects were able to perform this number of swings consistently with a driver, so the maximum number of swings per subject was set to 40 for the current studies.

**Table 6: Summary of previous study designs, in order of number of participants.**

| Reference | Subjects | Experience (numerical values represent Handicap) | Conditions | Trials per condition |
|---|---|---|---|---|
| Teu *et al.* (2006) | 1 | <10 | 1 | [a] |
| Wallace, Graham & Bleakley (1990) | 2 | 6/24 | 1 | 10 |
| Tsujiuchi, Koizumi & Tomii (2002) | 3 | 'two beginners, one experienced' | 6 | 5 |
| Kenny (2006, study 2) | 5 | 5.1 ±2 | 4 | 8 |
| Milburn (1982) | 5 | [a] | 1 | 1 |
| Neal & Wilson (1985) | 6 | '4 professionals, 2 low-handicap' | 1 | 1 |
| Egret *et al.* (2003) | 7 | 0-3 | 3 | 6 |
| Kenny (2006, study 3) | 7 | 0.2 ±2 | 4 | 8 |
| Coleman & Rankin (2005) | 7 | 0-15 | 1 | [a] |
| Burden, Grimshaw & Wallace (1998) | 8 | 7 ±1 | 1 | 20 |
| Wallace, Hubbell & Rogers (2004) | 9 | 5.4 ±2.8 | 4 | 10 |
| Wallace, Otto & Nevill (2007) | 9 | 5.4 ±2.8 | 4 | 10 |
| Coleman & Anderson (2007) | 10 | 1-5 | 3 | 3 |
| Wheat, Vernon & Milner (2007) | 10 | 1-17 | 1 | 8 |
| Egret *et al.* (2006) | 12 | 0-3 | 1 | 5 |
| Mizoguchi, Hashiba & Yoneyama (2002) | 13 | 'scratch' to 'unskilled' | 4 | 5 |
| Gatt *et al.* (1998) | 13 | 4-18 | 2 | 10 |
| Worobets & Stefanyshyn (2008) | 21 | <10 | 5 | 2*5 |
| Komi, Roberts & Rothberg (2008) | 20 | 0-22 | 1 | 10 |
| Harper (2006) | 30 | 0-12 | 4 | 10 |
| Stanbridge, Jones & Mitchell (2004) | 30 | 3 months to 5 years experience | 3 | 15 |
| Lindsay, Horton & Paley (2002) | 44 | Pro | 2 | 3 |
| Zheng *et al.* (2008b) | 50 | Pro | 1 | 10 |
| Ball & Best (2007a) | 62 | 11 ±8 | 1 | 10 |
| Mitchell *et al.* (2003) | 65 | <20 | 1 | 3 |
| Zheng *et al.* (2008a) | 72 | full Handicap range | 1 | 5-10 |
| Nesbit (2005) | 84 | 5.8 ±6 | 1 | [a] |
| Wallace & Hubbell (2001) | 84 | 11 ±8 | 3 | 3/10 |
| Myers *et al.* (2008) | 100 | 8 ±7 | 1 | 10 |

[a]unspecified

### 4.1.3 Population and sample selection

For many studies in sports science, it is not practical to select a random sample from the broader population because only individuals with very specific skills are suitable to participate. Often a specific population is defined prior to the study (e.g. highly skilled athletes) instead of a random sample from the broader population (e.g. all golfers), thereby reducing the ability of the researcher to draw general conclusions from the results of a study. However, this is often the only practical way to perform a study that requires a considerable amount of the participant's time and specific skills, in particular consistency. Setting tighter criteria when defining the sampling frame will potentially make the sample more homogeneous (increasing the statistical power) but at the same time reduce the validity of any result extrapolations. Previous studies showed that the absolute effects of shaft stiffness differences on outcome variables like club head speed (0.6 - 1.6 m/s, Worobets & Stefanyshyn, 2007) lie within the same range as the expected within-subject variations (standard deviation of ±0.2 to ±0.5 m/s for six repeated trials, Kenny, 2006, p. 100). This would result in high sample numbers being necessary to detect any changes. Therefore, it was decided to set the following criteria when inviting golfers to participate in this study:

- Gender: male golfers only, as it has been found that there are significant differences in body movement and outcome variables when comparing male and female players (Zheng, Barrentine, Fleisig, & Andrews, 2008b);

- Skill level: only category 1 golfers (handicap ≤ 5) and professionals were included as they were expected to be able to perform consistent golf swings even when using unfamiliar test clubs, thereby reducing within-subject variability.

In terms of sampling techniques, a convenience sample was chosen based on the availability and willingness to participate of local golfers.

### 4.1.4 Boundary conditions

When setting up an experiment, the internal as well as the external validity of the study design have to be considered (Atkinson & Nevill, 2001). They stated that the "optimization of external validity can impact negatively on internal validity in that the researcher may have less control over extraneous variables in a real-world setting" (Atkinson & Nevill, 2001, p. 812). A study looking at the effects of golf equipment on performance, for instance, would need to be carried out on a golf course during a competition with different test clubs randomly assigned to different players in order to maximise external validity. The outcome measure could be the number of strokes in a round to keep the test conditions as close as possible to a real-world scenario. However, this study design would introduce confounding variables, such as weather conditions, the course layout and the pressure of competition. The number of repeated trials per subject would be minimal, reducing the reliability of the data collected and the statistical power. For these reasons, it is common practice to accept a reduced external validity in order to ensure internal validity (Atkinson & Nevill, 2001).

In the case of the present work, a compromise was made by conducting all human tests in a hitting bay on a golf driving range, thereby minimising extraneous factors like competitors or course design, yet still presenting the participants with the challenge of performing straight, long shots instead of just hitting balls in a net with little or no feedback regarding the shot result.

### 4.1.5 Variability, sample size and number of trials

Even with the sample group being confined to highly skilled players, it is inevitable that there will be variability in the outcome measures due to the "complexity of the human system and its numerous functional degrees of freedom" (Dufek, Bates, & Davis, 1995, p. 289). Most likely, this variability will manifest itself in the lack of a singular response of the complete sample to the treatment as well as within-subject variability in repeated trials from each subject. The former is typically associated with the presence of different performance strategies among subjects (Dufek, Bates, & Davis, 1995), whereas the latter is increasingly seen as a useful component of motor control that enables a skilled athlete to adapt to unexpected environmental changes (Davids, Glazier, Arauacutejo, & Bartlett, 2003). Nevertheless, when inferential statistical tools are used, variability will reduce statistical power. Besides variability, statistical power will also be affected by sample size and effect size (Vincent, 2005) and unexplained error variance (Nevill, Holder, & Cooper, 2007). Whilst effect size can only be increased indirectly in some cases, for example by choosing a direct rather than an indirect outcome measure, researchers can directly influence statistical power by selecting an appropriate sample size. In standard scenarios, where experiments can be replicated several times and subject-specific performance strategies are absent, it is possible to calculate the sample size that is necessary to achieve a pre-set statistical power for a given effect size and variability in the replicates (Vincent, 2005). For instance, using equations provided by Mullineaux (2008), we can calculate that 17 samples would be required to detect a change in impact speed of 1 m/s for a skilled golfer (SD ±1 m/s) with a statistical power of 80%. The figures used for this estimate are based on increases in impact speeds of 1 m/s that were associated with changes in shaft stiffness (Worobets & Stefanyshyn, 2007) and the maximum within-subject standard deviation observed for repeated trials with identical clubs reported by Kenny (2006).

The situation is complicated in typical sport and exercise science studies, where both inter- and intra-subject variability as well as possible fatigue or learning effects have to be considered, often making it difficult to estimate power before conducting a study. Using simulated experiments, Bates, Dufek and Davis (1992) aimed to identify the number of trials that would allow rejecting the null-hypothesis that there were no differences in the averages of three different conditions when in reality there was a difference between conditions with a magnitude of one within-condition SD. The aim was to reach a statistical power greater than 90%. They found that 10, 5 or 3 repeated trials had to be performed for sample sizes of 5, 10 and 20 subjects, respectively, to meet these conditions. Identical guideline numbers could be used regardless of whether the statistical analysis was performed as a Condition × Subject, repeated-measures design (using one average score for each condition per subject) or a Condition × Subject × Trial factorial ANOVA. They argued that, whilst being more complex, the Condition × Subject × Trial type of analysis offers the advantage of providing the researcher with the possibility of identifying Trial × Condition interactions. There appears to be little consensus as to which type of analysis is preferable. After acknowledging that multiple trials should be recorded to determine a representative response of a subject, Mullineaux, Bartlett and Bennett (2001) argue that if within-trial consistency for subjects is high it may be justifiable to use a single ‘representative’ trial per subject and condition. Care has to be taken, however, how this trial is selected, as using the mean of repeated trials (as recommended by Kroll, 1967) may create a “mythical” trial that did not exist in reality (Mullineaux, 2008, p. 164).

For the present study, it was decided that a limited number of representative swings would be used because this would preserve information about the within-subject variability and any systematic changes that may have occurred whilst testing a club. The consequence of this approach is that trial number as well as player has to be included as factors in the statistical analysis, as otherwise the assumption of independence between samples would be violated (Field, 2005).

### 4.1.6 Selection of representative swings and treatment of outliers

When performing multiple trials per condition and participant, the question arises whether all trials should be included in the analysis or whether a number of representative trials should be selected. It appears that the majority of authors of golf studies included all recorded swings, although a number of exceptions were noted. For instance, Zheng *et al.* (2008a, p. 489) recorded 5 to 10 shots per subject but only “two trials that were determined to be good trials based on the subject and the quality of the data were analyzed”. Mitchell *et al.* (2003, p. 197) averaged three swings selected out of a minimum of five total swings and reported that acceptance “was based on data quality (lowest marker residuals, complete data on follow-through) and verbal feedback from the participant”. Similarly, trials have been selected based on dispersion or club head speed, with shots that were not within a dispersion range of ±10° and airborne being excluded (Stanbridge, Jones, & Mitchell, 2004) or with only the five fastest swings out of ten recorded swings being analysed (Myers *et al.*, 2008). Kroll (1967), looking at the problem of selecting an appropriate criterion score, argued that disregarding some of the available trials would be incorrect if the trial-to-trial error variance was random and uncorrelated. This assumption may be violated if fatigue or learning effects exist as this would cause systematic shifts in outcome variables, causing non-random changes in the data (Hopkins, 2000). Selecting only the trial with the ‘best’ (e.g. highest) score, in contrast, would imply that the researcher assumes that the error variances of all other trials are negative. Only if this was the case the ‘best’ trial would be an appropriate representation of the true criterion score (Kroll, 1967). Clearly, this scenario does not occur very often unless there is a rationale for the assumption that the highest score really is the most representative value, for example in a maximum strength test. Based on Kroll’s arguments, no attempt will be made in the studies presented in this thesis to select representative trials, because, as per the research questions presented in Chapter 3, the interest is not in effects of changes in the properties of golf shafts on the best shots but changes in general. Nevertheless, appropriate measures will be taken to ensure that the assumption of un-correlated, random trial-to-trial variations holds true and that there are no systematic changes between repeated trials.

It is possible that a small number of trials will be excluded either if technical problems arise during data collection or if results are suspicious and it is likely that the result from the trial was not representative (i.e. if a data value is outside a range of two standard deviations of the data set).

### *4.2 Selection of test clubs and balls*

To address the research questions formulated in Chapter 3, it was deemed necessary to use clubs that were matched in all properties apart from shaft stiffness. As manufacturing tolerances for mass-manufactured clubs were not known, it was decided to purchase the club components separately and to assemble the clubs after testing each component, thereby ensuring that the grip, club heads and shafts were matched as closely as possible in all aspects apart from shaft stiffness. It was further necessary to decide which club type was to be used. As players typically achieve highest club head velocities with drivers (Egret, Vincent, Weber, Dujardin, & Chollet, 2003) and driver shafts can be expected to be less stiff than iron shafts, it was assumed that the highest shaft deformation was likely to occur for drivers. This is in line with perceived wisdom in the golf community which says that shaft stiffness plays a more important role for drivers than for irons as it may influence club head speed and club head presentation at impact (Maltby, 1995). Hence, after pilot studies with other drivers, a set of six drivers was assembled for the studies performed as part of this thesis. This set of golf clubs consisted of three pairs of identical clubs, with the second club of each pair providing a spare club in the case of technical issues with the instrumentation (see Section 4.3) of the first one. The only difference between the three pairs of clubs was shaft stiffness. The sub-sections that follow will summarise the properties of the selected parts in more detail.

### 4.2.1 Shaft

Summitt (2004) presented a comprehensive database of test results, including frequency, for more than 300 driver shafts (see Figure 18). This data provided a thorough summary of the shaft market and was used to identify the stiffness range of shafts on the market at the time, thereby defining the target range for the shafts to be used in this investigation. At the same time, suitable shafts had to be as similar as possible in all other aspects (such as mass and torsional stiffness). Following a review of shaft information on manufacturer websites, a suitable set of shafts was identified. After sourcing the shafts, they were tested for their mass and stiffness properties using the test protocols described below.

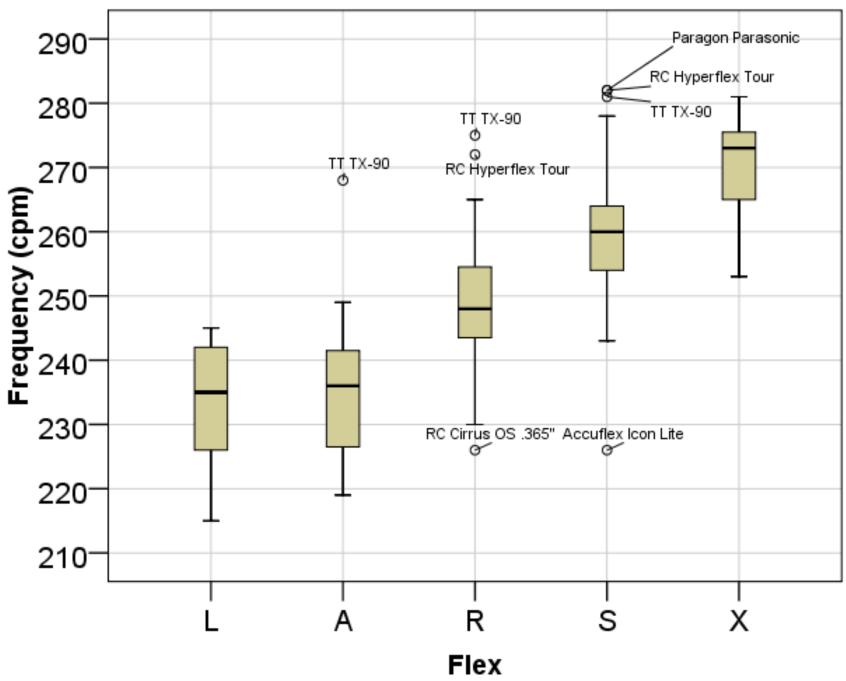



**Figure 18: Boxplot showing driver shaft frequency ranges for different flex codes (based on data for 300 driver shafts presented by Summitt, 2000)**

A Golfsmith Frequency Analyzer was utilised to determine the fundamental bending frequency of the shafts. Shafts were clamped without grips as shown in Figure 19 at a cantilever length of 1016 mm (40”). The tip mass (205 g) was manually pushed down by approximately 25 mm and released. The frequency analyser was then reset to initiate the measurement, and a reading was taken whilst the tip of the shaft was oscillating. This was repeated three times for each measurement position. Due to expected variations in frequency caused by seams (Huntley, Davis, & Strangwood, 2004), the frequency test was repeated with the shaft in different orientations. The shaft was rotated in 15° increments, and the test was completed when the 180° position was reached. After completing the test for a shaft, the average of all individual measurements was taken.

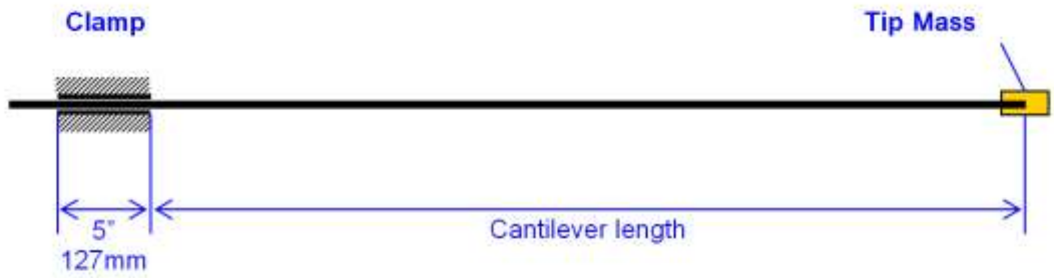



**Figure 19: Set-up of frequency test.**

Rigidity of the test shafts was determined using a protocol described by Brouillette (2002) using a cantilever length of 1 m and a mass of 2 kg (see Figure 20). The average rigidity for the full shaft was determined using the following equation:

$$EI = \frac{F\ell^3}{3\delta} \quad (4),$$

where: *EI* is the flexural rigidity (Nm$^2$),

$F$ is the load (N),

$\ell$ is the cantilever length (m) and

$\delta$ is the deflection at the point of force application (m).

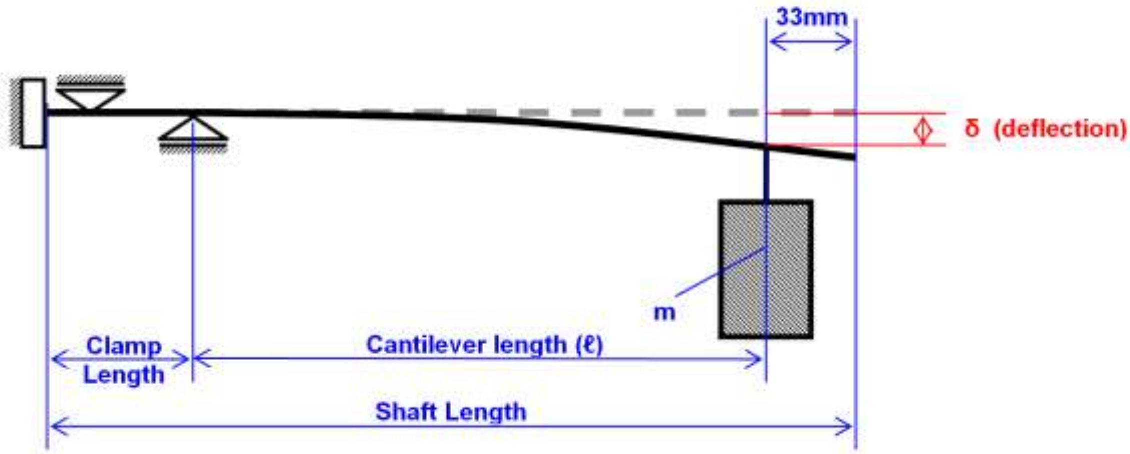



**Figure 20: Set-up of rigidity test.**

Based upon these measurements, the shafts were deemed suitable as their mass and geometry was closely matched, and there was a clear difference in rigidity and frequency (see Table 7). It was also found that the test shafts were representative of the range found in the data set provided by Summitt (2004) (see Figure 18). After assembly, length measurements were performed following the Rules of Golf length measurement procedure (The R&A, 2007), and swingweights were determined using a Professional Digital Swingweight Scale (Golfsmith, USA) (see Table 7). All shafts were painted black to provide participants with no visual indication as to which club they were testing.

**Table 7: Properties of selected shafts and assembled clubs.**

| # | Label | Shaft mass [g] | Rigidity[a] [$Nm^2$] | Frequency [cpm] | Length[b] [“] | Swing weight[b] | Total mass[b] [g] |
|---|---|---|---|---|---|---|---|
| 1a | l-flex | 56.8 | 38 | 217 | 45.0 | C9.7 | 306.8 |
| 1b | l-flex | 56.4 | 39 | 217 | 45.0 | D0.4 | 308.5 |
| 2a | r-flex | 57.2 | 48 | 244 | 45.0 | C9.6 | 305.6 |
| 2b | r-flex | 57.3 | 47 | 246 | 45.0 | D0.3 | 309.8 |
| 3a | x-flex | 57.7 | 58 | 271 | 45.0 | D0.0 | 307.7 |
| 3b | x-flex | 58.2 | 58 | 273 | 45.0 | D0.1 | 308.8 |
| Test tolerance[c] | | ±0.2 | ±0.5 | ±1 | ±0.02 | ±0.1 | ±0.2 |

[a]Rigidity at a cantilever length of 1 m.

[b]Measurement taken from the assembled club.

[c]Tolerance based on repeated measurements.

### 4.2.2 Club head

For the comparison of swing data obtained with different clubs to be valid, club heads have to be geometrically identical. One option to exclude club head differences as a factor is to use one club head with all shafts by attaching the club head using an interchangeable system (Worobets & Stefanyshyn, 2008). Such a system, however, would add mass to the tip end of the shaft and provided an unusual interface between the club head and the shaft. Therefore, eight 360 cc club heads of the same type were purchased and tested for mass, loft angle, lie angle and moment of inertia.

Mass, loft angle and lie angle were determined using a precision scale and a commercial loft/lie machine. The club head's moment of inertia was measured using the Rules of Golf procedure (The R&A, 2006). Variations of these variables between club heads were found to be within or close to test tolerances determined from repeated tests after two of the initially purchased eight club heads were excluded (see Table 8). The only exception to this was club head mass, which varied within a range of 1.4 g.

**Table 8: Club head properties.**

| Club head | Mass [g] | Loft [°] | Lie [°] | $MOI_z$ [$gcm^2$] |
|---|---|---|---|---|
| 1a | 197.0 | 10.8 | 59.5 | 3675 |
| 1b | 198.2 | 10.8 | 58.7 | 3682 |
| 2a | 197.4 | 10.9 | 59.0 | 3687 |
| 2b | 198.0 | 11.7 | 59.3 | 3715 |
| 3a | 198.4 | 11.5 | 58.8 | 3719 |
| 3b | 197.8 | 10.9 | 58.8 | 3654 |
| Test Tolerance[a] | ±0.2 | ±0.8 | ±0.8 | ±50 |

[a]Tolerance based on repeated measurements.

### 4.2.3 Grip

The instrumentation of the shafts with strain gauges (see next section) required a plug to be integrated within the grip. Due to the extra mass added to the club (approximately 14 g), it was expected that the grip end of the assembled test clubs would be heavier than for a normal, un-instrumented club. Therefore, the lightest available grips were chosen to offset the mass difference. These grips had a mass of 39 g, which is approximately 11 g lighter than the mass of a standard grip. For instrumentation purposes, a 10 mm hole was cut into the butt end of these grips, providing access to the plug that was integrated into the butt end of the shafts. The assembled clubs are shown in Figure 21.

**Figure 21: Assembled test clubs.**

### 4.2.4 Ball

For all experiments presented in this thesis, the same ball type was used. These balls were produced by a major golf ball manufacturer but unmarked to prevent the players from having preconceptions that may influence shot results. Balls were washed after each use and, after sufficient rest time, re-used approximately ten to fifteen times throughout each study. Any balls with visible damage to their surface were excluded from future test sessions and discarded.

## *4.3 Club instrumentation*

Based on published data (e.g. Butler & Winfield, 1994), it was expected that the shaft would change its shape both at a fast rate and in two planes. It was therefore decided to use strain gauges to measure shaft strain rather than measuring the deflection of the shaft optically. Measuring deflection directly would have required three-dimensional high-speed imaging, which is complex and can require multiple calibration points around the player (Smith, Mather, Gibson, & Jowett, 1998).

Hence, each shaft was equipped with four foil strain gauges (Kyowa, Japan), forming two half-bridges. These uni-axial strain gauges were 2 mm long and their resistance was 120 Ω. The strain gauges were placed at the location on the shaft where the highest magnitude of strain was expected during the swing. This location was assumed to coincide with the point of maximum bending curvature, as determined during a static bending test (see Figure 20). The position of maximum curvature was found to be located approximately 500 mm from the tip end of the test shafts, regardless of their stiffness rating. The strain gauges were aligned with the longitudinal axis of the shafts and placed so that one pair of strain gauges registered lead/lag deformation of the shaft and the other pair toe-up/down bending (see Figure 22 and Figure 23). Three reflective markers were fixed to the club just below the grip to track the movement of the club throughout the swing (see Section 4.5).

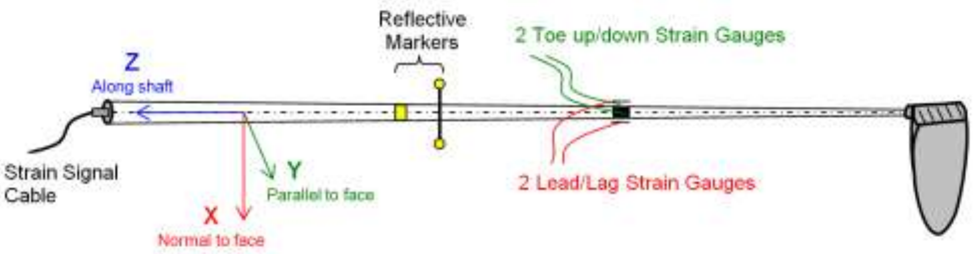



**Figure 22: Club instrumentation and coordinate system.**

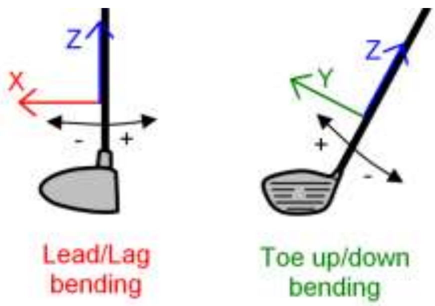



**Figure 23: Reference system and nomenclature for strain measurements.**

In order to process and record the strain data, a prototype of a Bluetooth device for wireless transmission of strain data to a USB receiver was obtained and trialled. It was found, however, that the maximum achievable sample rate was too low to characterise the change in strain during the downswing, and the device was perceived as too big in size by the golfers who tested it. Therefore, a cable connected to the butt end of the club was used to measure the strain signal. After testing different types of plugs, it was found that light plastic plugs and plugs without a bayonet locking mechanism were not suitable as they would break or unplug after a number of swings. As a result, metallic plugs with a locking mechanism (LF series, Hirose, Japan) were used, even though their mass (14 g) was relatively high compared to the other plugs.

## *4.4 Strain processing*

### 4.4.1 Calibration

When placing the strain gauges on the shaft, care was taken to align the strain gauges based on the definitions provided in Figure 23 but two possible error sources were identified. The axis of the strain gauges could be misaligned relative to the longitudinal shaft axis, which would result in sensitivity of the strain gauge to torsional strain instead of the intended sensitivity to tensile and compressive strain only. Secondly, one or both of the pairs of strain gauges may have been misaligned relative to the club reference system. For instance, the toe strain gauge may be misaligned with the toe of the club to a small degree. Theoretically, these errors could cause a systematic change in the strain results for one club, which would make a valid comparison of different clubs impossible. Therefore, steps were undertaken to quantify and reduce these errors.

Figure 24 depicts the strain field at a point on the surface of an object from a homogenous material subject to uniaxial stress. The variables $\varepsilon_p$ and $\varepsilon_q$ denote the maximum and minimum principal strains, with $\varepsilon_p$ being the tensile strain created by the uniaxial stress and $\varepsilon_q$ being the strain attributable to the Poisson deformation of the elongated object. It can be seen from the figure that, as long as $\varphi$ is close to 0°, a small angular misalignment of the strain gauge will result in relatively small errors in the measured strain because the strain diagram is flat at these points (Vishay, 2007). Previous studies have shown that, for a golf shaft swung by a player, the tensile and compression strain components will be far greater than the torsional strain (Butler & Winfield, 1994; Newman, Clay, &

Strickland, 1997). Therefore, we can assume that that the maximum principal strains will be directed close to the longitudinal axis of the shaft at all times. Hence, as the intended orientation of the strain gauges coincides with this axis, errors due to this type of misalignment can assumed to be low. For the simplified scenario shown in Figure 24, a strain gauge misalignment of ±4° would result in an error of ±1.1% for a single strain gauge aligned with the direction of principal strain (Vishay, 2007).

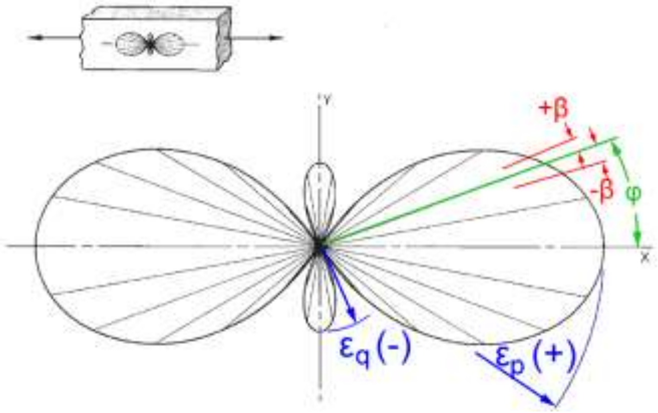



**Figure 24: Strain field created by a uniaxial stress field. $\varepsilon_p$ and $\varepsilon_q$ denote the maximum and minimum principal strains, $\varphi$ is the intended alignment angle of the strain gauge and $\beta$ is the alignment error (mod. from Vishay, 2007).**

The effect of the second error source from strain gauge placement, the misalignment of the pairs of strain gauges relative to the intended measurement plane, was quantified during a static calibration. For each club, this calibration was performed with the grip of the club clamped rigidly, with a mass of 2 kg attached to the tip end of the shaft and with an angle gauge attached to the grip. For the first data point, a spirit level was used to align the face of the club horizontally, and strain readings were taken from both pairs of strain gauges. Next, the club was rotated in 15° increments around the longitudinal shaft axis, and additional readings were taken until the club was rotated 180° relative to the starting position. The purpose of this procedure was to subject the shaft to known bending moments with the shaft in different orientations. Example results for one club are plotted in Figure 25; it can be seen from the solid lines that the maxima and minima of the measured data in the toe up/down and lead/lag plane are shifted by approximately 12° from their expected positions. If the strain gauges were aligned correctly, these peaks should have occurred at 0° and 180° for the toe up/down strain data and at 90° for the lead/lag gauges. It can further be seen from the figure that the toe strain data follow a sine curve, whereas the lead results follow a cosine curve when the given reference system is used.

(a)

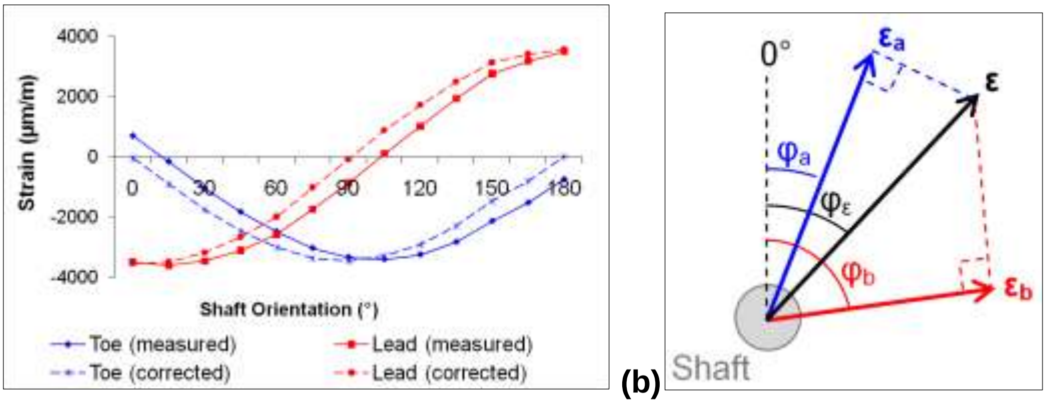



Figure 25: (a) Example results from strain gauge calibration. (b) Shaft cross section with nomenclature for calibration procedure.

In order to correct these shifts, the following procedure was developed. Using the variables shown in Figure 25 (b), the following equations can be used to determine the strain at any given point on the surface of the shaft cross section if the principal strain and the orientation of the principal strain are known:

$$\varepsilon_a = \varepsilon \cdot \cos(\varphi_\varepsilon - \varphi_a); \quad (5)$$

$$\varepsilon_b = \varepsilon \cdot \cos(\varphi_\varepsilon - \varphi_b), \quad (6)$$

where $\varepsilon_{a/b}$ is the magnitude of the strain at position *a* or *b* (µm/m),

$\varepsilon$ is the magnitude of the principal strain (µm/m),

$\varphi_\varepsilon$ is the orientation of the principal strain (rad), and

$\varphi_{a/b}$ is the orientation of position *a* and *b* (rad).

Rearranging and substituting the previous equations yields:

$$\varphi_\epsilon = \operatorname{atan}\left(\frac{\varepsilon_b \cos(\varphi_a) - \varepsilon_a \cos(\varphi_b)}{\varepsilon_a \sin(\varphi_b) - \varepsilon_b \sin(\varphi_a)}\right). \quad (7)$$

It is further possible to calculate the principal strain for any given output from the two strain gauges at positions *a* and *b*, by rearranging and adding equations (5) and (6):

$$\varepsilon = 0.5\left(\frac{\varepsilon_a}{\cos(\varphi_\varepsilon - \varphi_a)} + \frac{\varepsilon_b}{\cos(\varphi_\varepsilon - \varphi_b)}\right). \qquad (8)$$

Using the measurement procedure described above, the true orientation of the strain gauges ($\varphi_a$, $\varphi_b$) relative to a reference plane aligned with the toe of the club was determined for each shaft. Using a custom-written Matlab (Mathworks, USA) subroutine, the strain acting in the actual toe and lead/lag plane was calculated for each recorded trial using the previous two equations.

The effectiveness of this calibration procedure was tested using the data collected during the calibration. As can be seen from Figure 25 (a), the corrected (dashed) strain curves have their minima and maxima at 0°/180° and 90° for the toe up/down and lead/lag strain gauges, respectively, as expected.

### 4.4.2 Reduction of the strain data

A Matlab subroutine was used to process the recorded strain data. This subroutine identified impact using the lead/lag strain rate (giving the user the ability to check the result graphically and to adjust the impact time in case it was mis-identified), resampled the strain data to 1000 samples from take-away to impact using the Matlab function ‘resample’, and extracted the characteristic strain parameters defined in Figure 26.

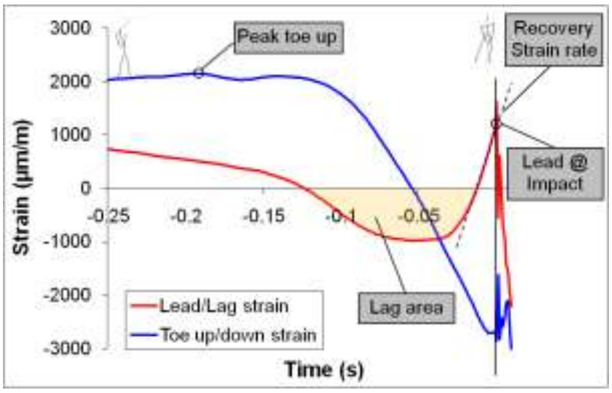



**Figure 26: Definition of characteristic downswing strain parameters.**

The rationale behind reducing the strain data to these parameters was as follows. From pilot trials, it was found that the peak toe up strain typically occurred close to the transition from backswing to downswing. Due to the change in direction, the shaft deforms significantly during this stage. Therefore, changes in shaft stiffness may result in changes to the pre-loading of the shaft and the proprioceptive feedback perceived by the golfer. The lag area (Figure 26) was used as a measure of the magnitude of strain energy stored in the shaft prior to recovery and impact. The rate of lead/lag recovery was included for its potential effects on club head speed at impact. To calculate this rate, the slope of the lead/lag strain curve was examined for the last samples before impact, covering a span of 0.005 s. Finally, the lead strain at impact was examined because, assuming the three-dimensional position of the grip at impact remained the same, increases in lead strain would contribute to increases in the effective loft angle of the club head at impact (see Figure 14, page 49).

### *4.5 Measurement of body movement*

In order to analyse the effects of different golf shafts on swing kinematics, it is necessary to record the body movement of the golfer. In previous studies, a number of different approaches have been used to accomplish this. These methods include:

- goniometers, which have for instance been used to quantify the movement of the left arm (Teu, Kim, Fuss, & Tan, 2004; Teu, Kim, Fuss, & Tan, 2006);

- combinations of gyroscopes and accelerometers ('inertial sensors'), which have been used to determine the position, orientation and velocity of putters (King, Yoon, Perkins, & Najafi, 2008);

- three-dimensional motion capture systems, which have been used for investigations into various aspects of the golf swing (see recent examples in Myers *et al.*, 2008; Zheng, Barrentine, Fleisig, & Andrews, 2008a, 2008b).

Each of these measurement approaches has its merits but also some disadvantages. For instance, goniometers allow the direct measurement of joint angles, but it has been reported that, in golf swing analysis, goniometer data for the shoulder joint can contain errors due to the movement caused by the dynamic contractions of the arm muscles, as discussed by Teu *et al.* (2006). Alternatively, gyroscopes and accelerometers may be used, but these have been found to be prone to measurement errors, particularly as double-integration is necessary to determine the positions of objects (Giansanti, Macellari, Maccioni, & Cappozzo, 2003), although it should be acknowledged that development in this area is rapid and it is likely that inertial measurement systems will become more popular in biomechanics research in the near future. Recently, a comparison of two inertial sensor systems with an optical system showed good agreement between all three systems when measuring accelerations for a reach and grasp movement (Thies *et al.*, 2007), yet the main area of application for inertial sensors currently appears to remain activity monitoring rather than movement analysis (Godfrey, Conway, Meagher, & ÓLaighin, 2008).

Several studies used optical, three-dimensional motion capture systems to record body kinematics of golfers performing swings. The majority of these systems consist of multiple cameras, each of which is equipped with an infrared light source. This infrared light is reflected from the markers, and a camera with an infrared filter registers the position of the marker. The three-dimensional position of the markers is then reconstructed using at least two sets of two-dimensional data. One advantage of these systems is that passive markers can be used, which are lightweight and can be fixed to the golfer’s skin without the need for cables or batteries. However, like other measurement approaches, optical motion capture also has some drawbacks and potential error sources that have to be considered. This will be discussed further in the sub-sections that follow.

### 4.5.1 Basic principles of optical three-dimensional motion capture

Cappozzo *et al.* (2005) performed a comprehensive review of the basic principles and the state of the art of three-dimensional motion analysis. The central aim of this type of analysis is to gather “quantitative information about the mechanics of the muscular-skeletal system during the execution of a motor task” (Cappozzo, Della Croce, Leardini, & Chiari, 2005, p. 186). To achieve this goal, researchers place reflective markers on anatomical landmarks. Using a system of definitions and conventions (see below), the three-dimensional trajectories of these markers can be used to determine the position and orientation of the body segments they refer to. If no other constraints are used, at least three non-collinear markers have to be placed on each body segment whose movement is to be studied. It is then possible to determine relative segment orientations based on this information. To do so, each body segment is usually assumed to be rigid and that markers are attached firmly. The following subsections discuss these steps in more detail.

#### *4.5.1.1 Camera set-up and instrumental errors*

Measurement results can be influenced by a number of errors, some of which are associated with the instruments used. These include camera lens distortion, camera placement, number of cameras and calibration (Nigg, Cole, & Wright, 2007). Some of these factors, such as lens distortion and calibration algorithms, are out of the researcher’s control when using commercial systems - they can only be controlled indirectly by performing validation measurements. Other factors, such as camera placement and lens settings can be optimised by the researcher using guidelines provided by manufacturers or in the literature (see, for example, the BASES guidelines provided by Milner, 2008).

#### *4.5.1.2 Estimation of segment position and orientation*

When the motion capture system has been set up and calibrated successfully, it is necessary to devise an efficient marker set which allows monitoring of the movement of the body segments under observation without providing unnecessary or redundant information. Typically, the markers contained in the set define one technical frame per body segment under observation. Most importantly, this marker set should allow the researcher to report body segment orientations in a useful reference system. In most cases, the preferred output reference system is anatomical. Hence, the relationship of the technical frame and the anatomical frame needs to be known (Cappozzo, Della Croce, Leardini,

& Chiari, 2005). This can either be achieved by placing the markers on relevant bony landmarks, so that the technical frame coincides with the relevant anatomical frame, or by performing a static calibration trial. During this calibration trial, additional markers or a digitising pointer (Cappozzo, Catani, Della Croce, & Leardini, 1995) are used to determine the position of the anatomical frame relative to the markers used to track the segment's movement. These tracking markers can be placed arbitrarily relative to the segment, which allows the researcher to place them so that visibility of the markers is maximised and skin movement artefact is minimised.

Skin movement artefact is caused by movements of the markers relative to the bone and can cause significant errors because the assumption of a rigid connection between the marker and body segment will be compromised. In gait analysis, errors of up to 10% for flexion/extension, 20% for abduction/adduction and 100% for internal/external rotation were found (Leardini, Chiari, Della Croce, & Cappozzo, 2005). After performing a review of the state of methods aiming to minimise skin movement artefacts, these authors state that "a reliable estimation of skeletal motion in *in vivo* experiments has not yet been achieved satisfactorily" (Leardini, Chiari, Della Croce, & Cappozzo, 2005, p. 223). One of the main difficulties lies in the fact that skin movement will cause un-correlated noise at the same time as systematic errors. For instance, a marker that is placed close to another segment at a joint may be influenced by random vibrations of the skin but also by another, joint angle-dependent, error component, as the skin will move relative to the bone when the joint angle changes.

As a result of these factors, accurate interpretation of joint angle histories is necessary, with the possible effects of skin movement artefacts in mind. This is a particular problem when looking at rotation components that are relatively small compared to the major rotation component (see above example for internal/external rotation of the knee).

#### *4.5.1.3 Determining joint angles*

Once the position and orientation of the segmental anatomical reference systems relative to the global coordinate system is known, it is often necessary to express this absolute data in relative terms to aid interpretation. For example, in a golf swing, information regarding the absolute orientation of the forearm may be difficult to interpret unless it is converted to orientations relative the humerus. If the local reference system of the segment was chosen to coincide with the relevant anatomical planes, these relative orientations of the forearm can then be interpreted as flexion/extension and pronation/supination. One of the standard approaches to this problem will be discussed in the section that follows, although it should be noted that other approaches exist (for example based on finite helical axes, see Woltring, 1991).

Grood and Suntay (1983) suggested the use of a joint coordinate system (JCS) to determine relative joint angles, using the knee joint as an example. Within this reference system, the first rotation axis ($e_1$) was part of the thigh and directed medial-laterally, the third rotation axis ($e_3$) was the longitudinal axis of the shank segment and the second rotation axis ($e_2$) was the cross-product of $e_1$ and $e_3$ ('floating axis'). Anatomical joint angles can then be expressed as rotation of the floating axis around $e_1$ (flexion/extension) and of the floating axis around $e_3$ (internal/external rotation). Grood and Suntay's approach was later extended to be applicable to joints other than the knee joint and was found to be equivalent to a series of Cardan rotations (Cole, Nigg, Ronsky, & Yeadon, 1993). Cardan as well as Euler rotations are commonly used to describe the orientation of one reference system relative to another (Hamill & Selbie, 2004). They generally consist of three rotations performed in a specific order (in Grood and Suntay's method this order could be interpreted as flexion/extension, abduction/adduction, internal/external rotation). Results will depend on the choice of rotation sequence, as demonstrated by Cole *et al.* (1993), although, if the range of angles is sufficiently small, it is possible that different sequences produce similar results (Schache *et al.*, 2001). In most cases, however, body segment rotations obtained using different definitions will produce different results and cannot be compared easily (as demonstrated for upper body alignment in the golf swing by Wheat, Vernon, & Milner, 2007).

The sequence-dependency resulted in the need for standardisation to ensure that comparisons between different studies would be valid. Hence, the International Society of Biomechanics (ISB) proposed standard definitions for the reference systems and rotation sequences for the lower body (Wu *et al.*, 2002) and the upper body (Wu *et al.*, 2005). Further details regarding the definition of segment coordinate systems and joint angles can be found in Chapters 5, 6 and 7.

### 4.5.2 Camera set-up and validation

A number of different camera set-ups were used throughout this thesis. Detailed descriptions of each set-up in terms of camera positions and data processing will be presented as part of the chapters describing each study. The purpose of this section is to present the results of validation studies performed using the different set-ups.

Different test methods are available to ensure the accuracy and precision of a motion capture system, as for example summarised in a review of instrumental errors in motion capture (Chiari, Croce, Leardini, & Cappozzo, 2005). Typically, two markers are positioned on a rigid rod and moved through the measurement volume whilst the camera system records the movement. The distance between these markers is then calculated for each frame, and the variation in this distance gives an indication of the precision of the measurement. If the true distance between the two markers is known, the accuracy of the system may also be quantified, for example by calculating the RMS error. The results for this test may be influenced by the type of movement performed and the size of the capture volume, so the movement performed during the test should be representative of the type of movement to be analysed in the study.

In the case of the current project, the distance between two markers attached to a rigid rod was used as a measure of accuracy and precision. For the studies involving human players (Study 1 and 2), this rod was identical to the one that was attached to the club to track the movement of the club (see reflective markers in Figure 22, page 76). For the robot study (Study 3), two markers that were attached to the arm of the robot were selected. From each study that involved human subjects, five trials were randomly selected to be included in the validation data set after confirming that there was little variation in accuracy and precision results throughout different trials. For the robot study, four trials representing different speeds were randomly selected for validation. In all cases, the swing was analysed for all periods for which the reference markers were visible between take-away to impact.

In addition to the inter-marker distances, average residuals were used to ensure that the marker data were reliable for all subjects. Residuals are an artefact caused by the fact that, in a real measurement scenario, rays from different cameras registering the centroid of a marker will not intersect in one point but pass each other with some distance. Therefore, it is necessary to use an optimisation algorithm to find the ‘best’ marker location, i.e. the location where the residuals are smallest (Nigg, Cole, & Wright, 2007). The motion capture systems used throughout this thesis report the average residual for each camera for a given measurement. The average of these residuals was computed using one randomly selected file per player as an additional measure of data quality.

Table 9 summarises the results of the error estimation performed with the motion capture systems. It can be seen that the average residuals for all systems were smaller than 1 mm, which is similar to the residuals reported by Nesbit (2005). Accuracy was also better than 1 mm in all cases, which compares well to RMS errors of 20.1 mm (Coleman & Rankin, 2005), 4.1 mm (Coleman & Anderson, 2007) and 2 mm (Myers *et al.*, 2008). The SD of a constant inter-marker distance, used as a measure of precision, were smaller than 0.5 mm for all set-ups, which also indicates acceptable precision of the measurement systems used.

**Table 9: Average residuals, accuracy and precision result for the different motion capture systems and set-ups used throughout this thesis.**

| System | Number of cameras | Frame Rate (Hz) | Use | Average reported residual (mm) | Accuracy (RMS error) (mm) | Precision (SD of inter-marker distance) (mm) |
|---|---|---|---|---|---|---|
| Pro Reflex | 8 | 240 | Study 1 | 0.749 | 0.858 | 0.405 |
| Oqus | 7 | 500 | Study 2 | 0.783 | 0.238 | 0.326 |
| Oqus | 3 | 1000 | Study 2 | 0.603 | 0.252 | 0.260 |
| Oqus | 7 | 1000 | Study 3 | 0.425 | 0.674 | 0.246 |

### 4.5.3 Marker set, body model and calculation of joint angles

Whenever possible, the ISB recommendations for the definition of local coordinate systems and Cardan/Euler sequences (Wu *et al.*, 2005) were used throughout this thesis. However, it was decided that the original conventions, suggested by Grood and Suntay (1983), were to be used for the nomenclature of the reference axes. This standard is consistent with the conventions used in the data collection software (QTM, Qualisys, Sweden) and the data processing software (Visual3D, C-motion, USA) used throughout this study and avoids the need to transform the data manually. With the athlete in the anatomical position, each segment coordinate system had its z-axis pointing along its proximal to distal axis, its y-axis to the front and its x-axis to the right (medially for the arm segments). The ISB standard for the upper body only defines reference systems for the right arm and recommends applying these to the left arm by mirroring the data. In this point it was also decided not to comply with the ISB standard as mirroring the data would effectively have introduced left-handed coordinate systems, which may lead to difficulties when using standard software to process the data and when interpreting the results.

Additional details concerning the calculation of joint angles will be included in the chapters describing each study.

### *4.6 Measurement of club head presentation and launch conditions*

It was deemed important to quantify the way that the player presented the club head to the ball at impact and the launch conditions of the ball so that changes in these variables could be monitored. The set-up used for the human tests consisted of a hitting bay adjacent to an open driving range (see Section 4.1.2). This would have allowed using total distance and dispersion as the only outcome measures; however, this would have made results susceptible to external influence from changes in weather conditions.

Various different systems are available to quantify club head presentation and launch data. Methods that are commonly used include radar devices taking advantage of Doppler effects (Flightscope, 2009; Tuxen, 2008), stereoscopic launch monitors (Accusport, 2009), multiple cameras (Williams & Sih, 2002), light gates (Betzler, Kratzenstein, Schweizer, Witte, & Shan, 2006) or laser grids (Golfachiever, 2003). The choice of systems for the studies presented in this thesis were based on the availability of launch monitors, the quality of the data obtained and the specific requirements of each study. For these reasons, a number of different systems (Table 10) were used for the different studies. The purpose of this section is to present results of studies performed to determine the accuracy and precision of the measurement devices that were used.

**Table 10: Launch monitor systems used in validation tests and studies**

| ID | System | For validation see Section | Application |
|---|---|---|---|
| 1 | Stereoscopic | 4.6.1 and 4.6.3 | Study 3 |
| 2 | Radar-based | 4.6.1 and 4.6.3 | Study 1 and 2 |
| 3 | Camera-based | 4.6.3 | Study 2 and 3 |

When estimating measurement errors, one possibility is to differentiate accuracy and precision. Accuracy is the difference between the true and the observed value in a measurement, whereas precision is quantified by deviations in repeated measurements of a true value that remains unchanged (Challis, 2008). This means that it is possible to measure a value with high precision (i.e., variations in repeated measurements are small) but with low accuracy (i.e., the mean of these repeated measurements does not represent the true value), and vice versa.

One option to assess the reliability of a measurement device is to investigate whether its results correlate with measurements taken simultaneously with a reference device. This is discussed in detail by Atkinson and Nevill (1998) in the context of reliability studies in sports science. As Atkinson and Nevill highlight, the outcome of this type of correlation will depend on how heterogeneous the sample was. That is, if the range of the measurements taken is small relative to the accuracy of the device, the coefficient of determination ($r^2$) will be small. Conversely, a high $r^2$ will be achieved easily if the range of measurements used in the validation study is large relative to the accuracy of a measure. Because of this effect, results of validation studies using $r^2$ as a measure of agreement between measurements and reference values can only be applied to studies using a sample taken from an identical or very similar population compared to the population used for the reliability study (Atkinson & Nevill, 2001). Therefore, root mean square error (RMS error) is used in this thesis rather than $r^2$ to quantify the discrepancies between measured and true values, and precision will be quantified by calculating the standard deviation (SD) of repeated measurements of a constant true value (Challis, 2008). In the two sections that follow, the accuracy and precision of the launch monitors used in this thesis will be assessed, and the development of a custom designed measurement system using motion capture cameras will be described.

### 4.6.1 Comparison of commercial measurement devices

As the human studies presented in this thesis involved golfers hitting balls on a driving range, the preferred launch monitor system was radar-based. This was motivated by the fact that this system would provide club head presentation and ball launch data as well as information regarding the trajectory of the ball. Furthermore, the radar system does not require any specific markers on the club head and the ball and is placed some distance away from the player, hence being less intrusive. It was felt that this would help to keep interference with the golfers’ normal swing pattern to a minimum. In order to assess the accuracy and precision of this launch monitor, a validation study was performed.

#### 4.6.1.1 Methods

A golf robot was used to compare launch monitors. This was because pilot studies showed that it could perform highly repeatable swings, thereby providing ideal conditions for the precision tests. This robot was set up to achieve club head speeds at impact of approximately 35, 40, 45 and 50 m/s with seven different drivers. These impact speeds were chosen to cover the range expected in the human tests. Five swings were recorded at each speed setting and with each club, resulting in 140 shots in total. Each shot was recorded with launch monitors 1 and 2 simultaneously. If data for one of the systems were not available for a shot, data for this shot were disregarded and additional shots recorded, if possible. Following data collection, the RMS of the discrepancies between values reported by the two devices for club head speed, ball speed, launch angle and spin were calculated. The purpose of calculating the RMS was to assess the accuracy of the launch monitor relative to an alternative device. Because no ‘gold standard’ launch monitor was available it was not possible to assess the absolute accuracy. Additionally, the SD of each set of five shots recorded under identical conditions (same club and robot settings) was calculated, and the mean value of all SDs was computed as a measure of precision.

#### 4.6.1.2 Results

Club speeds ranged from 36 to 50 m/s, ball speeds from 53 to 73 m/s, launch angles from 6 to 10° and spin from 1400 to 2800 rpm. It is worth noting that maximum launch angles were relatively low compared to those seen in pilot tests with human players but that all other variables were considered to cover a range that would be expected to occur in the actual studies. The results for the comparison of devices 1 and 2 are shown in Table 11. For the launch angle variable, a trend towards a curvilinear relationship between measurements from the two devices was noted[8].

[8] For reference, correlation plots for a comparison of launch monitor 1 and 2 are provided in Appendix B.1.

**Table 11: Results from comparison of launch monitors 1 and 2. The RMS error quantifies the magnitude of the discrepancies between the two systems. SD is a measure of the precision of measurements taken with system 2 from repeated robot swings.**

| | | Club speed (m/s) | Ball speed (m/s) | Launch angle (°) | Spin (rpm) |
|---|---|---|---|---|---|
| **Accuracy** | RMS error | 0.313 | 0.308 | 0.532 | 92.2 |
| **Precision** | SD | 0.114 | 0.100 | 0.189 | 71.5 |
| | COV | 0.265% | 0.159% | 2.34% | 3.69% |

#### *4.6.1.3 Conclusion*

Given that previous authors observed increases in ball speeds greater than 1 m/s associated with changes in shaft stiffness (Worobets & Stefanyshyn, 2007), the accuracy as well as the precision of the club speed measurement (see Table 11) appeared to be acceptable. No reference data were found that could be used to estimate the expected change in ball speeds, launch angle or spin, but the results were also deemed acceptable for the purposes of this study as smaller changes were expected to have no significant effect on the performance of a club as perceived by the golfer.

### 4.6.2 Development of a custom club head tracking system

Hocknell (2002) reported that, for a given club head speed, the resulting ball speed dropped significantly when impact between club head and ball did not occur at the centre of the club face. Furthermore, changes in impact location can have a significant effect on the trajectory of the ball because of side spin imparted to the ball through the gear effect (Cochran & Stobbs, 1968). Impact location can therefore be regarded as an important factor influencing the efficiency of impact. Changes in shaft stiffness have been associated with shifts in the impact locations for individual golfers (Stanbridge, Jones, & Mitchell, 2004). Therefore, measuring the impact location of the ball along with the other launch variables was considered, with a view to being able to resolve whether potential changes in the launch conditions of the ball were related to changes in club path and orientation or impact location. Being able to resolve the reason for potential changes may help in understanding the mechanism behind these changes.

At the time of testing, no launch monitor able to report impact location was available, so alternatives were sought. Manual methods for measuring impact location such as impact face tape (Golfworks, USA) or impact spray (as utilised by Stanbridge, Jones, & Mitchell, 2004) were considered but disregarded because of the testing time added by manually registering impact positions after each shot and the unknown effects of these methods on launch conditions. Furthermore, it is inevitable that these methods provide the golfer with feedback regarding the impact location. This feedback would go beyond what the golfer would normally perceive in terms of tactile feedback after impact. Previous authors gave direct feedback to golfers regarding their club head speed and commented that this may have affected the golfers by causing them to focus on achieving maximum club head speed and neglecting other factors (Egret, Vincent, Weber, Dujardin, & Chollet, 2003). Suspecting that a similar effect may occur when providing direct impact location feedback, the possibility of using other methods was investigated.

Williams and Sih (2002) suggested a method that provided no direct feedback and involved no changes to the club face by utilising a three-dimensional motion capture system to measure impact location. After performing a calibration procedure to register the position of the club face relative to three non-collinear markers attached to the butt end of the shaft and the club head, the tee position was determined by placing a reflective ball on the tee. After registering its position, this ball was replaced with a normal golf ball. Following the swing, the data were post-processed to determine the club head path and orientation as well as the impact location. Because this approach allowed the determination of the impact location with minimal interference to the golfer, it was decided to develop a similar club head and impact location tracking system using a three-dimensional motion capture system.

#### *4.6.2.1 Aims of development*

The aim of the development process was to design a system that accurately determined the club head path as well as the position of the ball and then combined these sets of data to calculate the impact location on the club face. The system had to meet the following additional conditions:

- Interference with the player's swing was to be kept to a minimum. Hence, markers added to the club head had to be small and attached securely.
- With cameras and additional equipment in position, the golfer should not feel restricted in his movement.
- Players should be free to adjust tee position and height, so use of a fixed tee was not acceptable.
- The system needed to operate in an open hitting bay with changing light conditions.
- The player was expected to be able to perform swings at his/her own pace, so the data processing had to be finished seconds after the shots or performed after the test session. The system needed to trigger automatically to allow the player to initiate the swing at any time.
- The number of cameras used for the system had to be kept to a minimum so that there would still be cameras available to record the player's body movement.

#### *4.6.2.2 Methods*

Based on the aim and the conditions presented above, it was decided to utilise an Oqus 300 (Qualisys, Sweden) camera system for club head tracking. This system consists of infrared cameras operating at a frequency of up to 500 Hz at full resolution (1280x1024 pixels) or at higher frequencies at a reduced resolution. Hence, a trade-off had to be found in terms of temporal accuracy (high frame rate) and spatial accuracy (high resolution). Another compromise had to be found in terms of capture volume and spatial resolution, as capture volume increases as cameras are moved away from the object but spatial resolution decreases at the same time (Milner, 2008). After pilot tests using tripods and capture rates of 500, 1000 and 2000 Hz, it was decided that a capture rate of 1000 Hz and attachment of the cameras to trussing extending from the lab ceiling would result in adequate data and would avoid interference with the golfer. As only two cameras are necessary to reconstruct the three-dimensional coordinates of a marker, pilot tests were carried out with two cameras. However, it was found that producing redundancy in the acquired data by introducing a third camera increased the robustness of the measurements. Therefore, three cameras were used. An acoustic trigger was placed approximately 1 m from the tee position to provide a trigger signal when registering the sound from the impact of the club head with the ball (see Figure 27).

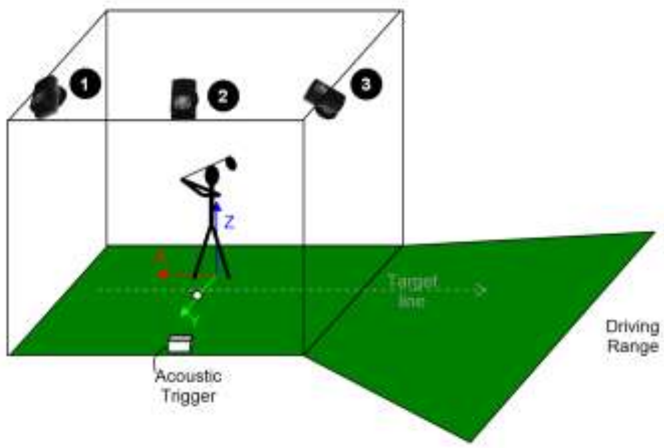



**Figure 27: Setup of custom club head tracking system (cameras: ➊-➌).**

Three reflective markers were attached to the crown of the club and another, self-adhesive flat marker was placed on the ball (diameter of all markers: 5 mm). Players were instructed to place the ball on the tee with the reflective marker facing upwards and aligned with the vertical axis of the global reference system, thereby ensuring that the marker was visible to the cameras. Before each test session, the software Visual3D (C-motion, USA) was utilised to record the offset of the corners of the club face and the face centre relative to the three tracking markers on the club head. It should be noted that the placement of all three markers on the crown of the club head will result in an increased measurement error when calculating the position of points that are not on the same plane as the marker triad, such as the sole markers on the face. Future studies should consider the use of an additional tracking marker placed on the hosel of the club to avoid this effect.

The cameras were set to collect data continuously before the beginning of each swing, but only camera data from 0.05 sec before receiving a trigger signal from the sound trigger until just after impact was transferred and saved to the computer controlling the camera system.

After labelling the markers, their trajectories were exported to the software Visual3D in order to calculate the trajectories of the virtual offset markers positioned at the corners of the club face and the face centre. Further processing was performed using a number of user-written subroutines in Matlab (Mathworks, USA). These subroutines loaded the face corner trajectories exported from Visual3D and identified the last frame captured before impact for each swing. This frame was identified based on the distance between a plane defined by the face markers and the ball marker (offset by half a ball diameter in the negative z-direction (downwards) and along the x-axis (backwards) to account for the fact that the ball marker was not placed at the contact point between club head and ball but at the top of the ball). The definition of the distance between club face and offset ball marker is illustrated in Figure 28.

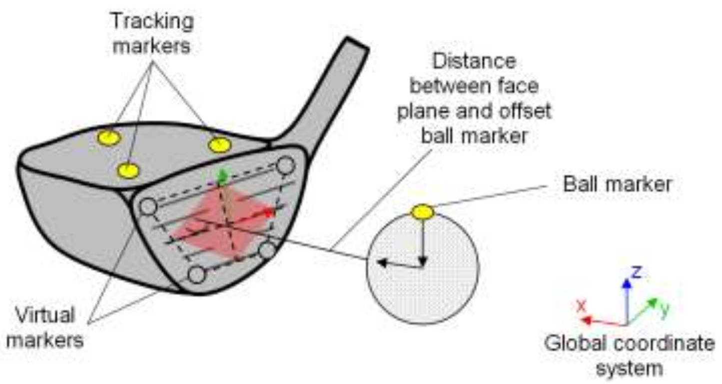



**Figure 28: Definition of face plane and distance to offset ball maker.**

Even at a sample rate of 1000 Hz, impact will typically occur at some point between two frames because contact between the club head and the ball only lasts approximately 450 µs (Hocknell, Jones, & Rothberg, 1996). The trajectory of the club head after impact will be influenced by the effects of the impact between the club head and the ball, so only data collected up to the last frame before impact can be used to calculate the impact location. Therefore, the x-, y-, and z-components of the markers defining the corners of the club face were extrapolated beginning from the last frame before impact. The extrapolation was performed by fitting a third order polynomial to the trajectory, neglecting any data collected post-impact, and evaluating the polynomial for each of the desired extrapolation points (see Figure 29). A total of 100 extrapolation points were used; each separated to the next one by one hundredth of the time between frames. These were subsequently used to determine the precise impact time.

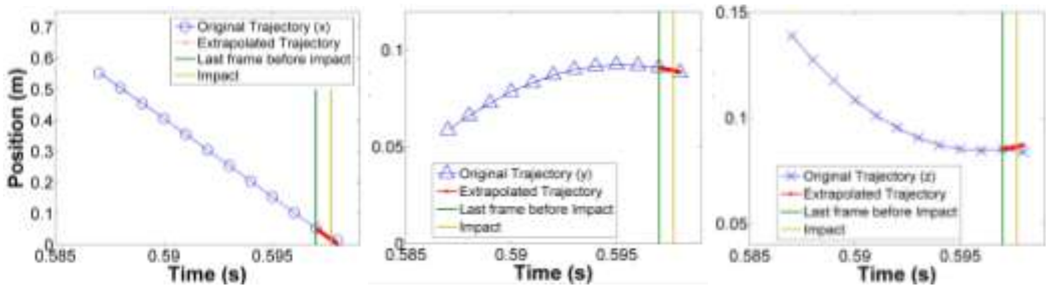



**Figure 29: Example for results from the extrapolation algorithm.**

The impact time was found by calculating the distance between the offset ball marker and a plane defined by the club face markers for each of the extrapolated sets of marker positions. This is a similar method to that used to identify the frame before impact. Once the impact time was found, the impact point was converted from the global coordinate system to a local club face coordinate system in order to determine the impact location on the club face.

The club head speed of the centre of the club face in the instant before impact was determined using third order backward finite differences. Extrapolating the trajectory of the face centre to the estimated impact time between frames required the derivation of a backward difference formula for non-uniform step sizes (see Appendix C, p. 205).

### 4.6.3 Validation of a custom club head tracking system

Validation of the custom club head tracking system was performed for impact location, club head speed and face angle data separately.

#### *4.6.3.1 Impact location*

A golf robot was utilised to perform the validation because of its ability to perform repeatable swings. It is further possible to adjust the tee position accurately whilst leaving all other swing settings the same. This functionality was used to assess the accuracy of the impact location algorithm by performing 16 sets of six repeated swings. Between these sets of swings, the tee position was adjusted systematically by a known distance so that a grid of impact positions was covered throughout the test ('face mapping', as described by Olsavsky, 1994). The grid consisted of three horizontal rows of five points, with a grid point separation of 6 mm vertically and 11 mm horizontally. One additional grid point was added at a position 11 mm from the last point of the middle row towards the toe.

The impact locations recorded from the face mapping swings are shown in Figure 30. It can be seen that the face mapping grid was accurately reproduced by the custom club head tracking system. However, central impacts (marked with red diamonds) were not registered at the centre of the coordinate system but slightly offset. This error was assumed to be related to different face centre definitions being used in the software and when setting up the robot. Therefore, the offset was removed before the numerical analysis of the test results. It is suggested that future studies should use an additional virtual offset marker at the face centre to ensure an appropriate placement of the reference system.

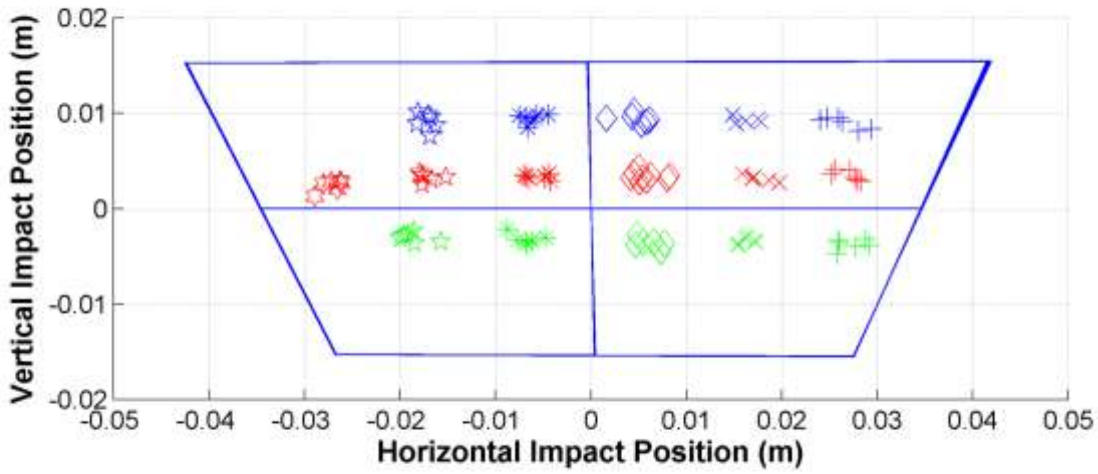



**Figure 30: Face mapping results. The rows of grid points (blue, red, green) were separated by 6 mm, columns by 11 mm.**

Numerical results for the impact location measurement system are summarised in Table 12. Accuracy was determined by calculating the RMS error based on the discrepancy between the pre-set tee positions and the reported impact locations. Precision was estimated by calculating the mean of the SDs of the six repeated swings per impact grid location. The accuracy results compare well to results presented by previous authors for a similar system, who reported mean absolute errors of 1 mm in the horizontal position and 2.4 mm in the vertical direction (Williams & Sih, 2002). It should be noted that RMS error is regarded as a more conservative measure of accuracy than the absolute mean error (Challis, 2008), so it is likely that the system used in this study is more accurate than the system presented by Williams and Sih (2002).

**Table 12: Numerical results from impact location measurement validation.**

| | | **Horizontal impact location (mm)** | **Vertical impact location (mm)** |
|---|---|---|---|
| **Accuracy[a]** | RMS error | 1.592 | 0.718 |
| **Precision** | SD | 0.131 | 0.151 |

[a]after removing a systematic offset of 6 mm (horizontally) and 3 mm (vertically) caused by different definitions of the face centre.

#### 4.6.3.2 Club head speed

In order to assess the accuracy of the club head speeds reported by the club head tracking system, two measurement systems were used simultaneously when performing Study 3 (see Chapter 7). For each of six different drivers, ten swings were performed at each of four different swing speeds using a golf robot. For five of these swings, the motion capture cameras were used to track the club head and ball position. For the other five swings, a commercial stereoscopic launch monitor was used to determine the club head speed. It was not possible to use both systems simultaneously because of different sets of reflective markers used by the two devices. After an initial warming up of the motor powering the robot, it was found to produce highly repeatable swings, so this was not deemed to be a problem.

To validate the precision of the club head speed results generated by the club head tracking system, the data set that was generated when validating the impact location component of the system was used. This was possible because the swing settings of the robot remained unaltered and only the tee position was adjusted during the face mapping test (see previous subsection).

Results for the club head speed validation are summarised in Table 11[9]. By comparing Table 11 and Table 13, it can be seen that the accuracy of the club head speed measurements was similar when comparing two commercial systems against each other (0.313 m/s) and when comparing the user-developed system to a commercial system (0.316 m/s). As discussed in Section 4.6.1, this level of accuracy was deemed acceptable. The precision of the motion capture based system was lower than that for the commercial system that was validated in Section 4.6.1. Nevertheless, it was decided to accept this level of precision because it was below the shaft-induced changes in club head speed reported by other authors (Worobets & Stefanyshyn, 2007).

[9] For reference, a correlation plot comparing the results from device 1 and 3 is prvided in Appendix B.2.

**Table 13: Results from club head speed validation.**

| | | Club head speed (m/s) |
|---|---|---|
| **Accuracy**[a] | RMS error | 0.316 |
| **Precision**[b] | SD | 0.171 |
| | COV | 0.321% |

[a]After removing a systematic offset of 1 m/s between the two systems that was most likely caused by the two systems using different reference locations.

[b]From 100 repeated robot swings performed with identical swing settings.

*4.6.3.3 Face angle*

To assess the accuracy of reported face angles, no direct comparison to reference data was possible because no alternative measurement device was available at the time of testing. However, the robot used for the rest of the validation studies provides the facility to adjust the face angle whilst keeping all other settings identical. This was used to perform a test in which five sets of five swings were carried out. Between each set of shots, the face angle was adjusted, and the resulting change in face orientation determined with the club held statically in the impact position. This will introduce some inaccuracies because the relationship between changes in static and dynamic face angle will not necessarily be linear. However, as it was expected that the effect of small face angle changes on the overall dynamics of the swings would be small and no alternative solution was available, this was deemed acceptable. After adjusting for a systematic offset between the static and dynamic measurements, the RMS of the discrepancies between the static and dynamic measurements was found to be 0.934°.

In terms of precision, the face mapping data set was used (see above) because it provided a data set of 100 swings performed with identical swing settings. The SD of the face angles determined for these swings was 0.200° (COV: 4.23%).

Williams and Sih (2002) reported an average absolute error of 0.57° for their face angle measurements, which is smaller than the RMS errors found in the present validation study. However, they obtained this value from a validation that was completely static, using an angle gauge and their motion capture system. It is likely that a more realistic, dynamic validation would have increased their error value as sampling the dynamic movement of the club head at a limited sample rate would have introduced an increased discretisation error. Furthermore, it is not possible to determine whether some of the errors seen in the validation performed here have to be attributed the fact that reference measurements were taken under static conditions. As the precision of the face angle measurements was good, and it was most important for the studies to detect relative changes, the face angle measurement system was accepted as suitable.

#### *4.6.3.4 Conclusion*

In conclusion, it was decided to accept the level of accuracy and precision provided by the motion capture based club head tracking system for the purposes of this study.

# 5 Effect of shaft bending stiffness on human joint kinematics, shaft bending and launch conditions

### *5.0 Introduction*

This chapter describes the specific aims and methods as well as the results of the first experimental study performed as part of this thesis.

As outlined in Chapter 3, the motivation for the present study was to improve understanding of the effects of shaft bending stiffness in three key areas:

(1) Club head speed at impact and ball launch conditions (ball speed, launch angle and side angle).

(2) The amount of shaft strain at the transition from backswing to downswing, shortly before impact and at impact.

(3) Thorax rotation and angular displacement at the elbow and wrist joint.

The rationale for including club presentation and launch conditions (1) was that if shaft deflection at impact changes with shaft stiffness (Maltby, 1995), this could have an effect on the club head presentation to the ball (see Section 2.6.3, p. 46) and on impact velocity (see Section 2.6.4, p. 49). In the literature review, however, little scientific evidence for these claims could be found.

The motivation for studying the bending patterns for different shafts (2) was that, whilst various studies presented bending patterns for one type of shaft and a limited number of subjects (Butler & Winfield, 1994; N. Lee, Erickson, & Cherveny, 2002; Milne & Davis, 1992; Newman, Clay, & Strickland, 1997), no previous study performed a comparison of bending patterns for different shafts. It was expected this data would complement findings in area (1) and aid their interpretation.

The rationale for studying (3) was that simulations performed by MacKenzie (2005) showed that shaft stiffness would have no significant effect on club head speed at impact, but only if the player adjusted the swing depending on shaft stiffness to maintain an efficient swing. So far, experimental validation of this finding has been limited. Key areas (2) and (3) are linked because even if the movement of the player did not change depending on the shaft used, it is likely that shaft stiffness would have an effect on the magnitude of bending that occurs throughout the swing. It is further expected that analysis of the player's body movement will help identifying the mechanism behind any potential changes in launch conditions induced by shaft effects.

Besides the primary objectives presented above, it was deemed important to ensure that learning and warm-up effects as well as fatigue effects would not affect the results, as it is not within the scope of the present study to analyse these effects.

## ***5.1 Methods***

### 5.1.1 Data collection

A group of 17 male golfers participated in the present study (Table 14). All of these golfers were able to hit shots consistently (handicap ≤ 5), as discussed in Section 4.1.3 (p. 65), and used right-handed golf clubs. Each player tested three test clubs blindly and in a randomised order. Randomisation was achieved by using the Latin square method (Laywine & Mullen, 1998), which ensured that each sequence of clubs was used in an identical number of test sessions. The same clubs were used by all players, comprising clubs with an l-flex, r-flex and x-flex stiffness rating (see Section 4.2, p. 70). All shafts were painted black to prevent the players from being able to recognise the different shaft types based on their colour and markings. Players were not told how each differed, and they were asked not to manipulate the clubs between swings to detect where the difference lay (e.g. bending shaft manually or 'waggling' the club). Practice swings without hitting the ball were allowed.

Informed consent was obtained from each player (see Appendix D, p. 208), and the study was approved by the Ethics Committee of Edinburgh Napier University's Faculty of Health, Life and Social Sciences.

**Table 14: Mean characteristics of participants (±SD).**

| Handicap | Age (years) | Height (m) | Body mass (kg) |
|---|---|---|---|
| 1.76 (±1.86) | 32.12 (±9.37) | 1.78 (±0.06) | 81.39 (±9.71) |

After the researcher attached clusters of reflective markers to the player's body, each player performed a self-selected warm-up, followed by the marker calibration procedure described below (see Section 5.1.2 for details regarding the marker set). For each of the test clubs, recording of the test trials commenced immediately after the player performed a self-selected number of familiarisation swings. Six shots were recorded for each of the three clubs (see Section 4.1.5, p. 67). After testing the three test clubs in randomised order, the club that was tested first was presented to the player again as a 'fourth club', without revealing that it was identical to the first club. This repetition was included to detect changes in the test setup or the player's swing that may have occurred throughout the duration of the test. The resulting order of conditions for each subject is presented in Table 15. Testing concluded with a full disclosure of the test protocol to the golfer (including the repeated test of the first club).

**Table 15: Order of test conditions.**

| | Test conditions | | | | | Test conditions | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Player** | **First** | **Second** | **Third** | **Fourth[a]** | **Player** | **First** | **Second** | **Third** | **Fourth[a]** |
| **1** | L | R | X | L | **10** | X | L | R | X |
| **2** | L | X | R | L | **11** | X | L | R | X |
| **3** | L | X | R | L | **12** | L | R | X | L |
| **4** | X | R | L | X | **13** | X | L | R | X |
| **5** | R | L | X | R | **14** | L | R | X | L |
| **6** | L | X | R | L | **15** | X | R | L | X |
| **7** | X | R | L | X | **16** | R | X | L | R |
| **8** | R | X | L | R | **17** | R | X | L | R |
| **9** | R | L | X | R | | | | | |
| **swing** | 1-6 | 7-12 | 13-18 | 19-24 | **swing** | 1-6 | 7-12 | 13-18 | 19-24 |

[a]Note that the fourth condition is identical to the first condition for each player.

Movement trajectories of the reflective markers were recorded using an eight camera ProReflex motion capture system (Qualisys AB, Sweden), operating at 240 Hz (see Figure 31). The system was calibrated according to the manufacturer's instructions and appropriate checks performed to ensure that the collected data were accurate (see Section 4.5.2, page 86). The analogue strain signals from the instrumented golf clubs were amplified with two P-3500 analogue strain amplifiers (Vishay, USA) and recorded synchronously with the body movement via a Qualisys A/D board at a sample rate of 960 Hz.

Launch conditions were recorded with a commercial launch monitor (see Section 4.6.1, p. 90, for details).

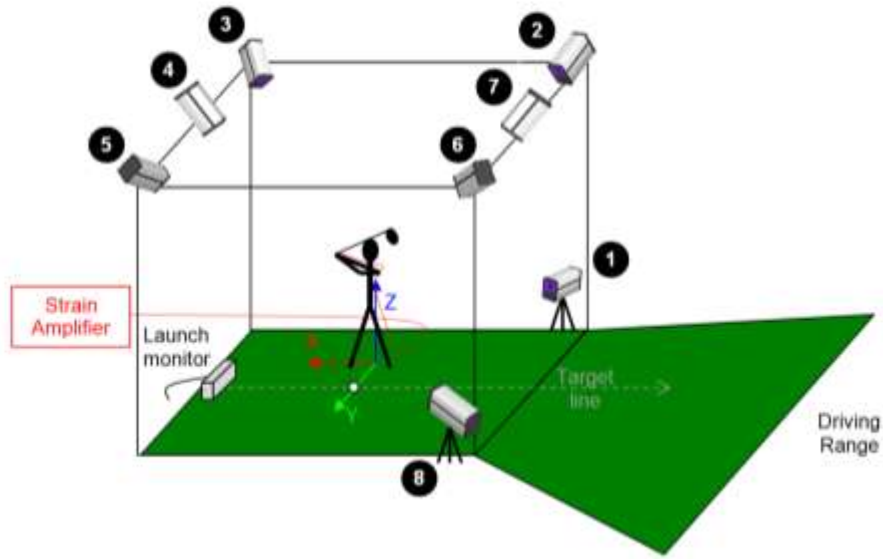



**Figure 31: Set-up for player testing (cameras: ❶-❽).**

### 5.1.2 Calculation of angular joint displacements

In order to quantify the body movement throughout the swing, the players wore a pelvis belt, a vest, a humerus arm band, a wrist arm band, and a golf glove, all of which had markers attached to them (see Figure 32). The marker diameter was 12 mm for the arm markers and 19 mm for the trunk markers, with the smaller markers chosen for the arms to keep the size of the marker clusters as small as possible. The items holding the markers were designed so that at least three non-collinear markers could be attached to the corresponding body segment whilst keeping restrictions to the range of movement of the player to a minimum. It was felt that this solution, although expected to be potentially less accurate than attaching the markers directly to the skin (Milner, 2008), was more appropriate for the golfers in this particular study because the golf swings were performed in an open hitting bay.

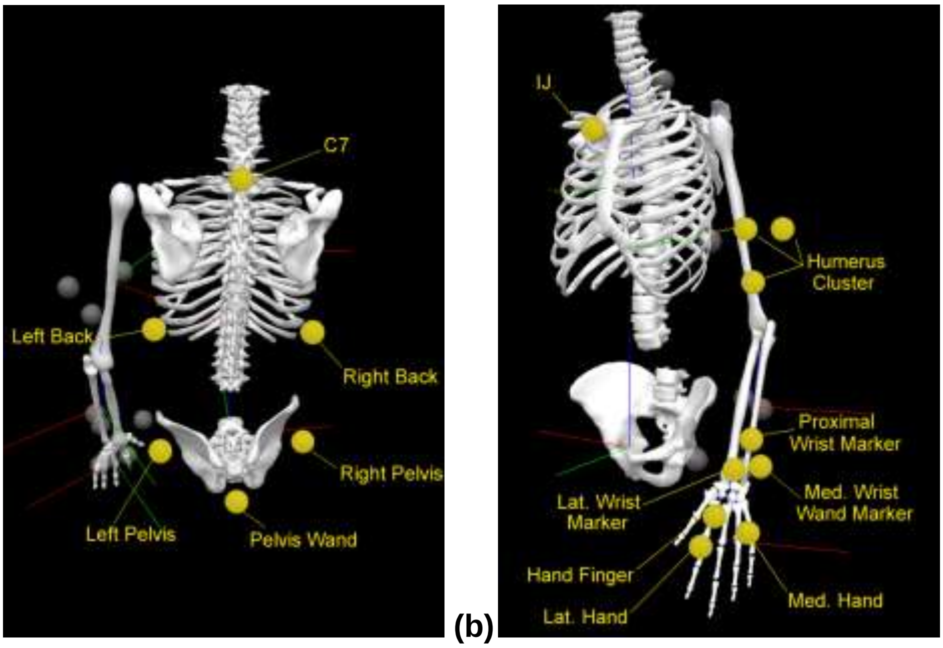
(a) (b)



**Figure 32: Placement of (a) posterior and (b) anterior markers.**

The software Visual3D (C-Motion, USA) was used to process the marker data, first by using its gap-fill algorithm to fill gaps in the marker trajectories of up to five samples, then by filtering the data with a low pass filter at a cut-off frequency of 15 Hz. The choice of this cut-off frequency was based on visual inspection of the frequency spectrum of selected markers. A similar level of cut-off frequency has been used in previous golf studies (Coleman & Rankin, 2005; Wheat, Vernon, & Milner, 2007). It is possible that data were not always smoothed sufficiently at this cut-off rate, but this was accepted as the derivates of the marker trajectories were not required. Following this, Visual 3D was used to associate local coordinate systems (Cappozzo, Della Croce, Leardini, & Chiari, 2005) with each of the following body segments:

- pelvis
- thorax

- left humerus
- left forearm
- left hand

Assuming each of these segments to be rigid, the three-dimensional position and orientation of the associated local coordinate system could be determined at any given time using the marker coordinates. A detailed definition of the local coordinate systems can be found in Appendix E (p. 211) and a general discussion of this topic can be found in Section 4.5 (p.81). Using a calibration procedure, the local coordinate system for each segment was defined so that its axes corresponded with the anatomical axes of the corresponding segment (Figure 33). When the golfer was in the anatomical position, each segment coordinate system had its z-axis pointing along the distal to proximal segment axis, its y-axis to the front and its x-axis to the right (medially for the arm segments).

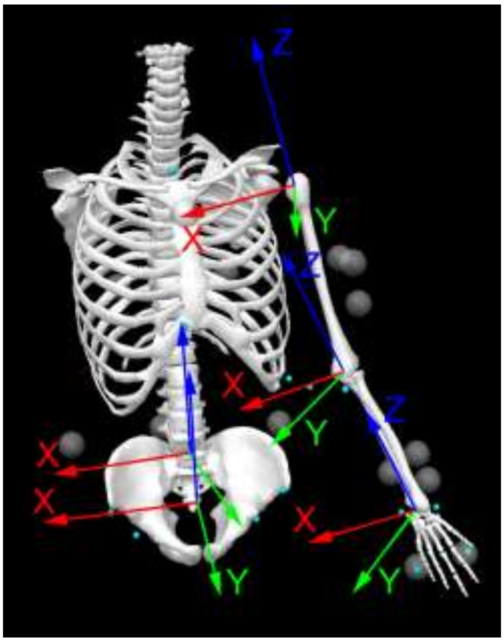



**Figure 33: Definition of segment coordinate systems. For each segment, the x-axis points medially, the y-axis frontally and the z-axis proximally when the player is in the anatomical position.**

During the calibration procedure, the positions of anatomical landmarks were identified using a pointing device with three markers attached to it (Cappozzo, Catani, Della Croce, & Leardini, 1995). Furthermore, the rotation centres of the glenohumeral, elbow and wrist joint were identified using a dynamic calibration. For this, golfers were requested to move the distal body segment according to the instructions of the experimenter whilst the camera system was tracking the movement in real-time. The calibration movements applied included approximately 10 cycles of all applicable joint movements (e.g. pronation/supination and flexion/extension for the elbow), following recommendations available for the hip joint (Begon, Monnet, & Lacouture, 2007). An algorithm supplied by the Visual3D software was then used to estimate the joint centre position (Schwartz & Rozumalski, 2005). It has been shown with simulated data that, whilst being computational demanding and relatively slow, this algorithm is one of the most accurate for determining joint centre positions (Ehrig, Taylor, Duda, & Heller, 2006).

Whilst the functional joint centre method has been used extensively for the lower leg, use of functional methods for determining the joint centres of the upper limbs is still in its infancy. Recent validation studies showed that accuracy may be as low as 20 mm when using one simple marker triad per segment (Roosen, Pain, & Begon, in press). Therefore, additional digitisation points were placed close to the expected joint centre position so that it was possible to perform a visual check after the algorithm calculated the functional joint centres. For instance, the position of the medial and lateral epicondyles of the elbow were marked relative to the forearm marker triad and the functional joint calibration was repeated in case the functional joint centre did not fall approximately on a line connecting the two epicondyles.

After the local coordinate systems were established, angular joint displacement was calculated using the Euler/Cardan-sequences listed below. Each sequence consists of three coordinate system transformations ($e_1$, $e_2$, $e_3$), whose interpretation is given below and illustrated in Appendix E (p. 211). The sequences are based on recommendations given by Wu *et al.* (2005) whenever possible:

- Pelvis relative to global coordinate system: X-Y-Z (not provided by Wu *et al.* but consistent with their sequence proposed for global thorax orientation):
    - $e_1$: forward / backward tilt (not reported)
    - $e_2$: lateral obliquity (left/right tilt) (not reported)
    - $e_3$: axial rotation
- Thorax relative to global coordinate system: X-Y-Z
    - $e_1$: flexion / extension (not reported).
    - $e_2$: lateral flexion / extension (not reported).
    - $e_3$: axial rotation.
- Humerus relative to thorax: Z-Y-Z
    - $e_1$: Sets the position of the plane of humerus elevation. With $e_1$=0°, elevation will be in the plane of abduction; with $e_1$=90°, elevation will be in the plane of forward flexion.
    - $e_2$: Elevation of the humerus relative to the thorax.
    - $e_3$: Axial rotation of the humerus (internal/external rotation).
- Forearm relative to humerus: X-Y-Z
    - $e_1$: Elbow flexion/extension.
    - $e_2$: Carrying angle (not reported).
    - $e_3$: Pronation and supination of the forearm.
- Hand relative to forearm: X-Y-Z (was not defined by Wu *et al.* but was chosen so that it was consistent with the elbow sequence.)
    - $e_1$: Hand flexion/extension.

- $e_2$: Adduction and abduction, or ulnar and radial deviation.

- $e_3$: Circumduction (not reported).

### 5.1.3 Event detection

After inspection of pilot trials, the following limits were set for automatic threshold functions that were used to identify swing events in the software Visual3D for each trial:

- Take-away (TA): x-component of velocity of the frontal shaft marker exceeds 0.2 m/s. This threshold was chosen because it allowed a consistent placement of the event at the initiation of backswing. Lower thresholds were tested but resulted in erratic placements due to noise in the velocity data or when the player performed small movements in preparation for the backswing.

- Transition from backswing to downswing (TOB): x-component of velocity of the frontal shaft marker changes from negative (towards target) to positive (away from target). This marker was selected for its good visibility at the top of the backswing.

- Impact: Strain rate of lead/lag strain exceeds -3000 $s^{-1}$. This level was chosen because pilot testing showed that this level of strain rate did not occur during the backswing or downswing but it was exceeded just after impact.

A visual check was performed to verify that the events were identified correctly.

### 5.1.4 Statistical analysis

As discussed in Section 4.1.6 (page 69), all trials that were recorded during the data collection will be included in the statistical analysis rather than just one mean value per player and condition. This requires that condition, player and trial are included as factors in the statistical analysis to account for the fact that repeated trials recorded from the same player cannot be regarded as independent observations. A similar approach has been used in a previous study looking at the effect of shaft length (Wallace, Otto, & Nevill, 2007), albeit with the inclusion of additional covariates.

As the effect of shaft stiffness on multiple outcome measures was examined, a multivariate analysis of variance (MANOVA) was performed rather than multiple analyses of variance (ANOVAs) for each outcome variable. Performing multiple ANOVAs would inflate the "familywise error rate" (Field, 2005, p. 572) and therefore increase the likelihood of Type 1 errors. A total of three MANOVAs will be performed, each of which is related to one of the three objectives addressed in the present study (launch data, strain, body movement). If shaft effects were detected, *post-hoc* comparisons would be performed using Bonferroni correction or, if violations of the assumption of equality of variances existed, Games-Howell correction. The Games-Howell correction method was selected for its statistical power compared to other correction methods (Field, 2005). The α-level for the complete statistical analysis was set to 0.05, and the analysis was performed with SPSS 16 (SPSS, Inc., USA).

## *5.2 Results*

This section will present the results of the first study in the following order. First, the validity of the assumptions made when performing the statistical analysis is examined. Then, results for a within-subject reliability study are presented, which is based on a comparison of the first and fourth set of swings recorded for each subject. Last, results for a comparison of the different shafts are summarised.

### 5.2.1 Assumptions of MANOVA

For MANOVA to be valid, a number of assumptions have to be met (Field, 2005): observations have to be independent and from a random sample; multivariate normality must exist; and the covariance matrices must be homogeneous. Vincent (2005) added that it is also important to ensure that the dependent variables are likely to be independent from each other as including highly correlated variables would reduce the degrees of freedom without adding information. Furthermore, he points out that the subjects-to-dependent-variable ratio should be 3 to 1 to avoid loss of statistical power (i.e. the minimum number of total observations is at least three times the number of dependent variables).

Whilst the requirements given by Vincent (2005) were inherently met by the study design, further steps were necessary to ensure that the assumptions listed by Field (2005) were valid. For the independent observations assumption to be met, no systematic trends in the data can be present apart from those accounted for by the player and trial factors. To ensure that this was the case, a comparison of the results obtained under the first and fourth condition was performed for all subjects. As each subject performed these trials with identical clubs, no difference in results between these two data sets was expected in the absence of systematic changes occurring throughout the course of a test session. As discussed in Section 4.1.3 (p. 65), use of randomisation methods was not feasible in the present study, so a convenience sample was selected. Secondly, when comparing different club conditions, the trial number was included to test whether trial results fluctuated in any pattern. The second part of this procedure is similar to a recommendation given in the literature to check for systematic trends in repeated trials (Kroll, 1967). Only if there was no main effect due to the trial factor for a variable was it included for further analysis.

As there are no standard tests for multivariate normality, variables were tested separately (on a univariate basis) for normality. Although this provides some justification for assuming multivariate normality, it should be noted that this test method “does not guarantee multivariate normality” (Field, 2005, p. 593). After identifying and removing a small number of outliers, each variable was tested for normality using Shapiro-Wilk tests, as recommended in the literature (Stevens, 2002). Additionally, histograms and normal probability plots were examined to confirm that data were normal.

Additionally, for a MANOVA to be valid, the covariance matrices have to be homogeneous. To test this assumption, Levene’s and Box’s tests were applied (Field, 2005). For the majority of variables, Box’s tests indicated that the covariance matrices were not homogeneous ($p < 0.05$). Field (2005) cautions that the results of Box’s test are sensitive to small deviations from multivariate normality. As there are no standard tests available to test for multivariate normality, it is unknown whether the Box's test produced significant results because of deviations from multivariate normality or because of a lack of homogeneity of covariance matrices. Stevens (2002, p. 278) argues that if group sizes are equal, "the Type 1 error rate will be only slightly affected" if the covariance matrices are not homogeneous. As group sizes in the current study were equal, it was decided to proceed with the analysis despite the significant results in the Box's tests, although this may result in reduced power (Stevens, 2002).

### 5.2.2 Tests for within-player reliability

This section of the results focuses on the within-subject reliability, which was assessed by comparing the results from the first and last set of swings performed by each subject. These two sets of swings were performed with identical clubs. Therefore, in the absence of confounding factors like learning effects or fatigue, it would be expected that there would be no difference between these result sets.

#### *5.2.2.1 Launch conditions*

Descriptive statistics for the two data sets are presented in Table 16[10]. It can be seen that there were slight differences in the means of the four launch variables between the first and last set of swings. These were further analysed by performing a MANOVA. The multivariate test statistics (Pillai's trace) indicated that there was a significant difference in launch characteristics between the first and the repeated (fourth) condition ($F(1) = 7.93$, $p < 0.001$). Looking at the source of this effect using individual ANOVAs for each variable, it was found that there was a main effect on club speed, ball speed and side angle due to the factors player, condition and the interaction player×condition (see Table 17). The only exception to this was launch angle, where the factor condition was not a main effect.

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[10] Note: data from two players were excluded (bad club head speed data due to improper positioning of radar device).

**Table 16: Descriptive statistics (mean ±SD) summarising the launch data from the first and last set of swings recorded for each subject (performed with identical clubs).**

| Condition | *n* | Club head speed (m/s) | | Ball speed (m/s) | | Launch angle (°) | | Side angle (°) | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 90 | 45.5 | ±2.58 | 67.0 | ±4.02 | 11.6 | ±3.16 | -0.545 | ±2.78 |
| 4 | 86[a] | 45.8 | ±2.53 | 67.6 | ±3.78 | 11.7 | ±2.79 | 0.126 | ±2.18 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

**Table 17: ANOVA results for launch variables comparing data collected for the first and last set of swings recorded for each subject.**

| | | Club head speed | | Ball speed | | Launch angle | | Side angle | |
|---|---|---|---|---|---|---|---|---|---|
| | ***df*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 14 | 267 | <.001 | 127 | <.001 | 38.7 | <.001 | 10.3 | <.001 |
| **Condition** | 1 | 16.0 | <.001 | 10.9 | 0.001 | 0.319 | 0.573 | 6.37 | 0.013 |
| **Player× Condition** | 14 | 2.73 | 0.001 | 1.81 | 0.042 | 1.99 | 0.023 | 4.00 | <.001 |

These results indicate that there was a significant difference ($p < 0.001$) between players, which was expected even at an elite level based on a previous study (Kenny, Wallace, & Otto, 2008a). It was also found that launch conditions changed significantly from the first to the last experimental condition. In particular, both club head and ball speed were affected by the condition factor ($p < 0.001$). It is not deemed necessary to present the results for the strain and body movement variables here, because the changes in launch condition between the first and last condition show that subjects did not perform consistently at the beginning and the end of test sessions. These differences led to concerns regarding the consistency of the players. Therefore, possible sources for these differences were examined further before moving on to a comparison of the results obtained for the different shaft conditions.

#### *5.2.2.2 Possible learning effects*

As an identical club was used in Condition 1 and 4, the observed changes must be due to factors other than changes in the properties of the golf club used. To further explore these differences, the estimated marginal means (Vincent, 2005) for club head and ball speed for the first and second repeat are shown in Figure 34. Marginal means “are obtained taking the average of the means … for a given condition” (Field 2005, page 468). Therefore, marginal means characterise a variable after variations due to other factors accounted for by the model have been removed. In this case, this allows removing the variability that can be accounted for due to the player effect and focusing on the condition effect.

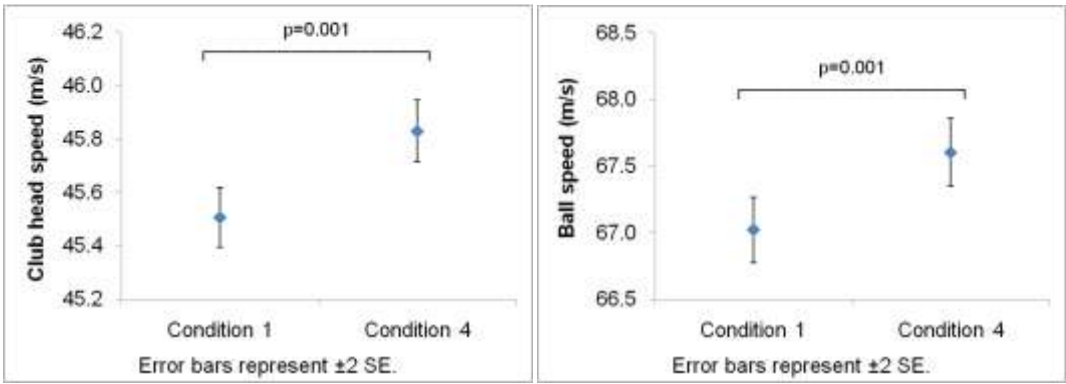



**Figure 34: Estimated marginal means for club head and ball speed (controlling for player variation).**

As both club head and ball speed were found to increase when comparing Condition 1 and 4 (Figure 34), it was hypothesised that a learning or warm-up effect may have occurred. This would indicate that the self-selected number of warm-up swings performed by the players may not have been sufficient for them to warm up or to familiarise themselves with the type of club used in the present study. To explore this in more detail, club head speeds of each player were transformed by dividing each club head speed by the player’s mean club head speed. This effectively normalised the club head speed and removed differences between players. The resulting club head speeds were then examined for correlations with a swing counter, where swing number 1 was the first swing performed in a test session and 24 the last swing (four club conditions * 6 trials = 24 swings in total).

It was found that there was a significant positive correlation between swing number and club head speed ($p < 0.001$), albeit with a low Pearson correlation coefficient ($r$ = 0.208). Obviously, any such systematic change in the swing characteristics would add bias to a comparison of different test conditions (e.g. between l-, r- and x-flex shafts) when looking at results for individual players. Therefore, the data were analysed further after disregarding the initial six swings performed by each subject. Now, the correlation of club head speed and the swing counter (now swing 7-24) was re-examined, and it was found that there was no longer a correlation between swing number and club head speed ($p$ = 0.682). This lack of correlation could be explained by the reduced range of swing numbers caused by disregarding the first six swings of each subject. Therefore, the normalised swing speeds for swings 1-18 were also examined for correlations between the two variables. For swings 1-18, there was still a correlation between swing number and normalised club head speed ($p$ < 0.001, $r$ = 0.252). This supports the hypothesis that a warm-up or learning effect occurred throughout testing and that this effect was most pronounced when the initial sets of swings (1-6) were included in the analysis. Based on the findings presented above, it was assumed that swings 7-24 of each subject would provide a valid data source for the analysis of shaft effects, and swings 1-6 of each subject were removed from the data set.

### 5.2.3 Shaft effects

The majority of players were able to detect that the test clubs differed in their shaft properties despite the blinding that took place. In most cases, players correctly identified the l-flex shaft as the shaft with the lowest stiffness. Only a minority of players, however, were able to correctly identify the difference between the r-flex and x-flex shaft.

The analysis of the different shaft conditions was performed in a similar way to the tests for repeatability in the previous section in that a factorial MANOVA was applied for each group of variables. The first two factors were player and shaft. The model was customised to only contain main effects. Including interaction terms would have allowed a comparison of the shaft conditions on a player-by-player basis, but these were not included as an additional precaution because of the learning or warm-up effects described in the previous section (see Section 5.2.2, above). It was assumed that these effects would only influence the data on a subject-by-subject level and not the data set as a whole because the order of conditions was randomised. Nevertheless, order and trial number were added to the model as an additional precaution. The order factor represented information whether a shot was part of the first, second or third condition tested, and trial represented the trial number (1-6).

If the multivariate test statistics indicated that a group of variables was affected by any of the factors, the results of individual ANOVAs for each variable were examined. If there were significant differences in a variable due to a main effect of shaft, *post-hoc* tests were performed to determine which shaft conditions were affected. Due to inconsistencies in variances (see Section 5.2.1), *post-hoc* tests were performed using Games-Howell correction of $p$-values as this method does not assume equal variances.

#### *5.2.3.1 Launch conditions*

As can be seen from Table 18, launch conditions were very similar for the different shaft conditions[11]. The multivariate test statistics (Pillai's Trace) indicate that the factors player ($F(14) = 1069$, $p < 0.001$) and shaft condition ($F(2) = 3.46$, $p = 0.001$ ) had an effect on the launch variables, but the order ($F(2) = 0.998$, $p = 0.437$) and trial ($F(5) = 0.809$, $p = 0.705$) factors did not. This provides a justification to perform ANOVAs for each launch variable to determine which variables were affected. On this level, a main effect of player as well as shaft on all other launch variables was found (see Table 19), with the exception of side angle. In contrast, the order and trial factors were not main effects, as already indicated by the non-significant result from the multivariate test. It should be noted that if there were any significant ANOVA results for the order or trial factors, these should be ignored because of the non-significant results for these factors in the MANOVA (Field, 2005).

[11] As for the within-player reliability analysis presented in the previous section, data from two players was excluded (bad club head speed data due to improper positioning of radar device).

**Table 18: Descriptive statistics (mean ±SD) for launch variables.**

| | *n* | Club head speed (m/s) | | Balls speed (m/s) | | Launch angle (°) | | Side angle (°) | |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | 87[a] | 45.8 | ±2.57 | 67.8 | ±3.97 | 11.4 | ±2.89 | 0 | ±2.32 |
| **r-flex** | 87[a] | 46.0 | ±2.51 | 68.0 | ±3.95 | 11.3 | ±2.70 | -0.37 | ±2.04 |
| **x-flex** | 89[a] | 45.7 | ±2.40 | 67.5 | ±3.83 | 12.0 | ±2.98 | -0.10 | ±2.29 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

**Table 19: ANOVA results for launch variables.**

| | | Club speed | | Ball speed | | Launch angle | | Side angle | |
|---|---|---|---|---|---|---|---|---|---|
| | ***df*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 14 | 491 | <.001 | 200 | <.001 | 65.2 | <.001 | 15.5 | <.001 |
| **Shaft** | 2 | 5.13 | 0.007 | 4.61 | 0.011 | 6.37 | 0.002 | 0.703 | 0.496 |
| **Order** | 2 | 0.065 | 0.937 | 1.60 | 0.205 | 0.999 | 0.370 | 0.929 | 0.396 |
| **Trial** | 5 | 0.518 | 0.763 | 1.328 | 0.253 | 0.393 | 0.854 | 1.045 | 0.392 |

The findings summarised above were further examined by plotting the estimated marginal means for each shaft condition and performing pair-wise comparisons (Figure 35). These pair-wise comparisons showed that there was no systematic change in any of the launch variables depending on the shaft condition. It was not possible to attribute the shaft effects seen in the ANOVA to any particular pair-wise shaft comparison. Comparisons were performed using Games-Howell correction because it was noted that variances across conditions were not equal (see Section 5.2.1 p. 112). When using Bonferroni correction as a less conservative correction method, significant differences were identified for club speed ($p = 0.001$) and ball speed ($p = 0.001$) between the l-flex and x-flex condition. Significant differences were also found for the launch angle between the l-flex and x-flex condition ($p = 0.009$) and the r-flex and x-flex condition ($p = 0.019$). This agrees with the ANOVA results (Table 19). A list of all significance values form the pair-wise comparisons can be found in Appendix F (p. 213).

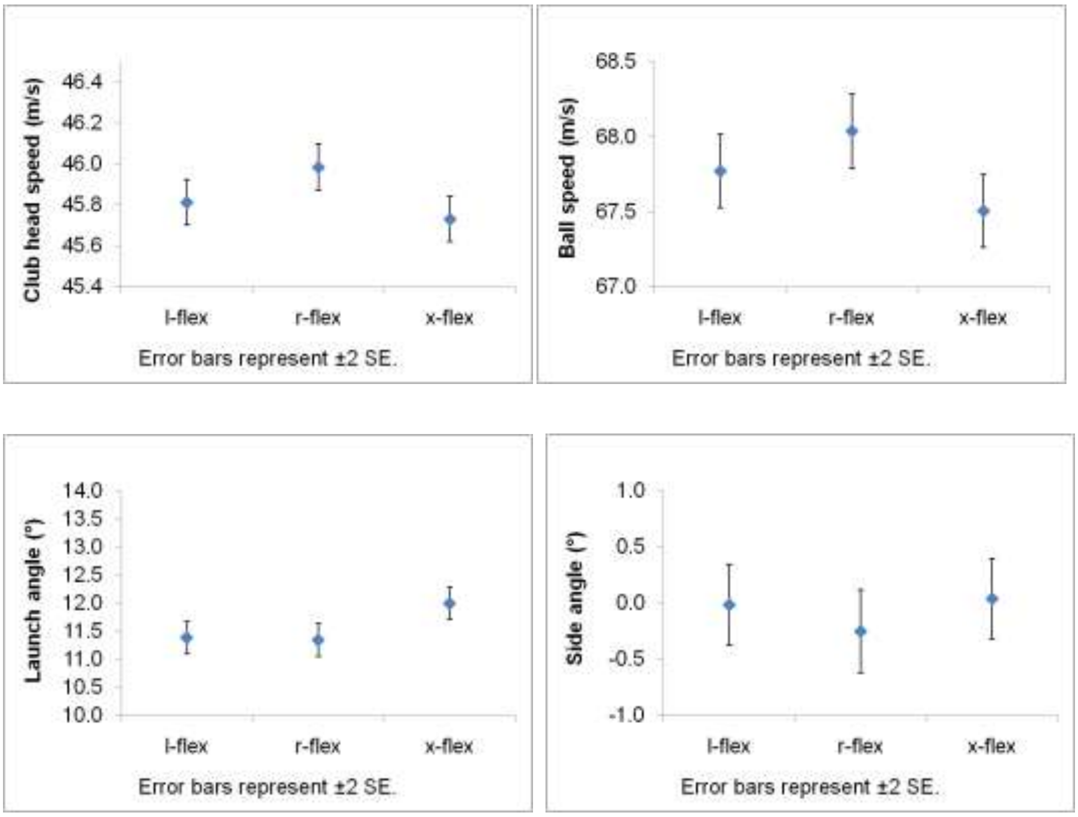



**Figure 35: Estimated marginal means for different shaft conditions for the variables club head and ball speed, launch angle and side angle.**

### *5.2.3.2 Strain*

Figure 36 shows traces of the overall mean strain for the l-flex, r-flex and x-flex shafts[12]. To obtain these graphs, each swing was normalised to the downswing duration after identifying the transition point from backswing to downswing based on the marker data (see Section 5.1.3). For each of the time-normalised sample points, the average strain value and SD across all subjects was determined. Visual inspection of Figure 36 (a) reveals that the ranges of lead/lag strains recorded for the different shafts appear to overlap and there appears to be no systematic difference depending on the shaft used. In terms of the toe-up/down component (b), a separation of the l-flex strain curve from the other two curves can be noted for the first quarter of the downswing, but

[12] Strain data from three subjects were excluded from the entire strain data analysis because of artefacts caused by technical difficulties with a cable.

towards impact the toe-up/down strain recorded for the different shafts becomes increasingly similar. It can also be seen that the variation in strain values recorded for the different subjects (highlighted by the shaded areas) becomes smaller when the impact point is approached.

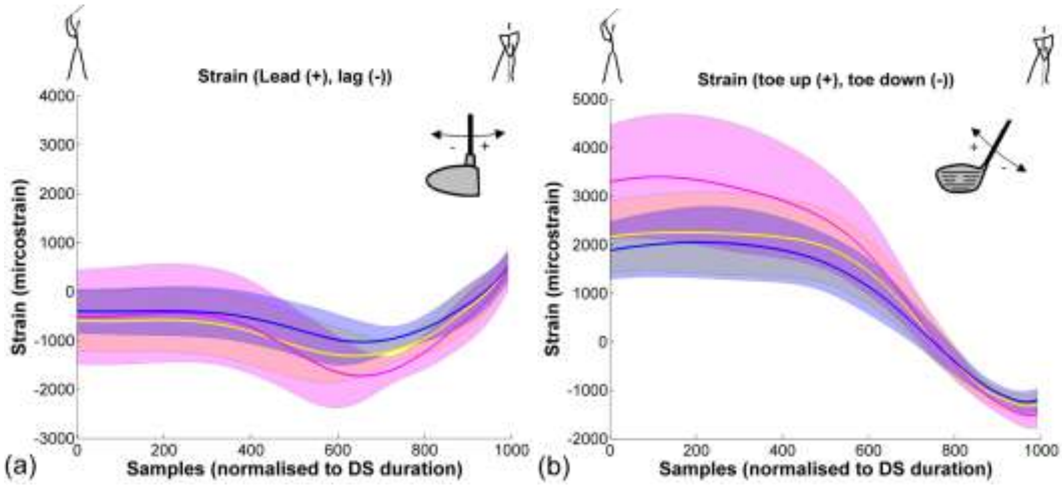



**Figure 36: Mean strain patterns in lead/lag direction (a) and toe up/down direction (b). Lines represent mean strain for all subjects for the l-flex (pink), r-flex (yellow) and x-stiff (blue) shaft. Shaded areas indicate ±1 SD.**

Descriptive statistics summarising the characteristic strain values indicate markedly higher peak toe strain values for the l-flex club (Table 20). There appears to be a trend for recovery rate and lag area to increase as the shaft stiffness decreases, whereas lead strain at impact appears to be unaffected by shaft stiffness. Examination of the multivariate statistics (Pillai's Trace) reveals main effects due to the player ($F(14) = 122$, $p < 0.001$) and shaft factors ($F(2) = 53.6$, $p < 0.001$). There was no main effect due to the test order ($F(2) = 0.794$, $p = 0.608$) or trial factors ($F(5) = 0.464$, $p = 0.979$), confirming that the test represented a valid comparison of the different shafts. When performing univariate ANOVAs for each variable, no main effects due to the order and trial factors were identified, as expected (see Table 21). However, there were significant differences in the strain variables depending on the player factor. There was also a main effect on the peak toe strain value, the recovery rate and lag area due to the shaft factor, but the shaft factor did not affect the magnitude of lead strain at impact.

**Table 20: Descriptive statistics (mean ±SD) for strain variables.**

| Shaft | *n* | Peak toe strain (μm/m) | | Recovery rate (1/s) | | Lag area (μm/m · s) | | Lead strain (μm/m) | |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | 82[a] | 3692 | ±1079 | 0.0574 | ±0.017 | 384 | ±211 | 544 | ±394 |
| **r-flex** | 77[a] | 2807 | ±781 | 0.0467 | ±0.015 | 264 | ±142 | 513 | ±295 |
| **x-flex** | 85[a] | 2258 | ±648 | 0.0437 | ±0.014 | 248 | ±142 | 589 | ±281 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

**Table 21: ANOVA results for strain data.**

| | | Peak toe strain | | Recovery rate | | Lag area | | Lead strain at impact | |
|---|---|---|---|---|---|---|---|---|---|
| | ***df*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 13 | 203 | <.001 | 89.6 | <.001 | 341 | <.001 | 196 | <.001 |
| **Shaft** | 2 | 662 | <.001 | 102 | <.001 | 327 | <.001 | 2.96 | 0.054 |
| **Order** | 2 | 0.208 | 0.813 | 0.372 | 0.690 | 0.853 | 0.428 | 2.54 | 0.081 |
| **Trial** | 5 | 0.240 | 0.945 | 1 | 0.414 | 0.184 | 0.969 | 0.110 | 0.990 |

In order to closer examine the changes in strain associated with shaft stiffness modifications, estimated marginal means were plotted and pair-wise comparisons performed (Figure 37). Again, *p*-values were corrected using Games-Howell's method when performing multiple comparisons to account for a lack of homogeneity of variances (as detected with Levene's test and evident from Figure 36 which shows that the variability in strain data was higher for the l-flex shaft). As can be seen from Figure 37, peak toe strain increased significantly as shaft stiffness decreased. Recovery rate, which characterises the unloading of the shaft (typically from a lagging to a leading position) just before impact, was significantly higher for the l-flex shaft than for the other two shafts. The same was observed for the lag strain area that characterised the loading of the shaft in the lag direction before impact. No significant differences were observed for lead strain at impact, as expected based on the ANOVA results. For reference, all *p*-values from the pair-wise comparisons are presented in Appendix F (p. 213)

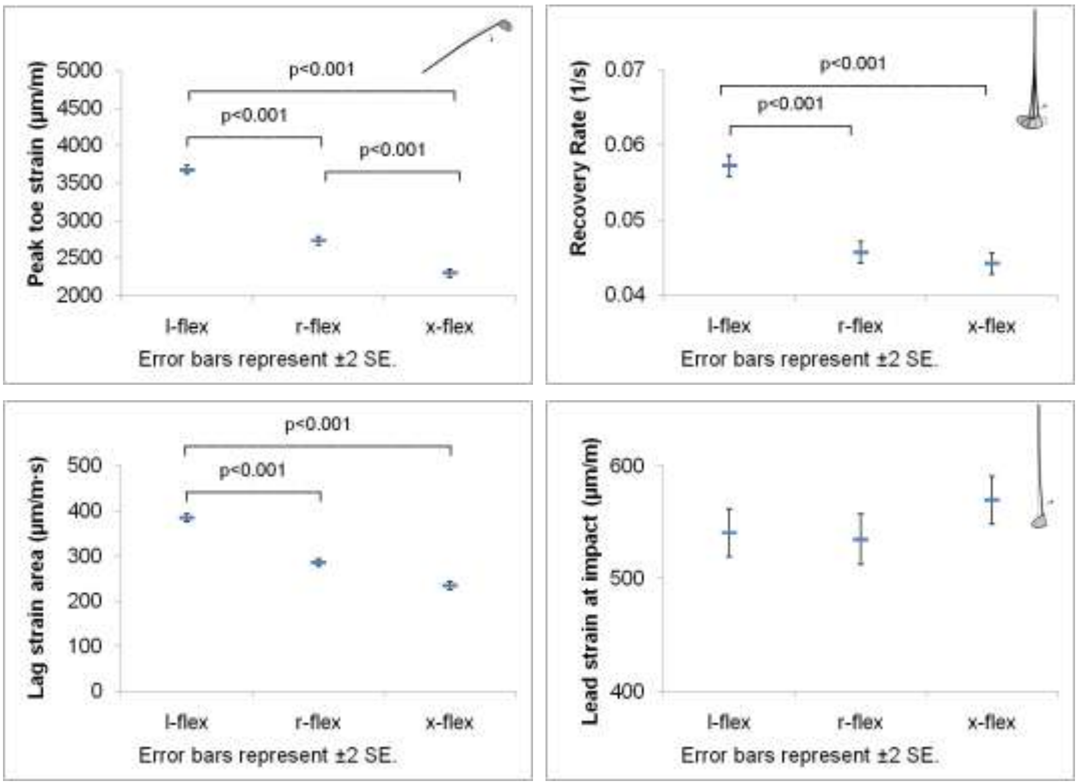



**Figure 37: Estimated marginal means for strain variables.**

### *5.2.3.3 Body kinematics*

For brevity, only four angular displacements are presented in detail: axial thorax rotation, forearm flexion/extension, forearm pronation/supination and ulnar/radial deviation at the wrist. For each trial, discrete values of these angles were extracted at the top of backswing and impact events. As can be seen from Table 22, there were virtually no changes in the mean joint angles depending on the shaft used[13]. However, the multivariate test statistics indicated that there were main effects due to player ($F(15) = 287$, $p < 0.001$), shaft ($F(2) = 1.75$, $p = 0.036$) and test order ($F(2) = 7.03$, $p < 0.001$) but not due to the trial factor ($F(5) = 0.820$, $p = 0.781$). This indicates that there were significant differences associated with the player, shaft and test order factors in at least some of the body kinematics.

[13] Data from one player was removed from the data set due to difficulties with a marker cluster.

**Table 22: Descriptive statistics (mean ±SD) for selected angular displacements.**

| | *n* | Thorax rotation (°) | | Forearm flexion/ extension (°) | | Forearm pronation/ supination (°) | | Ulnar/radial deviation (°) | |
|---|---|---|---|---|---|---|---|---|---|
| **Event: Top of backswing** | | | | | | | | | |
| **l-flex** | 93[a] | -88 | ±9 | 27 | ±13 | -129 | ±14 | 18 | ±8 |
| **r-flex** | 94[a] | -88 | ±10 | 27 | ±14 | -129 | ±14 | 18 | ±7 |
| **x-flex** | 93[a] | -88 | ±9 | 27 | ±14 | -129 | ±13 | 18 | ±8 |
| **Event: Impact** | | | | | | | | | |
| **l-flex** | 95[a] | 36 | ±8 | 10 | ±7 | -100 | ±11 | -25 | ±8 |
| **r-flex** | 94[a] | 36 | ±8 | 10 | ±7 | -100 | ±11 | -25 | ±8 |
| **x-flex** | 93[a] | 35 | ±8 | 9 | ±7 | -100 | ±11 | -25 | ±9 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

Again, further analysis consisted of ANOVAs for each variable, the results of which are summarised in Table 23. It can be seen that there were significant differences between players for all of the joint angles at both events but no differences depending on the shaft used. The fact that shaft condition was identified as a factor in the multivariate statistics but not in the individual ANOVAs indicates that this factor was potentially too weak to be attributable to a particular joint angle. It is surprising that a main effect due to the order factor was noted for the elbow flexion/extension angle. This could be an indication that artefacts due to experimental errors influenced the results obtained for this particular joint angle because further adaptation or learning effects are deemed unlikely (as discussed in Section 5.2.2.2). Given that the multivariate statistics as well as ANOVAs did not indicate that there were significant changes in the body movement variables depending on the shaft used, marginal mean plots and pair-wise comparisons were not examined for these variables.

**Table 23: ANOVA results for selected body kinematics.**

| | | Thorax | | Forearm flexion/ extension | | Forearm pronation/ supination | | Ulnar/radial deviation | |
|---|---|---|---|---|---|---|---|---|---|
| | *df* | *F* | *p* | *F* | *p* | *F* | *p* | *F* | *p* |
| **Event: Top of backswing** | | | | | | | | | |
| **Player** | 15 | 659 | <.001 | 1952 | <.001 | 4208 | <.001 | 1004 | <.001 |
| **Shaft** | 2 | 1.37 | 0.256 | 2.18 | 0.115 | 0.478 | 0.621 | 0.511 | 0.601 |
| **Order** | 2 | 1.90 | 0.152 | 43.08 | <.001 | 5.85 | 0.003 | 0.632 | 0.532 |
| **Trial** | 5 | 0.483 | 0.789 | 1.34 | 0.248 | 0.76 | 0.580 | 0.175 | 0.322 |
| **Event: Impact** | | | | | | | | | |
| **Player** | 15 | 498 | <.001 | 435 | <.001 | 507 | <.001 | 500 | <.001 |
| **Shaft** | 2 | 2.52 | 0.083 | 0.942 | 0.391 | 0.875 | 0.418 | 1.73 | 0.179 |
| **Order** | 2 | 0.333 | 0.717 | 5.36 | 0.004 | 2.48 | 0.086 | 1.26 | 0.287 |
| **Trial** | 5 | 0.430 | 0.827 | 0.394 | 0.853 | 0.327 | 0.897 | 0.739 | 0.595 |

## *5.3 Discussion*

The objectives of the present study were threefold and concerned an examination of the effects of shaft stiffness on launch conditions, shaft bending patterns and the body movement of golfers. Before discussing the primary outcomes of the present study, the following section will focus on the within-player reliability.

### 5.3.1 Within-player reliability

In summary, the test of within-player reliability showed low consistency for results obtained from swings performed by the same player with the same club at the beginning and the end of his test session. It appeared that these changes were not due to fatigue effects, which were considered when deciding on the maximum number of swings performed by each subject (see Section 4.1.2, page 62). Instead, learning or warming-up processes appeared to be present as, for the majority of players, club head speed increased throughout the test session. This result was unexpected and demonstrates that reliability checks are an essential element of studies such as the present one.

It appears that so far, there has been little research in this area, as only one other golf study could be identified that included the repeat of a condition (Worobets & Stefanyshyn, 2007). In that study, subjects performed five shots with each of five differently-shafted drivers and then repeated the same protocol. All swings were recorded during one test session. The authors commented that “fatigue was not found to be an issue” (Worobets & Stefanyshyn, 2007, p. S279), but they did not include further details as to how they treated the repeated condition statistically to come to this conclusion. It is also not known whether Worobets and Stefanyshyn examined the data for learning or warm-up effects that would lead to an increase in club head speed as observed in the present study. In other studies looking at equipment-induced changes in swing performance, no repeated condition was included to control for changes in swing kinematics due to fatigue or learning effects (Kenny, Wallace, & Otto, 2008b; Stanbridge, Jones, & Mitchell, 2004; Wallace & Hubbell, 2001; Wallace, Hubbell, & Rogers, 2004; Wallace, Otto, & Nevill, 2007).

Despite the positive correlation of swing number with club head speed it was possible to remove this effect by discarding the first six swings performed by each subject. It is suggested that further research into the adaptation of players to unusual or unknown clubs is necessary to better understand the processes identified in the present study. It may be beneficial to allow players extended periods of time (several days or weeks) with the clubs so that they can learn to swing the test clubs optimally before the effect of the equipment on performance is measured. However, this would reduce the feasibility of such study because additional test clubs and more of the participant’s time would be required.

### 5.3.2 Effect of shaft stiffness on launch conditions

Contrary to what was expected based on the literature review, the *post-hoc* tests indicated that there were no differences in launch conditions depending on the shaft condition. This finding contradicts the mechanism proposed by Maltby (1995). According to Maltby, it should be expected that, as shaft stiffness decreases, forward bending of the shaft at impact and, hence, dynamic loft increases, resulting in higher launch angles for less stiff shafts (see Section 2.6.4, p. 49). This may be explained by differences in the mechanical properties of the shafts used by Maltby (1995). Other possible mechanisms that would explain the results seen for the launch data in the current study will be discussed in the context of shaft deflection and body kinematics in the following sections.

Indirectly, the finding of no changes in launch conditions is in agreement with results from Stanbridge, Jones and Mitchell (2004), who found no changes in distance and dispersion for a group of players using 7-irons with composite shafts of three different stiffnesses. Launch conditions were not measured directly in their study but it seems plausible that launch conditions did not change if no change in distance and dispersion was seen.

In terms of club head speed, simulation studies suggested that total club head speed would not be affected by changes in shaft stiffness (MacKenzie, 2005), which again is in agreement with the results from the present study. In contrast, Wallace and Hubbell (2001) studied the effects of iron shaft stiffness on launch conditions and found a significant increase in club head speed associated with decreased shaft stiffness, although they noted this change was probably not relevant in practice because of the small magnitude (0.3 m/s). Worobets and Stefanyshyn (2008) examined the effect of shaft stiffness on club head speed. However, a comparison of their results with the present study is not possible because they chose to analyse their data on a subject-by-subject basis rather than group-based.

The high skill level of the players in the current study may have enabled them to adapt their swings to the changes in shaft stiffness, resulting in consistent launch conditions regardless of shaft stiffness. This aspect will be discussed further in the following sections.

### 5.3.3 Effect of shaft stiffness on shaft loading

In summary, it was found that shaft stiffness affected the amount of shaft bending throughout the swing but not at impact. Temporal strain patterns were highly repeatable within each subject, even when comparing the stiffest to the most flexible shaft. However, the magnitude of strain appeared to change by a scaling factor depending on the stiffness of the shaft that was used (Figure 36).

No previous study could be identified comparing strain or deflection patterns for shafts of different stiffness, so comparisons are restricted to a comparison of general bending patterns seen in the literature. As expected, the initiation of downswing approximately coincided with the global maximum toe-up strain (see Figure 1 (b), page 6) (Butler & Winfield, 1994; N. Lee, Erickson, & Cherveny, 2002; Newman, Clay, & Strickland, 1997). The toe up/down strain component then dropped until the club head began bending in the toe-down direction just before impact. This sequence can be explained by the fact that the toe of the golf club is typically pointing down at the transition from backswing to downswing, and the shaft is loaded as the player has to overcome the inertia of the club head when changing the swing direction between backswing and downswing. At some point during the downswing, the player then 'squares up' the club face relative to the target line by rotating the club through 90° around the longitudinal axis of the shaft. This action has been associated with the shaft "kicking forward" prior to impact (Butler & Winfield, 1994, p. 261), as seen in the lead/lag strain data in the current study (Figure 36). This general bending pattern was observed regardless of differences in individual swing styles, although it should be noted that subject-specific differences were detected for all strain variables in the MANOVA.

When comparing the characteristic strain values for the different shafts, greatest differences were found at the transition from backswing to downswing which appears logical given that the shaft bends most at this point. The amount of lag bending prior to impact (characterised by the lag area variable) was significantly higher for the l-flex shaft. At impact however, there was no difference in the amount of forward bending depending on the stiffness of the shaft. The finding that the amount of forward bending at impact did not differ depending on the shaft stiffness is in good agreement with the observation of no changes in launch conditions (in particular launch angle).

The lack of difference in forward bending at impact may also explain why significantly faster recovery rates occurred for the l-flex shaft as it arrived at impact with the same amount of lead bending compared to the other shafts but started to recover from a position with significantly more lag bending. If the hand path and angular velocity of the grip were identical between different shafts, it could be expected that the increased unloading rate would result in an increase in club head speed. This, however, was not observed in the current study (see previous section).

After analysing the strain data, the question remains whether players actively adapted their swings to achieve identical launch conditions regardless of shaft stiffness. Based on the strain data, it could also be hypothesised that shaft behaviour during the last few milliseconds before impact and the amount of shaft bending at impact is governed by the club head properties rather than the shaft properties, as proposed in previous studies (Horwood, 1994; Mather & Jowett, 1998). In this context it is interesting to note that, on average, the amount of lead strain was smaller than the amount of toe-down strain at impact. If the bending profile of the shaft at impact was indeed controlled by the COG position in the club head, this difference could be explained by the fact that the offset between the COG and the longitudinal shaft axis in the lead/lag plane is smaller than in the toe-up/down plane.

### 5.3.4 Effect of shaft stiffness on body kinematics

No changes in selected body kinematics where found depending on the shaft that was used. This is evident from the descriptive data (Table 22) and confirmed by the statistical analysis (Table 23).

Few previous studies examined the effects of changes in shaft stiffness on body movement related to shaft stiffness. Wallace and Hubbell (2001) commented that shoulder angular kinematics appeared to be unaffected when shaft stiffness changed. Using a simulation model, McGuan (1996) demonstrated that increasing shaft stiffness through increasing the Young's modulus of the shaft material by 30% would result in inefficient swings unless the player compensated them by changing his swing. However, McGuan provided sparse details as to how this finding compared to experimental work, so it is not known whether a comparison with the present experimental work is valid.

One limitation of the body data collected in the present study is that body angles were examined at only two events. It may be beneficial to examine just one joint angle (e.g. at the wrist) but at number of events throughout the swing so that temporal changes could be detected.

### *5.4 Summary*

Prior to analysis of any potential shaft effects, it was noted that players achieved different club head and ball speeds at the beginning and end of their test sessions, even though they were using identical test clubs. It was found that it was possible to remove this effect by discarding the initial sets of swings for each player.

Changes in shaft stiffness were not associated with changes in the launch variables club head speed, ball speed, launch angle and spin. This was in agreement with the finding that the amount of forward bending at impact did not differ between shafts. Yet, there was an effect of shaft stiffness on the parameters peak toe-up strain, lag strain area and lead/lag strain recovery rate. It is not known whether the lack of a change in launch or strain variables at impact is a result of the pure mechanical interaction of the involved parts or a result of active adaptations by the players, although the lack of an effect on the examined body kinematics suggests that players did not change their swing to adjust.

One limitation of the present study was that it was not possible to examine shaft effects on a player-by-player basis (shaft×player interaction). This was due to the fact that, as discussed above, club head speed at impact and ball speed increased throughout the test sessions. Therefore, some potential effects of shaft stiffness on individual swings may have cancelled each other out.

Overall, the present study showed that the relationship between shaft stiffness and dynamic loft as well as club head speed may not be as simple as the traditional paradigms suggest.

# 6 Effect of shaft bending stiffness on club head presentation, wrist kinematics and shaft bending in human swings

## 6.1 Introduction

The study presented in the previous chapter provided an insight into the complex interaction of the golfer's body movement with the equipment being used and the resulting effects on launch conditions. It was found that there was no effect of shaft stiffness on the amount of shaft bending at impact and the resulting ball launch conditions. This was true regardless of the fact that the amount of bending at earlier stages in the swing differed significantly between shafts. The lack of an effect on launch conditions could be explained if the club head arrived in the impact area with the same amount of shaft bend and with the same path regardless of the shaft used, but only if the impact location on the club face remained unchanged. Previous studies found a shaft effect on impact location (Stanbridge, Jones, & Mitchell, 2004). It was therefore deemed necessary to expand the analysis of club presentation and launch conditions to include the ball impact location and the club head orientation at impact.

No changes in the gross body movement of the player were identified in the study presented in Chapter 5. It is therefore possible that the lack of a shaft effect on launch conditions is a result of the mechanical interaction of the involved segments and not a result of swing adaptations by the player. Yet, this cunjecture warrants further investigation, as measurement of body movement in Study 1 (Chapter 5) was restricted to a limited number of joint angles at only two discrete events.

Based on these observations, the aim of the present study was to investigate the effects of shaft stiffness on impact location, club head presentation, strain and body movement on a more detailed level than in the previous study.

The following hypotheses were formulated based on the findings and observations obtained in Study 1:

(1) Impact location and club face angle at impact will not change with changes in shaft stiffness.

(2) The recovery process of the shaft from a lagging to a leading shape will generate additional club head speed. This effect will increase with decreasing shaft stiffness. (This hypothesis is based on the finding that there was a difference in recovery rate between shafts).

(3) Strain at the top of the backswing will increase for a more flexible shaft; the amount of lag bending before impact will increase for a more flexible shaft; and the strain rate prior to impact will be higher for a more flexible shaft. There will be no difference in strain at impact as a result of different shaft stiffness. (This set of hypotheses is based on the findings from Study 1 and is included to confirm these.)

(4) There will be no change in wrist kinematics depending on the shaft used. (This hypothesis is also based on the findings from Study 1. However, the present study (Study 2) will focus solely on the wrist joint rather than on the joints examined in Study 1.)

As has been shown previously, it has been deemed necessary to include reliability checks in the study design. These checks will provide a means to confirm whether players changed their swing throughout the course of their test session because of factors other than shaft stiffness.

## *6.2 Methods*

### 6.2.1 Data collection

Twenty right-handed, male golfers (see Table 24 for details) participated in the present study. As in the previous study, all subjects had a handicap equal to or lower than five. Three of the participants were professional golfers and were assumed to have a scratch handicap (zero) for the purposes of calculating the mean handicap of the sample shown in Table 24. Eight participants had served as subjects in the study presented in Chapter 5 approximately six months prior to the present study. Due to the limited number of available subjects, these players were included in Study 2, with the assumption that this would have negligible effects on the result.

**Table 24: Mean characteristics of participants (±SD)**

| Handicap | Age (years) | Height (m) | Body mass (kg) |
|---|---|---|---|
| 0.25 (±1.68) | 31.75 (±10.52) | 1.78 (±0.06) | 79.53 (±8.65) |

As discussed by Atkinson and Nevill (2001), the number of levels in a design should be kept as small as possible to achieve maximum statistical power. It was noted in Chapter 5 that including a third level of shaft stiffness added little benefit. Therefore, it was decided to include only two levels of shaft stiffness in the present study, and each subject tested the same two clubs with shafts having 'ladies' (l) and 'x-stiff' (x) stiffness ratings. These were the same clubs that were used in the previous study (see Section 4.2, p. 70, for club details). As in the previous study, shafts were painted black to anonymise them, and players were not told which property differed between clubs. As with the previous study, players were asked not to manipulate the clubs between swings to detect differences but were allowed practice swings.

The study was approved by the Ethics Committee of Edinburgh Napier University's Faculty of Health, Life and Social Sciences, and informed consent was obtained from each player (Appendix D, p. 208) prior to testing.

After the experimenter attached reflective markers to the skin of the players (see following section for details), players were given time to perform a self-selected number of swings with their own irons or driver. Players were then presented with the first test club, which was equipped with either the l- or the x-flex shaft. Recording of six successive swings commenced after the subject performed two warm-up swings with the first club. The same procedure was followed for the second club (including additional warm-up swings), which was then immediately followed by a repeat of this test protocol. It was felt that asking each subject to perform two warm-up swings with each club would help to standardise the warm-up procedure and reduce the effect of the potential lack of familiarisation with the clubs seen in Study 1 (see Section 5.2.2.2, p. 115). This test protocol left two possible test sequences (either l-x-l-x or x-l-x-l), which were alternated between subjects. Subjects were not made aware that they tested the same clubs twice during the test. Testing concluded with a full disclosure of the test protocol.

Movement of the reflective body markers was recorded using a seven camera Oqus 300 motion capture system (Qualisys AB, Sweden), operating at 500 Hz (see Figure 38). A second motion capture system, consisting of three Oqus 300 cameras operating at 1000 Hz connected to a separate computer, was used to track the movement of the club head for approximately 0.015 s before impact occurred (see Section 4.6.2, p. 92). Both systems were calibrated according to the manufacturer’s instructions using the same reference system. Details regarding the accuracy and precision of the systems can be found in Section 4.5.2 (p. 86). For each trial, cameras were set to record continuously until a trigger signal was received from an acoustic trigger (Shutter-Beam, Wood Electronics, USA). On receiving the trigger, the body movement system saved 1.5 s of data before and 0.5 s after the trigger to a file. The impact system similarly saved data from 0.1 s before impact until 0.05 s after impact to a separate file. Gaps of up to five frames in the data from the body system were filled using the software Visual3D (C-motion, USA). Trajectory data were not filtered because it was found that if filters were applied, events after impact would be affected by the pre-impact data, even at high cut-off rates.

The analogue strain signals from the instrumented golf shafts were amplified with a FE-366-TA amplifier (Fylde, U.K.) and recorded simultaneously with the body movement and the trigger signal via a Qualisys A/D board at a sampling rate of 2000 Hz. After identifying the time of impact in the strain data, a low pass filter with a 50 Hz cut-off frequency was used to remove high-frequency noise from the strain data. The cut-off rate was chosen based on visual inspection of the frequency spectrum of the strain data, and residuals between filtered and un-filtered data were examined to confirm that an appropriate cut-off rate was chosen. This filter was only applied up to the time of impact to avoid sudden changes in strain after impact affecting the pre-impact strain data (see Section 4.4, p. 77, for details). After removing the post-impact data and prior to applying the filter, a sufficient number of samples were padded at the beginning and end of the data set to ensure that end point artefacts from the filtering process would not affect the data range of interest. The number of reflected samples was equal to the number of samples between take-away and impact. Ball speeds were recorded using a radar-based launch monitor (see Section 4.6, p. 89, for details).

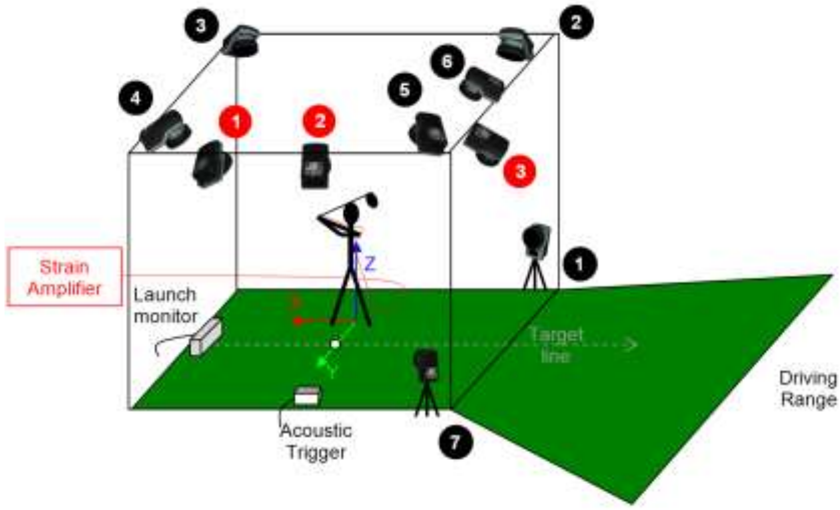



**Figure 38: Test set-up. Numbers in black circles denote positions of the body motion capture system, numbers in red circles denote cameras pertaining to the impact location motion capture system.**

### 6.2.2 Kinematic variables

Impact positions were registered for each swing as described in Section 4.6.2 (p. 92) and reported using the coordinate system shown in Figure 39. The same motion capture data that were used to calculate the impact location were also utilised to determine the face orientation and the speed of the centre of the club face in the instance before impact as described in Section 4.6.2 (p. 92) and Appendix C (p. 205).

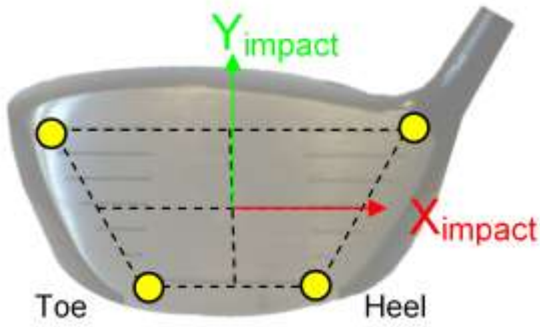



**Figure 39: Club face reference system for reported impact coordinates.**

Movement of the forearm was tracked using three reflective markers (diameter 12 mm) forming a triangle on the posterior side of the distal end of the forearm. The position of the elbow joint was defined relative to these markers using a dynamic calibration procedure (Schwartz & Rozumalski, 2005) implemented into the software Visual3D (C-motion, USA). This method was based on the movement of the forearm relative to the humerus in a calibration trial when the subject performed approximately ten cycles of forearm flexion/extension and pronation/supination prior to commencing the test session. It was assumed that the wrist joint centre was located half-way between a medial and distal landmark at the wrist. These landmarks were located using a digitising pointer (Cappozzo, Catani, Della Croce, & Leardini, 1995).

The grip of the club was tracked using four markers: one placed at the butt end of the shaft, covering the plug that was used to transmit the strain signals (see Section 4.3, p. 75); another marker placed just below the grip; and two markers placed on an extension wand to avoid colinearity with the other two markers (see Figure 22, p. 76). All of these markers were placed close to the grip end of the club to avoid shaft deflection influencing the calculated grip orientation. This allowed the use of Visual3D to place a virtual offset marker at the tip end of the shaft, whose position was defined relative to the grip markers. Using this marker, it was possible to calculate the theoretical speed of the tip end of the shaft in the absence of shaft deflection. Subsequently, this was compared to the actual speed of a marker that was placed at this position and recorded using the impact location motion capture system. The modified backward difference algorithm presented in Appendix C (p. 205) was used for all speed calculations.

Trajectories were extrapolated to the time of impact to ensure appropriate results. This was because impact typically occurred between frames (see Figure 29, p. 97).

Rather than including a number of different joints at a limited number of events in the analysis of the body kinematics, it was decided to focus on the wrist joint angle in the present study. This was motivated by the fact that no changes that could be attributed to shaft stiffness were found in the study presented in Chapter 5. The number of events at which wrist angles were compared between the different conditions was increased to four in comparison to two events that were used in the study presented in the previous chapter. Further pilot work after conducting Study 1 showed that correctly differentiating the two anatomical components of the wrist angle (flexion/extension, radial/ulnar deviation) can be challenging due to skin movement artefacts and alignment errors in the anatomical axes. It has been suggested that correction procedures may be necessary to account for these (R. Schmidt, Disselhorst-Klug, Silny, & Rau, 1999). As a decomposition of the wrist angle into its anatomical components was not crucial for the purposes of this study, it was decided to characterise the wrist kinematics using one planar angle (without reference to the anatomical planes) instead. This angle was defined using four points, two of which defining the centreline of the forearm and another two defining the centreline of the unbent shaft (see Figure 40). In addition, a global arm angle was defined representing the angle of the longitudinal axis of the forearm relative to the vertical z-axis.

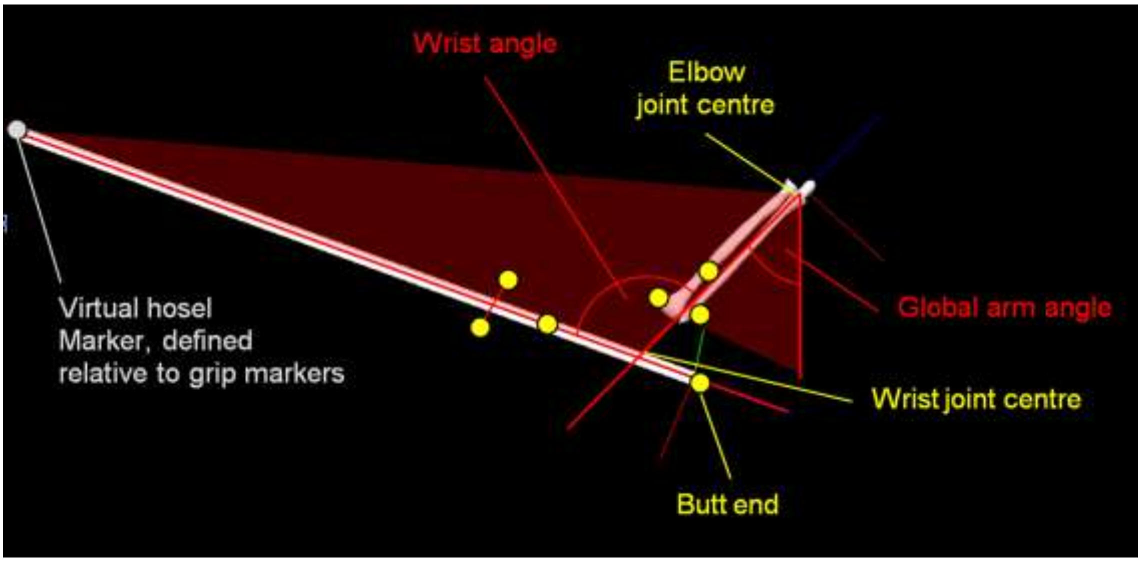



**Figure 40: Definition of four-point wrist angle and position of virtual offset marker placed at tip end of shaft.**

In order to characterise the global movement of the grip section of the club, the following steps were performed. For each swing, a plane was fitted to the path of the grip based on the position of the grip at the grip-horizontal and impact event (see below for definitions of these events). Care was taken as to determining the position of the grip segment at the time of impact accurately. To do so, a third order polynomial was fitted to the grips trajectory and extrapolated from the last pre-impact sample up to the time of impact (as registered with the sound trigger). Then, the trajectories of two markers defining the longitudinal axis of the grip were projected onto the plane by evaluating the polynomial at 100 equidistant time points and transforming the coordinates (see Figure 41, only every fifth grip position is drawn for clarity). This allowed for calculation of the angular velocity of the grip just before impact using the same conventions as MacKenzie (2005), thereby facilitating a comparison of the experimental results from the present study with simulation results obtained by MacKenzie.

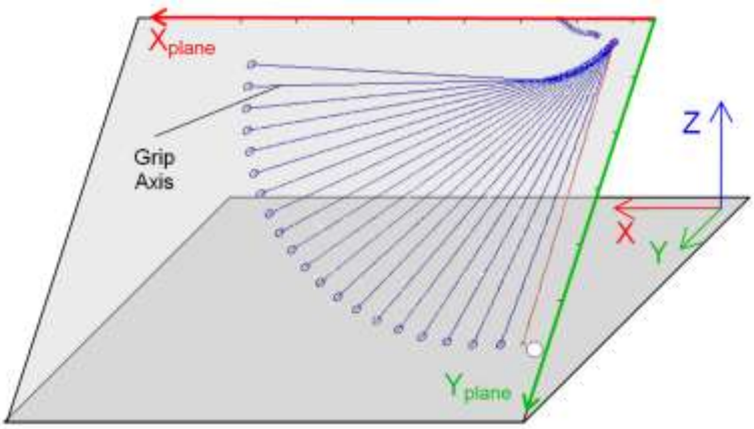



**Figure 41: Planar projection of the club path to determine grip angle and angular velocity at impact.**

The raw strain data were post-processed as described in Section 4.4 (p. 77) to extract the peak toe-up strain at the transition from backswing to downswing, the lag area, the lead/lag recovery rate and the amount of lead strain at impact (see Figure 26, p. 80).

### 6.2.3 Event detection

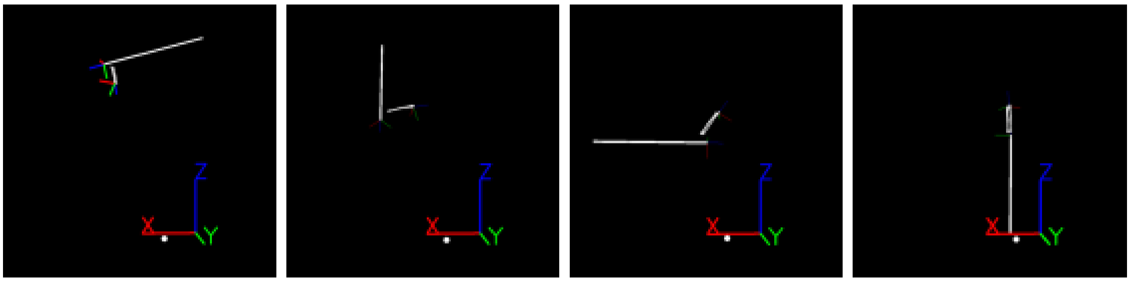
As discussed above, the number of events used in the analysis of the wrist kinematics was increased from two to four (see Figure 42):

- Transition from backswing to downswing (TOB): x-component of velocity of the frontal shaft marker changes from negative (towards target) to positive (away from target). This marker was selected for its good visibility at the top of the backswing.

- Grip-vertical: the longitudinal axis of the grip, projected onto a plane defined by the global x- and z-axis, is parallel to the vertical z-axis and pointing upwards.

- Grip-horizontal: the longitudinal axis of the grip, projected onto a plane defined by the global x- and z-axis is parallel to the horizontal x-axis.

- Impact: For the body motion capture system (7 cameras), this was placed based on the signal recorded from the acoustic trigger. For the impact motion capture system (3 cameras), this was determined by the impact position algorithm as described in Section 4.6.2 (p. 92).




**Transition** **Grip vertical** **Grip horizontal** **Impact**

**Figure 42: Events used in Study 2.**

The grip-vertical and grip-horizontal events have also been used in previous studies (Ball & Best, 2007a, 2007b) and were selected because they sub-divide the downswing in three parts of approximately equal duration.

### 6.2.4 Statistical analysis

Similar to the procedure used in Study 1 (see Chapter 5.1.4, p. 111) and as discussed in Section 4.1.2 (p. 62), all recorded trials were included in the statistical analysis rather than just one mean value per player and condition. A requirement was that shaft condition, player and trial were included in the analysis to account for the fact that repeated trials recorded from the same player under the same test conditions cannot be regarded as independent observations. Prior to conducting the statistical analysis related to the research questions addressed in the present study, data were inspected for any systematic trends that may have been caused by factors other than shaft stiffness.

Following the reliability check, a series of three MANOVAs was performed for each group of outcome variables (club head presentation, strain and body kinematics). Additionally, the difference in speed between an actual hosel marker and a virtual hosel marker were examined using a mixed-design ANOVA. This included the speed for the two reference markers as repeated measures for each shot as well as player, shaft condition, test order and trial number as between-sample factors.

One advantage of including only two different shaft conditions in the present study (l-flex and x-flex) was that any significant difference between shaft conditions could be attributed to the difference between these shafts without the necessity for pair-wise comparisons. The α-level for the complete statistical analysis was set to 0.05 and the analysis was performed using SPSS 16 (SPSS, Inc., USA).

## ***6.3 Results***

Results will be presented in the order the statistical analysis was performed. Initially, tests were run to confirm that the assumptions for the statistical analysis were met. Then, a within-player consistency check was carried out. This was performed to detect systematic changes in swing kinematics that may have occurred regardless of the experimental conditions. Following this, the main analysis was carried out with regards to the hypotheses presented in the introduction.

### 6.3.1 Assumptions for the statistical analysis

Similar to Study 1 (Chapter 5), a number of assumptions have to be met for the MANOVA to be valid. In particular, observations have to be independent, multivariate normality is required, and the covariance matrices must be homogeneous (Field, 2005).

Whilst independence of observations was assured by including all independent variables as factors in the model (player, shaft condition, trial), it was more difficult to test the data for multivariate normality as no standard tests exist to do so (Field, 2005). As discussed in Section 5.2.1 (p. 112), it was decided to test each variable individually for normality because univariate normality is one of the prerequisites for multivariate normality. To do so, the data set was split into subsets based on the fixed factors and tested for normality using Shapiro-Wilk tests (Stevens, 2002). With very few exceptions, all subsets were found to be normally distributed. Box's test was then applied to test whether the covariance matrices were homogeneous. This test indicated that covariances were not homogeneous for the majority of variables ($p < 0.05$). To understand the cause of these deviations, the data were further analysed by calculating the variances for subsets of the data for each variable and by applying Levene's tests. This showed that the variances for the two different club conditions were relatively similar, as indicated by a variance ratio that was smaller than 1.5 for all variables[14]. In contrast, variances of the different subjects differed much more widely for the majority of variables, thereby violating the assumption of homogeneity of variances. However, it was decided to accept the violation of this assumption for two reasons. Firstly, as shown in a review of relevant Monte Carlo studies by Stevens (2002), "equal [group sizes] keep the actual α very close to the level of significance (within a few percentage points) for all but the extreme cases" if variances are inhomogeneous (Stevens, 2002, p. 270). Groups in the current study were equal because players performed the same number of swings with the l-flex and x-flex shafts. Secondly, the lack of homogeneity in variances was only found to be pronounced when comparing different players. As the focus of the present study is on a comparison of different shaft conditions, and variances of the two shaft conditions were homogeneous for all variables, it was decided that MANOVAs would be used regardless of the significant results from Box's test.

### 6.3.2 Within-player consistency

It was found in the previous study (Chapter 5, p. 103) that the club head speed at impact as well as the ball speed increased significantly throughout the test sessions for some of the subjects, regardless of the club used. This could be attributed to learning or warm-up effects. In Study 1, the first six shots performed by each player were discarded from subsequent analyses to remove this effect. The purpose of this section is to examine the results from the second study for similar effects.

For this reliability check, an additional independent variable was introduced. This variable was named 'set', and its value was defined based on whether a player tested a given club for the first or second time during his test session.

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[14] The variance ratio was calculated by dividing the largest variance of a variable for a given condition by the smallest variance found for the same variable but for a different condition.

(i.e. its value was “1” for the first time the shaft was presented to the player, “2” for the repeat during the second half of the test session, see Table 25). Following this, a univariate ANOVA was performed, using player, club and set as the factors. The model was customised to only include main effects because interaction effects were not assumed to be relevant at this point of the analysis.

Based on the descriptive statistics (Table 26), it was deemed unlikely that there were any systematic trends that would cause differences depending on the set factor. When performing the ANOVA, however, it was found that set was a main effect ($p$ = 0.006) along with the factors player and club (see Table 27).

**Table 25: Example for the use of the independent variable ‘set’ that was introduced for the within-player consistency analysis.**

| Player ID | Shaft | Set | Trial | Dependent variables | |
|---|---|---|---|---|---|
| ... | ... | ... | ... | ... | ... |
| 5 | l-flex | 1 | 1 | ... | ... |
| 5 | l-flex | 1 | ... | ... | ... |
| 5 | l-flex | 1 | 6 | ... | ... |
| 5 | x-flex | 1 | 1 | ... | ... |
| 5 | x-flex | 1 | ... | ... | ... |
| 5 | x-flex | 1 | 6 | ... | ... |
| 5 | l-flex | 2 | 1 | ... | ... |
| 5 | l-flex | 2 | ... | ... | ... |
| 5 | l-flex | 2 | 6 | ... | ... |
| 5 | x-flex | 2 | 1 | ... | ... |
| 5 | x-flex | 2 | ... | ... | ... |
| 5 | x-flex | 2 | 6 | ... | ... |
| ... | ... | ... | ... | ... | ... |

**Table 26: Descriptive statistics summarising club head speeds recorded for the first and second set of swings (mean ±SD).**

| Set | *n* | Club head speed (m/s) |
|---|---|---|
| 1 | 231[a] | 46.22 ±2.59 |
| 2 | 230[a] | 46.27 ±2.57 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

**Table 27: ANOVA results for reliability analysis that was performed to check for consistency in club head speed throughout the course of the test sessions.**

| | Club head speed | | |
|---|---|---|---|
| | *df* | *F* | *P* |
| **Player** | 19 | 542 | < 0.001 |
| **Shaft** | 1 | 38.4 | < 0.001 |
| **Set** | 1 | 7.57 | 0.006 |

In order to further examine the effect of the set factor, estimated marginal means were plotted for each level of set. As each set of swings (first and second) consisted of the same number of swings performed with the I-flex and the x-flex shaft, potential shaft effects will not affect this part of the analysis. Figure 43 shows that club head speed increased marginally, but significantly ($p = 0.006$), when comparing the first and second sets of swings. As the same clubs were tested in the first and second half of the test session, it is most likely that this change in club head speed was due to factors other than shaft stiffness.

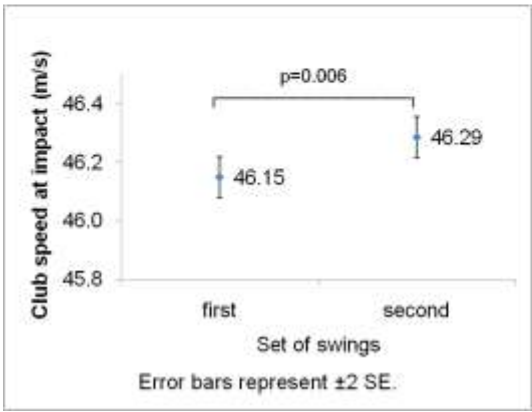



**Figure 43: Estimated marginal means for club head speed for swings performed as part of the first and second set of swings.**

The absolute difference in club head speeds was small (see Figure 43), so to confirm this finding, the club head speeds were normalised by dividing each club head speed by the mean club head speed of the player that performed the shot. The purpose of this normalisation was to remove differences between players. After this, the correlation of a swing counter with the normalised club head speed was examined. It was found that, despite a very low Pearson correlation coefficient ($r$ = 0.155), there was a significant correlation ($p$ = 0.001) between swing counter and club speed. Further inspection of the data revealed that this correlation was not present ($p$ = 0.498, $r$ = 0.045) if only swings performed during the second half of the test session were included (set = 2). It was therefore decided to remove data recorded for the first two experimental conditions and to only include data recorded for the third and fourth condition for further analysis.

### 6.3.3 Shaft effects

Following the results of the within-player consistency analysis, this section details the results regarding the main research questions addressed in this section. Each sub-section is related to one of the hypotheses presented in the introduction to this chapter (see Section 6.1, above).

#### *6.3.3.1 Club head presentation*

The first set of variables that was examined characterised the club head presentation to the ball at impact. Table 28 summarises the descriptive statistics for these variables for the two shaft conditions. It can be seen that there were no obvious trends depending on the shaft condition for any of the variables. Yet, the test statistic of the MANOVA (Pillai's trace[15]) indicated main effects due to the factors player ($F$(19) = 14.7, $p$ < 0.001) and shaft condition ($F$(1) = 8.35, $p$ < 0.001). The factor trial ($F$(5) = 0.682, $p$ = 0.846) was not a main effect and will not be analysed further. MANOVA also indicated that the interaction player×shaft was significant ($F$(19) = 1.473, $p$ = 0.007).

[15] Pillai's trace was selected as test statistic for its robustness against violations of the homogeneity of variances and normality assumptions, as discussed in the literature (Bray & Maxwell, 1985; Field, 2005).

**Table 28: Descriptive statistics (mean ±SD) for club head presentation.**

| Shaft flex | Club head speed (m/s) | | Horizontal Impact location (mm) | | Vertical impact location (mm) | | Face angle (°) | |
|---|---|---|---|---|---|---|---|---|
| l | 46.4 | ±2.66 | -1.61 | ±8.73 | 8.06 | ±6.20 | 2.48 | ±3.32 |
| x | 46.1 | ±2.47 | -0.461 | ±8.48 | 7.02 | ±6.80 | 2.01 | ±2.95 |

The shaft effect was further examined using univariate ANOVAs for each variable (Table 29). It can be seen that there was an effect of shaft stiffness on the variable club head speed at impact ($p$ < 0.001) but not on the other club head presentation variables ($p$ > 0.05). For impact location, the lack of a shaft effect was also evident from impact location plots for the individual players, an example of which is shown in Figure 44 (see Appendix H, p. 220, for impact location plots for all players).

**Table 29: ANOVA results for club presentation variables.**

| | | Club speed | | Face angle | | Horizontal impact location | | Vertical impact location | |
|---|---|---|---|---|---|---|---|---|---|
| | ***df*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 19 | 28.4 | <.001 | 19.2 | <.001 | 6.35 | <.001 | 2.09 | <.001 |
| **Shaft** | 1 | 28.4 | <.001 | 1.84 | 0.176 | 0.986 | 0.907 | 2.09 | 0.774 |
| **Player ×Shaft** | 19 | 2.72 | <.001 | 1.9 | 0.016 | 0.907 | 0.575 | 1.17 | 0.289 |

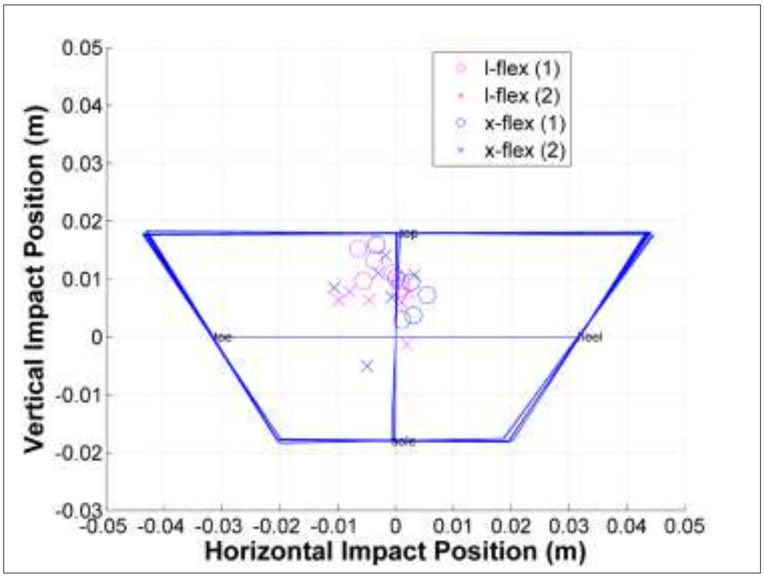



**Figure 44: Typical example for impact positions recorded for one player. Club number (1) and (2) refer to the first and second data set recorded.**

To aid interpretation of the ANOVA results, marginal means (Field, 2005) were plotted for club speed. The plot (Figure 45) shows that the club head speed at impact was significantly higher for the club with the l-flex shaft compared to the x-flex shaft. This increase, however, was relatively small (0.34 m/s or 0.73 %, $p < 0.001$). The player × shaft interaction was examined using an interaction plot and estimated marginal means (data not presented). It was found that the majority of players followed the trend to achieve higher club head speeds with the l-flex shaft. The only exception to this were three players whose club head speeds for the l-flex were slightly lower than for the x-flex club.

To confirm the finding of a significant increase in club head speed associated with a decrease in shaft stiffness, ball speed data from the launch monitor was used. It was found that the mean ball speed for the l-flex club was higher than for the x-flex club (67.6 ±3.6 m/s and 67.1 ±3.4 m/s, respectively). Using an ANOVA with player and shaft as factors, it was found that this difference was statistically significant ($F(1) = 7.19$, $p = 0.008$). Estimated marginal means (Figure 45) confirm that ball speeds were higher for the l-flex shaft than for the x-flex shafts, albeit by a small magnitude (0.7 %).

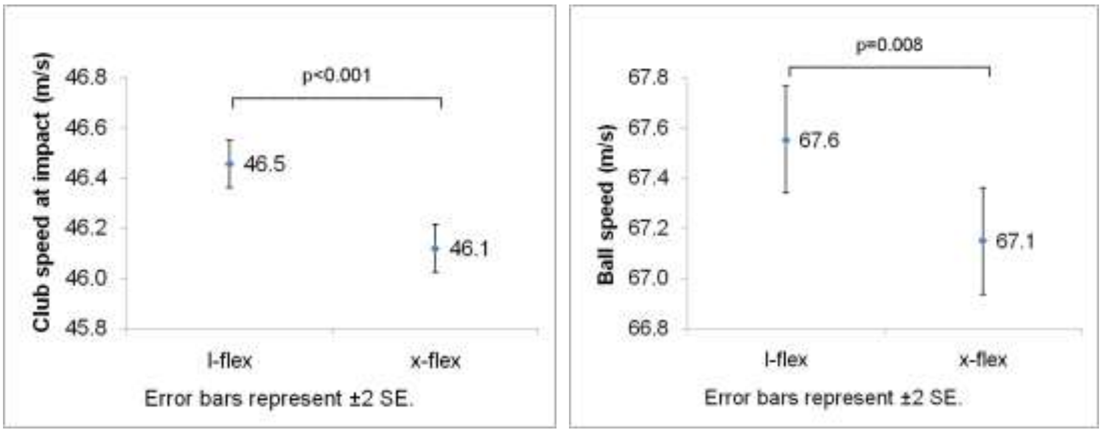



**Figure 45: Estimated marginal means plot for club head speed at impact and ball speed.**

### *6.3.3.2 Club head speed generated from shaft recovery*

The purpose of this part of the result section is to analyse the speed of a marker that was placed close to the tip end of the shaft in more detail. This marker was placed at the hosel, covering the junction of the shaft and the club. During post-processing, it was duplicated using a virtual marker. This virtual marker was defined relative to the grip markers. Hence, its position and velocity was deemed representative of the behaviour of the marker if the shaft was in the un-flexed or neutral position (see Figure 40, p. 138).

Descriptive statistics (Table 30) show that the speed of the actual hosel marker was marginally higher than the speed of the projected marker. The magnitude of this difference was greater for the l-flex shaft (0.33 m/s) than for the x-flex shaft (0.15 m/s).

**Table 30: Descriptive statistics for hosel speed at impact (mean ±SD) as measured directly and as calculated based on a virtual marker.**

| | *n*[a] | **Speed without shaft bending (m/s)** | | **Speed with shaft bending (m/s)** | | **Difference (m/s)** | **Difference (%)** |
|---|---|---|---|---|---|---|---|
| **l-flex** | 117 | 42.36 | ±2.67 | 42.69 | ±2.42 | 0.33 | 0.7 % |
| **x-flex** | 115 | 42.26 | ±2.33 | 42.41 | ±2.26 | 0.15 | 0.4 % |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

In order to further examine these differences, a mixed-model ANOVA was applied. The model consisted of one within-sample factor and three between-sample factors. The within-sample factor was termed speed difference and represented the difference between the speed of the virtual and the actual hosel marker. As for the MANOVA presented in the previous section, the between-sample factors were player, shaft condition and trial. It was felt that higher order interactions would not aid testing the hypotheses regarding club head speed. Therefore, only main effects and interactions of the within-sample factor (speed difference) with the between-sample factors were included in the analysis.

The results of the mixed model ANOVA are summarised in Table 31. It can be seen that speed differed depending on which reference location was used to calculate it (speed difference factor, $p < 0.001$). Interestingly, two of the interaction terms were also found to be significant, namely the speed difference × player and speed difference × club terms. The speed × player term ($p < 0.001$) indicates that speed differences changed depending on which player performed the swing. More importantly in the context of the present study, the speed × club interaction term indicates that speed differences were affected by the stiffness of the shaft ($p = 0.002$). As expected, the interaction with the factor trial was not significant, which means that the effect of the speed difference factor did not vary depending on the time at which a club was tested.

**Table 31: Mixed model ANOVA results.**

| | | **Club speed** | |
|---|---|---|---|
| | ***df*** | ***F*** | ***p*** |
| **Speed difference** | 1 | 29.20 | <0.001 |
| **Speed difference × player** | 19 | 17.55 | <0.001 |
| **Speed difference × club** | 1 | 10.24 | 0.002 |
| **Speed difference × trial** | 5 | 0.494 | 0.781 |

The findings from the mixed model ANOVA were further examined using marginal means and interaction plots. As illustrated by Figure 46, the speed of the actual hosel marker was on average 0.213 m/s higher than the speed of the virtual hosel marker (a change of 0.5%, $p < 0.001$). As indicated by the significant interaction term (speed difference × club), the magnitude of this speed difference varied depending on which shaft was used. An interaction plot of the two factors illustrates this effect (see Figure 47). The plot shows that the difference between the virtual and the actual marker speed was greater for the l-flex than for the x-flex shaft.

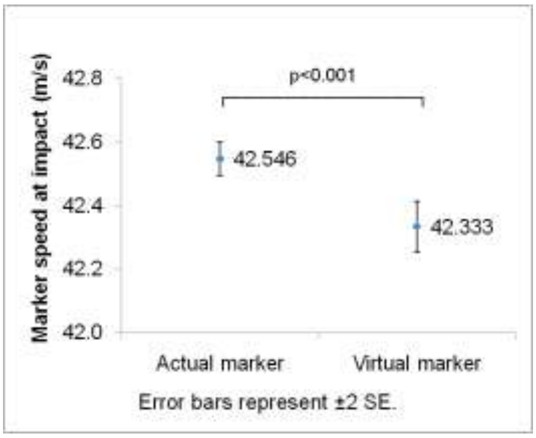



**Figure 46: Estimated marginal mean speed for the hosel marker as measured directly with the motion capture system and as calculated for a virtual marker.**

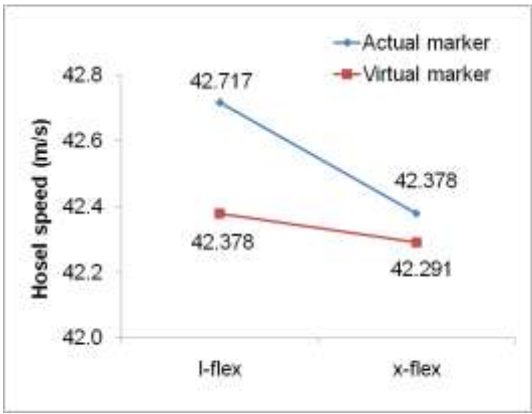



**Figure 47: Interaction of speed difference and shaft stiffness factors.**

### *6.3.3.3 Strain*

As in Study 1, strain was recorded to examine the bending patterns of the different shafts to complement the other variables. The descriptive statistics (Table 32) indicate that the peak magnitude of toe strain – typically occurring at the transition from backswing to downswing – was higher for the l-flex shaft. The mean recovery rate and lag area (see Section 4.4.2, p. 80) were also greater for the more flexible shaft. In contrast, the amount of lead strain at impact was slightly higher for the x-flex shaft.

**Table 32: Descriptive statistics for strain variables (mean ±SD).**

| Shaft | *n*[a] | Peak toe strain (µm/m) | | Recovery rate (1/s) | | Lag area (µm/m · s) | | Lead strain at impact (µm/m) | |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | 118 | 3682 | ±869 | 0.0525 | ±0.022 | 439 | ±230 | 692 | ±481 |
| **x-flex** | 114 | 2208 | ±493 | 0.0444 | ±0.013 | 275 | ±136 | 714 | ±424 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

A plot of the typical strain patterns generated by one player (Figure 48) helps to visualise these results. It can be seen that the strain curves for the two different clubs are separated for most parts of the swing, in particular for the toe-up/down component at the transition from backswing to downswing (peak toe strain variable). The amount of lag bending during the first half of the downswing is also markedly greater for the l-flex shaft (lag area variable). During approximately the last 0.1 s before impact, however, traces for the two different shafts begin to overlap and are not possible to distinguish at impact, in particular for the lead/lag component (lead strain at impact variable). These features are typical for the sets of strain data for all twenty players, even if loading patterns often differed between subjects[16]. These results will be analysed statistically in the remainder of this section.

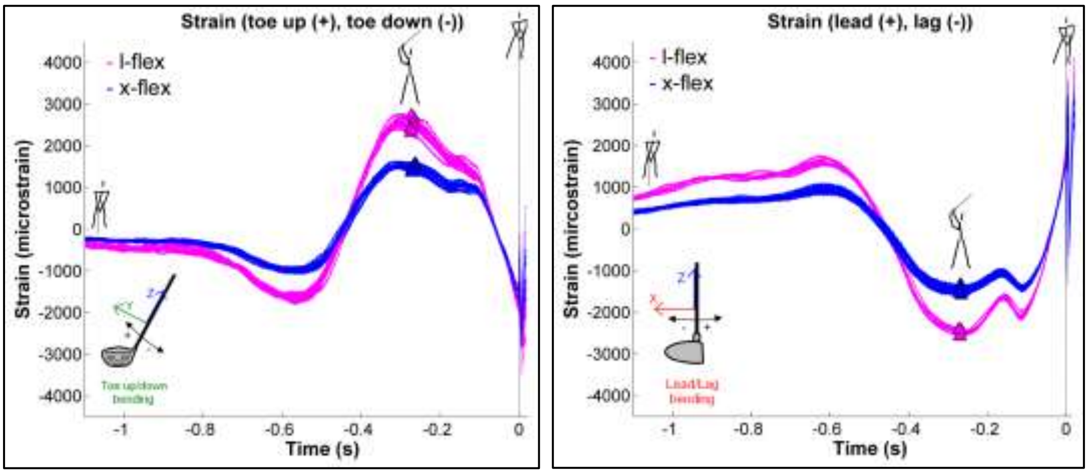



**Figure 48: Typical strain patterns (all swings shown were performed by one player). The transition from backswing to downswing is marked with a △ symbol.**

[16] Strain plots for all participants can be found in Appendix F, p. 211.

Using the Pillai's trace test statistic of MANOVA, it was found that there were main effects due to the player ($F(19) = 72.7$, $p < 0.001$ and shaft factors ($F(1) = 1470$, $p < 0.001$). The trial factor, however, was not a main effect ($F(5) = 0.368$, $p = 0.995$), indicating that there were no systematic trends present within the repeated trials of the subjects. The MANOVA results justify further analysis of the results with individual ANOVAs for each of the four variables. The results of these tests are summarised in Table 33 and indicate that there was a main effect for all four strain variables due to the player and shaft factors.

**Table 33: ANOVA results for strain variables.**

| | | Peak toe strain | | Recovery rate | | Lag area | | Lead strain at impact | |
|---|---|---|---|---|---|---|---|---|---|
| | ***df*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 19 | 86.0 | <.001 | 41.9 | <.001 | 127 | <.001 | 209 | <.001 |
| **Shaft** | 1 | 1944 | <.001 | 47 | <.001 | 495 | <.001 | 8.72 | 0.004 |

For further analysis and to determine the magnitude and direction of the observed effects, estimated marginal means for each variable were plotted (Figure 49). These plots confirmed the trends observed in the descriptive statistics. The peak toe strain for the l-flex shaft was significantly higher than for the x-flex shaft ($p < 0.001$). Both the recovery rate and the lag area were also greater for the l-flex shaft ($p < 0.001$), but the lead strain at impact was greater for the x-flex shaft ($p = 0.004$).

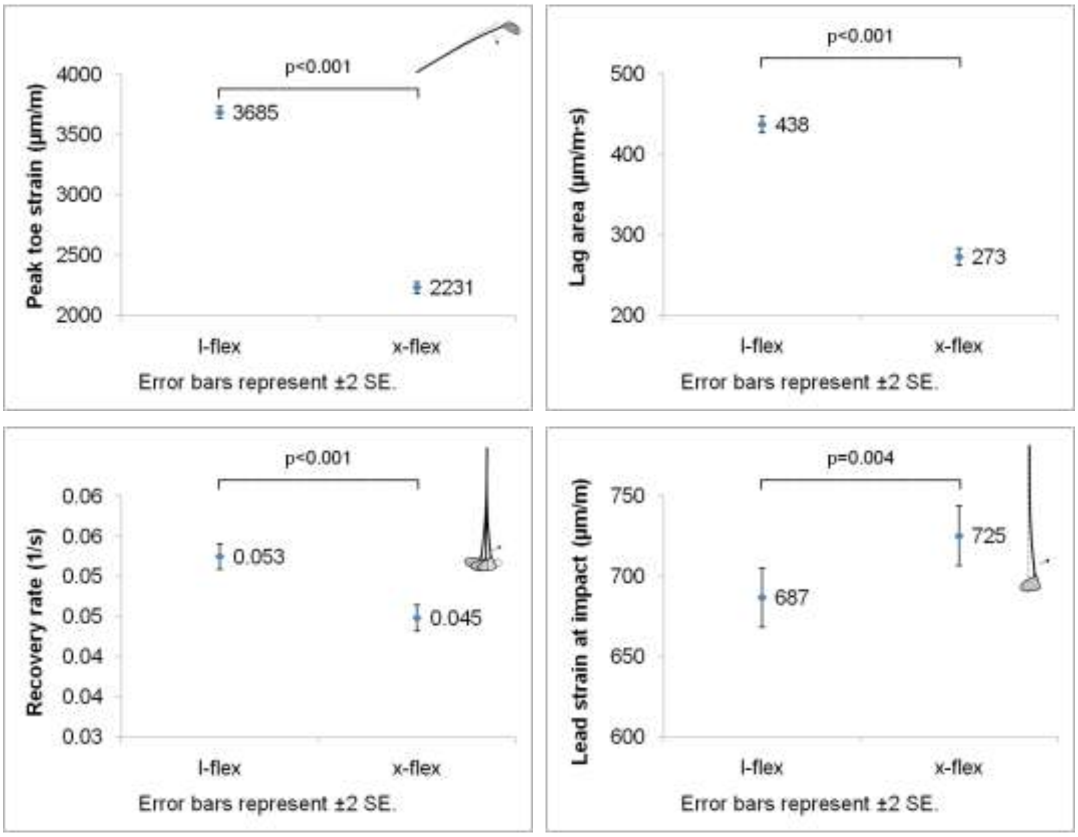



**Figure 49: Estimated marginal means for strain variables.**

### *6.3.3.4 Body movement*

In order to attempt to understand the mechanism behind the behaviour of clubs with different shafts, the kinematics of the wrist joint were analysed in more detail. As described in Section 6.2.2, the main focus of this analysis was on a simplified, planar wrist angle (see Figure 40, p. 138). The descriptive statistics (Table 34) indicated that there was little, typically less than 1°, difference between wrist angles measured for the two shaft conditions at the four discrete events defined above (see Figure 42, p. 140).

**Table 34: Descriptive statistics for a simplified four-point wrist angle at four downswing events.**

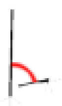
| **Shaft** | ***n*[a]** | **Top of Backswing** | | **Grip vertical** | | **Grip horizontal** | | **Impact** | |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | 111 | 86.5 | ±13.3 | 93.6 | ±8.7 | 122.7 | ±5.1 | 151.7 | ±6.9 |
| **x-flex** | 107 | 86.7 | ±13.7 | 94.4 | ±8.6 | 123.6 | ±4.8 | 151.7 | ±6.7 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

As previously, the selected variables were examined for shaft effects using MANOVA. It was found that for this set of variables as a whole, there were main effects both due to the player (Pillai's trace: $F(19) = 91.4$, $p < 0.001$) and club factors ($F(1) = 7.69$, $p < 0.001$), whereas there was no main effect due to the trial factor ($F(5) = 0.830$, $p = 0.728$). These findings justify performing individual ANOVAs for each variable to detect which variables caused the detected effects (Field, 2005).

The ANOVA results for the wrist angle are summarised in Table 35. It was found that there were main effects due to the player factor for all four variables (each representing the wrist angle at one event, $p < 0.001$). The shaft factor, in contrast, was only associated with changes in the wrist angle at the grip-vertical and grip-horizontal events ($p < 0.001$). The wrist angle at the top of the backswing was unaffected ($p = 0.113$), as was the wrist angle at impact ($p = 0.065$). The direction and magnitude of the shaft effect was further examined using estimated marginal means. As shown in Figure 50, the wrist angle at the grip-vertical and grip-horizontal events was smaller for the l-flex than for the x-flex shaft. The magnitude of this difference was small (approximately 1°).

**Table 35: ANOVA results for the angle formed between the longitudinal axes of the forearm and the grip segment at four events.**

| | |  **Top of backswing** | |  **Grip vertical** | |  **Grip horizontal** | |  **Impact** | |
|---|---|---|---|---|---|---|---|---|---|
| | **df** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** | ***F*** | ***p*** |
| **Player** | 19 | 1197 | <.001 | 785 | <.001 | 255 | <.001 | 567 | <.001 |
| **Shaft** | 1 | 2.53 | 0.113 | 28.9 | <.001 | 37.8 | <.001 | 3.45 | 0.065 |

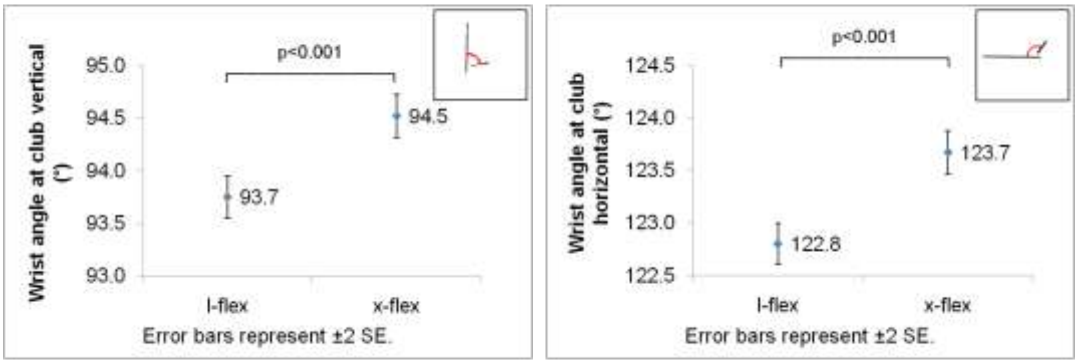



**Figure 50: Estimated marginal means for planar wrist angle at the grip-vertical and the grip-horizontal events.**

To aid interpretation of the wrist angle results, wrist angle plots were created for individual subjects. One option to examine changes in the coordination of complex movements are angle-angle plots (Mullineaux, 2008). It was found that, in the present study, these were better suited to examine the shaft effect on wrist angles than using time histories of the joint angles. Plotting time histories had the disadvantage that phases with relatively slow movement (e.g. at the top of the backswing) were shown with more detail than fast phases (e.g. the last few milliseconds before impact). The resulting plots (see Figure 51) showed that players appeared to ‘release’ the x-flex club slightly earlier than the l-flex club. This can be seen from the shift to the left of the curve for the x-flex shaft relative to the l-flex shaft in Figure 51. Similar plots were also examined without discarding the first two test conditions, so that the repeated test of identical clubs was shown. These confirmed the findings summarised above.

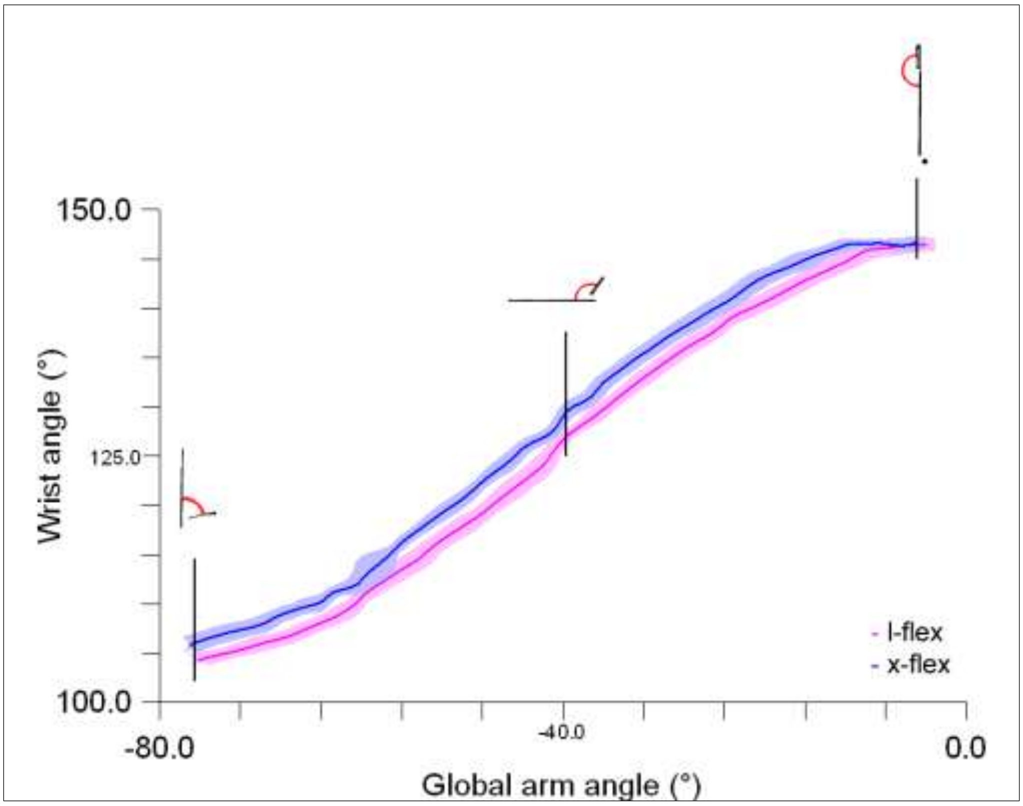



**Figure 51: Example for wrist angle joint history for one subject. For clarity, wrist angle is plotted as a function of global arm angle rather than time (see Figure 40 for angle definitions). Shaded areas indicate ±1 SD.**

Changes in the mechanical properties of the shafts may have prompted players to adapt their swing to reach impact with a different grip position, for example to compensate an increase in dynamic loft that may have been associated with a certain shaft. Hence, the absolute orientation of the grip relative to a vertical axis was examined in the present study. The resulting grip angle and the angular velocity of the grip segment are both listed in Table 36. As discussed earlier in this section, MANOVA indicated significant shaft effects for the set of body movement variables. Individual ANOVAs (see Table 37) revealed that shaft effects were not present for the grip angle variable ($p$ = 0.934) but for grip angular velocity ($p$ = 0.005).

**Table 36: Orientation and angular velocity of the grip section of the club at impact.**

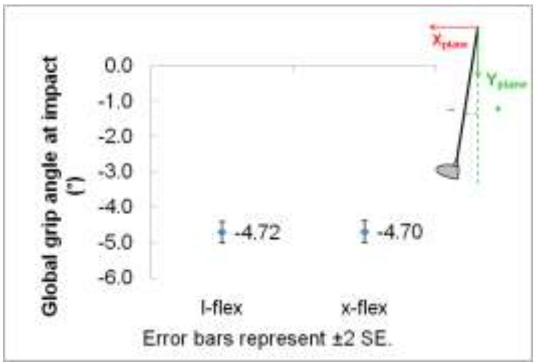
| Shaft | *n* | Planar grip angle (°) | | Grip angular velocity (°/s) | |
|---|---|---|---|---|---|
| **l-flex** | 119[a] | -4.63 | ±2.96 | 2270 | ±168 |
| **x-flex** | 115[a] | -4.61 | ±2.81 | 2261 | ±143 |

[a]See Section 4.1.6 (p. 69) regarding discarded trials resutling in a reduced *n*.

**Table 37: ANOVA results for the orientation of the longitudinal axis of the grip of the test clubs.**

| | | Planar grip angle | | Grip angular velocity | |
|---|---|---|---|---|---|
| | *df* | *F* | *p* | *F* | *p* |
| **Player** | 19 | 27.5 | <0.001 | 294 | <0.001 |
| **Shaft** | 1 | 0.007 | 0.934 | 7.94 | 0.005 |

As for the previous variables, shaft effects were further analysed using estimated marginal means (Figure 52). As expected, there was no difference in the recorded grip angles, and players generally hit the ball with a negative grip angle. In contrast, for the angular velocity of the grip there was a significant difference between shaft conditions ($p$ = 0.005), and players achieved a higher angular velocity of the grip at impact with the l-flex shaft (relative difference: 0.5 %).



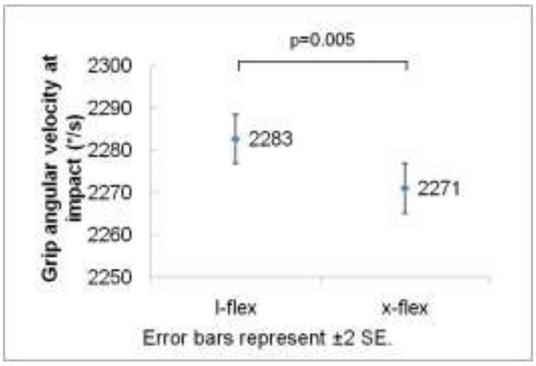




**Figure 52: Estimated marginal means for the planar club angle and angular velocity. This angle was calculated after projecting the longitudinal axis of the grip on the x-z-plane (vertical) and is relative to the z-axis.**

## *6.4 Discussion*

### 6.4.1 Within-player consistency

The first part of the analysis focused on whether players performed consistently throughout their test session regardless of any potential shaft effects. For this purpose, an additional factor (named 'set') was introduced into the analysis and found to be a main effect, indicating that players did not perform consistently. It was therefore decided that the first six swings with each club had to be discarded to remove these systematic trends. As players typically performed slower swings at the beginning of the test session, it is likely that this effect was caused by an inadequate warm-up or familiarisation with the test club. The existence of differences in swing speed throughout test sessions, even for identical clubs, supports some of the findings from Study 1, where a similar effect was observed (see Section 5.3.1, p. 125). As already discussed in Study 1, this effect warrants further investigation in separate studies to ensure that comparisons of different versions of sports equipment are not biased due to a lack of warm-up or familiarisation with equipment that the subject has not used before.

### 6.4.2 Club head presentation

Based on Study 1, it was hypothesised that there would be no effect of shaft stiffness on the club head presentation variables (impact location, face angle, club head speed). The results of the present study confirmed this hypothesis for impact location and face angle, but club head speeds were significantly faster for the l-flex shaft than for the x-flex shaft. Ball speeds were also higher for the l-flex shaft. As it can be assumed that club head speed at impact and ball speed are closely related, the ball speed results – measured with a separate measurement system – support the finding that club head speed was higher for the l-flex shaft. Changes in ball and club head speed are also above the precision levels of the measurement equipment (see Table 11, p. 92, and Table 13, p. 101). The disagreement between the findings from Study 1 and 2 regarding club head speed at impact maybe be explained by the increased statistical power (more subjects, less conditions) and by the direct measurement of club head speed with an optical motion capture system (Study 2) instead of a radar device (Study 1).

The finding of increased club head speed is in agreement with data presented by Wallace and Hubbell (2001). The authors found a difference of 0.3 m/s (0.8 %) between the stiff and most flexible shaft when analysing swings performed by 84 golfers with 5-irons with stiff (336 cpm), regular (310 cpm) and very flexible (283 cpm) shafts. It may also be possible to compare the findings from the present study to results obtained in another study, which found no change in golf ball distance for a group of junior golfers as a whole (Stanbridge, Jones, & Mitchell, 2004). This may indicate that club head speeds were also unaffected by shaft stiffness, although it should be noted that club head speed was not measured directly in the study by Stanbridge *et al.*. The lack of an effect on distance does not necessarily mean that there was no change in club head speed because changes in one component of the launch conditions of the ball may be cancelled out by changes in other components. The effect of shaft stiffness on club head speed generation will be discussed further in the following sub-section.

It is interesting to note that shaft effects can also be interpreted on an individual basis, as suggested previously (Worobets & Stefanyshyn, 2008). In the present study, for example, three out of twenty players did not follow the trend for increased club head speed with the l-flex shaft. However, as this is a minority of players, the treatment of the results on a pooled basis appears to be justified in the present study.

### 6.4.3 Club head speed generated from shaft recovery

Based on the literature review and the strain results from Study 1, it was hypothesised that the recovery of the shaft from backward (lag) to forward (lead) bending would generate additional club head speed. This hypothesis was tested by comparing the speed of a virtual marker placed at the hosel (with its position defined relative to the grip) with the speed of the actual marker at this location. It was found that the virtual marker was moving significantly slower than the actual marker, supporting this hypothesis.

The second part of the hypothesis stated that this effect would be more pronounced for a more flexible shaft. There was a significant interaction of the speed difference and shaft factors. Furthermore, the difference in speeds for the two reference locations was higher for the l-flex shaft than for the x-flex shaft. Hence, experimental results also support the second part of the hypothesis.

This result confirms findings from some golf studies (Butler & Winfield, 1994; Wallace & Hubbell, 2001) but disagrees with others (MacKenzie, 2005; Stanbridge, Jones, & Mitchell, 2004). In one case, no comparison is possible as the statistical approach chosen by the authors did not allow the data to be analysed for the group as a whole (Worobets & Stefanyshyn, 2008).

Butler and Winfield (1994) stated that approximately 5 % of the club head speed at impact could be attributed to the flexibility of the shaft, which is much higher than the 0.5 % difference in speed between a virtual and an actual marker at the tip end of the shaft observed in the present study. A simulation study performed by MacKenzie (2005) confirms the first finding of this section that additional club head speed is generated by the ‘recoil’ of the shaft before impact. In his simulations, the velocity generated from the ‘recoil’ process for a fast swing (53 m/s) with a regular shaft was 9.7 m/s (18 %). This is considerably higher than the differences seen in the present study (0.5 %) and the shaft effect that was reported previously (5 %, Butler & Winfield, 1994). In case of MackKenzies’s results, this may be explained by the fact that the dampening parameters for different shaft segments were not determined in isolated experiments but were chosen so that the model outputs matched experimental results from live golfer testing. Yet, all three studies agree in associating an increase in club head speed with the recovery of the shaft. MacKenzie’s (2005) work does not, however, support the result from the present study that the resulting total speed differs depending on the stiffness of the shaft. MacKenzie concluded that “no particular level of shaft stiffness had a superior ability to increase club head speed” (MacKenzie, 2005, p. 122).

Finally, the finding of increases in club head speed linked to the flexibility of the shaft is in agreement with studies performed for other skills such as ice hockey wrist shots (Worobets, Fairbairn, & Stefanyshyn, 2006) and lacrosse (Crisco, Rainbow, & Wang, 2009).

### 6.4.4 Strain

The present study found shaft effects for all four strain variables (peak toe strain, lag area, recovery rate and lead strain at impact). Based on Study 1, it was hypothesised that these effects would only occur for the first three variables listed above but not for lead strain at impact. This, however, was not the case. This may be explained by the increased statistical power of the second study resulting from the reduced number of experimental conditions (two instead of three) and the increased number of subjects (twenty instead of seventeen). Another explanation for this finding may be that it was caused by a small systematic offset in the coordinate systems that were used to report the strain data between the l-flex and the x-flex clubs. However, as a calibration was performed to remove any such offset (see Section 4.4.1, p. 77) and the factors used to remove the offsets remained unchanged between the two studies, this is deemed unlikely.

No previous study could be identified that compared strain patterns for shafts of different stiffness levels. It is surprising that the present study found an increase in the amount of lead strain at impact for the x-stiff shaft compared to the l-flex shaft. This does not support the mechanism presented by a previous author (Maltby, 1995), who predicted that lead strain would increase as shaft stiffness decreases, leading to higher launch angles for more flexible shafts.

### 6.4.5 Body movement

Based on the literature review and Study 1, it was hypothesised that players would not adapt their body movement depending on the shaft stiffness of the club they were using. Contrary to this hypothesis, it was found that, depending on shaft stiffness, the wrist angle of the players differed significantly at two out of four downswing events. This may be interpreted as a delayed ‘wrist release’ occurring for the l-flex shaft. Delayed wrist action has been found to be a characteristic element of the swings of more skilful golfers, who also achieve higher impact velocities (Zheng, Barrentine, Fleisig, & Andrews, 2008a).

There was very little information regarding the effect of shaft stiffness on wrist kinematics in the literature. One study examined shoulder but not wrist kinematics for 84 golfers and found little effect of shaft flex variations (Wallace & Hubbell, 2001). In a single-subject simulation study, McGuan (1996) demonstrated the need for adaptations in body movement when shaft stiffness was varied. This is supported by the findings from the present study, although it should be noted that McGuan provided little detail as to what changes were necessary to maintain an efficient swing when shaft stiffness was altered.

One limitation of the assessment of wrist joint kinematics in the present study is that it is difficult to validate the accuracy of the obtained angles. Accuracy and precision of the motion capture system were determined prior to the study (see Section 4.5.2, p. 86), but it is also important to ensure that the definition of the local coordinate systems relative to the relevant landmarks is accurate. For example, it can be estimated that an offset[17] of the markers relative to the longitudinal axis of the shaft may cause a systematic error of approximately 0.5° in wrist angle for a given club. Yet, as the differences in wrist angles for the two shafts at the grip-vertical and grip-horizontal events were above 0.5° and it is deemed unlikely that the marker placement error was above the levels assumed for this calculation, it is unlikely that the observed change in wrist kinematics was caused by instrumental artefacts. Furthermore, it is likely that instrumental errors like this would have caused a change in the wrist angle at all four downswing events.

Two additional kinematic variables were studied: the orientation of the grip at impact relative to the vertical and the angular velocity of the grip segment at impact. No differences were found for the orientation of the grip at impact, which indicates that players did not adjust the global position of the grip at impact to compensate changes in dynamic loft caused by changes in shaft stiffness. However, there was a main effect due to the shaft factor for the angular velocity at impact. Again, the second finding is contrary to the hypothesis that body

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[17] Assuming the two markers defining the longitudinal axis of the shaft are placed at a distance of 1.1 m and both markers are placed erroneously 5 mm off the longitudinal shaft axis.

kinematics would remain unchanged when shaft stiffness is altered and will be examined in more detail in the following paragraphs.

The mean difference in angular velocity for the two clubs was 12 °/s (or 0.2 rad/s). In order to estimate the effect of this change on the linear velocity of the club head at impact, the finite centre of rotation of the club segment just before impact was calculated for each trial using an algorithm available in the literature (McCane, Abbott, & King, 2005). Typically, the centre of rotation was located to the right of the player's hands (away from the target) at the height of the left hand. Hence, the distance of the tip end of the shaft to the centre of rotation can be estimated to be approximately 1 m. Based on this, it can be calculated that the observed increase in grip angular velocity (0.2 rad/s) would result in an increase in linear club head speed of approximately 0.2 m/s. This tends to support the finding from Section 6.3.3.2 that the speed of the virtual tip marker was approximately 0.1 m/s faster for the l-flex shaft than for the x-flex shaft (see Figure 47, p. 150).

One of the simulations performed by MacKenzie (2005) compared a flexible shaft to a rigid shaft. One of the variables presented was the angular velocity of the grip segment of his model just before impact. MacKenzie found that, for a rigid shaft, angular velocity of the grip segment would increase by 8.95 rad/s (5 %) compared to the flexible shaft when optimising the swing for maximum club head speed and keeping the same torque limits in place for both shafts. MacKenzie explained that this difference was most likely caused by the rigid shaft's inability to store and release torque prior to impact. It may be possible to deduce from MacKenzie's (2005) findings that a stiffer shaft would rotate at a faster angular velocity at impact than a more flexible shaft. This, however, is contrary to the results of the current study, which indicated that angular velocity decreased slightly by 0.2 rad/s (0.5 %) with increasing shaft stiffness. The discrepancy in the results from the two studies could be explained by a number of factors. For example, players in the current study may have changed the peak torque values acting at some of their joints, whereas MacKenzie's model used identical peak torque limits for both shaft conditions. It is also possible that the optimisation algorithm chosen by MacKenzie selected a different adaptation strategy compared to the players in the current study.

### *6.5 Summary*

Regardless of the level of shaft stiffness, the speed of the club head was found to be underestimated by approximately 0.5 % when shaft bending was not taken into account. This was due to the recovery of the shaft from a lag to a lead position just before impact, which was observed for all recorded swings. This finding was confirmed using the strain data, which showed that in all cases shafts were in the process of changing from lag to lead bending just before impact. Typically, the club head was leading relative to the centreline of the unbent shaft at impact.

When comparing the two shafts, a marginal but statistically significant increase of 0.7 % in club head speed at impact was associated with decreasing shaft stiffness from x-flex to l-flex. Impact location and face angle were not affected by the change in shaft stiffness. A number of factors contributed to the increase in club head speeds for the more flexible shaft. Firstly, wrist release appeared to be slightly delayed for the more flexible shaft; the angle formed by forearm and grip was greater for the x-flex than for the l-flex club at two downswing events. This may have resulted in the increase in angular velocity at impact of the grip segment that was observed for the l-flex compared to the x-flex shaft. However, this effect would not fully explain the magnitude of club head speed increase seen for the l-flex shaft. The recovery process of the shaft just before impact was found to be another contributing factor as it generated more additional speed for the l-flex than for the x-flex shaft. This was evident from the comparison of a virtual and the actual shaft tip marker and the strain data (recovery rate).

Unexpectedly, lead strain at impact was marginally higher for the x-flex club. This is contrary to mechanisms presented previously by Maltby (1995) and would indicate that launch conditions may not be affected by changes in shaft stiffness as predicted in the literature.

Increased bending in the toe-up/down plane was registered for the l-flex shaft at the top of the backswing compared to the x-flex shaft, but it is not known to what extent this affects the behaviour of the shaft just before impact. It was seen that players typically rotate the shaft through 90° when squaring up the club face before impact, so bending in the toe-up/down plane at the top of the backswing would only affect the behaviour of the shaft in the lead/lag plane if the two strain components were coupled. Future studies will need to determine the amount of coupling between the two bending planes.

It is important to point out that the observed changes in club speed were on a very small scale. It is likely that few, if any, golfers would be able to detect their effect. Future studies need to determine whether further modifications of the shafts (e.g. lesser stiffness) would allow golfers to take advantage of the effects.

It remains difficult to understand cause and effect in the complex interaction of player and golf shaft, so the next study will utilise a golf robot that is unable to adjust its swing actively when shaft stiffness changes. This may also facilitate a comparison of more direct outcome variables, such as the full set of launch conditions.

# 7 Effect of shaft bending stiffness in robot swings

## 7.0 Introduction

The first two studies found that shaft stiffness had an effect on the characteristics of the recovery process just before impact (Study 1) as well as, to some extent, club head speed and the kinematics of the wrist joint (Study 2). It was not possible to identify previous experimental studies that determined whether these changes are the result of an active adaptation of the player or just a passive reaction of the equipment itself. Yet, it is important to distinguish between these two possible scenarios because the latter would allow changing (or optimising) the equipment without taking potential swing changes by the player into account.

Simulation methods have been used to examine questions similar to the one discussed in the previous paragraph, looking at the effect of changes in shaft stiffness (McGuan, 1996) and shaft length (Kenny, Wallace, Brown, & Otto, 2006). However, neither of these studies examined the wrist action in detail, but it is in the wrist where Study 2 identified changes associated with changes in shaft stiffness. As creating, validating and applying a simulation model of the human wrist action is deemed too complex a task, it was decided that an experimental method would be used to allow the shaft effects to be studied in the absence of active adaptations of the kinematics. This method consisted of the use of a golf robot.

As discussed in Section 2.4.2 (p. 26), golf robots are generally regarded as valid tools to replicate human launch conditions, but the ability of commercial robots to replicate human shaft loading is limited (Harper, Jones, & Roberts, 2005). It is therefore necessary to incorporate a comparison of human and robotic shaft loading before generalising the results. Following this, the question of whether changes in shaft stiffness would affect the following swing characteristics is addressed:

(1) shaft loading;

(2) wrist kinematics;

(3) impact location;

(4) ball launch conditions (ball speed, launch angle, spin).

## 7.1 Methods

### 7.1.1 Data collection

The present study was designed to include a number of different boundary conditions in terms of club head speed at impact. Three pairs of clubs were tested, each pair consisting of two clubs with an identical commercial stiffness rating (l-, r-, x-flex). One club from each pair was previously used for the human testing described in Study 1 (Chapter 5) and Study 2 (Chapter 6). Detailed information regarding the mechanical properties and the matching of the clubs can be found in Section 4.2 (p. 70). Four different impact speed conditions were used: 35, 40, 45 and 50 m/s. These were chosen to cover the range of driver club head speeds for skilled golfers reported in previous studies (Egret, Vincent, Weber, Dujardin, & Chollet, 2003; Zheng, Barrentine, Fleisig, & Andrews, 2008b). This range of club head speeds also covered the range of club head speeds achieved by the players in Study 1 and 2 (40 to 53 m/s).

Clubs were tested using the setup shown in Figure 53. Each of the six clubs was subject to twenty repeated tests under each of the four swing speed conditions. During ten of these trials, swing kinematics and club head presentation to the balls was recorded with a 7-camera motion capture system (Qualisys AB, Sweden), sampling at a rate of 1000 Hz. During calibration, the x-y plane of the coordinate system was set to coincide with the movement plane of the ‘arm’ of the robot (see next section for details). Strain data were amplified using a FE-366-TA device (Fylde, U.K) and recorded by means of a Qualisys analogue board at a sample rate of 4000 Hz. After identifying the time of impact in the strain data, a low pass filter with a 50 Hz cut-off frequency was used to remove noise from the strain data. This cut-off rate was chosen based on the frequency spectrum of the strain data, and residuals between filtered and un-filtered data were examined to confirm that an appropriate cut-off rate was chosen. This filter was only applied up to the time of impact to avoid sudden changes in strain after impact affecting the pre-impact strain data (see Section 4.4, p. 77, for details regarding further strain processing). For the remaining ten trials, a stereoscopic launch monitor was utilised to measure the launch conditions of the ball (see Section 4.6.1, p. 90, for details regarding the launch monitor). It was not possible to use the motion capture system and the stereoscopic launch monitor simultaneously due to differences in the required marker setup. As pilot testing had shown that the repeatability of the robot swings was very good, this was not deemed to be a problem.

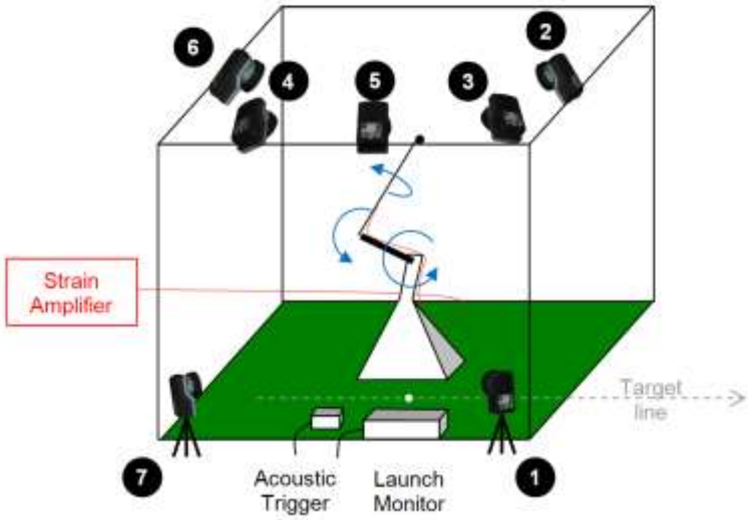



**Figure 53: Setup for robot testing. ➊-➐ denote motion capture cameras.**

### 7.1.2 Robot settings

A Golf Laboratories (USA) robot was used in the present study (Golflabs, 2007). Analogous to a human player, the first link of this robot will be referred to as ‘arm’ with a ‘shoulder’ and ‘wrist’ joint at its proximal and distal ends, respectively. The shoulder joint has only one degree of freedom, which restricts the arm to movement within one fixed plane. The wrist joint has two rotation axes, one of which is orthogonal to the arm swing plane, thereby allowing the club to swing. The wrist’s second rotation axis is aligned with the longitudinal axis of the shaft and allows the club face to close during the downswing. Both wrist rotations are coupled by a gearing mechanism. Hence, the wrist joint only adds one additional degree of freedom to the system.

Figure 54 shows the key settings that were used to alter the characteristics of the robot swing. The torque curve is defined as a function of shoulder angle, which is the relative angle between the arm segment and the arm's start position at ball address. These settings define the amount of torque that the robot uses to accelerate its arm at the shoulder joint for any given shoulder angle. As the 'wrist' of the robot is entirely passive, the four settings shown in the figure are the only available variables to alter swing kinematics. As shown in Figure 54, the shape of the torque profile is defined by its start value (as a percentage of the peak value), its peak value (swing speed) and the arm angle at which peak torque occurs (ramp distance). Furthermore, the arm position at the top of the backswing can be altered using the release point setting.

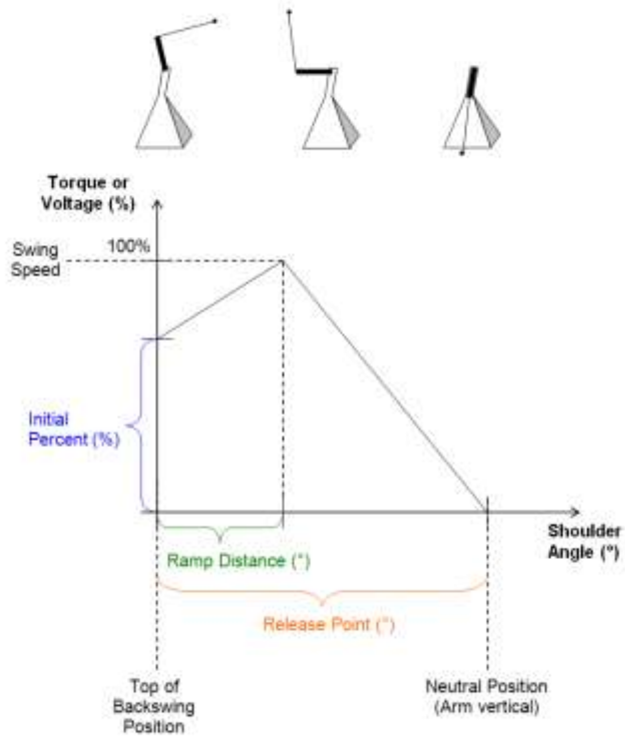



**Figure 54: Control settings of the robot (based on Golflabs, 2007).**

An optimisation of the robot settings to replicate a human swing was attempted but was found to be too complex to be completed as part of the present study. Hence, robot settings were chosen based on previous experience and adjusted manually until the club head reached the desired speed at impact (see Table 38), resulting in one group of settings for each speed condition. Identical settings were then used for all clubs for any given speed condition. Another significant difference between a human golfer and the robot used here is that the robot swing does not include a smooth transition from backswing to downswing. Instead, the robot pauses for a pre-set amount of seconds at the top of the backswing. This pause was set to three seconds. No attempt was made in the current study to analyse the robot's actions during the backswing.

**Table 38: Swing speed conditions and robot settings.**

| Swing speed condition | Initial Percent (%) | Swing speed (dimensionless) | Ramp distance (°) | Release point (°) |
|---|---|---|---|---|
| 35 m/s | 25 | 23 | 60 | 200 |
| 40 m/s | 25 | 32 | 65 | 200 |
| 45 m/s | 25 | 41 | 70 | 200 |
| 50 m/s | 25 | 52 | 70 | 200 |

### 7.1.3 Calculation of joint angles

In order to characterise the swing kinematics for the different shaft conditions, the robot was divided into three segments: arm, clamp and club head. The longitudinal axis of the arm was defined by markers placed at the shoulder and wrist axis, whereas the longitudinal axis of the clamp segment was defined to coincide with the longitudinal axis of the shaft. Before further analysis took place, both axes were projected onto the x-y plane of the global reference system, which in turn was set to coincide with the movement plane of the robot's arm during calibration. Following this, two planar angles (shoulder angle and wrist angle) were defined according to Figure 55. It should be noted that the planar wrist angle used in the present study for the robot arm differs from the four-point wrist angle used in Study 2 for the human arm. The marker set and reference system used for the club head was the same as described in Section 4.6.2 (p. 92).

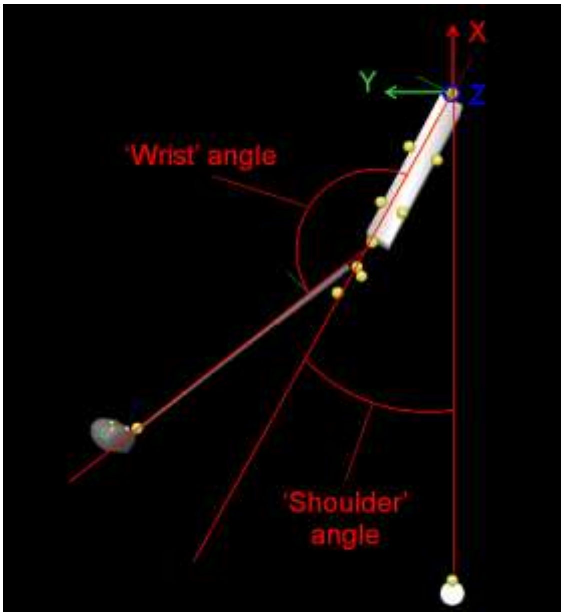



**Figure 55: Definition of shoulder and wrist angle for the golf robot. The z-axis of the global coordinate system runs perpendicular to the arm.**

### 7.1.4 Event detection

The following events were defined and located for each file using the software Visual3D (C-Motion, USA) to aid interpretation of the kinematic results (see also Figure 56):

- Initiation of downswing: the shoulder angular velocity exceeds 20 °/s. Ideally, this threshold would be as low as possible but was chosen high enough to ensure a reliable identification of this event.

- Wrist-release: the wrist angular velocity exceeds 20 °/s. This threshold was chosen to ensure a consistent identification despite possible artefacts in the angular velocity data.

- Grip-vertical: the longitudinal axis of the clamp segment, projected onto a plane defined by the global x- and y-axis, is parallel to the x-axis, with the club pointing upwards.

- Grip-horizontal: the longitudinal axis of the clamp segment, projected onto the global x-y-plane, is parallel to the y-axis.

- Impact: this was determined by the impact location algorithm as described in Section 4.6.2 (p. 92).

The grip-vertical and grip-horizontal events are defined in a similar way to the corresponding events used in Study 2. For each recorded trial, a manual verification and, for a small number of cases, correction of the events was performed.

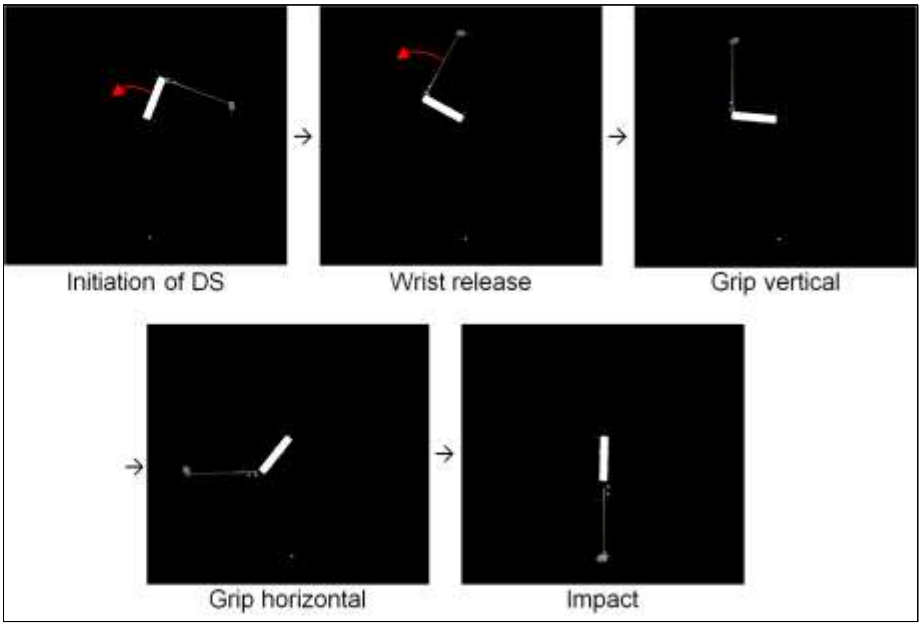



**Figure 56: Events used when analysing kinematic data.**

## *7.2 Results*

### 7.2.1 Comparison of human and robotic swing characteristics

Prior to analysis of the behaviour of the different shafts, it is deemed necessary to compare human and robotic swing characteristics. This is to ensure that any potential observations made for the robot are transferable and comparable to human swings. Figure 57 shows a comparison of human and robotic shaft loading patterns for an x-flex shaft. Human data are shown for a player with a mean club head speed of 45.4 m/s (SD ±0.33 m/s), which is similar to the speed reached by the robot for the swings shown in the same figure (44.6 m/s, SD ±0.05 m/s).

Human shaft loading patterns were found to vary across subjects (see Appendix G, p. 214) for more examples of human shaft loading patterns). Yet, repeated oscillations, as seen in the robotic strain data (Figure 57), were not observed for any of the players. It is also evident from the toe-up/down strain patterns that the downswing for the robot commences earlier (approximately 0.4 s before impact) than for the human player. Across all subjects and conditions analysed in Study 2, the average downswing duration was 0.26 s (SD ±0.02 s). In contrast, the average downswing duration for the robot was found to be 0.42 s (SD ±0.003 s) when the robot was set up to reach an impact speed of approximately 45 m/s. This impact speed is similar to the mean club head speed achieved by the human players in Study 2 (46.3 m/s, SD ±2.5 m/s). Hence, a comparable downswing duration should be expected for the robot if the swing kinematics were more similar between the robot and human players.

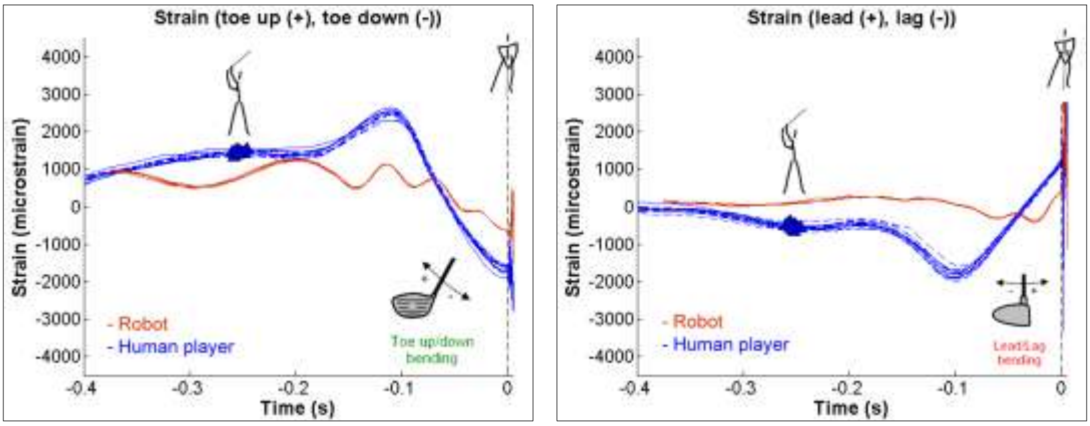



**Figure 57: Comparison of human and robotic shaft loading for two clubs with identical stiffness ratings (x-flex). Stick figures indicate the time of the transition from backswing to downswing and impact for the human player.**

Given the marked differences in shaft loading patterns (Figure 57) and swing kinematics (in particular the difference in downswing duration) between human players and the robot, only limited comparisons between shaft effects in robotic and human swings are possible. Therefore, the following sections will focus on key results found from the robot testing rather than including a full statistical analysis similar to that presented in Study 1 and Study 2.

### 7.2.2 Strain

This section will focus on strain results for the 45 m/s (Figure 58) and 50 m/s condition (Figure 59) because the majority of players studied in the first two studies achieved club head speeds in this range. Strain plots for the other two impact speed conditions are included in Appendix I (p. 223).

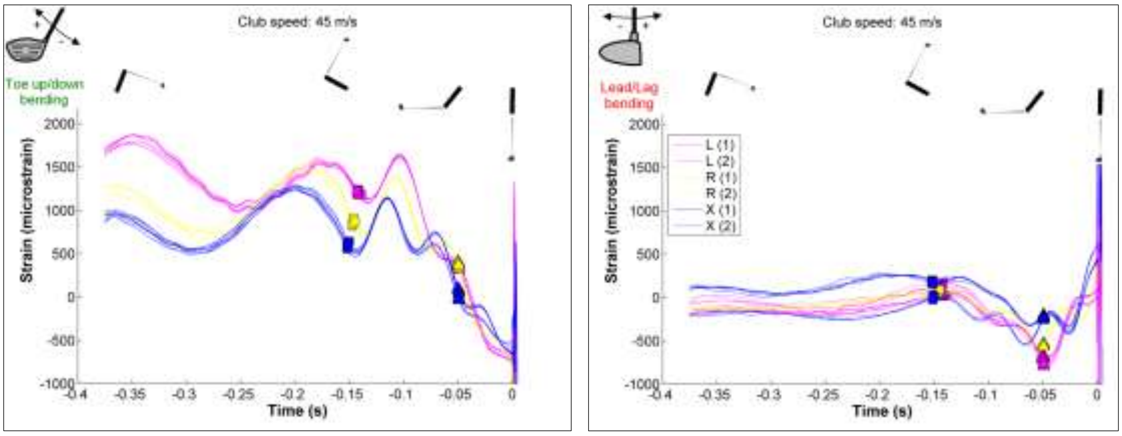



**Figure 58: Strain patterns recorded for robot swings performed with an impact speed of approximately 45 m/s. Symbols indicate wrist release (☐) and grip-horizontal event (△).Club numbers (1) and (2) refer to the first and second club replicate, respectively,**

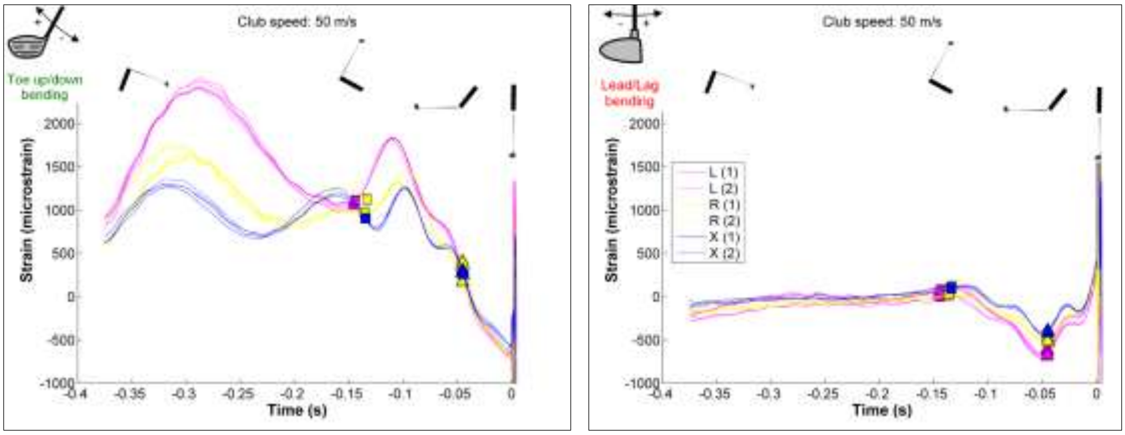


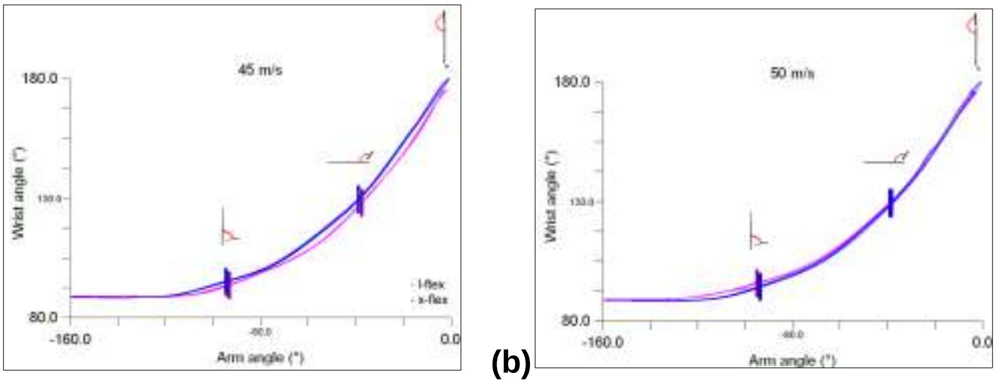

**Figure 59: Strain patterns recorded for robot swings performed with an impact speed of approximately 50 m/s. See previous figure for details.**

As can be seen from the strain plots, there were marked differences in strain magnitude between shafts during some stages of the downswing, in particular in case of the toe-up/down strain component at the beginning of the downswing. The magnitude of toe-up/down strain recorded at the initiation of the downswing increased with decreasing shaft stiffness. This was followed by a number of oscillations during which the wrist released, causing the club head to accelerate relative to the arm of the robot. After the grip-horizontal event, toe-up/down strain became increasingly similar for the different shafts to a point where there is little difference between the shafts at impact.

In terms of lead/lag bending, there is little of note until the club-horizontal event, when the strain reaches its global minimum in most cases. After this event, the ‘recovery’ process of the shaft from a lagging to a leading position begins, and the club arrives at impact with forward bending (i. e. a positive strain value). For the 45 m/s condition, the magnitude of this lead strain is highest for the x-flex shaft. No differences in lead strain magnitude at impact are visible when the robot was set to reach an impact club head speed of 50 m/s.

### 7.2.3 Angular kinematics

The purpose of this section is to analyse the wrist kinematics of the robot in more detail to determine whether the changes in human wrist kinematics found in Study 2 are the result of an active adaptation or the result of the mechanical interaction of the involved segments. As can be seen in Figure 60 (a), there appears to be a change in the wrist kinematics of the robot for the 45 m/s condition depending on shaft stiffness. A similar change was detected for the human players (see Figure 51, p. 156, for an example), consisting of an earlier wrist release for the x-flex shaft, which resulted in an overall shift of the wrist angle curve for this shaft. This, however, was only the case for the robot swings performed using the robot settings for the 45 m/s condition. When the impact speed was increased to 50 m/s, wrist release appears to occur earlier for the l-flex shaft, resulting in a separation of the wrist angle patterns for the l-flex and x-flex shafts in the graph (Figure 60 (b)). This, however, did not result in an overall shift of the wrist angle curve. Instead, there is little discrepancy between the two curves for the rest of the downswing (after the club-horizontal event marked in the graph).




(a) (b)

**Figure 60: Wrist angle as a function of arm angle for swings with a club head speed of 45 m/s (a) and 50 m/s (b). Plot shows a mean curve for all recorded swings. Standard deviations are shown as shaded areas but are barely visible due to the consistency of the robot. Vertical lines indicate swing events as defined in Section 7.1.4.**

### 7.2.4 Impact location

All impact positions recorded for the 45 m/s and 50 m/s conditions on the robot are plotted in Figure 61 using the reference system defined in Figure 39 (p. 136). Given the scale of the plots, it is evident that the variation in impact positions for each club was very small. Nevertheless, some systematic trends may exist, with the highest impact positions typically occurring for the l-flex shaft. This could be interpreted as a result of the robot's missing ability to adjust its swing, but it is likely that changes in impact locations on this scale would not be relevant for human players because of the variability in impact positions that was even found to be present in highly skilled golfers (see for example Figure 44, p. 147).

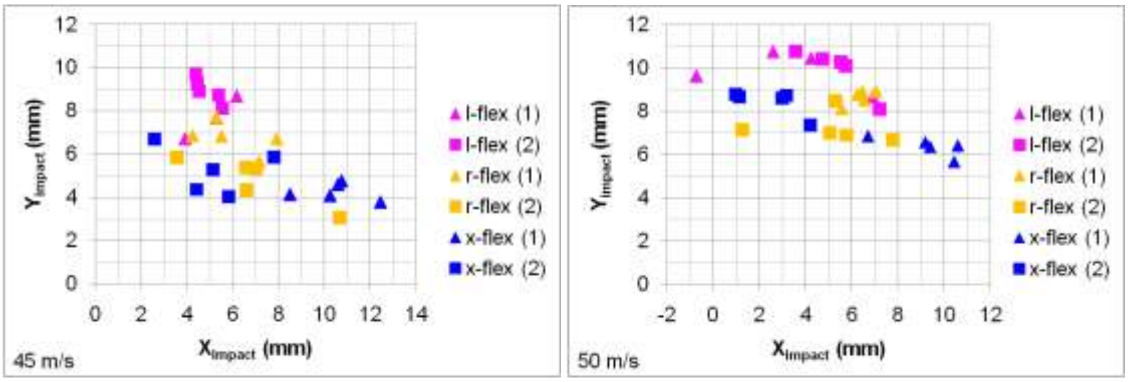



**Figure 61: Impact positions for different shaft conditions for impact speeds of approximately 45 m/s (left) and 50 m/s (right). Club numbers (1) and (2) refer to the first and second club replicate, respectively.**

### 7.2.5 Ball launch variables

The purpose of this section is to examine the effect of shaft stiffness on ball launch conditions. These are the most direct outcome variables that can be measured without taking environmental factors (such as wind) into account. Environmental factors would inevitably affect more relevant outcome measures such as distance and dispersion.

Whilst the previous sections focused on short, qualitative descriptions of the results and did not include a full statistical analysis, a full analysis is deemed necessary for the ball launch data. One reason for this is that the observed differences between shafts were small relative to the noise in the results for some of the variables (see below). Furthermore, most of the variables that were examined in the previous sections were already subject to a detailed analysis in Study 1 and Study 2, which was not the case for the ball launch variables that will be analysed here.

The following set of figures (Figure 62, Figure 63, Figure 64) displays boxplots of the launch results for the 45 m/s and 50 m/s speed settings after pooling results of replicate shafts with identical shaft flex. It can be seen that patterns in the ball speed results were not identical for the two speed settings, but similar trends existed for the launch angle and spin data.

As in the previous chapters, statistical analysis commenced with a verification of whether data met the normality assumption. To do so, Shapiro-Wilk tests were performed on subsets of the data for each shaft and swing speed condition. Ball speed data ($p$ = 0.043) as well as launch angle data ($p$ = 0.024) were found not to be normally distributed for one of the conditions. Histograms confirmed this result. Therefore, it was decided to use nonparametric tests for the analysis of the ball launch data, which can be performed regardless of the distribution of the data (Vincent, 2005). The analysis consisted of Kruskal-Wallis tests to detect whether there were any changes in the variables associated with shaft stiffness. If shaft effects were detected, a series of three pair-wise Mann-Whitney tests were carried out to determine where these differences lay. Bonferroni correction was used to account for multiple comparisons, resulting in an adjusted α-level of 0.0167 (which is equal to one third of 0.05) for the pair-wise comparisons.

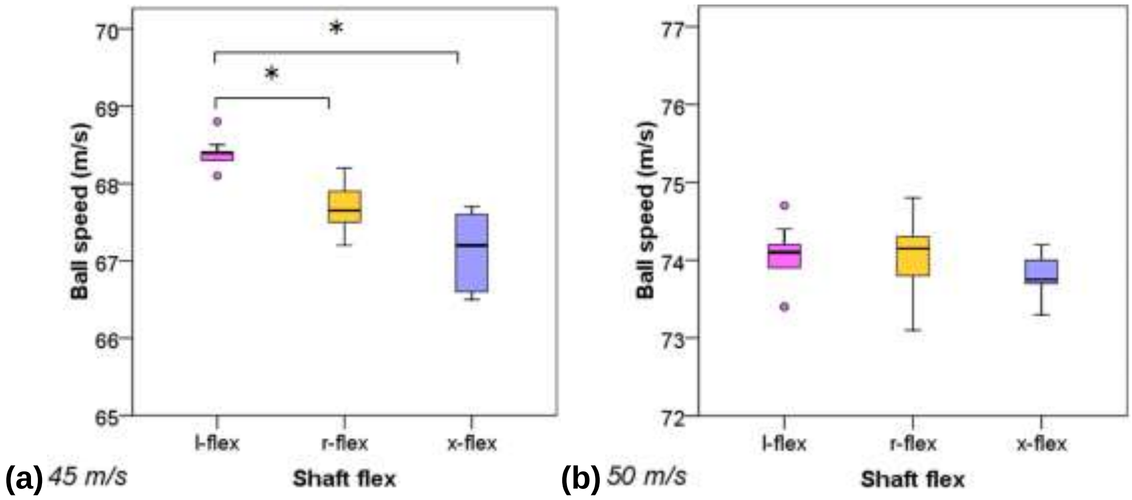



**Figure 62: Ball speeds measured for club head speeds of 45 m/s (a) and 50 m/s (b). Shaft pairs with significant differences are marked with '*'. Dots indicate outliers (only present in the l-flex data sets).**

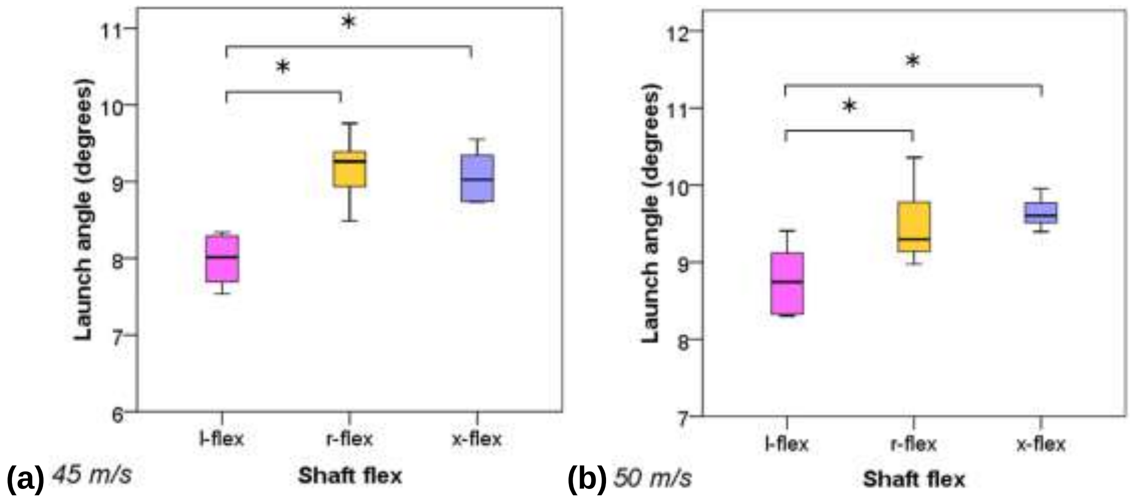



**Figure 63: Launch angles measured for club head speeds of 45 m/s (a) and 50 m/s (b). Shaft pairs with significant differences are marked with '*'.**

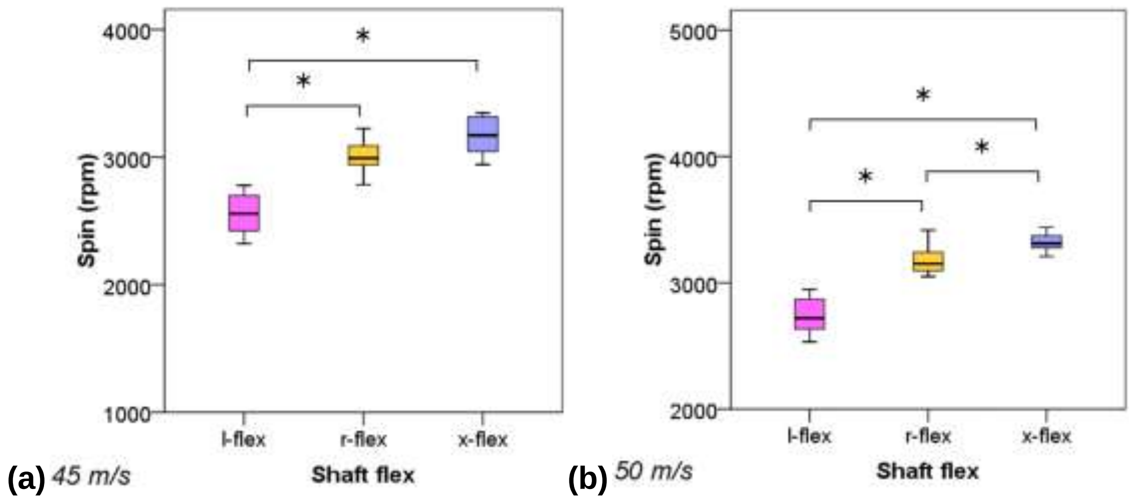



**Figure 64: Spin rates measured for club head speeds of 45 m/s (a) and 50 m/s (b). Shaft pairs with significant differences are marked with '*'.**

For the 45 m/s condition, the Kruskal-Wallis test indicated that ball speed ($H(2) = 21.7$, $p < 0.001$), launch angle ($H(2) = 19.8$, $p < 0.001$) and spin ($H(2) = 21.7$, $p < 0.001$) were affected by shaft stiffness. This result was followed up using pair-wise Mann-Whitney tests. Full test results, including the Mann-Whitney U-test statistic and differences between the conditions in percent, are listed in Table 39 and Table 40, and significant differences are highlighted in Figure 62, Figure 63 and Figure 64. As can be seen from these figures, the general trend for the 45 m/s condition was that differences were only found between the l-flex shaft and the other two shafts, but not between the r-flex and x-flex shaft. Ball speed increased for the l-flex shaft, whereas there was a decrease in launch angle and spin for this shaft.

**Table 39: Results from pair-wise comparisons using Mann-Whitney tests. Bonferroni correction was applied to account for multiple comparisons.**

| | Ball speed | | Launch angle | | Spin | |
|---|---|---|---|---|---|---|
| **Comparison** | ***U*** | ***p*** | ***U*** | ***p*** | ***U*** | ***p*** |
| **Speed setting: 45 m/s** | | | | | | |
| **l vs. r** | 1 | < 0.001 | < 1 | < 0.001 | < 1 | < 0.001 |
| **l vs. x** | < 1 | < 0.001 | < 1 | < 0.001 | < 1 | < 0.001 |
| **r vs. x** | 19 | 0.019 | 37 | 0.353 | 20 | 0.023 |
| **Speed setting: 50 m/s** | | | | | | |
| **l vs. r** | 46.5 | 0.796 | 14 | 0.005 | < 1 | < 0.001 |
| **l vs. x** | 28 | 0.105 | 1 | < 0.001 | < 1 | < 0.001 |
| **r vs. x** | 28 | 0.105 | 29 | 0.123 | 11 | 0.002 |

**Table 40: Variation between conditions where significant differences were found as percentages between mean values.**

| | Speed setting: 45 m/s | | | Speed setting: 50 m/s | | |
|---|---|---|---|---|---|---|
| **Comparison** | **Ball speed** | **Launch angle** | **Spin** | **Ball speed** | **Launch angle** | **Spin** |
| **l vs. r** | 1% | 15.3% | 17.9% | not sign. | 8% | 16.2% |
| **l vs. x** | 1.9% | 13.5% | 24.3% | not sign. | 10% | 21.2% |
| **r vs. x** | not sign. | not sign. | not sign. | not sign. | not sign. | 4.4% |

When club head speed at impact was increased to 50 m/s, the Kruskal-Wallis test indicated that ball speed was not affected by shaft flex any longer ($H(2)$ = 3.82, $p$ = 0.156). Yet, launch angle ($H(2)$ = 15.9, $p$ < 0.001) and spin ($H(2)$ = 23.3, $p$ < 0.001) still appeared to change depending on the level of shaft stiffness. The general trends for launch angle and spin were identical for the 50 m/s condition and the 45 m/s condition: both variables increased with increasing shaft stiffness.

## *7.3 Discussion*

### 7.3.1 Comparison of human and robotic swing characteristics

A comparison of strain data recorded for a robot swing compared to that recorded for a human player highlighted that there were marked differences in shaft loading between the different swings. One of the characteristics of the robot swing was that the general strain patterns were overlaid by repeated oscillations, in particular in the toe-up/down plane. Oscillations like this have not been reported in any previous experimental study presenting data for human swings (Butler & Winfield, 1994; Horwood, 1994; N. Lee, Erickson, & Cherveny, 2002; Milne & Davis, 1992; Newman, Clay, & Strickland, 1997). It is likely that a number of factors contributed to these differences, including the simplistic construction of the robot - which results in a circular path of the hands -, the lack of dampening compared to a human hand and the type of torque curve that is applied to accelerate the arm. These discrepancies highlight the need to further optimise robot setups such as the one used in the current study if they are used for shaft testing. Such optimisation has previously only been performed on fully-articulated robots (Harper, Jones, & Roberts, 2005; Harper, Roberts, Jones, & Carrott, 2008), and no previous study could be found that performed a similar optimisation of the torque input for an under-actuated robot like the one that was available for the present study. When interpreting the results in the following sections, this limitation has to be taken into account, but some general trends can still be observed and contrasted with the human results from Study 1 and Study 2.

### 7.3.2 Strain

One of the trends observed for the human strain data was that strain differences between shafts often diminished shortly before impact (see Figure 36, p. 121, Figure 48, p. 151, and Appendix G, p. 214). The strain data recorded for the robot swings tends to support this observation, in particular for the toe-up/down strain component and more for the 50 m/s than for the 45 m/s speed condition. This would indicate that the lack of a difference in lead strain at impact for the human players is a mechanical effect rather than caused by an active adaptation by the players. As no previous study could be identified that reported strain for clubs that were identical in all properties apart from shaft stiffness, only limited comparisons are possible. Yet, the general strain patterns observed for the robot, including the problem of repeated oscillations, were similar to those reported previously for a simulation model that did not include dampening (Tsunoda, Bours, & Hasegawa, 2004). The problem of repeated oscillations has also been observed for a Miyamae Robo 5 golf robot (Harper, 2006), even after specifically matching its swing kinematics to those of a human golfer. It is interesting to note that the oscillations that appear to overlay the strain curves are reduced after the club-horizontal event for the 50 m/s impact speed condition. This may be a result of increased centrifugal forces acting on the system.

### 7.3.3 Wrist kinematics

The present study found that wrist kinematics were affected by shaft stiffness if the club head speed at impact was set to 45 m/s. This agrees with the results for the human players from Study 2. If the same changes are seen for human players and the robot, this would again suggest that players did not adapt actively when shaft stiffness was altered. At an impact speed setting of 50 m/s, however, changes in wrist kinematics did not follow this trend. In fact, there was a tendency for an earlier wrist release for the l-flex shaft opposed to the x-flex shaft, which is the opposite to what was seen for the 45 m/s condition. The mean club head speed for the human players was 46 m/s, so it could be argued that the changes in wrist kinematics were specific to a club head speed of approximately 45 m/s. However, given the marked differences in shaft loading patterns between the robot and human players, it is more likely that the wrist release was affected by the oscillations of the shaft, resulting in changes to the wrist timing that were not related to shaft flex. Further work using an enhanced control system is needed to verify this.

### 7.3.4 Impact location

There appeared to be a pattern in impact positions with a trend towards higher impact positions for the l-flex shaft. Given the small scale of these changes, this could be an artefact of small deviations in the robot setup when clamping the shaft or a difference in shaft lengths. Two replicate clubs were tested for each condition to avoid any such artefact. However, it can be noted in Figure 61 (b) that there was a difference in horizontal impact location for the two x-stiff shafts. The magnitude of this difference was similar to the difference in vertical impact location between the l-flex and the other two shafts. It is therefore difficult to conclude whether changes in impact location were indeed shaft induced or were caused by other factors. For the human subjects, no change in impact positions depending on shaft stiffness was observed (see Section 6.3.3.1, p. 145). The magnitude of the potential changes observed for the robot are probably too small to be noted in human subjects, so it is unlikely that this is the result of a lack of adaptability of the robot compared to human players.

It was notable that the horizontal spread of impact positions for the robot was greater than the vertical spread. This agrees with the findings from the validation of the club head tracking system (see Section 4.6.3.1, p. 98) and may be caused by the placement of the ball marker on the surface of the ball and the subsequent subtraction of the ball's radius to determine the position of the centre of the ball. If the ball marker is not perfectly aligned with the vertical axis, it is likely that this tilt would result in errors in the calculation of the horizontal position of the ball centre position, whereas the effect on the vertical ball position would be small as long as the tilt is small. This warrants further work to investigate the error sources associated with the club head tracking system, although it should be noted that the scale of these errors relative to the typical variation in impact positions for humans is likely to be small enough to have no significant effect when human swings are analysed.

### 7.3.5 Launch data

Launch results were ambiguous: on the one hand changes in ball speeds agreed well with human results for the 45 m/s impact speed condition, on the other hand there was no difference in ball speed depending on shaft stiffness for the 50 m/s condition. This situation is similar to the results for the wrist kinematics, so the same explanations are possible. Either, the findings for the human players only applied at impact speeds of approximately 45 m/s (mean club speed in Study 2 was 46.3 m/s), or the differences between human and robotic swing kinematics had an effect on the results for the robot. One possible explanation would be that the oscillations prevented the earlier wrist release seen for the x-flex shaft at the 45 m/s condition when the club head speed was increased.

In terms of launch angle and spin, results were consistent between the 45 m/s and 50 m/s condition, suggesting that it is more likely that it is possible to generalise them. In agreement with the strain results from Study 1 and 2, launch angles did not increase with decreasing shaft stiffness as suggested by other authors (Maltby, 1995). In fact, launch angles for the l-flex clubs were significantly lower than for the r-flex and x-flex clubs. As previously, the magnitude of changes was relatively small, but according to the literature (Tuxen, 2008) even these small changes in spin and launch angle may have a significant effect on the outcome of the swing. Only studies that include an analysis of the ball flight or comprehensive simulations of the ball flight would allow answering whether this is the case, but these are beyond the scope of this work.

### *7.4 Summary*

The purpose of the present study was to examine the effect of shaft stiffness on ball launch conditions, impact location, shaft bending and wrist kinematics during swings performed by a golf robot. It was found that there were marked differences between human and robotic shaft loading, and it is unknown to what extent these influenced the results.

Nevertheless, the general trends in the strain results confirmed the finding from the human testing that there were significant differences in strain during the early stages of the downswing depending on shaft stiffness but little or no difference between shafts at impact. There appeared to be a weak trend for impact to occur higher on the club face for the l-flex clubs compared to the other two clubs, but, as the magnitude of this difference was small (< 5 mm), it is unlikely that this would be relevant for human players.

The change in wrist kinematics for the robot was similar to that seen for the human subjects if the impact speed was set to 45 m/s. At impact speeds of 50 m/s, however, there appeared to be a different trend. It is not possible to determine whether this discrepancy was caused by the strain oscillations or because human impact speeds were on average slower than 50 m/s. The situation was similar for the ball speeds: when the robot was set up to reach an impact speed of 45 m/s, ball speeds confirmed the trend seen for the human data in that the l-flex speeds were significantly higher. This, however, was not the case when the impact speed was set to 50 m/s, when there was no difference in ball speeds depending on shaft flex. Launch angle results did not support the conventional view that decreasing shaft stiffness would result in a higher launch angle.

Overall, there appears to be some limited evidence from the robot testing that it is unlikely that players adapted actively to changes in shaft flex.

# 8 Summary, conclusions and future research

### *8.0 Research overview*

The aims of this thesis as outlined in Chapter 3 were to determine the effect of changes in golf shaft stiffness on outcome variables (research question 1), shaft loading (2) and body movement (3). The research conducted to address these aims included a comprehensive literature review; the development and validation of dedicated research methods, including instrumented golf clubs and a novel club head tracking system to determine the ball impact location on the club face; and three experimental studies involving human players and a golf robot. The purpose of this final chapter is to summarise and to compare the findings of the experimental studies with regards to the research questions, to draw conclusions and to make suggestions for future research.

### *8.1 Summary*

#### 8.1.1 Launch conditions and club presentation (Research question 1)

*Post-hoc* tests conducted in Study 1 identified no changes in ball speed, spin, launch angle and side angle within any combination of shafts. In terms of launch conditions, Study 2 focused on the variable ball speed, which was found to be significantly higher for the l-flex shaft compared to the x-flex shaft. However, the magnitude of this difference was small (0.7 %). The reason for not detecting this difference in Study 1 may be a lack of statistical power because three different shaft conditions were included (Study 2: two conditions) and a smaller number of participants in Study 1.

When clubs were subject to robot testing rather than player testing (Study 3), again an increase in ball speed was associated with performing shots with the l-flex shaft. This, however, was only the case when the robot was set up to achieve a club head speed of 45 m/s, which is similar to the mean club head speed achieved by the players in Study 2. When the club head speed was increased to 50 m/s, there was no longer a difference in ball speed depending on the shaft condition.

Club head speed was found to be unaffected by shaft stiffness in Study 1, but in Study 2, a small but significant increase in club head speed at impact was found for the l-flex shaft compared to the x-flex shaft. As for the ball speed, this may be due to improved statistical power of Study 2. As mentioned above, the magnitude of the increase in club head speed was small (0.7 %) but agreed well with the increase in ball speed discussed in the previous section, which was also 0.7 %.

The role of shaft stiffness in club head velocity generation was further examined by performing a speed comparison between a marker placed on the hosel of the club and a virtual marker in the same place but with its position defined relative to the grip markers. It was found that the speed of the actual marker was on average 0.5 m/s faster than that of the virtual marker. Due to its definition, the virtual marker was unaffected by shaft bending, whilst the actual marker was affected by shaft bending. Therefore, it is likely that the reason for the speed increase for the actual marker was the ‘recovery’ or ‘recoil’ process of the shaft from a lagging to a leading position just before impact (see 8.1.2 for details). Ignoring this process by assuming the shaft to be rigid would underestimate club head speed at impact. There was a significant interaction between shaft flex and the magnitude of this speed difference. An interaction plot indicated that this was due to the speed difference between actual and virtual marker being more pronounced for the l-flex shaft (0.8 % increase due to recovery process) than for the x-flex shaft (0.2 % increase).

Study 2 also showed that there was no change in impact location or face angle depending on the shaft used.

### 8.1.2 Shaft loading (Research question 2)

There is good agreement between Studies 1 and 2 regarding the observed shaft loading patterns. Both studies found toe-up/down shaft strain to increase significantly with decreasing shaft stiffness at the top of the backswing. During the course of the downswing this was also the case for the amount of lag bending prior to impact, quantified by the variable ‘lag area’. As a consequence, there was typically more lag bending for the l-flex club prior to the recovery process that took place for all golfers during the last milliseconds before impact. Because of this recovery process, shafts were bending in the lead direction at impact. It is likely that the difference in shaft bending before the recovery process contributed to an increase in strain rate for the l-flex shaft just before impact. As the different shafts generally arrived at impact with the same amount of lead bending, the recovery process for the l-flex shafts had to happen at a faster rate, hence the increased recovery rate for this shaft. Assuming that there is no change in wrist kinematics during this phase, it is very likely that this process contributes to the speed differences between the virtual and actual marker discussed in the previous section.

The only difference between the strain results from Study 1 and 2 was that the latter study's lead strain at impact was found to be higher for the x-flex shaft than for the l-flex shaft. The magnitude of this difference, however, was small compared to the differences in strain variables seen at other swing events

In the final study (Study 3), strain results were not analysed statistically as it was deemed likely that oscillations overlaying the general strain pattern may lead to misleading results when strain was characterised at isolated events. Yet, qualitative inspections of the strain plots tended to support the finding from the human testing that whilst there were significant differences between shafts at the initiation of the downswing, the strain patterns became increasingly similar shortly before impact. Regardless of the robot not having the ability to adjust its swing to changes in shaft stiffness there was still a trend for strain curves to be very similar for the different shafts shortly before impact. This suggests that the lack of a difference in lead strain at impact between shafts seen in the human testing is the result of the mechanical interaction of the involved segments rather than an active adaptation process.

### 8.1.3 Body movement (Research question 3)

No change in axial thorax rotation, forearm flexion/extension, forearm pronation/ supination and ulnar/radial deviation at the transition from backswing to downswing and impact could be associated with changes in shaft stiffness in Study 1. Therefore, Study 2 did not examine these variables again but focused on angular wrist kinematics instead. The study confirmed that there was no change in the angular displacement of the wrist at the transition from backswing to downswing and at impact. However, there was a change in wrist kinematics during the downswing when the club was pointing vertically upwards and when it was horizontal. It appeared that these differences were caused by an earlier 'wrist release' for the x-flex shaft. A later wrist release has been associated with better swing performance (Zheng, Barrentine, Fleisig, & Andrews, 2008a) and may be a factor causing the reduction in angular velocity for the grip segment that was detected for the x-flex club in comparison to the l-flex club in Study 2.

In Study 3, a trend for an earlier wrist release for the x-flex club was also observed but only if the club head speed at impact was set to be 45 m/s. It is unknown if the wrist kinematics were affected by the differences in shaft bending patterns between robot and human players. Therefore, care has to be taken when performing direct comparisons between the human and robot wrist data and further improvements of the robot swing settings are necessary to remove unwanted shaft oscillations.

### *8.2 Limitations and suggestions for future research*

Based on the previous chapters, it is contended that this thesis adequately addressed the research questions that were formulated for this study. Yet, this thesis gives rise to some suggestions for future research that would extend the work presented herein.

Only highly skilled players were included in the experimental studies to increase statistical power and in an attempt to reduce any other systematic factors such as learning effects. Yet, even within this group it was found that it was necessary to remove shots recorded at the beginning of test sessions because players did not perform consistently, presumably due to a lack of practice time with the test clubs before test sessions. For this reason, only pooled data from the complete subject group were analysed because it was feared that individual data would be affected by factors other than shaft stiffness. This is an important observation for future studies examining the effect of changes in equipment variables and warrants further investigation, e.g. to determine how much practise time players require prior to testing to achieve consistent performance.

The mechanical club property that was isolated in this thesis was shaft stiffness, characterised for the shaft as a whole. However, it is often claimed by shaft manufacturers that the stiffness distribution along the shaft is another instrument to modify launch conditions for a given swing and club head. After the effects of varying overall shaft stiffness were addressed in this thesis, future work could examine the effects of stiffness distribution.

The results of the second study presented in this thesis showed that decreasing shaft stiffness was associated with an increase in club head speed at impact. Shafts tested in the current study were selected to be representative for the stiffness range that is commercially available. Future studies could reduce shaft stiffness beyond the commercially available level to examine if further gains in club head speed could be achieved by doing so. However, it is likely that this would have a deteriorating effect on accuracy and dispersion. Dispersion was not examined in the current study because it is influenced by environmental factors such as wind, but future studies could consider the effects of reducing shaft stiffness further and include accuracy as an outcome variable.

It was found that, at the transition from backswing to downswing, the amount of shaft bending differed significantly between shafts. It is likely that golfers will perceive these changes, resulting in a different ‘feel’ depending in shaft stiffness. This perception may indirectly affect performance, for example if players subjectively prefer a particular feel, and could also be considered in future studies.

### *8.3 Practical implications*

Results from this study indicate that the mechanisms that underlie the dynamic interaction between players and the flexible shaft are more complex than thought traditionally. Results did not support the notion that forward bending at impact, and hence launch angle, would increase for a more flexible shaft. Contrary to this expectation, Study 2 detected significantly more forward bending at impact for the stiffest shaft. Results suggest that a small increase in club head speed and ball speed (0.7 %) can be achieved by using an l-flex shaft rather than an x-flex shaft, but it is not known which effect this change would have on accuracy. Players did not appear to adjust their body movement when shaft flex was varied with the exception of an angle formed by the grip of the club and the forearm (wrist angle). Changes in this angle indicated that players released the x-flex club earlier than the l-flex club, but arrived at the impact point with the same wrist angle for both shafts. A similar trend was found for tests performed with a golf robot that does not have the ability to actively adapt to changes in shaft flex. This suggests that changes in human wrist kinematics were not the result of an active adaptation by the players.

Only highly skilled players (handicap < 5) participated in this study and only the overall shaft stiffness, not the stiffness distribution along the shaft, was varied. Future studies need to quantify the effect of changes in stiffness distribution and whether findings from this study hold true for high-handicap players. Overall, it appears that shaft stiffness primarily affects the ‘feel’ of a golf club or other psychological aspects and not performance *per se*.

### *8.4 Conclusions*

Overall, it was found that it is unlikely that changes in overall shaft stiffness in themselves have a marked effect on driving performance.

Changes in shaft stiffness had no effect on the ball impact location on the club face or face angle. There was no evidence to support the traditional notion that dynamic loft and, consequently, launch angle would increase as shaft stiffness decreased. In fact, one of the studies found lead strain at impact for the x-flex shaft to be significantly higher than for the l-flex shaft, albeit by a small amount. Nevertheless, marked differences in strain between shafts were detected for other phases of the swing, in particular at the transition from backswing to downswing.

Club head speed at impact was found to increase by a small amount (0.7 %) but significantly for the group of golfers when shaft stiffness was reduced. This was confirmed by the ball speed results, which indicated that ball speeds also increased by 0.7 %. A number of factors were identified that contributed to the increase in club head speed. First, club head speed was found to increase due to the dynamic recovery process from lag to lead bending before impact, and this effect was more pronounced for the l-flex shaft (0.8 % increase in club head speed) than for the x-flex shaft (0.2 % increase). This was confirmed by the strain measurements, which showed that the recovery rate from lag to lead was significantly higher for the l-flex shaft. Second, the angular velocity of the grip of the club was significantly higher for the l-flex shaft than for the x-flex shaft (0.5 %), potentially caused by an earlier wrist release that was detected for the x-flex shaft. Current evidence from the robot study would tend to suggest that human players did not adapt actively to changes in shaft stiffness, but further robot testing is necessary to confirm this after removing oscillations in shaft bending.

Apart from changes in wrist angles at two downswing events, no change in body kinematics was detected depending on the shaft conditions. This suggests that either the players did not adapt their swing actively to shaft changes, or that these adaptations were too small to be registered using an optical system.

Tests with a robot that supplied the same amount of ‘shoulder’ torque for a given arm angle regardless of shaft stiffness showed similar shaft effects on wrist kinematics (later wrist release) and launch data (increase in ball speed) for the l-flex club when the robot club head speed was set to approximately match the mean club head speed achieved by the players. However, it is possible that results obtained using the robot may not be directly comparable to the human data due to differences in the shaft loading pattern.

# Appendix

## *A. Mechanical club head properties*

The purpose of Appendix A is to describe the mechanical variables that are commonly used to characterise golf club heads. The motivation for this is that a number of these variables are mentioned throughout this thesis, so definitions and background information may be required for some readers.

### A.1 Role of the club head

The club head is a relatively rigid body, in most cases made of metal. The club head plays a role in the swing before impact because a great proportion of the club's total mass is in the club head, thereby affecting the inertia the player has to overcome when accelerating the club. Furthermore, the centre of gravity of the club head is not aligned with the longitudinal shaft axis, which affects how the shaft bends throughout the swing.

Whilst the club head presentation to the ball is determined by the body motion of the player and the shaft deflection, it is not deemed possible for the player to adjust the club head position during ball contact time (0.5 milliseconds), and the shaft is regarded as being too flexible to influence the club head's response to the impact while the club head is still in contact with the ball (Cochran & Stobbs, 1968; Mather & Jowett, 2000; Strangwood, 2003). Therefore, the club head will behave like a projectile during impact and, hence, its mechanical characteristics will have a marked effect on its dynamic interaction with the ball. For this reason, the mechanical properties will be described in more detail in the following section.

### A.2 Materials and construction

#### *A.2.1 Woods*

Woods are golf clubs that golfers use when they are aiming for distance either off the tee (drivers) or off the ground (fairway woods). As the name implies, these clubs were traditionally made of wood, either cut from a solid block (usually persimmon) or from block of laminated wood (Maltby, 1995). Based on a master model, these were cut to the correct shape using a lathe. After this, various operations were performed to seal and finish the club head. Because the base material is a natural product, there could be weight differences amongst seemingly identically shaped club heads (Maltby, 1995). Furthermore, the range of feasible design variations was small. This changed with the advent of hollow metal club heads. From a design perspective, the advantage of these club heads was that, after designing all walls with sufficient strength, there was "free weight" available that could be used to adjust the weight distribution of the club head (Long, 1995). According to Maltby (1995), most metal wood club heads of the time were made of stainless steel, and less common materials include alloys containing aluminium, titanium, beryllium, copper or cobalt. Strangwood (2003) provides more detailed information regarding material compositions of alloys that are used in club head production: 14-4 PH (hardened steel) was used in early designs in the 1970s; the modern, large drivers are made of other steels, aluminium-based alloys, titanium-based alloys and amorphous zirconium-based alloy inserts (Strangwood, 2003). When looking at driver club heads currently on the market, it appears that titanium-based alloys are dominating.

When building a club head from metal, two to three pieces are cast or forged individually and welded together. After this, all traces of the weld are removed by grinding and polishing (Maltby, 1995). Typical options to construct a metal wood are (Strangwood, 2003):

- face and sole cast in one piece, welded together with crown
- face and crown cast in one piece, welded together with sole
- face, crown and sole cast or forged in three different pieces and welded together
- face is a separate insert, combined with cast or forged body

It is also possible to use polymers as a material from which to construct club heads. The base material consists of graphite and plastic pellets that are formed using injection moulding (Maltby, 1995). When looking at the current state of the market, however, it appears that these non-metal club heads are not in use. Another option is to build composite golf clubs based on carbon or Kevlar fibres in an epoxy matrix (Maltby, 1995). According to Maltby, these clubs are typically formed and cured using compression moulding. Recently, multi-material club heads came on the market, which, for example, combine a carbon/epoxy composite crown with a metal face and sole.

### *A.2.2 Irons*

Because irons are the golf clubs used for shorter shots when aiming for precision and repeatability, their design and properties differ from those of woods. In contrast to the hollow metal wood club heads, iron club heads are solid. Maltby (1995) describes two methods that are available to manufacture iron club heads: forging and casting. Until the 1970's, the majority of iron club heads were forged. The clubs were based on a master model with some oversized areas to account for tolerances during the forging process. Based on this model, a two piece plaster casting was made and mounted in a forge hammer. This hammer then formed red hot steel bars to the desired shape. Small details, like logos and scorelines, had to be milled after the basic shape was finished (Maltby, 1995).

Due to the fact that forging facilities are expensive and forging limits the range of design variations, today investment casting is the dominant manufacturing method for irons. During the investment casting process, a master model made of aluminium or brass is duplicated to form a female mould. This mould is filled with hot wax to form a number of wax replicas. These replicas are attached to a "tree", which is then dipped into liquid ceramic material. Now, warming the tree causes the wax to melt and to run out, forming a ceramic shell. This shell is filled with molten steel. After the steel is cured, the ceramic shell is broken away, so that the club heads can be cut off. According to Maltby, common materials are 17-4 or 431 stainless steel, sometimes also alloys containing titanium, aluminium, bronze and beryllium copper (Maltby, 1995).

Whilst the advantages of casting are that it allows producing complex structures and that creating new designs requires a relatively small investment, the disadvantage is that the materials are less malleable because of their grain structure. Forged irons outperform cast irons in this property, but mass and shape tolerances are bigger for these due to the forging process (Maltby, 1995).

### A.3 Club head mass

Whilst the previous section summarised common material types and manufacturing routes for club heads, the following sections will focus on the resulting mechanical club head properties and their effect on club performance. The mass of the club head mainly determines how difficult it is for a player to accelerate and to control a golf club, because the inertia the player has to overcome when accelerating the club is determined by the length and mass of the shaft and by the club head mass. The effects of club head mass and mass distribution were analysed in player tests performed by Cooper and Mather (1994), who concluded that high-handicap players often lack sufficient coordination and strength to control the forces produced by their clubs. This work was further extended by Mather (2000), who suggested that more of the club mass should be distributed closer to the rotation axis of the wrist by using lighter club heads and heavier grips. The rationale behind this was to make the club more stable during the initiation of the downswing and to prevent less competent golfers from accelerating the club too early. According to Mather (2000), these clubs performed better in independent tests than conventional designs. However, details regarding these tests were not included in Mather’s publication. Further tests of these clubs (Mather, 2002) by four players indicated that lighter club heads could indeed improve head speed, even for professional golfers. Unfortunately, ball velocities were not taken into consideration in Mather’s study, although it is likely that they were also affected by changing the club head mass through a change in momentum. In contrast to Mather’s line of argument, Maltby (1995) states that heavier clubs are easier to control. Maltby does not provide any scientific rationale and does not include test results, but most likely his claim is based on the fact that the path of a heavier club will be more difficult to change due to its increased inertia. In Maltby’s opinion, each golfer has to find an optimum trade-off between clubhead velocity (lighter clubhead) and control (heavier clubhead).

Whilst requiring more force input by the player, heavier club heads do allow the player to transfer more kinetic energy to the club head if club head speed is maintained, potentially resulting in higher launch velocities (Cochran & Stobbs, 1968). However, energy transfer at impact becomes less efficient the heavier the club head, because substantial increases in club mass will only have a minor effect on the ball velocity (Cochran & Stobbs, 1968). Cochran and Stobbs base this on the following. Assuming that the club head behaves like a projectile at impact and neglecting the loft angle, the conservation of momentum principle can be used to show that:

$$v_b = \frac{(1+e)v_c}{1+ m_b/m_c} \qquad \text{(A-1),}$$

where: $v_b$ is ball velocity,

$e$ is the coefficient of restitution,

$m_C$ is club head mass,

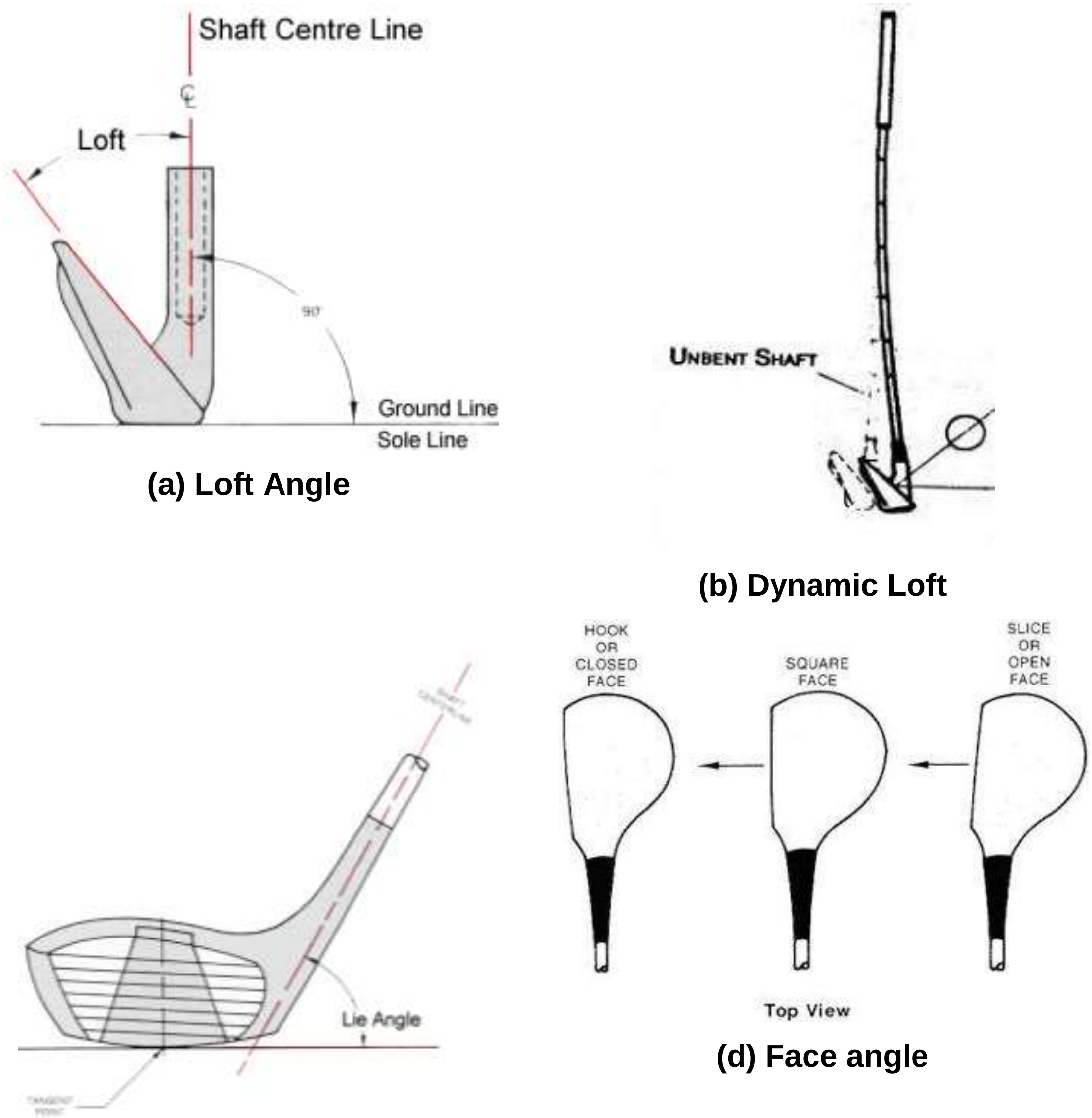
$m_b$ is ball mass,

$v_C$ is the club head velocity before impact.

From equation (A-1) it can be seen that, when $m_c >> m_b$, ball velocity will approach a maximum of $(1+e)v_c$ (Penner, 2003).

In summary, the trade-off between ease of overcoming the inertia of the club, the stability of the club head path, the possibility to transfer the maximum kinetic energy to the club head and achieving an efficient weight ratio between club head and ball is complex. Cochran and Stobbs (1968) calculated that the optimum club head mass is between 170 and 225 g. As many modern driver heads on the market are designed to have a mass of approximately 200 g, this range still seems to be realistic, although no study other than Cochran and

Stobb's early work could be found that provides justification for this particular mass range.




**(a) Loft Angle**

**(b) Dynamic Loft**

**(c) Lie angle**

**(d) Face angle**

**Figure A-1: Definitions of basic club head parameters: (a) loft angle (Maltby, 1995, p. 406), (b) effect of shaft bending on dynamic loft (Horwood, 1994, p. 249), (c) lie angle (Maltby, 1995, p. 418), (d) face angle (Maltby, 1995, p. 434).**

## A.4 Geometry

The fundamental variables describing the geometry of club heads are the following (see Figures A-1 and A-2): loft angle, lie angle, face angle, and horizontal face curvature (Maltby, 1995). Each of these variables has a distinct influence on the characteristics of a golf club, which are summarised in the following paragraphs.

### *A.4.1 Loft Angle – static and dynamic loft*

A club head's loft angle is the angle of the face to a vertical line that is perpendicular to the ground when the club is in a neutral position with the sole and the scorelines parallel to the ground (Maltby, 1995). The loft angle is the most important variable affecting the launch angle of the ball. In general, increasing the loft angle results in a higher launch angle of the ball and gives the ball more backspin. This results in higher, shorter trajectories and reduced forward roll of the ball after impacting the ground. The loft of a club head can be measured statically with a gauge (static loft) or measured during the actual swing just before impact (dynamic loft), for example by using high-speed imaging. Combining the launch conditions a particular player produces with an impact and a ball trajectory model allows optimising the loft angle for a given player for maximum distance (Winfield & Tan, 1994).

Due to the flexibility of the golf shaft, it has been suggested that the static and dynamic loft can differ significantly, depending on the characteristics of the shaft (Maltby, 1995). Using a swing model including a flexible shaft, MacKenzie (2005) estimated that for every centimetre the club head bends forward at impact, the dynamic loft increases by approximately 0.8°. This is similar to findings from Mather and Cooper (1994), who measured that 5 cm lead deflection resulted in a 5° increase in dynamic loft.

### *A.4.2 Lie Angle*

The lie angle is the angle between the centreline of the shaft and the ground when the sole of the club is aligned with the ground (Maltby, 1995). The lie angle of a club should be matched to the height and the swing style of a player. Furthermore, it has secondary effects on two other variables (Maltby, 1995):

- side spin of the ball: if the face is angles at impact (e.g. toe end higher than heel end), the ball will not only have backspin but also a small amount of side spin due to the loft angle of the club

- initial trajectory of the ball: if the heel touches the ground at impact this results in a tendency to hit the ball left of the target (vice versa if the toe touches the ground)

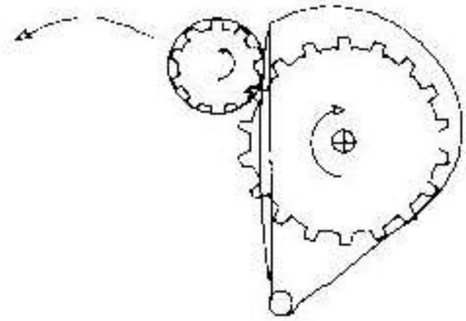
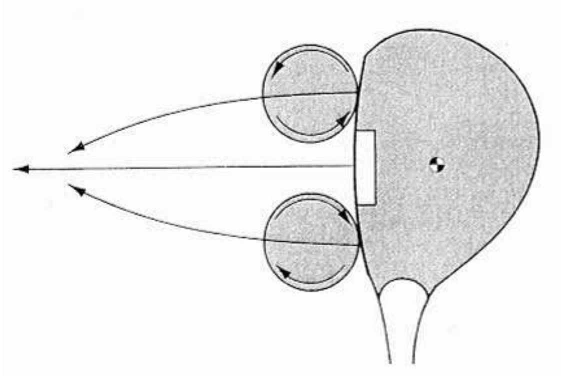
### *A.4.3 Face Angle*

The face angle is the angle between the club face and a horizontal line that is perpendicular to the target line (Maltby, 1995). An open or closed face angle results in a slicing or hooking tendency as the face of the club will not be aligned perpendicular to the target line when the player brings the rest of the club back to a square position. This effect can be used to adjust the club in order to compensate systematic swing errors. For example, a player that tends to hit the ball when the face is still open could use a club with a closed face angle to account for the error and to arrive at impact position with a square face.

Similarly to the loft angle, the face angle that can be measured with the shaft in a static position differs from the dynamic face angle the club head reaches just before impact. This is due to the deformation of the shaft and the swing path. MacKenzie (2005) performed swing simulations and found that the face angle closed by approximately 0.7° for every centimetre the club head was bending forward just before impact.

### *A.4.4 Horizontal Face Curvature*

If the centre of gravity (COG) and the impact position between ball and club face are aligned with the club head's trajectory and impact occurs at the centre of the clubface, the face curvature has no effect on the trajectory. Off-centre hits, however, cause sidespin due to the rotation of the club head about a vertical axis through its COG ("gear effect", Figure A-2) (Cochran & Stobbs, 1968). This sidespin can cause significant dispersion of the ball to the left or to the right. Face curvature can compensate for this dispersion by changing the initial ball direction to the left (heel hits) or to the right (toe hits). The trajectory will still be curved, but the ball will curve back to the target line if the amount of face curvature was sufficient. However, the distance covered will be reduced compared to a straight shot without sidespin.

**(a) "Gear effect"** **(b) Effect of horizontal face curvature**
**(Chou, 2004a, p. 23).** **(Maltby, 1995, p. 443).**

**Figure A-2: Gear effect and effect of face bulge.**

## A.5 Position of the centre of gravity of the club head (COG)

Because of the very short duration of the impact and the flexibility of the shaft, the club head is usually considered to behave as a freely moving projectile during impact (Cochran & Stobbs, 1968). Therefore, the position of the centre of gravity (COG) of the club head plays an important role during the impact as all rotation of the club head occur around this position, for example if the player hits the ball off-centre. In this case, the impact causes the club head to rotate around a vertical axis, which gives the ball undesired sidespin ("gear effect", see Figure A-2 (a)). The magnitude of sidespin depends on the distance between the pivot point of club head rotation and the impact position: the further away the pivot point, the greater the amount of sidespin imparted to the ball for a given amount of club head rotation. Due to the fact that the club head is regarded as a projectile during impact, all rotations will occur about its COG, and, hence, the further away the COG is from the club face, the greater the sidespin of the ball (Maltby, 1995). Furthermore, it has been suggested that a COG position that is further away from the clubface leads to a higher trajectory due to increased forward bending of the shaft at impact and the resulting higher degree of dynamic loft (Butler & Winfield, 1995; Chou, Gilbert, & Olsavsky, 1995).

In terms of COG height relative to the sole of the consensus is that a lower position will make it easier for the golfer to achieve an optimal launch angle. This is due to the fact that, for an efficient swing, the COG of the club has to be aligned with or below the COG of the ball. If the ball's COG is lower than the COG of the club, this will lead to a downward rotation of the club head during impact and a shot during which the ball barely leaves the ground (Chou, Gilbert, & Olsavsky, 1995).

### A.6 Moment of inertia (MOI)

Several researchers have analysed the effect of a golf club's MOI on club performance. While changing the club head's MOI only has a minor effect on the inertia the player feels during the swing, the effect of the club head's MOI on the club head's reaction to off-centre hits is more significant (Nesbit et al., 1996). Off-centre hits cause the club head to rotate about its COG. This rotation transfers to the ball as sidespin ("gear effect", see above). This sidespin causes deviations to the right (heel hits) or to the left (toe hits). The MOI of a club head around a vertical axis through its COG describes the club head's resistance to this rotation. The MOI can either be increased by increasing the mass of the club head or by distributing weight further away from the COG of the club head. Robot tests (Olsavsky, 1994), swing models (Whittaker, 1999) and FE simulations (Iwatsubo, Kawamura, Miyamoto, & Yamaguchi, 2000) have been used to demonstrate this effect.

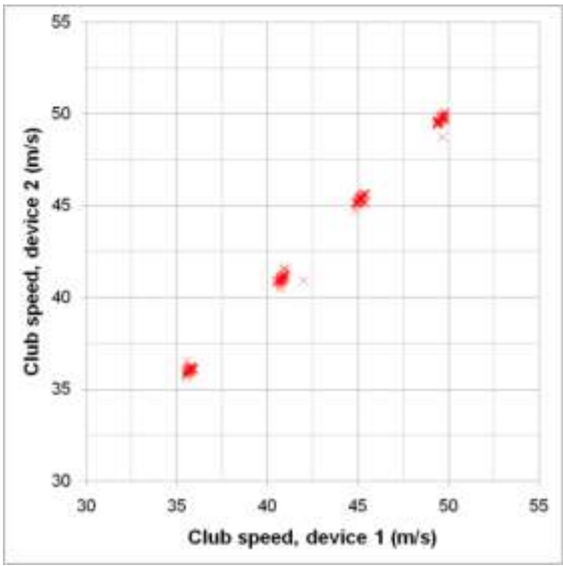
Club designers aim to maximise the effect described in the previous paragraph to make club heads more forgiving when the player hits the ball off-centre. Hartzell and Nesbit (1996) demonstrated how optimisation algorithms can support this process. They developed a computer programme that suggested club head geometries with previously specified MOI and COG properties.

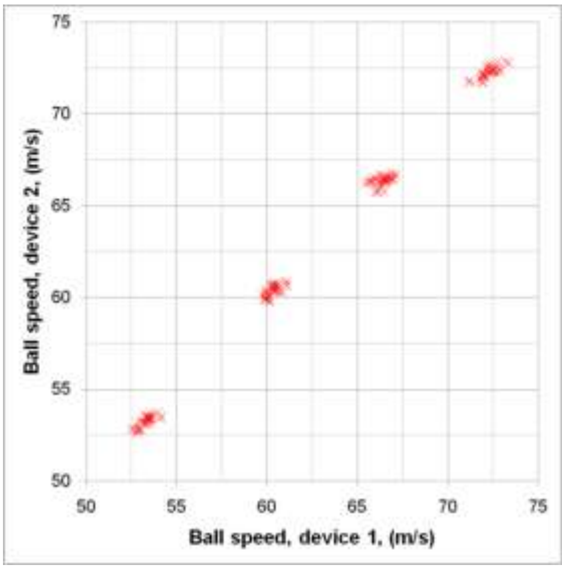
In summary, MOI is a design variable that appears to make club heads more forgiving to off-centre hits. Whilst most beginners and average players will appreciate the effects of an increased MOI, advanced players may prefer low MOI designs, which give them the ability to control the trajectory of the ball.

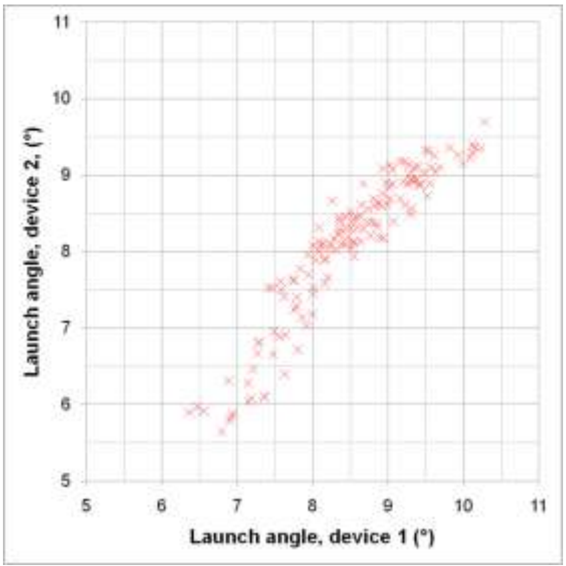
## *B. Launch monitor validation*

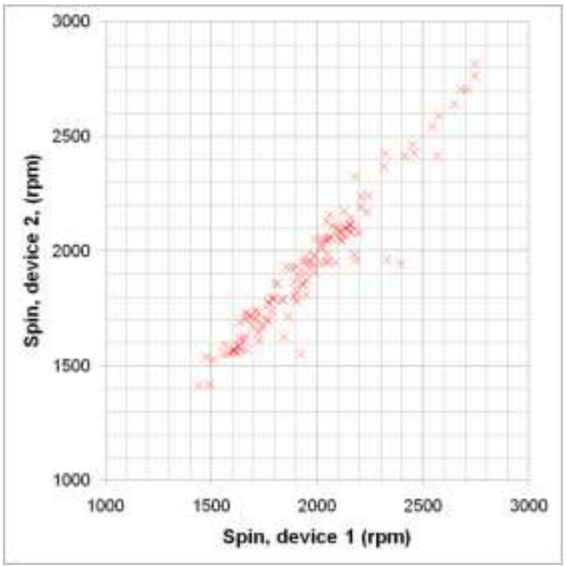
### B.1 Comparison between Device 1 and 2

Comparison of club head impact speed, balls speed, launch angle and spin measured with two different launch monitors.

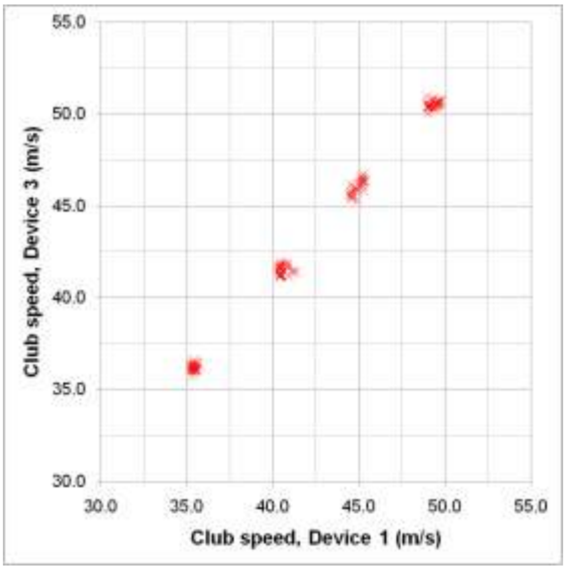


## B.2 Comparison between Device 1 and 3



### *C. Derivation of finite difference equation for non-uniform step size*

The purpose of this section is to describe how a finite difference formula for non-uniform step sizes was derived. This formula was used to compute the speed of the club head just before impact. The following is adapted from the classical derivation of finite difference formulas from Taylor series.

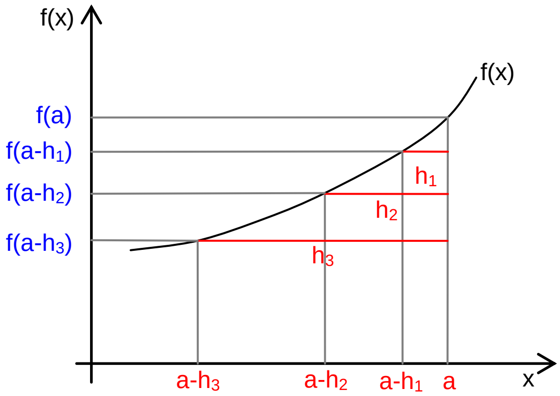



**Figure C-1: Definition of the variables used throughout this section.**

Using the variables defined in the above figure, a third order backward difference formula can be obtained by an expression of the form (omitting the truncation error):

$$f(a) = A\,f(a) + \ B\,f(a-h_1) + C\,f(a-h_2) + D\,f(a-\ h_3) + \cdots \qquad \text{(C-1)}$$

The coefficients (*A*, *B*, *C*, *D*) can be found from a Taylor series expansion of *f* (*a-h₃*), *f* (*a-h₂*) and *f* (*a-h₁*) around *f* (*a*):

$$f(a-h_1) = f(a) - h_1\,f^{'}(a) + \frac{h_1^2}{2}f^{''}(a) - \frac{h_1^3}{6}f^{'''}(a) + \cdots \qquad \text{(C-2)}$$

$$f(a-h_2) = f(a) - h_2\,f^{'}(a) + \frac{h_2^2}{2}f^{''}(a) - \frac{h_2^3}{6}f^{'''}(a) + \cdots \qquad \text{(C-3)}$$

$$f(a-h_3) = f(a) - h_3\,f^{'}(a) + \frac{h_3^2}{2}f^{''}(a) - \frac{h_3^3}{6}f^{''}(a) + \cdots \qquad \text{(C-4)}$$

Multiplying equation (C-2) with *B*, (C-3) with *C* and (C-4) with *D* leads to

$$A\,f(a-h_1) = A\,f(a) - A\,h_1\,f^{'}(a) + \mathrm{A}\,\frac{h_1^2}{2}f^{''}(a) - \mathrm{A}\,\frac{h_1^3}{6}f^{'''}\,(\mathrm{a}) + \cdots \quad \text{(C-5)},$$

$$B\,f(a-h_2) = \mathrm{B}\,f(a) - B\,h_2\,f^{'}(a) + \mathrm{B}\,\frac{h_2^2}{2}f^{''}(a) - \mathrm{B}\,\frac{h_2^3}{6}f^{'''}\,(\mathrm{a}) + \cdots \quad \text{(C-6)},$$

$$C\,f(a-h_3) = \mathrm{C}\,f(a) - C\,h_3\,f^{'}(a) + \mathrm{C}\,\frac{h_3^2}{2}f^{''}(a) - \mathrm{C}\,\frac{h_3^3}{6}f^{'''}(a) + \cdots \quad \text{(C-7)}.$$

Now, adding equations (C-5), (C-6) and (C-7) and adding *A f* (*a*) yields

$$Af(a) + Bf(a-h_1) + Cf(a-h_2) + Df(a-h_3) =$$

$$Af(a) + Bf(a) + Cf(a) + Df(a) - Bh_1f^{'}(a) - Ch_2f^{'}(a) - Dh_3f^{'}(a)$$

$$+B\frac{h_1^2}{2}f^{''}(a) + C\frac{h_2^2}{2}f^{''}(a) + D\frac{h_3^2}{2}f^{''}(a)$$

$$-B\frac{h_1^3}{6}f^{'''}(a) - C\frac{h_2^3}{6}f^{'''}(a) - D\frac{h_3^3}{6}f^{'''}(a) \quad \text{(C-8)}.$$

Because the left-hand side of (C-8) is identical to the right-hand side of (C-1) we can now obtain the four conditions

$$A + B + C + D = 0$$

$$B\,h_1 + C\,h_2 + D\,h_3 = -1$$

$$B\,h_1^2 + C\,h_2^2 + D\,h_3^2 = 0$$

$$B\,h_1^3 + C\,h_2^3 + D\,h_3^3 = 0 \quad \text{(C-9)},$$

Equation (C-9) expressed as matrices yields:

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & h_1 & h_2 & h_3 \\ 0 & h_1^2 & h_2^2 & h_3^2 \\ 0 & h_1^3 & h_2^3 & h_3^3 \end{pmatrix} \begin{pmatrix} A \\ B \\ C \\ D \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 0 \\ 0 \end{pmatrix} \qquad \text{(C-10).}$$

From (C-10), the coefficients of (C-1) are now known, and (C-1) can be used to calculate the first derivative at point *a* using a third order accurate backward difference method.

## *D. Information sheet and consent form*

### D.1 Information sheet

**EDINBURGH NAPIER UNIVERSITY**

**Information Sheet: "Dynamic testing of golf club shaft characteristics"**

My name is Nils Betzler and I am a postgraduate student from the School of Life Sciences at Napier University in Edinburgh. As part of my MPhil/PhD studies, I am undertaking a research project. The title of my project is: "Dynamic testing of golf club shaft characteristics".

This study will investigate how golf shaft properties influence the interaction of player and golf club. The study looks both into how golfers adapt to different clubs and into how shaft behaviour changes depending on individual swing styles.

The findings of the project will be useful to gain a better understanding of the interaction between golf club and player.

This research is being partly funded by

- R&A Rules Ltd. (R&A Rules Ltd.; St Andrews; Fife; KY16 9JD)
- The Napier University Knowledge Transfer Fund. The purpose of this fund is to help organisations from outside the University to access knowledge and skills from Higher Education institutions.

I am looking for volunteers to participate in the project, especially highly skilled, male golfers with a consistent swing pattern.

If you agree to participate in the study, you will be asked to perform a number of golf swings using your own golf clubs or equipment provided by us.

An infrared camera system will be used to film your motion. This system consists of 12 cameras that record the body and club motion from different points of view. Spherical, reflective markers will be placed on all relevant body landmarks using removable, double-sided tape. Each camera emits infrared light, which is reflected by these markers and allows the cameras to record the motion of these markers. The cameras only film the motion of the markers – the actual motion of your body will not be visible on the footage and will be reconstructed indirectly based on the recorded marker motion.

The researcher is not aware of any specific risks associated with this procedure. You will be free to withdraw from the study at any stage, you would not have to give a reason.

All data will be made anonymous. Your personal details will only be known to the core of the research team, e.g. in order to arrange appointments. Before any recorded data is analysed, your name will be replaced with a pseudonym, and it will not be possible to identify you in any reporting of the data gathered. Any data collected will be kept in a secure place to which only the researcher has access. Your personal details will be kept separately from any other data files in a locked file cabinet. Data will be kept till the end of the examination process of my PhD, which is anticipated to be in November 2009.

The results may be published in a journal or presented at a conference after being made anonymous.

If you would like to contact an independent person, who knows about this project but is not involved in it, you are welcome to contact Dr Tony Westbury. His contact details are given below.

If you have read and understood this information sheet, any questions you had have been answered, and you would like to be a participant in the study, please now see the consent form.

Contact details of the independent adviser

| | |
|---|---|
| Name of adviser: | Dr Tony Westbury |
| Address: | Lecturer |
| | Napier University |
| | School of Life Sciences |
| | Napier University |
| | Merchiston Campus |
| | 10 Colinton Road |
| | EDINBURGH |
| | EH10 5DT |

Email / Telephone: T.Westbury@napier.ac.uk / 0131 455 2520

## D.2 Consent form

**Consent Form**

**"Dynamic testing of golf club shaft characteristics"**

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in this study.

I understand that I have the right to withdraw from this study at any stage without giving any reason.

I agree to participate in this study.

Name of participant: ______________________________

Signature of participant: ______________________________

Signature of researcher: ______________________________

Date: ______________

## *E. Definitions of local coordinate systems used in Study 1*

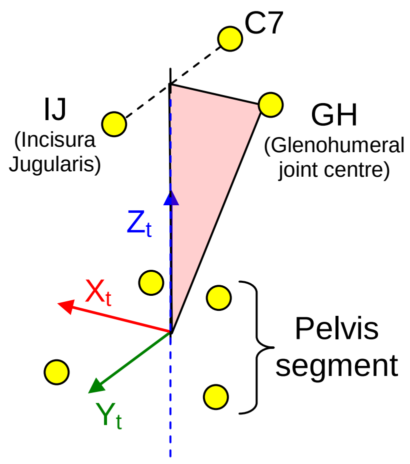
**Thorax segment:**

Origin:
- Offset landmark relative to pelvis segment

Digitised landmarks:
- IJ

Functional joint centres:
- GH (landmark to define orientation of $X_t$ axis)

Tracking markers:
- three markers on the back of the player

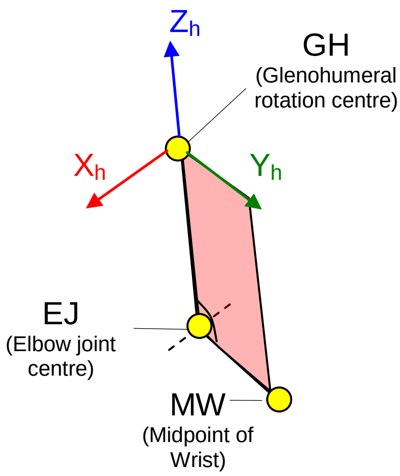



**Humerus segment:**

Functional landmarks:
- GH, EJ

Digitised landmarks:
- MW (midpoint of wrist with elbow flexion = 90°. This is to define the orientation of the frontal plane of the humerus)

Tracking markers:
- Cluster of three markers

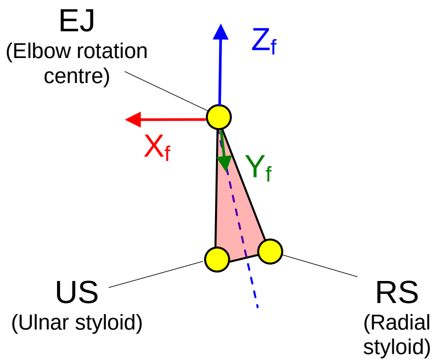


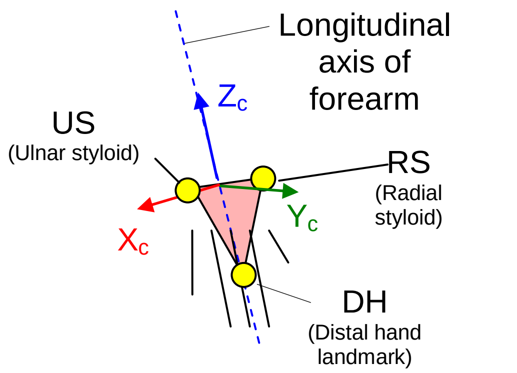

**Forearm segment:**

Functional landmarks:
- EJ

Digitised landmarks:
- US, RS

Tracking markers:
- Wrist band with three markers



| Hand segment: | |
|---|---|
| Digitised landmarks:<br>- US, RS<br><br>Other landmarks:<br>- DH (lateral hand tracking marker projected onto longitudinal forearm axis to ensure correct alignment of coordinate system)<br><br>Tracking markers:<br>- Three markers attached to golf glove |  |

### *F. Results for pair-wise comparisons in Study 1*

The following tables show *p*-values for all pair-wise comparisons performed in Study 1. For reference, results for the less conservative Bonferroni correction are included but should be interpreted with caution due to differences in variance between conditions.

#### F.1 Launch conditions

| Comparison | | Club speed Bonferroni | Club speed Games-Howell | Ball speed Bonferroni | Ball speed Games-Howell | Launch angle Bonferroni | Launch angle Games-Howell | Side angle Bonferroni | Side angle Games-Howell |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | **r-flex** | .080 | .890 | .423 | .904 | 1.000 | .993 | .796 | .672 |
| | **x-flex** | .365 | .943 | .106 | .813 | .009 | .353 | 1.000 | .994 |
| **r-flex** | **l-flex** | .080 | .890 | .423 | .904 | 1.000 | .993 | .796 | .672 |
| | **x-flex** | .001 | .703 | .001 | .546 | .019 | .390 | .624 | .595 |
| **x-flex** | **l-flex** | .365 | .943 | .106 | .813 | .009 | .353 | 1.000 | .994 |
| | **r-flex** | .001 | .703 | .001 | .546 | .019 | .390 | .624 | .595 |

#### F.2 Strain

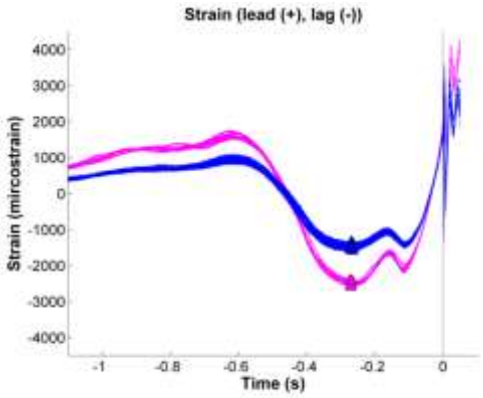
| Comparison | | Peak toe strain Bonferroni | Peak toe strain Games-Howell | Recovery Rate Bonferroni | Recovery Rate Games-Howell | Lag area Bonferroni | Lag area Games-Howell | Lead Strain Bonferroni | Lead Strain Games-Howell |
|---|---|---|---|---|---|---|---|---|---|
| **l-flex** | **r-flex** | .000 | .000 | .000 | .000 | .000 | .000 | .116 | .834 |
| | **x-flex** | .000 | .000 | .000 | .000 | .000 | .000 | .002 | .603 |
| **r-flex** | **l-flex** | .000 | .000 | .000 | .000 | .000 | .000 | .116 | .834 |
| | **x-flex** | .000 | .000 | .012 | .423 | .347 | .904 | .000 | .165 |
| **x-flex** | **l-flex** | .000 | .000 | .000 | .000 | .000 | .000 | .002 | .603 |
| | **r-flex** | .000 | .000 | .012 | .423 | .347 | .904 | .000 | .165 |

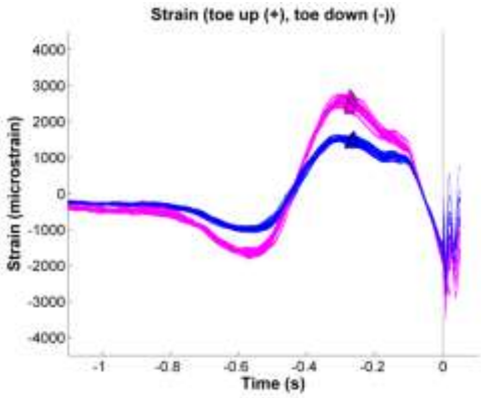
## *G. Strain results Study 2*

Strain traces for the x-flex shaft are shown in blue colour; traces for the l-flex shaft are shown in magenta colour. The instant when the player started the swing (take-away) is marked with a □ symbol; the transition from backswing to downswing is marked with a △ symbol. If the take-away event is not shown this indicates that take-away occurred before the time range shown in the graph. Left column: lead/lag strain; right column: toe up/down strain.

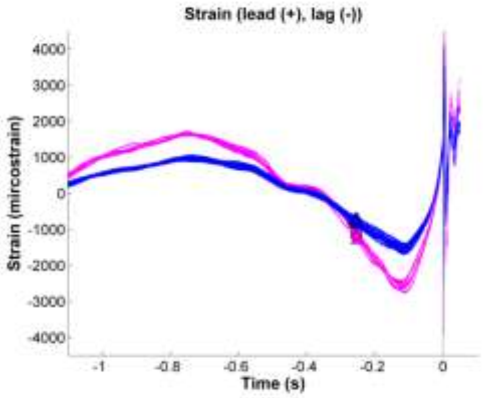
Note that whilst there are typically marked differences in strain throughout the swing, there is typically very little difference in strain at impact ($t$ = 0).

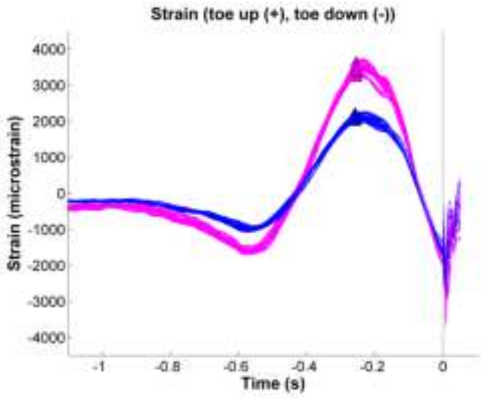
Player 1:



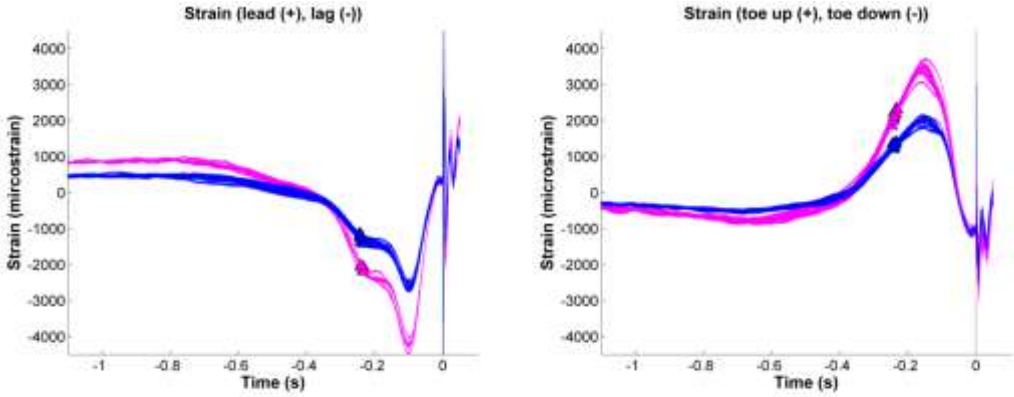




Player 2:

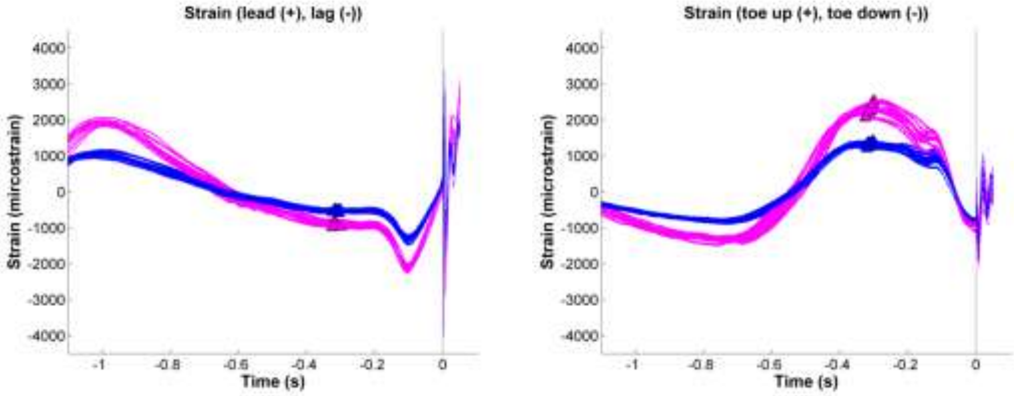


Player 3:




Player 4:

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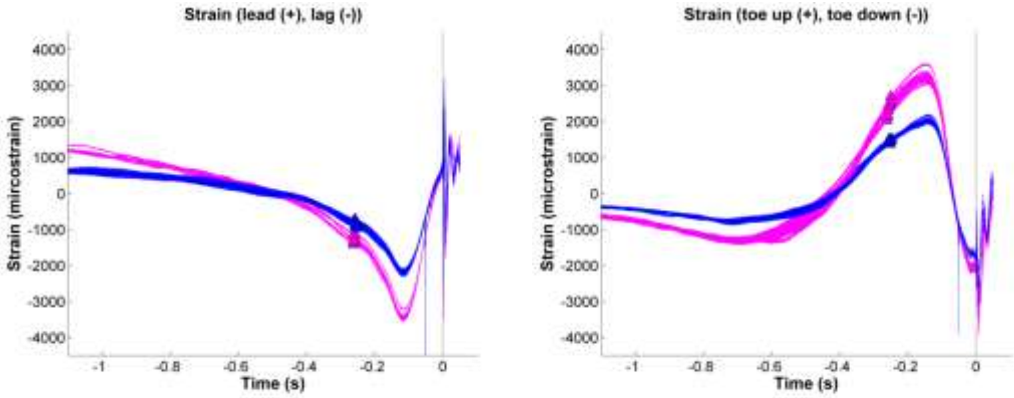


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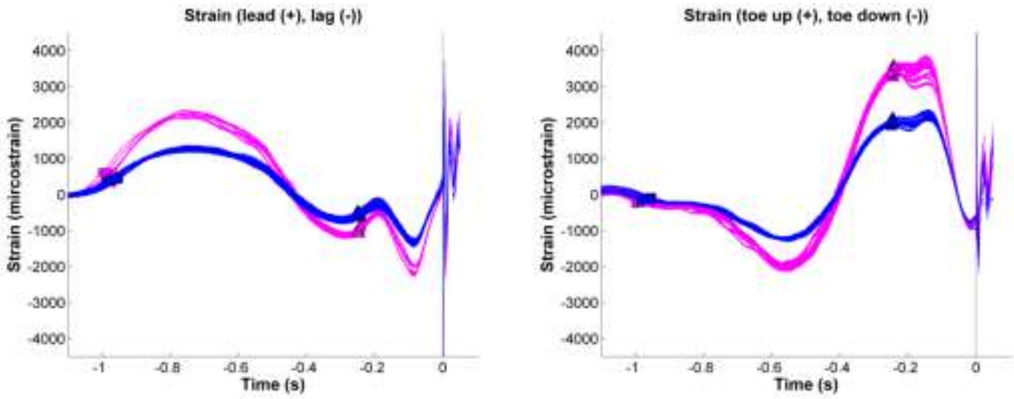

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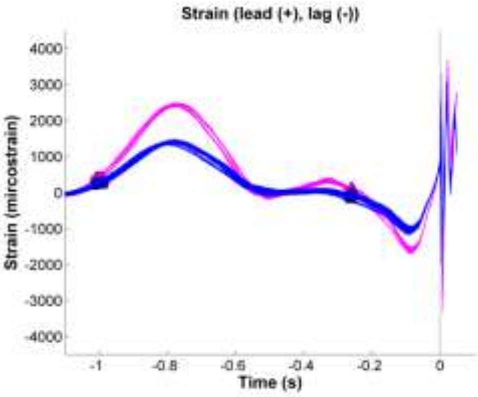


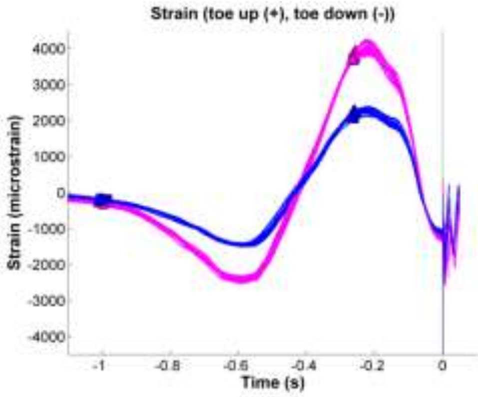


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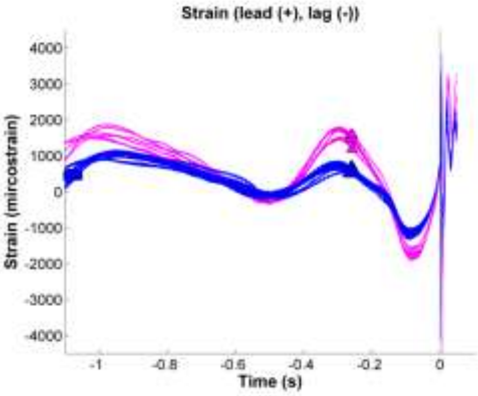
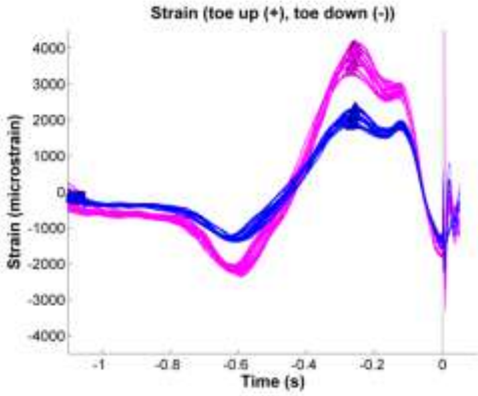
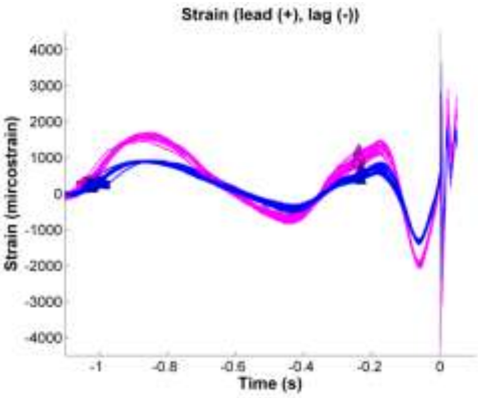
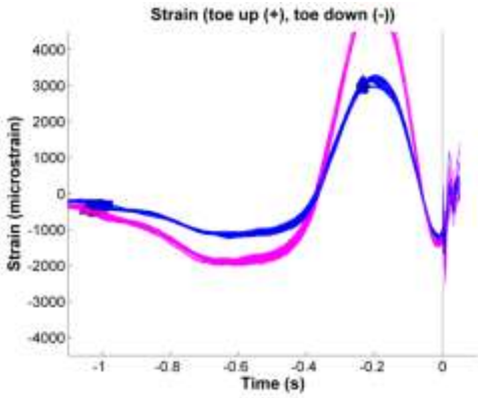


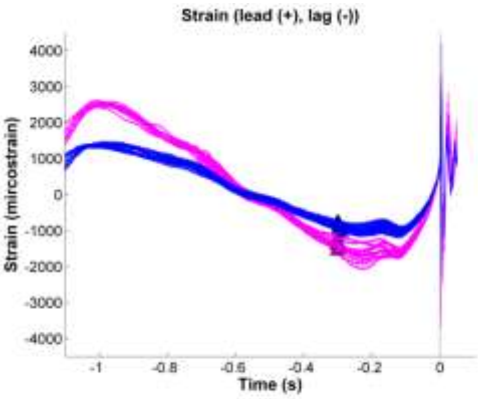



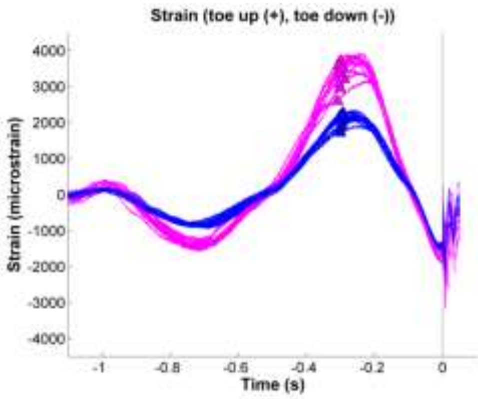

Player 9:



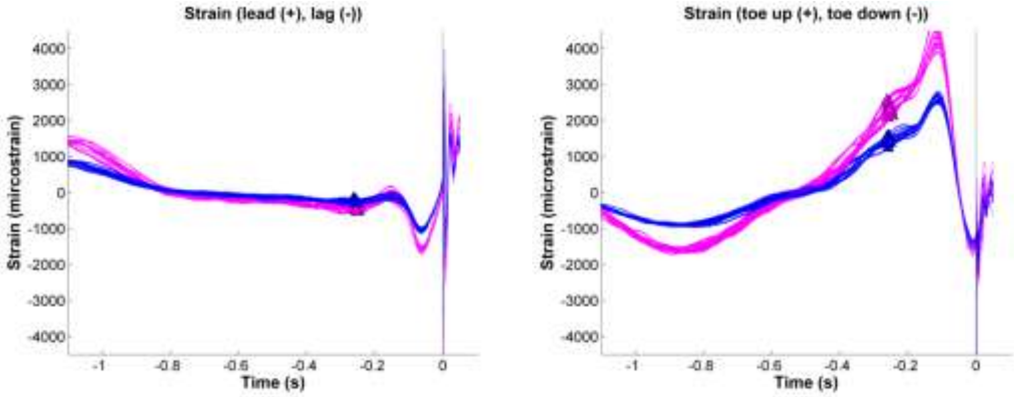




Player 10:



Player 11:

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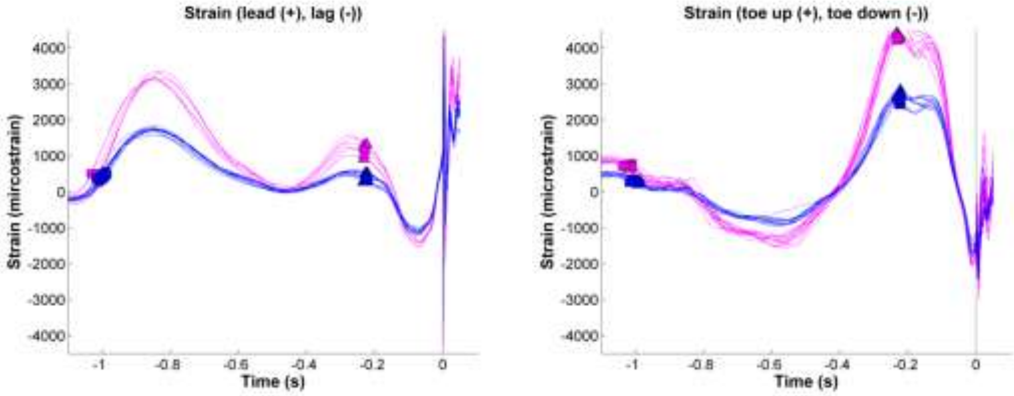
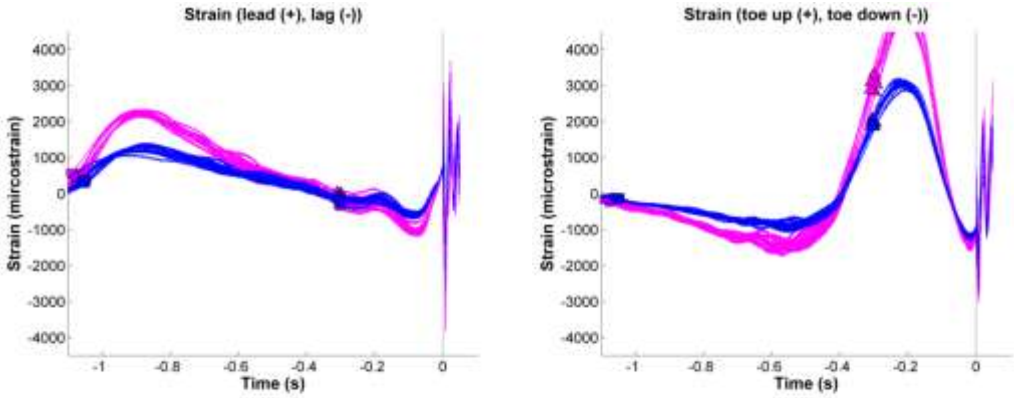
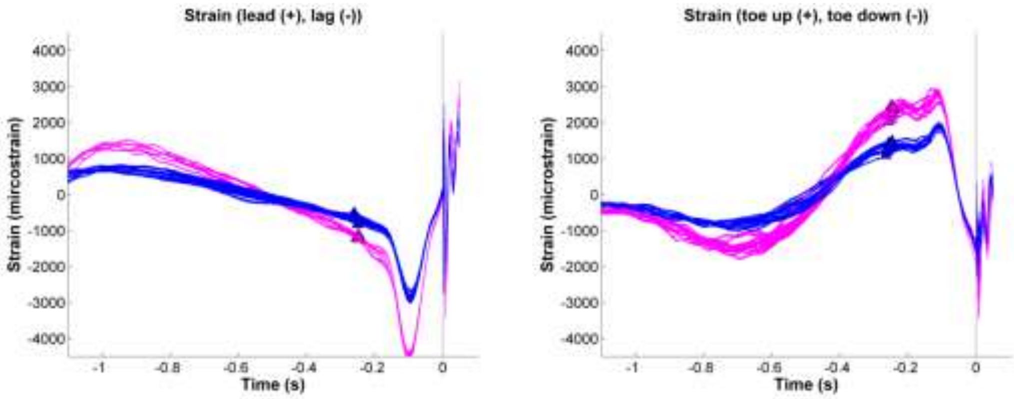



Player 13:




Player 14:



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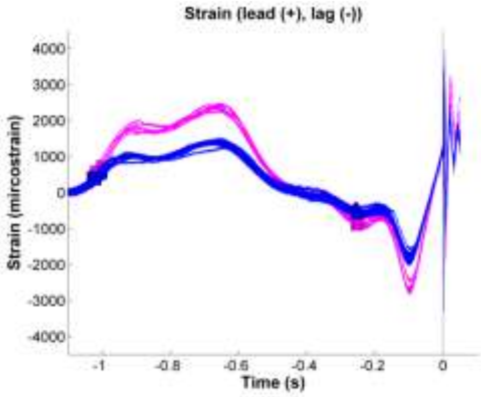


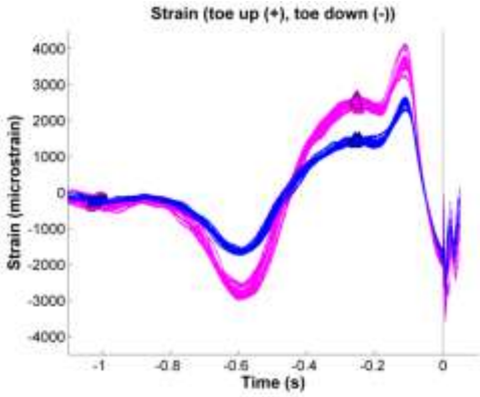


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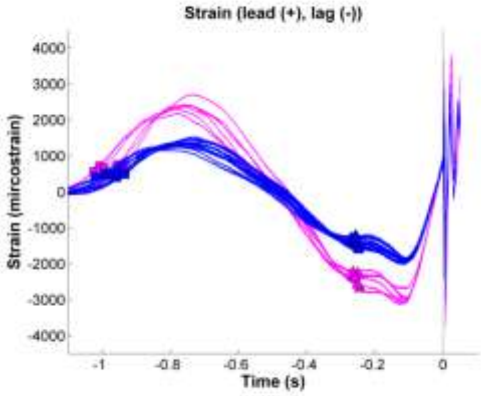
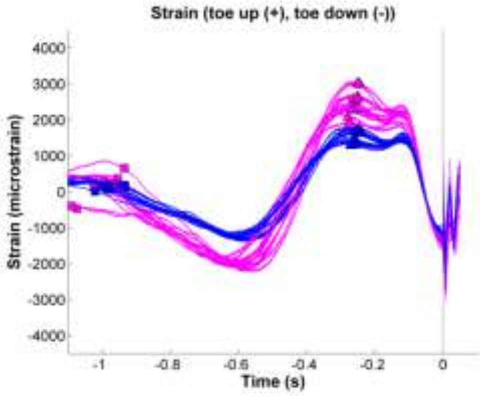
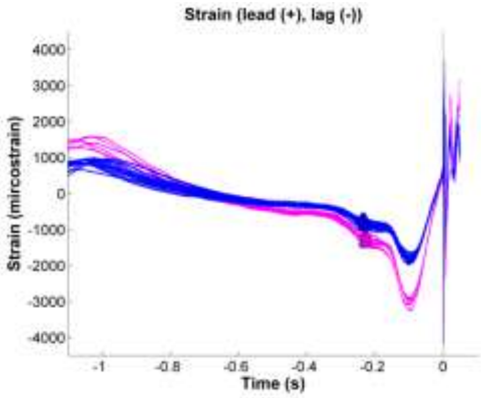
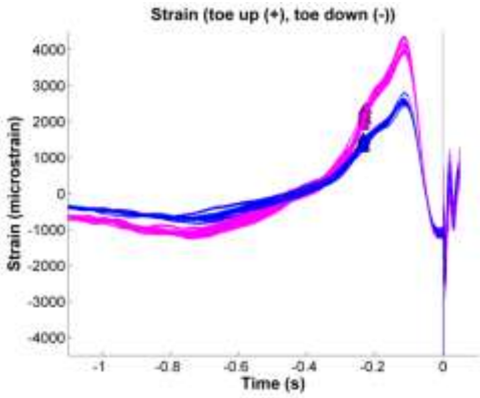


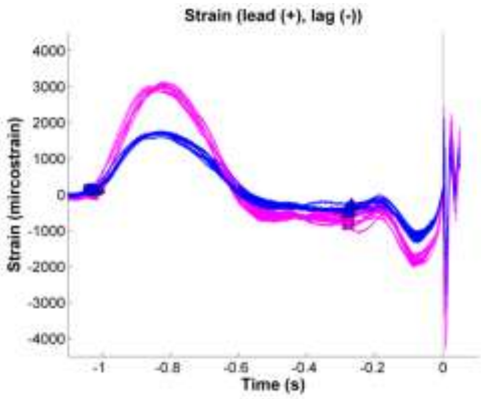



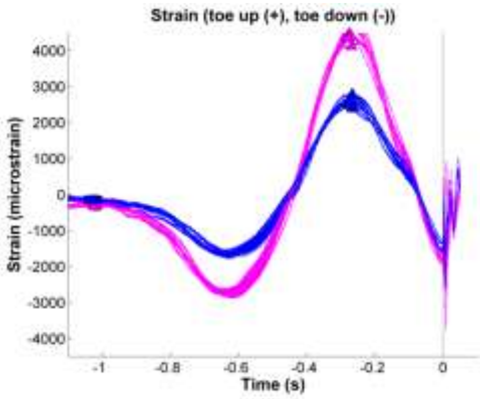

Player 17:



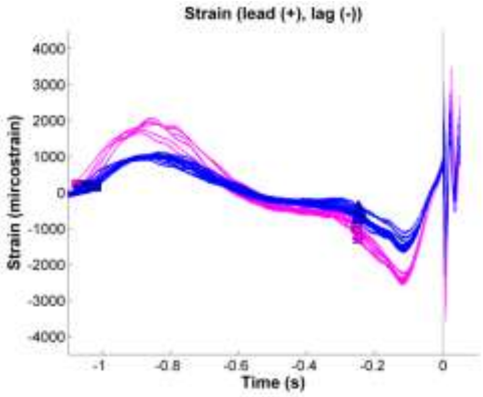



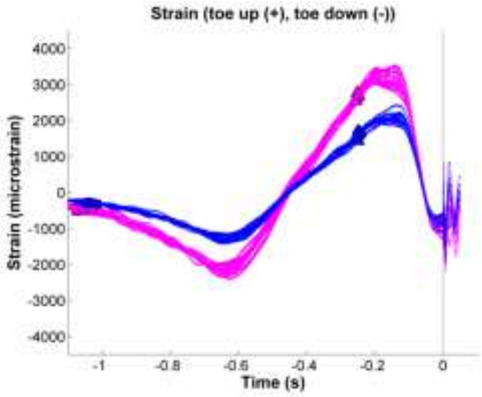

Player 18:



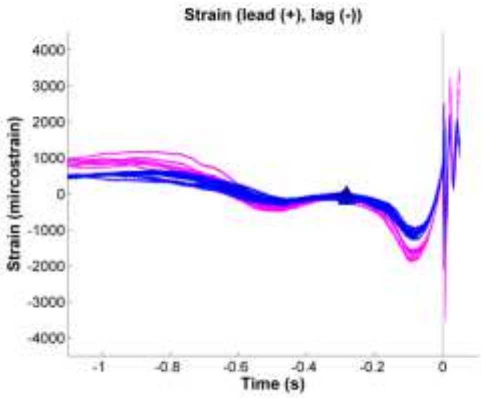



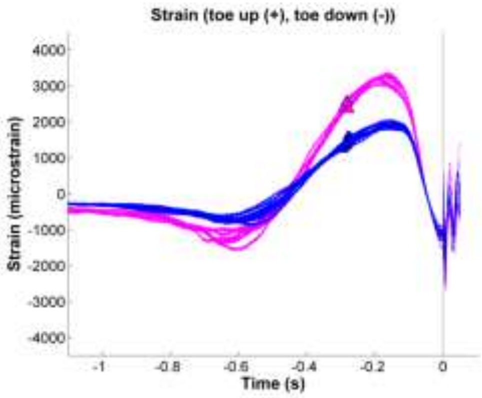
Player 19:




Player 20:



## H. *Impact location results Study 2*

The coordinate system for impact locations is defined as shown in Figure G-1. (1) and (2) in the legends refers to the first and second set of swings that subjects performed with each club.

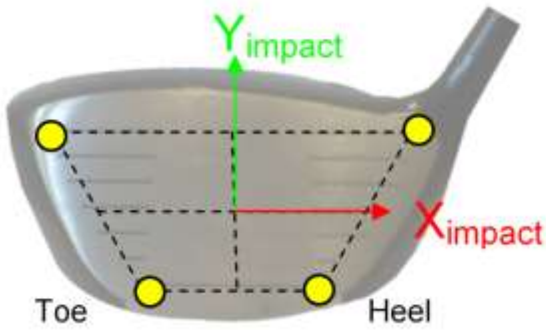
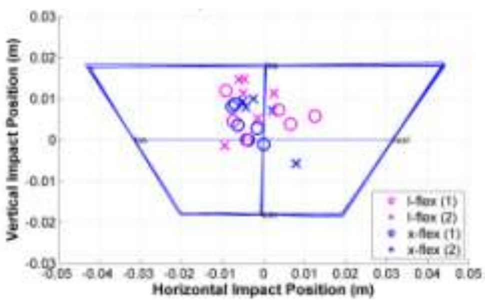
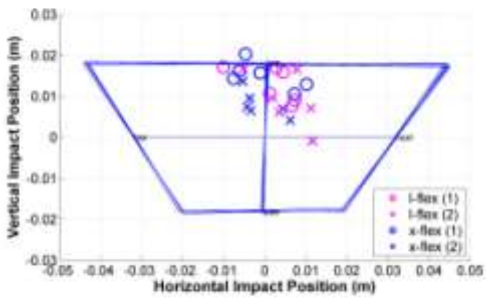



**Figure G-1: Impact location coordinate system.**

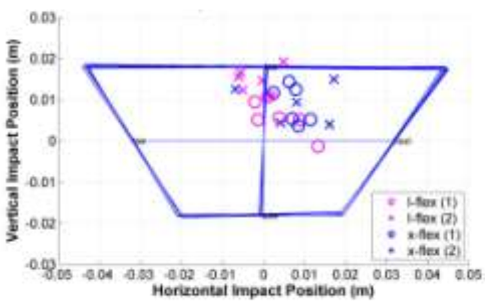
Player 1:



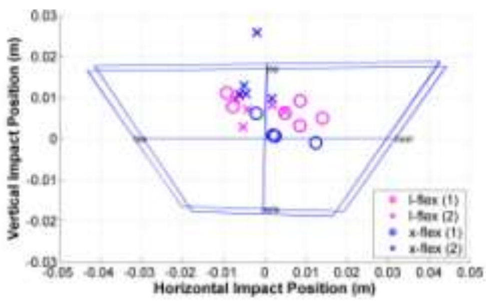

Player 2:



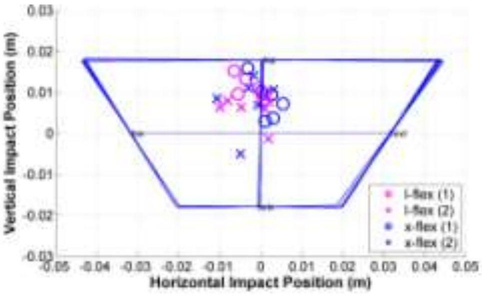

Player 3:



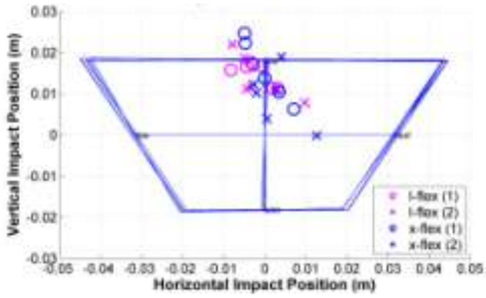

Player 4:



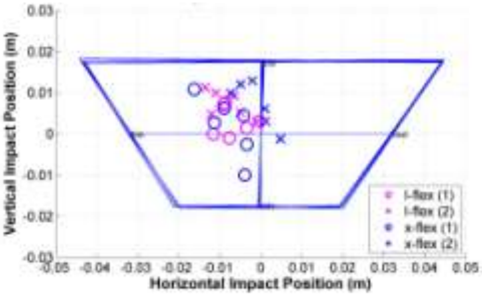
Player 5:



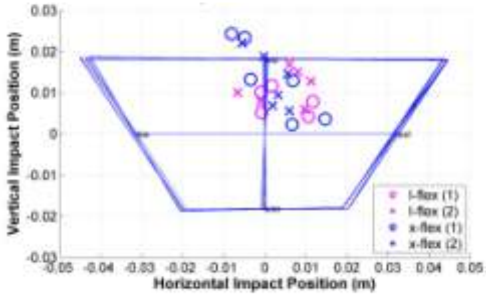

Player 6:



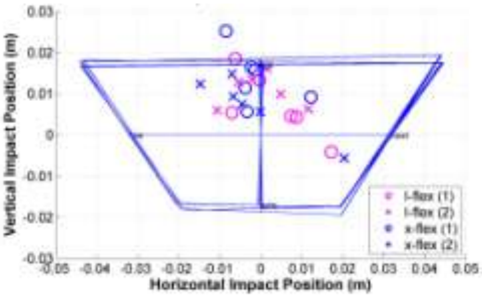

Player 7:



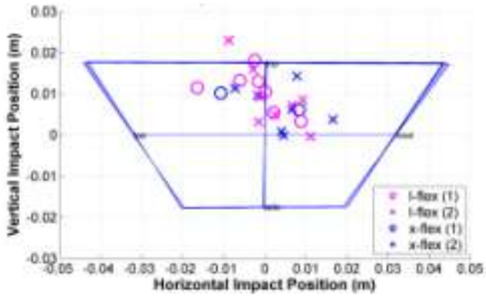

Player 8:



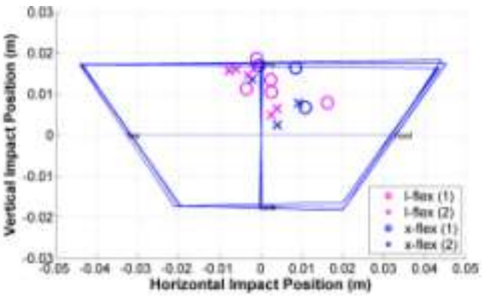

Player 9:



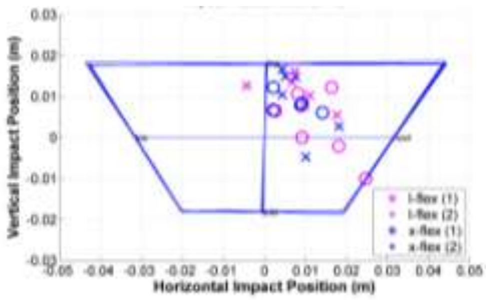

Player 10:



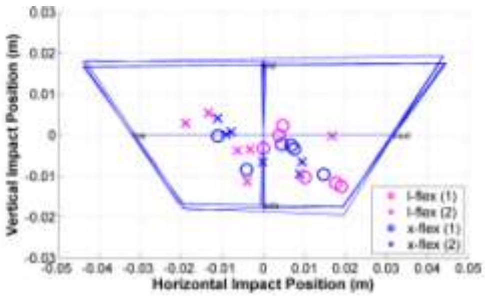

Player 11:



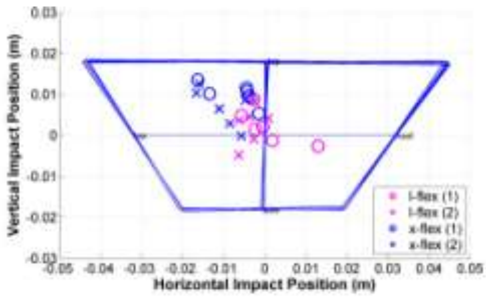

Player 12:



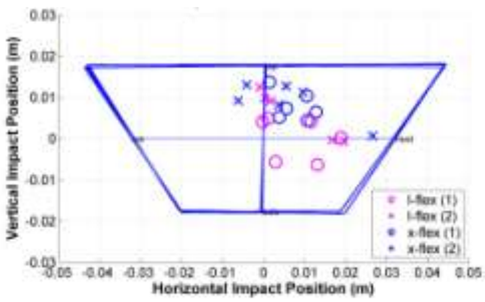
Player 13:



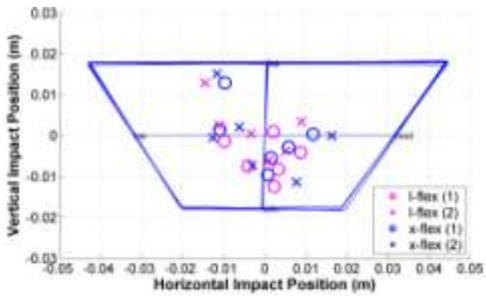

Player 14:



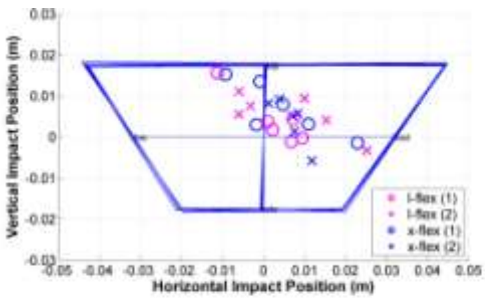

Player 15:



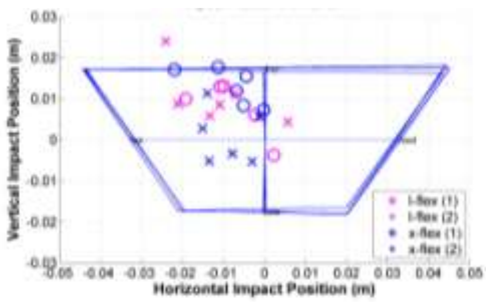

Player 16:



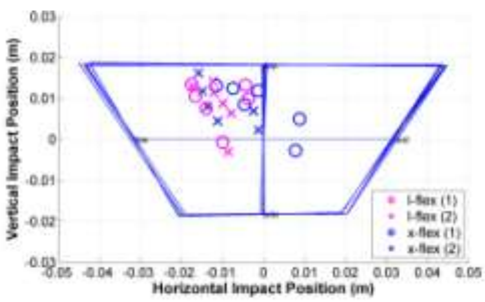

Player 17:



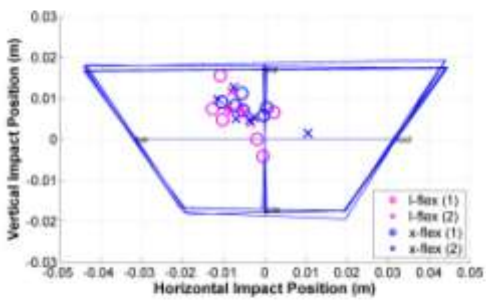

Player 18:




Player 19:



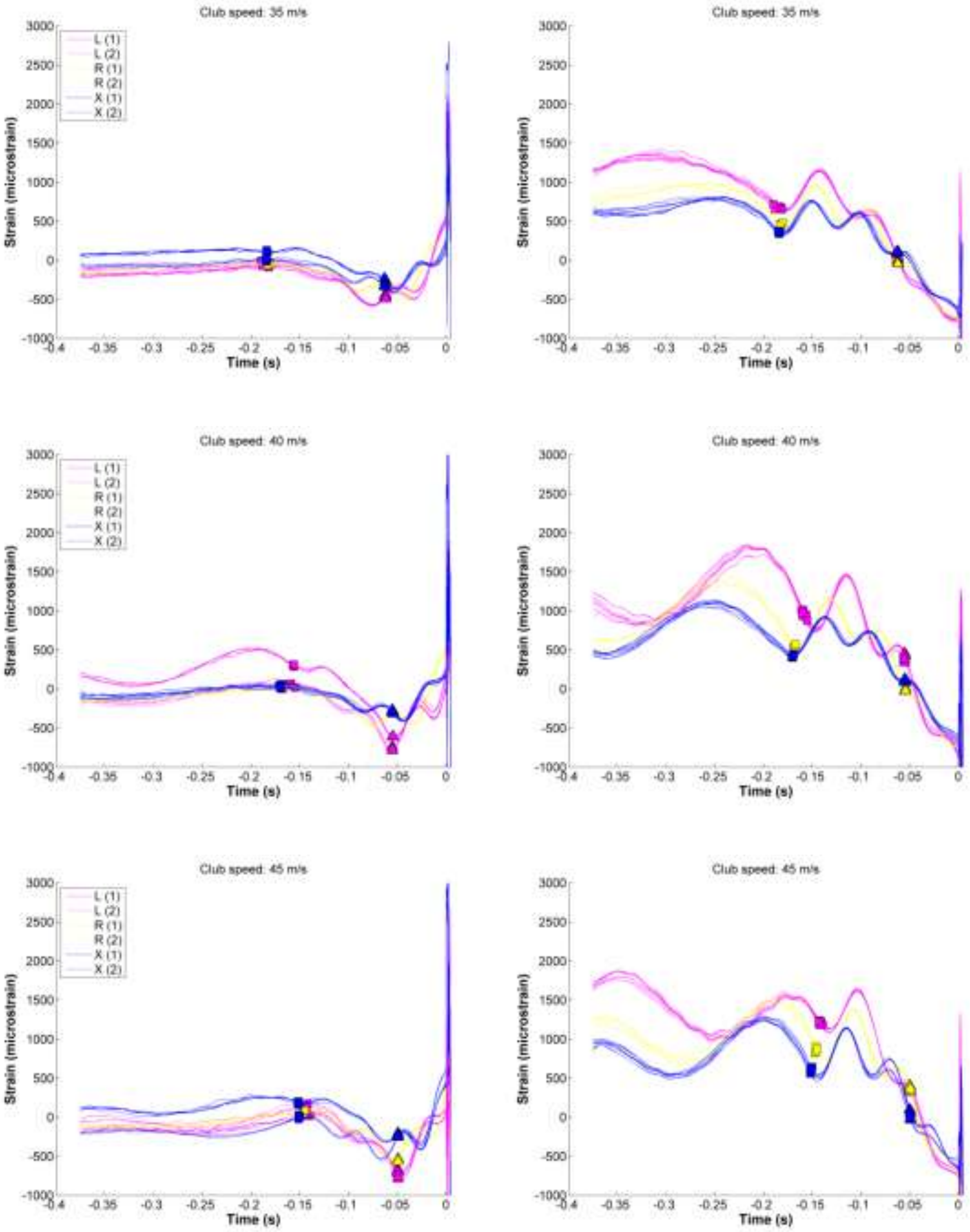

Player 20:

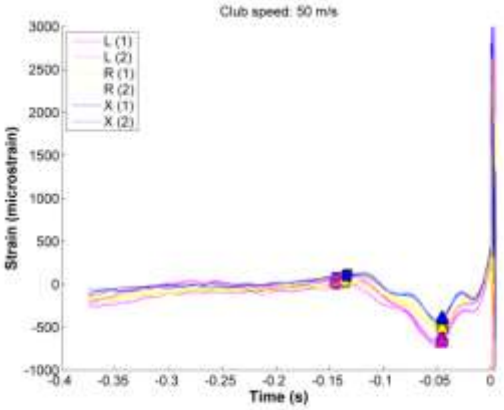


## *I. Strain results Study 3*

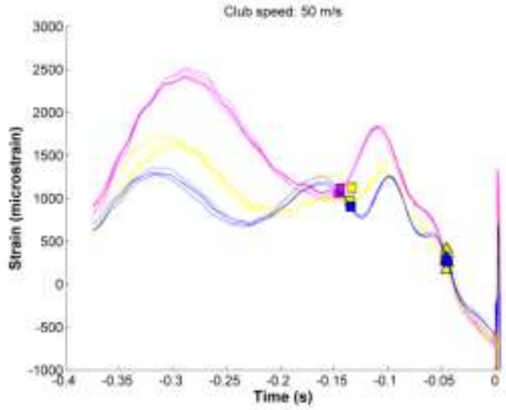
Events: Wrist release (△) and club-horizontal (☐).

Left column: lead/lag strain; right column: toe up/down strain.





Club speed: 50 m/s
L (1)
L (2)
R (1)
R (2)
X (1)
X (2)
Strain (microstrain)
Time (s)

Club speed: 50 m/s
Strain (microstrain)
Time (s)

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