INTERIM REPORT: STUDY OF SPIN GENERATION

7th August 2006

1. SUMMARY

The dynamics of oblique impact between the golf ball and club head are complex and have been the subject of investigation by the ruling bodies for a long time. However, recent work on the behaviour of the golf ball in particular has extended the knowledge of the ruling bodies considerably. This understanding has prompted a thorough review of the effect of club head face treatments and how they have evolved since the common use of V-shaped grooves.

A series of player tests were recently conducted in order to provide a benchmark of performance from various lies under playing conditions. Starting with un-grooved muscle back forged heads, the USGA fabricated two sets of irons, one having traditional V-shaped grooves and the other having U-grooves with dimensions that would be considered at the limit of conformance. The playing properties of the clubs were otherwise identical. Additionally, balls were selected that were representative of the modern era and the era prior to the common use of U-grooves. Players hit shots from both clean, dry lies and from the rough. Data on the club head presentation and the ball launch were collected.

It is clear from the player data that the configuration of modern club faces has significant performance improvements over the traditional V-shaped groove in grassy lies. For some lofts, it was found that spin using the U-groove club in the rough was actually higher than from a clean lie.

The player data and the equipment used for the player testing was next used in the laboratory to establish that two different materials could be used to mimic the effect of grassy lies on the impact between the club and the ball. Using real grass in the laboratory is not feasible given the number of tests that are planned. Therefore, the use of these grass surrogates permits the ruling bodies to efficiently and in a repeatable manner conduct oblique impact experiments.

Previous work by the ruling bodies has established that the performance of face treatments of club heads can be reasonably described by a number of parameters such as groove shape, edge radius, width, depth, spacing and land area roughness. In order to better understand how each of these factors affects the performance of the club face, a series of test plates has been designed and fabricated. Using wire electrical discharge machining (EDM), seventy test plates were created. Each of these plates will be tested at a variety of angles using both grass surrogate materials.

Thus far, the basic groove shapes have been tested along with the traditional V-shaped groove and a U-shaped groove with groove parameters at the conformance limit. The results of the testing thus far have confirmed the player test observations. The basic groove shape plates will also be tested with a number of different ball constructions in order to evaluate the effect of those properties on conclusions about club face parameters; this will ensure that spin generation is well understood for ball/groove combinations. The use of modelling here will be extremely valuable.

In addition to the experimental work, various models will be used to provide a framework for interpreting the results of the plate impacts. Also, it is recognised that the launch of the ball is only a portion of the golf shot. Therefore, studies on the aerodynamics and trajectories of iron shots, as well as the bounce and roll behaviour upon impact with the turf, will be undertaken.

Finally, it is envisioned that conclusions reached on the performance of the various face treatments under laboratory conditions will be tested with a subsequent set of player testing.

2. INTRODUCTION

A significant component of the mandate of the technical staff for golf's ruling bodies is to undertake basic research studies on the mechanics and dynamics of the game. One aspect of particular interest is the oblique impact between lofted clubs and the ball under clean and grassy conditions. This topic received considerable attention in the late 1980's.

Recently both experimental and analytical works have been undertaken to advance the ruling body's understanding of the behaviour of the golf ball in oblique impacts. In order to extend this work to include the effect of the face treatments of club heads, a comprehensive study has been initiated. This study is intended to build upon previous work on the subject and to establish a thorough understanding of how such face treatments affect the launch of the ball and from that, the trajectory and bounce behaviour on impact with the turf.

3. PROJECT OUTLINE

The project is comprised of five main components:

- Field Benchmark performance testing ***(completed)***
- Establishment of a surrogate (or surrogates) for grass ***(completed)***
- Face treatment performance testing ***(in progress)***
- Study the effect of face treatment performance on shot trajectory and landing behaviour
- Confirm laboratory testing with field testing

3.1. Field Benchmark Performance Testing

Before embarking on a full study of such face treatments it was necessary to determine if indeed the modern clubs have significantly improved performance compared to V-shaped grooves and standard sand blasted faces. To that end, a field testing program using professional golfers was carried out. Generally, that study covered player testing using a range of iron lofts with:

- V-groove, sandblasted face, balata covered wound balls

- U-groove, sandblasted and/or milled face with modern tour ball
- No groove, light sandblasted face (in order to establish the performance of an "extreme" limit)

The performance from both clean and grassy lies was established.

3.2. Establishing a Grass Surrogate

The use of actual grass to test face treatments in the lab is impractical. Therefore, grass substitute mediums have been established. The clubs used for the player field testing were fixtured in the lab and a variety of moistened papers and fabrics were placed on the club face. The balls used for the field testing were then fired at the club heads and the resulting launch conditions were compared to the field results. Two media were selected that enveloped the player results. These media permit efficient and repeatable testing of the face treatments.

3.3. Face Treatment Performance Testing

Considerable work by the USGA has been previously conducted on the effect of some different face treatment design parameters. The observations made in these previous studies were reviewed and provided the basis for a range of face treatments.

Four basic profiles were created, characterised by dimensions that are at or near the limits currently specified by the Rules of Golf. These include (all with moderately sandblasted faces):

- U-groove (90° groove sidewalls), with 0.010" edge radius, 0.035" wide and 0.020" deep, 0.140" groove spacing
- V-groove (55° groove sidewalls), with 0.010" edge radius, 0.035" wide and 0.020" deep, 0.140" groove spacing
- Intermediate groove (65° groove sidewalls), with 0.010" edge radius, 0.035" wide and 0.020" deep, 0.140" groove spacing
- Intermediate groove (75° groove sidewalls), with 0.010" edge radius, 0.035" wide and 0.020" deep, 0.140" groove spacing

The design parameters of the basis profiles were then varied in a systematic manner such that the effect of each parameter was isolated. The parameters studied are shown schematically in Figure 3.1. As a result of modifying each of the design parameters independently, 70 individual plate designs were developed. Wire EDM was used to create these profiles. The plate designs are given in Appendix E.

Each of the plates has been, or soon will be, tested at four angles with two types of grass surrogate media. Impact speeds were set to be consistent with the impact angle.

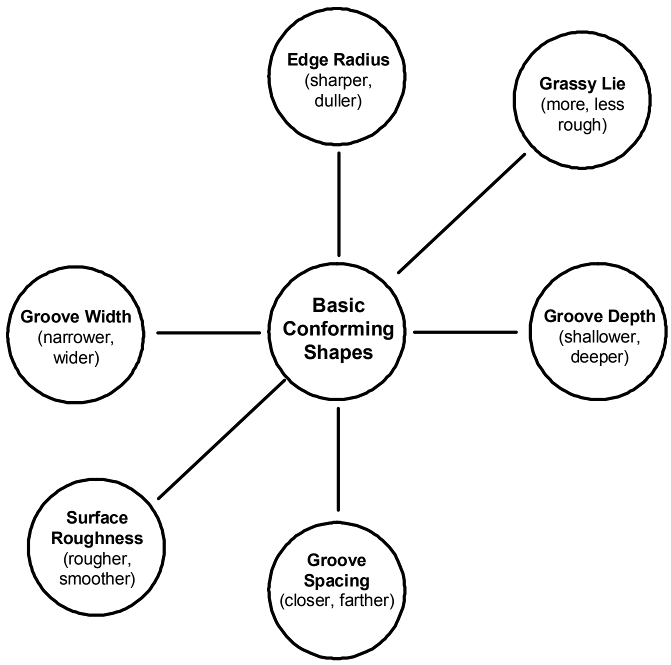


Figure 3.1: Plate testing experimental parameters

3.4. Evaluation of Face Treatment Specification Parameters

Upon completion of the testing of the face treatments, various conclusions will be made about the effectiveness of the range of face treatments. These conclusions will then be verified with additional test plates and by player testing with procedures similar to those followed for the field benchmark process.

3.4.1. Ball Aerodynamics and Turf Impact

The result of the face treatments on the launch conditions will affect both the ball flight trajectory and the resulting bounce and roll on the turf. Studies of both ball aerodynamics for iron trajectories and the subsequent impact with the turf are ongoing.

3.5. Consideration of Additional Ball Types

Previous research has been conducted considering the properties of the ball on oblique impact. Briefly, this has comprised quantifying the effects of grooved versus un-grooved and roughened versus smooth plates on the spin magnitudes of different types of golf ball at different angles of incidence (loft) and velocity. Generally, and in line with many other studies, it has been found that ball construction dominates frictional behaviour, quantified through spin.

The aim of this portion of the project is to test the plates described above with different types of solid golf balls, encompassing the full range of construction types.

3.6. Project Overview

Figure 3.2 shows schematically the project tasks.

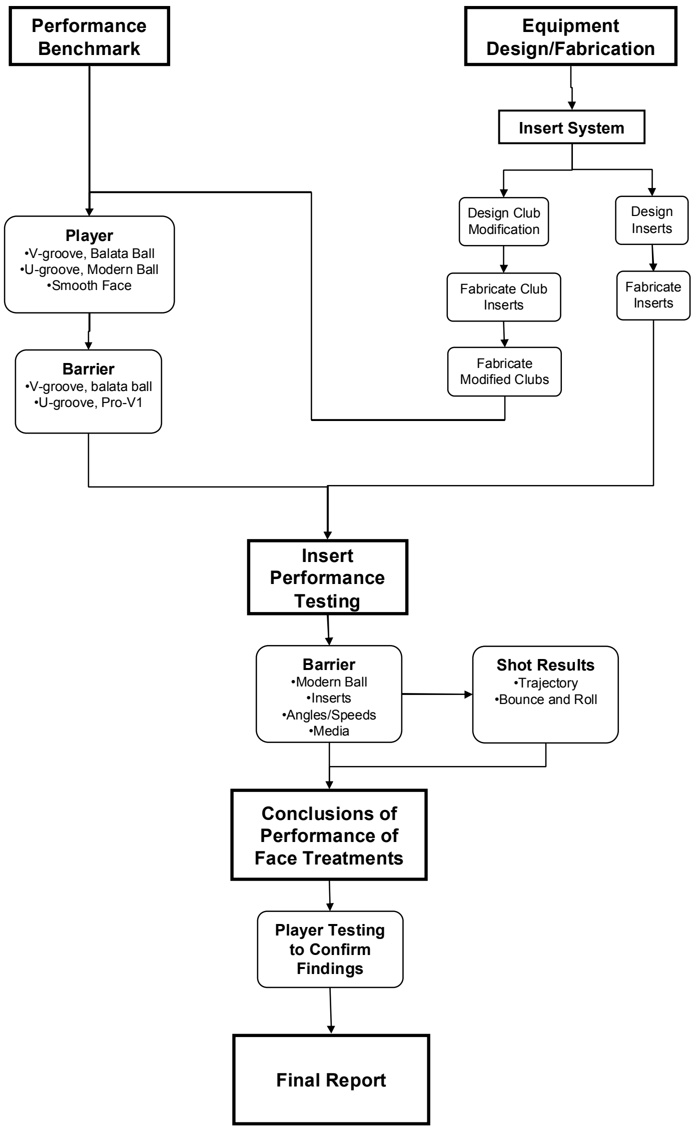


Figure 3.2: Project flowchart

4. PLAYER TESTING

The objective of the player testing was to obtain launch conditions using equipment representative of today's conformance limits and that of the period prior to the common use of U-grooves from a variety of lies.

Three sets of clubs (comprised of 5 and 8 irons and a sand wedge) were produced with grooves representative of the two eras of interest. Balls typical of those two periods were also selected based on a previous study (see Section 4.1.4). A third set of irons was used having no grooves (but with typical sandblasted face roughness) to provide an indication of the practical limit of groove specifications. Impact conditions, determined using high speed video, and the launch conditions, measured by a radar tracking unit, were obtained from both fairway and light rough lies. Appendix A contains a full report on the player testing.

4.1. Equipment Used

4.1.1. Clubs

Grooveless, forged, muscle back blades were provided by Cleveland Golf (CG1 for the 5 and 8 irons, Tour Action 900 56° sand wedge). All subsequent modifications to these heads were performed by the USGA and the R&A. The club heads were mounted in a computer controlled mill and a shallow pocket was machined into the face of each iron. Matching U-groove and V-groove inserts were then bonded into the pockets using an acrylic epoxy. Finally, the face of the club was abrasive blasted to provide a nominal surface roughness (see Section 4.1.3).

The specifications for the finished irons are given in Table 4.1.

Table 4.1: Player Test Club Finished Specifications

Club	Loft	Lie	Length	Swing Weight
5 Iron	29°	61°	38"	D-2
8 Iron	38°	63°	36.5"	D-1
SW	56°	65°	35"	D-3

4.1.2. Club Inserts

Wire electrical discharge machining (EDM) was used to produce inserts for the pocketed club heads. This method was chosen as it provided extremely accurate groove profiles without the need to produce a cutting tool. The U and V groove specifications are shown in Figures 4.1 and 4.2.

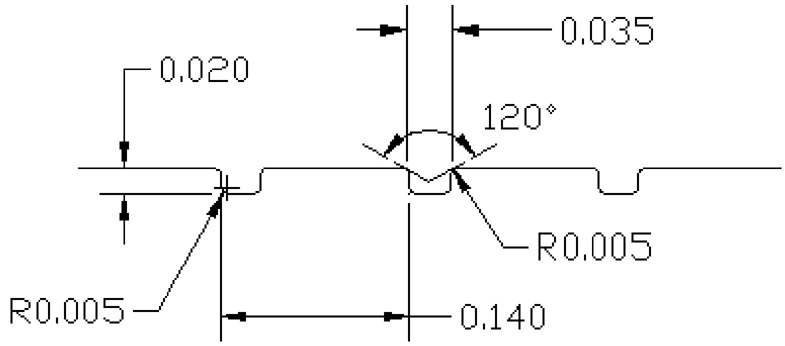


Figure 4.1: U-groove specification (all dimensions in inches and angles in degrees)

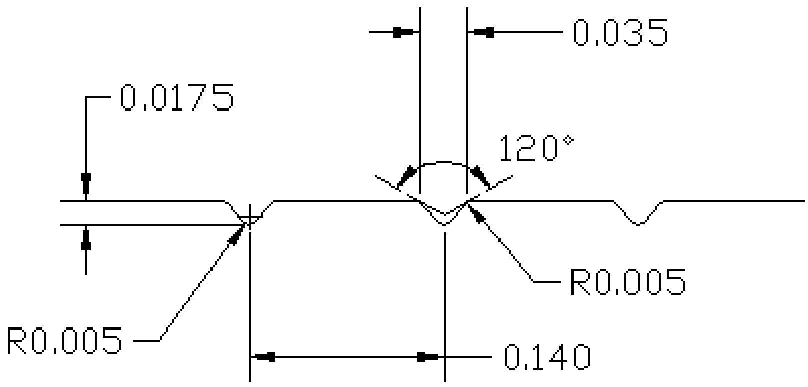


Figure 4.2: V-groove specification (all dimensions in inches and angles in degrees)

An image of the raw, pocketed and finished clubs is shown in Figure 4.3.

Figure 4.3: Groove-less, pocketed and finished club head

4.1.3. Abrasive Blasting

In order to provide predictable and consistent surface roughness by abrasive blasting, a brief study was conducted to investigate the effects of blasting media and blasting time on surface roughness. In order to minimise operator influence, the outlet of the spray gun was set at 24” from the target. This ensured uniform coverage over the target without manipulating the gun. Figure 4.4 shows schematically the experimental setup.

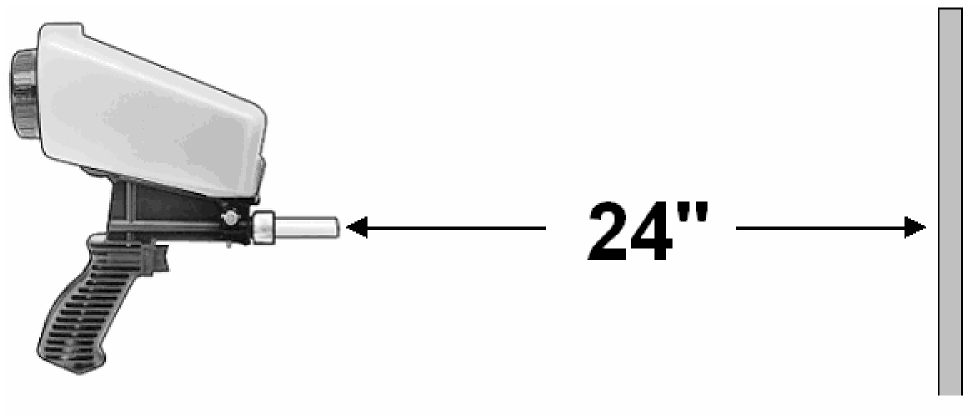


Figure 4.4: Abrasive blasting schematic

Aluminium oxide media in four grit sizes (36, 60, 80 and 180) along with slag having particles in the range of 20-40 mesh were tested. Two target materials, soft 304 stainless and harder 17-4 stainless were used. Blasting times of 10, 30 and 60 seconds were used. The surface roughness (Ra) of the plates was measured after blasting. The results are shown in Figure 4.5. It can be seen that the grit size can be used effectively to obtain the desired surface roughness value.

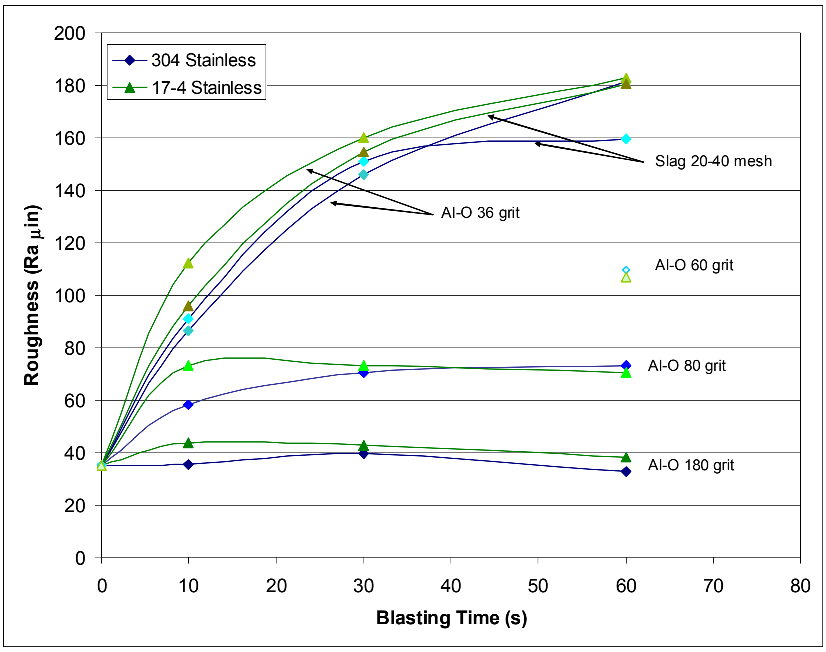


Figure 4.5: Abrasive blasting results

For the player test clubs, 60 grit aluminium oxide was used with a 40 second blasting time, resulting in surface roughness (Ra) of approximately 100 μin. A summary report on the abrasive blasting study is included in Appendix D.

4.1.4. Ball Selection For Player Testing

The objective of the player testing portion of the project was to obtain launch conditions for equipment representative of today's conformance limits and that of the period prior to the common use of U-grooves. To that end, it was necessary to select balls of that represent the performance of these two periods.

The selection of a modern ball was made on the basis of current tour usage. The choice of a ball representative of the period prior to the common use of U-grooves however was somewhat more difficult.

It is well understood that the performance of golf balls degrades over time, especially those of liquid centre, wound construction. Therefore, a study was conducted to quantify this degradation. Data from the 1987 groove study was used as the basis for performance in the period prior to the common use of U-grooves. The same balls used in the study (Titleist Tour 384) were retested and the two results were compared. In addition, newer (but not new) wound, liquid centre balls (Titleist Tour Balata 100) were tested (of which the ruling bodies have a reasonably quantity).

It was found that at high loft angles, the spin and normal direction coefficient of restitution of the original study balls had degraded only modestly. However, at lower lofts more significant degradation was observed. The newer wound balls however, somewhat mitigated this performance degradation. Spins at the various test conditions ranged from 17% lower to 5% higher than the spins measured in the 1987 study. It was concluded therefore, that the newer Titleist Tour Balata 100 was the best choice of balls with which to obtain representative launch conditions from the period prior to the common use of U-Grooves. A report on the ball selection study is included in Appendix C.

4.2. Player Test Methodology

The testing was performed by six touring professional golfers. Each player was asked to hit shots from two different lies; one representing a fairway lie (where there is no grass/debris between the clubface and ball, hereafter referred to as the dry condition) and another from light rough (where there is grass between the clubface and ball, hereafter referred to as the wet condition) using both the modern ball/groove configuration and the ball/groove combination representative of the period prior to the common use of U-grooves. All three lofts for both ball/club combinations were tested. The players were also asked to hit shots using the modern club/ball combination with a wet paper interface on the clubface.

Figure 4.6 shows a typical lie in the Bermuda grass rough.

Figure 4.6: Typical lie in the rough

4.2.1. Player Test Procedure

Steps were taken in order to minimise the effect of player fatigue on the results. These include randomising of the club/ball order and alternating starting lies from player to player. For each test condition (lie, ball/groove combination, loft), the following procedure was followed:

1) The ball was placed in the predetermined lie.
2) The player was provided a target (for direction only.)
3) The player struck the ball with the predetermined club, groove profile and ball type.
4) The radar was used to track the launch and the resulting trajectory.
5) The high speed video, using an audio trigger, was used to capture the incoming club trajectory and the initial ball launch.

4.3. Player Test Results

It was found that the results from individual players were similar enough from player to player to justify using average results of the six players in subsequent portions of the study. Figure 4.7 shows the average results for the two ball/groove combinations in both the dry and the rough.

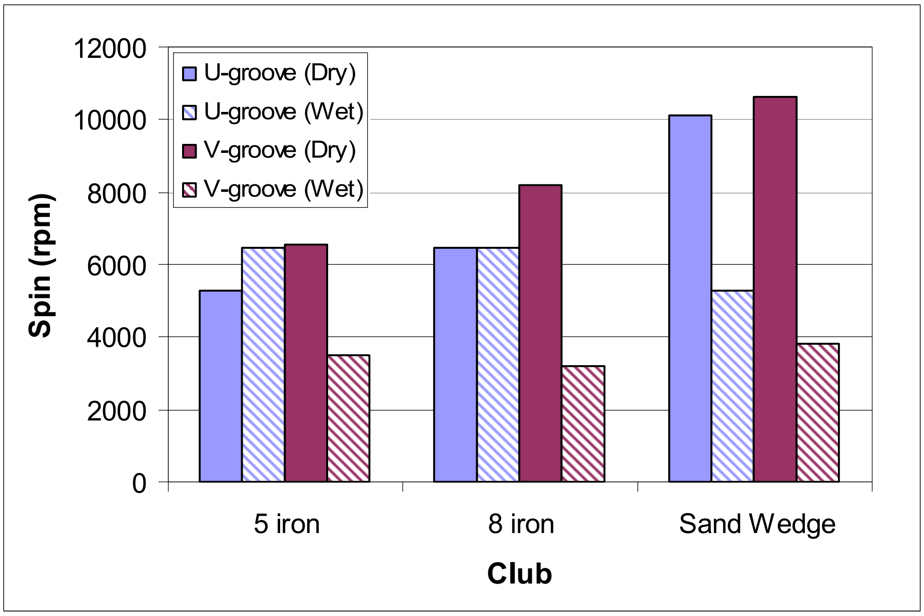


Figure 4.7: Average player results

Figure 4.7 reveals three important results. First, in the dry the balata ball/V-groove combination spins more than the modern combination at all lofts. Second is that the modern ball/U-groove combination spins more out of the rough lie then the balata ball/V-groove combination at all lofts. Finally, it can be seen that the modern equipment has the potential to actually spin more out of the rough than from a dry lie. This last result, whilst being somewhat counterintuitive is well predicted by various models and will be discussed later in this report.

In addition to the grooved clubs, grooveless clubs where also tested using the modern ball from the rough lie. The results are shown in Figure 4.8 along with the grooved club results.

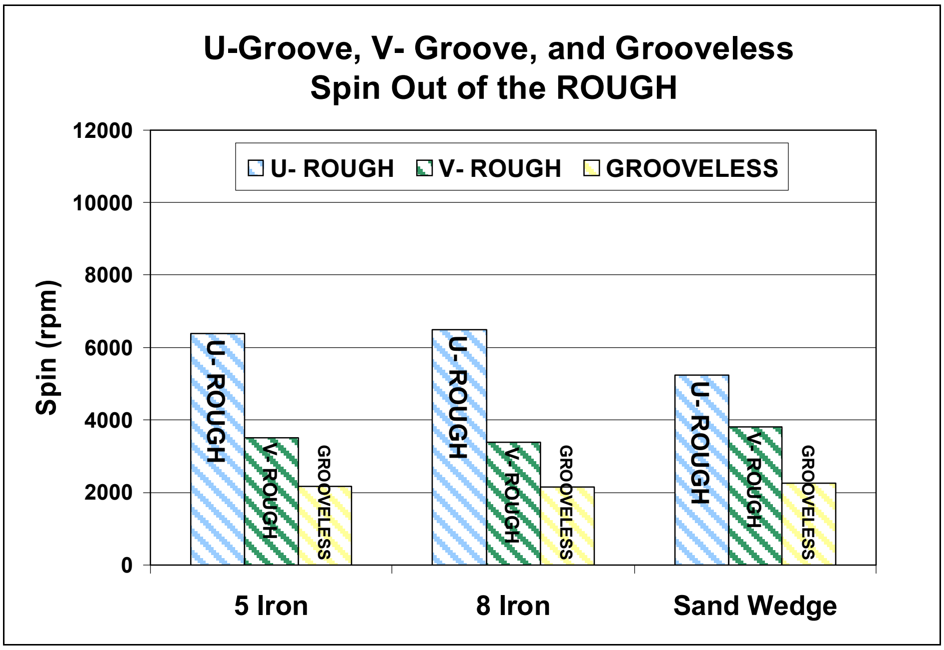


Figure 4.8: Average player results from rough lie (U-groove, V-groove, groove-less clubs)

It can be seen in Figure 4.8 that the performance of the V-groove is only a modest improvement over no grooves at all whereas the U-groove offers a substantial improvement over both the grooveless and the V-groove clubs. A full report of the player testing, including further details on the data collection system and tabulated results is included in Appendix A.

5. Establishing a Surrogate Material for Grass

The use of actual grass as a test media for laboratory investigations has been shown to be difficult to maintain consistency over time. It is therefore necessary to identify a suitable replacement that behaves in a similar manner and that attempts to capture some of the important impact phenomena observed when testing in grassy conditions. To that end, a number of interfacial materials were tested using the U and V groove clubs from the player testing.

5.1. Test Equipment

As with the player testing, the pre-1990 ball club combination (V-groove irons with the Titleist Tour Balata) and the modern ball club combination (U-groove irons with the Titleist Pro V1 392) were tested.

For the testing, the shafted test club was mounted in a test fixture (Figure 5.1) that held the club at the grip. During set-up for each club, the fixture was rotated to the correct lie angle. In addition the fixture was pivoted to obtain the impact loft angle that was measured for each club during player testing (including de-lofting). The appropriate golf balls were fired at the fixtured clubs at impact speeds equivalent to those measured for each club during player testing. The pre- and post- impact ball speed, angle and spin rate were measured and recorded for each shot.

Figure 5.1: Test set up for grass surrogate investigation

5.2. Candidate Materials

A total of seven candidate material configurations were evaluated, these are listed in Table 5.1.

Table 5.1: Candidate Grass Surrogates

Candidate Surrogate Material	Description
Wet Newsprint	Standard newsprint soaked in water
Wet Fabric	Dupont Sontara EC (PR821) spunlaced fabric soaked in water
Wet Tissue	Tissue paper soaked in water
Wet Slitted Newsprint	Standard newsprint with a series of 3/16" wide slits soaked in water
Slitted Wet Fabric	Dupont Sontara EC (PR821) spunlaced fabric with a series of 3/16" wide slits soaked in water
2 Drop Slitted Newsprint	Standard newsprint with a series of 3/16" wide slits moistened with two drops of water
2 Drop Tissue	Tissue paper moistened with two drops of water

5.3. Results

It was found that two materials, the wet newsprint and the wet, slitted fabric (Dupont Sontara EC) provide an envelope around the measured, average player spin results from the rough: that is, the newsprint had resulting spins lower than or equal to the average player result for all clubs whereas the slitted fabric had spins greater than the average player results for all clubs. Since no one individual material matched the grass for all clubs, it was decided that future testing would be done with both media. The resulting spin values for the various clubs and materials are given in Figure 5.2.

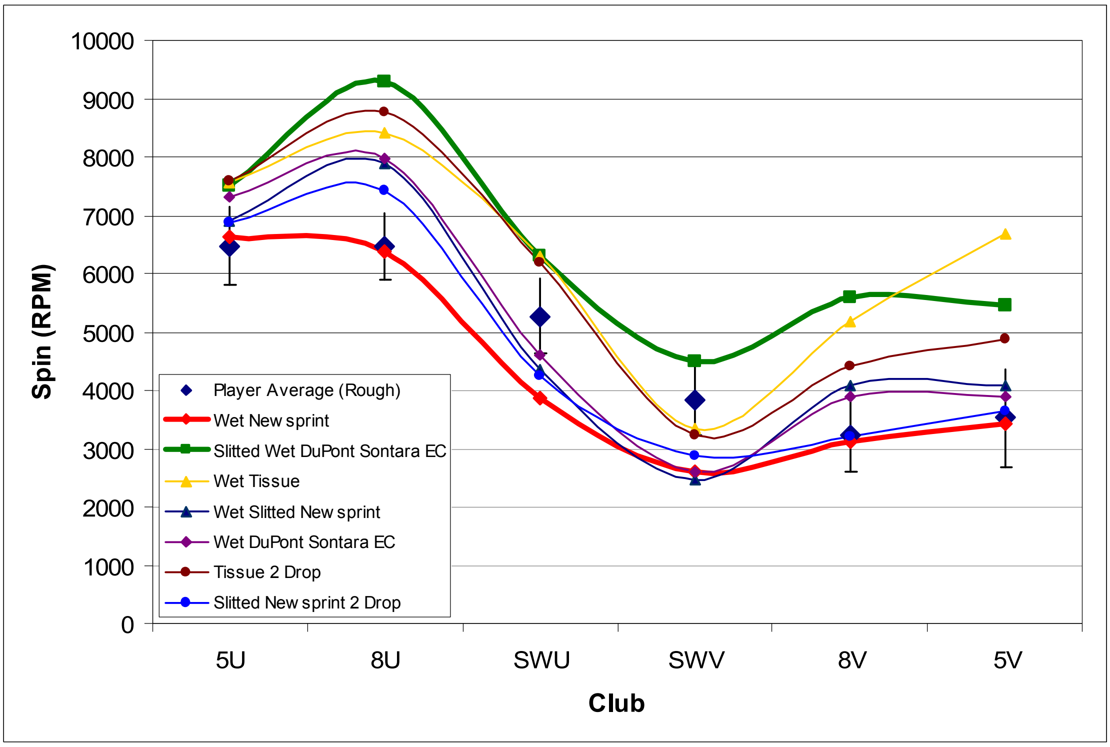


Figure 5.2: Results of various interface material configurations on spin

A report on the testing of grass surrogate materials is included in Appendix D.

6. Plate Testing Methodology

The objective of this portion of the project is to provide a broad assessment of the effects of the various grooves and face treatment parameters on spin in the presence of an interfacial material (representative of grassy lies). Seventy test plates were fabricated and are in the process of being tested at a range of angles.

6.1. Equipment

Plates were fabricated using the wire EDM method using 17-4 stainless steel in the annealed condition. The groove profiles and surface treatments are given in Appendix A. Figure 6.1 shows the cross section of the finished basis (B-series) plates. The wire EDM method has proven to be an excellent method of producing such plates because (i) the machining is highly accurate, (ii) individual cutters are not required for each groove profile and (iii) the required lead time from design to finished product is very short. In addition to the machining of the grooves, the faces of the plates were abrasive blasted or milled as indicated in Appendix E

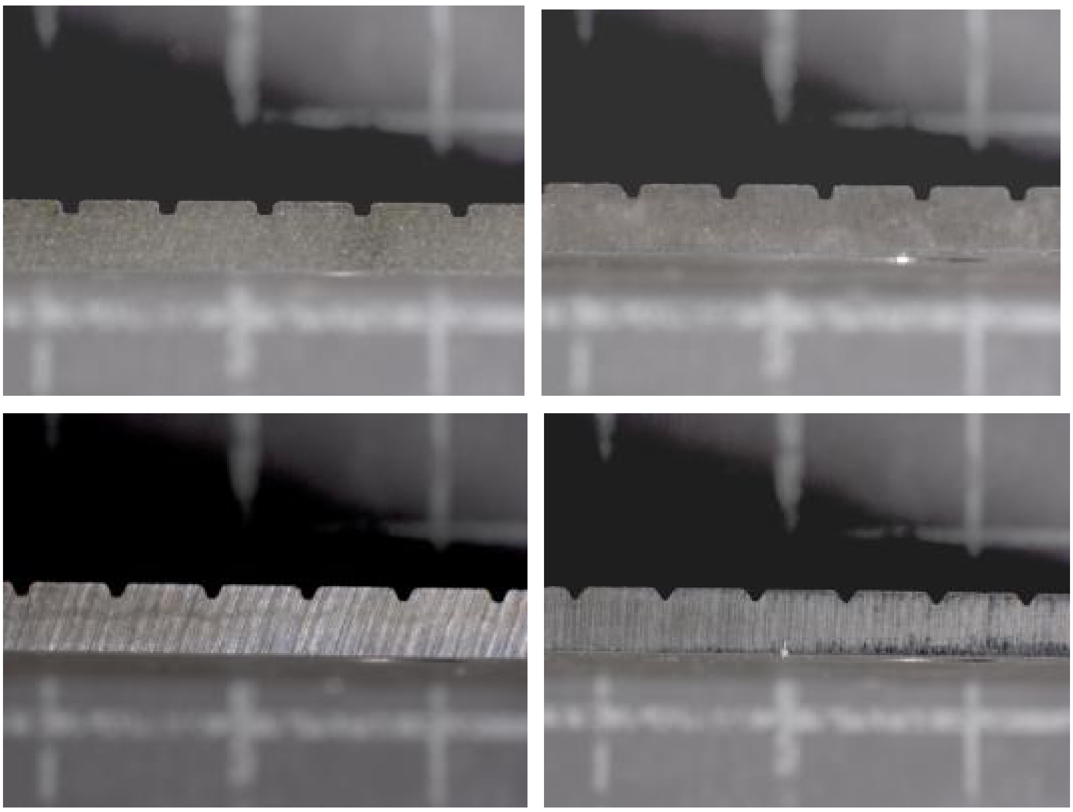


Figure 6.1: Cross section of grooved test plates (B-series shown)

All plates have six mounting holes that match holes in a base plate which in turn is affixed to a multi-axis force transducer (plate dimensions are given in Appendix F). This entire assembly is bolted to a large massive block attached to an adjustable angle machinists table. The force transducer permits the normal and tangential direction force time histories to be recorded. Figure 6.2 shows a typical plate installed on the transducer in an oblique orientation.

Figure 6.2: Grooved test plate oblique impact test setup

6.2. Impact Conditions

It is intended that the oblique impacts be representative of impacts in playing conditions. Specifically, the impact speed decreases with impact angle. Figure 6.3 shows the relationship between the plate loft angle and the inbound ball speed. The test protocol is included in Appendix G.

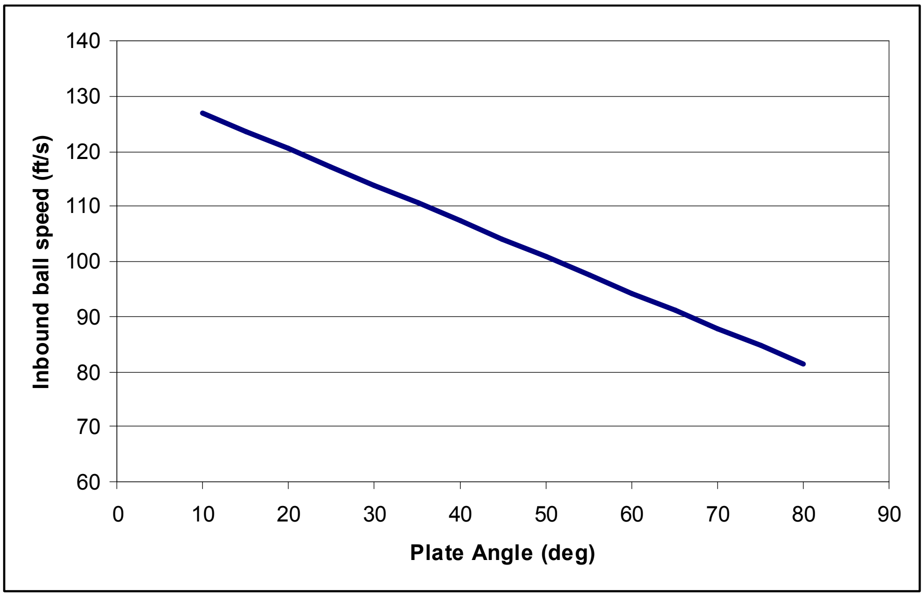


Figure 6.3: Inbound ball speed as a function of test plate angle

6.3. Data Collection

The inbound and outbound speed, angle and spin rate are captured using an automated camera system for every shot. At each test condition, shots are fired until the confidence interval for the mean of the spin rate is less than or equal to 300 revolutions per minute. Force time histories from the multi axis force transducer are captured for one impact at each test condition. An example of such a time history is shown in Figure 6.4 (for a plate loft angle of 60 degrees).

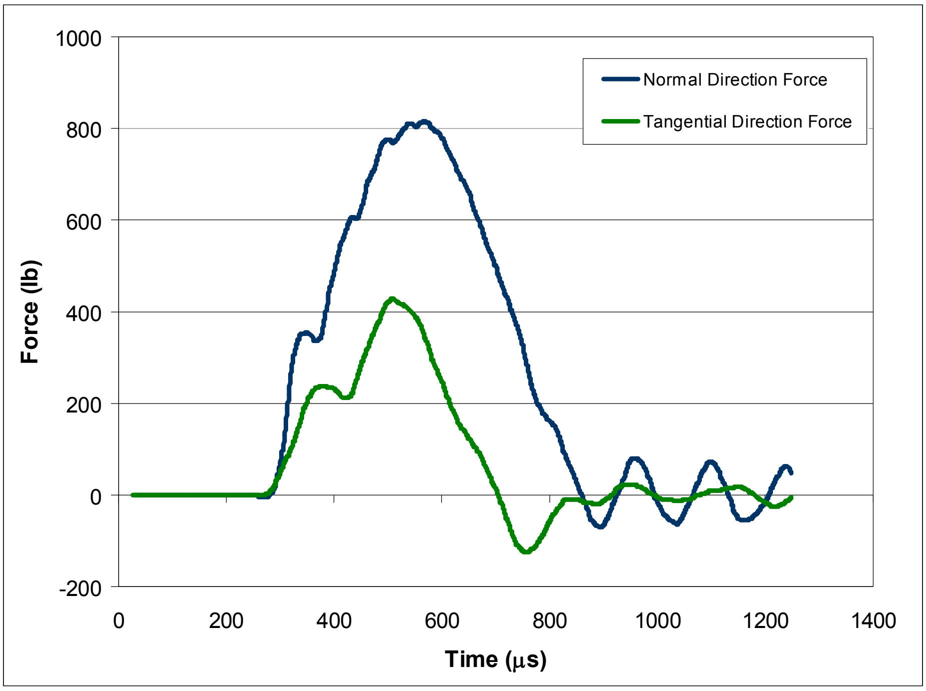


Figure 6.4: Example force time history (60 degree plate loft angle)

6.4. Ball Construction Type Testing

An initial study was conducted to determine which currently commercially available golf balls would enable the most comprehensive test protocol. Spin rates and Shore D hardness values were measured and used to summarise the differences in spin magnitude and material properties between the balls. All dynamic testing was undertaken on a grooved plate with surface roughness (R_a) = 40 µin, at 100 ft/s. Three loft angles were used, 40, 50 and 60°.

Generally, two, three and four piece balls will be considered, each with low, medium and high spin rates.

Figure 6.5 shows the approximate spin magnitudes of the eight balls selected following a dry impact with plate B100 at 100 ft/s at a loft angle of 60°.

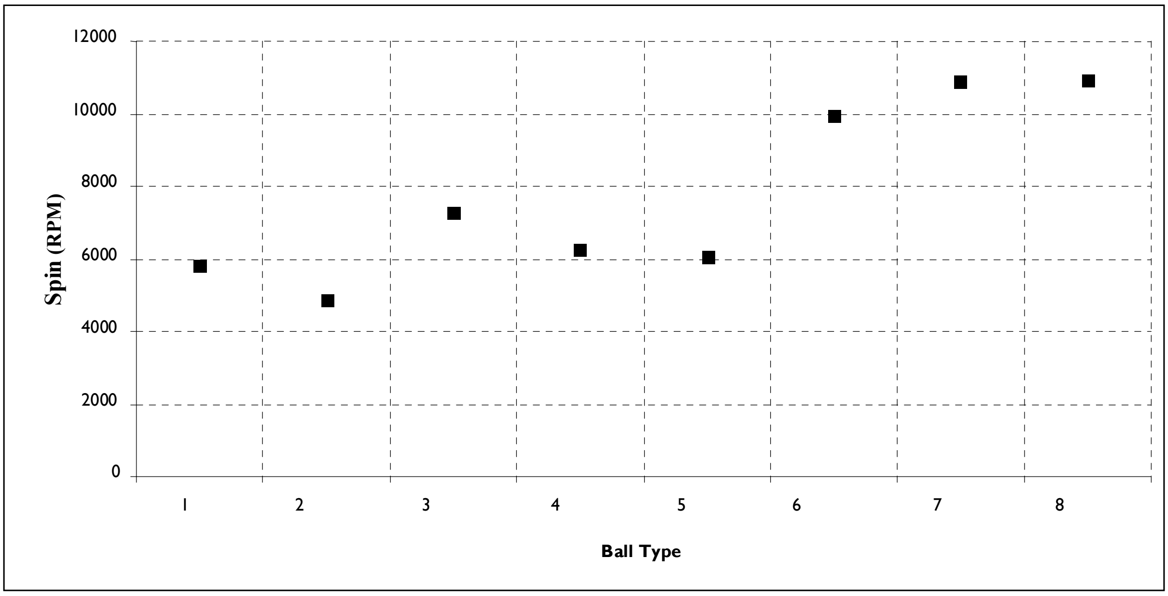


Figure 6.5: Spin as a function of ball type following impact with B100 grooved plate under dry conditions at 100 ft/s at a loft angle of 60°.

7. MODELLING

Modelling of oblique impact has been of special interest to golf's ruling bodies for some time. Efforts using finite element, lumped parameter and elasticity based formulations have been effectively used to understand the phenomena of oblique impact. It has been found that finite element analysis provides an extremely powerful tool for detailed analysis of impact behaviour, especially when coupled with advanced knowledge of rubber material constitutive models. However, the flexibility and efficiency of an elastic continuum based formulation such as that due to Maw (see Appendix I for reference information) has proven to be a valuable means of interpreting experimental data. A report on the use of this model for oblique impact of golf balls in included in Appendix I.

It should be noted that the use of the model is not intended to be a definitive explanation of the behaviour of the oblique impacts but rather as a basis of understanding the character of the response over the range of test conditions.

7.1. Model Parameters

The Maw model requires three inputs in addition to the mass properties of the ball. These are:

- Equivalent elastic modulus
- Dimensionless tangential behaviour parameter, χ
- Coefficient of friction (static and dynamic assumed to be the same)

The equivalent elastic modulus defines the contact time for the impact and so its value is obtained from the normal direction force time history. The other two parameters affect the tangential time history and the spin rate as a function of the impact angle. These two parameters were set to give the best fit of the spin rate over the range of tested angles in the dry condition. The parameters for the test ball are given in Table 7.1.

Table 7.1: Maw model parameters

Parameter	**Value**
Equivalent Elastic Modulus	110 MPa
Dimensionless Tangential Parameter, χ	1.35
Coefficient of Friction (Dry)	0.55

As a check of the parameters, force time histories of impacts at various angles (under dry conditions) were compared to the model predictions. A typical example of such a comparison is given in Figure 7.1.

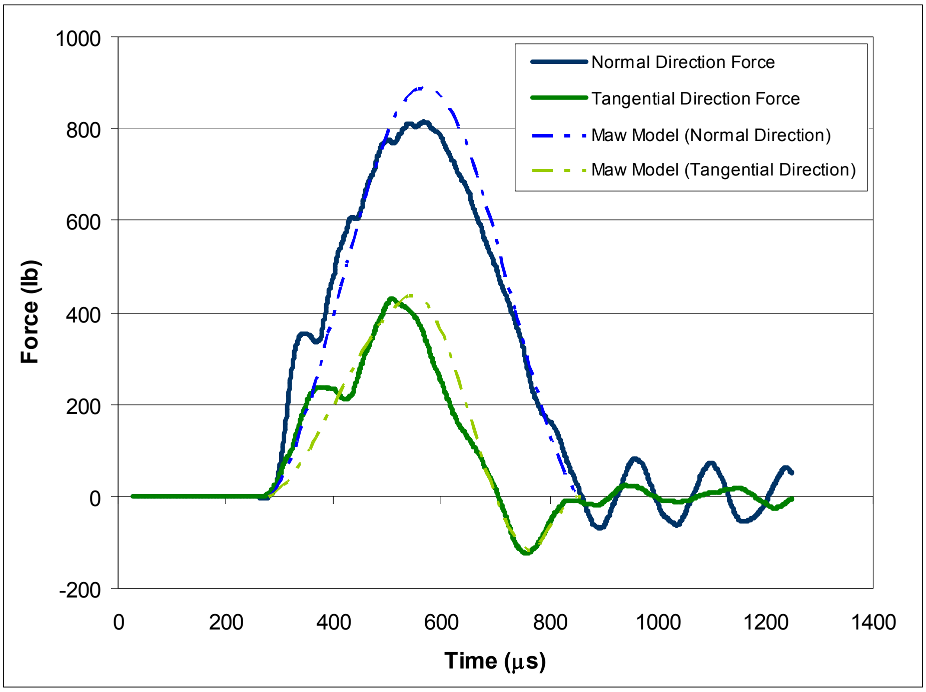


Figure 7.1: Typical comparison of measured and predicted force time histories (60 degree plate angle)

It can be seen in Figure 7.1 that there is very good agreement between the predicted and measured forces.

7.2. Effect of Coefficient of Friction on Test Ball Response

Having established reasonable model parameters for dry condition impact, the model was then used to study the effect of the coefficient of friction on the rebound. The coefficient of friction was varied from 0.025 up to 0.55 (the dry condition friction coefficient). The relationship between plate loft angle and inbound ball speed given in Figure 6.3 was used in the model inputs. The results of the effect of the friction coefficient are presented in Figure 7.2.

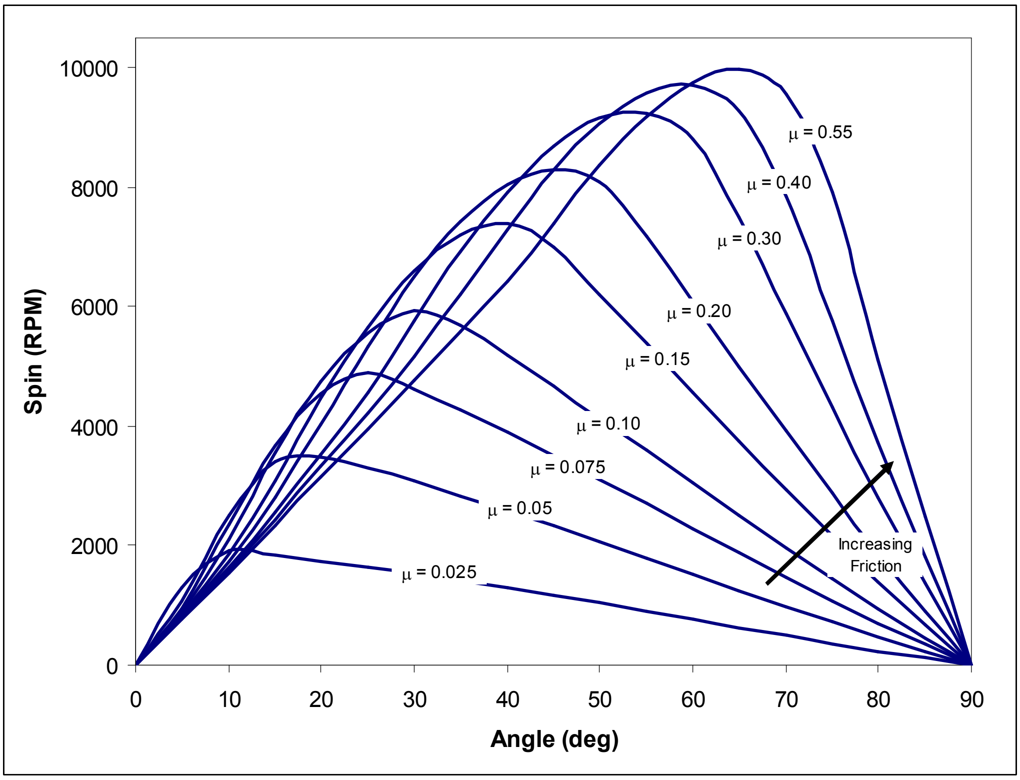


Figure 7.2: Effect of coefficient of friction on spin rate using Maw model

Several important observations can be made from Figure 7.2. These include:

- The maximum spin rate and the angle at which that occurs depends heavily on the coefficient of friction
- Often, reducing the friction can actually lead to greater spin
- Spin does not uniquely specify the coefficient of friction
- In order to make meaningful observations of the effect of friction on spin, a range of impact angles must be tested

8. Interim Plate Testing Results

To date testing has been completed on the basis plates as well as groove configurations that would be considered at the current limit of conformance. The results of the remaining plates will be presented later, as will the results of the additional ball constructions.

8.1. Dry Conditions

Previous testing has shown that the groove configuration and face treatment make little difference to the dry rebound. Therefore, only the base U and V groove plates (B100 and B400 respectively) were tested in the dry condition. The resulting spin as a function of plate angle is shown in Figure 8.1. It can be seen that the results from the two plates are indistinguishable.

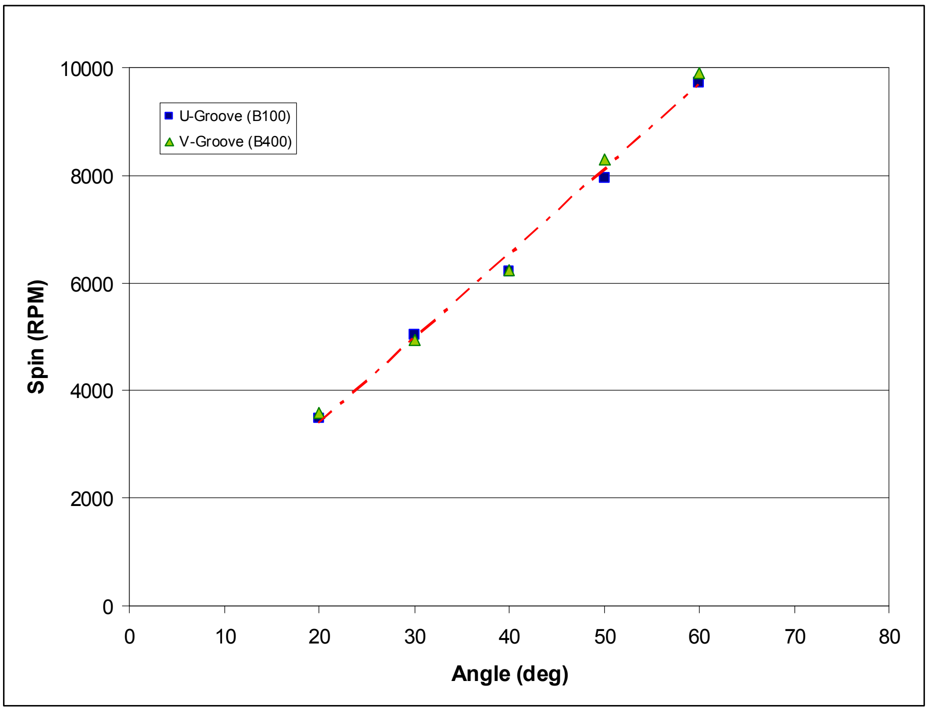


Figure 8.1: Spin rate in dry conditions (U and V groove plates)

Superimposing these test results on the model results presented in Figure 7.2 shows the good agreement between the experimental results and the model.

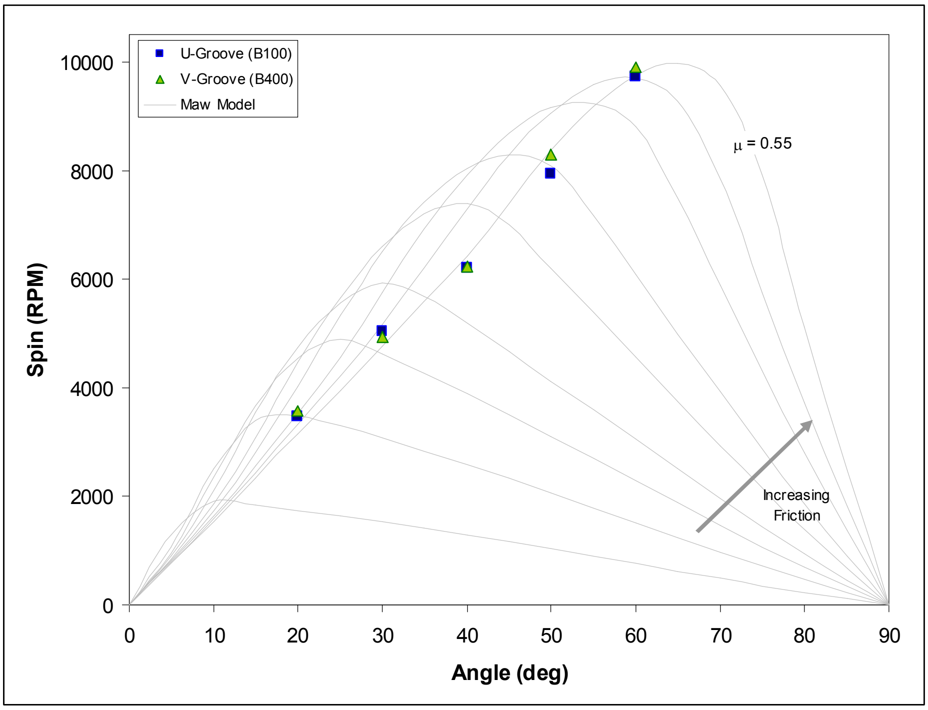


Figure 8.2: Comparison of spin rate in dry conditions (U and V groove plates) to Maw model

8.2. Impact in the Presence of Interfacial Material

To date, testing using the two grass surrogate media has been completed for the basis plates (B-series) comprising the U and V groove plates and two intermediate grooves (75 and 65 degree sidewall angles), all with 0.010" edge radius. Additionally, U and V groove plates having 0.005" edge radius (plates R102 and R402 respectively) have been tested.

The results of these tests are shown in Figures 8.3 (for the Dupont Sontara EC product) and 8.4 for the newsprint. As in Figure 8.2, the results are presented superimposed on the Maw model predictions for several coefficients of friction.

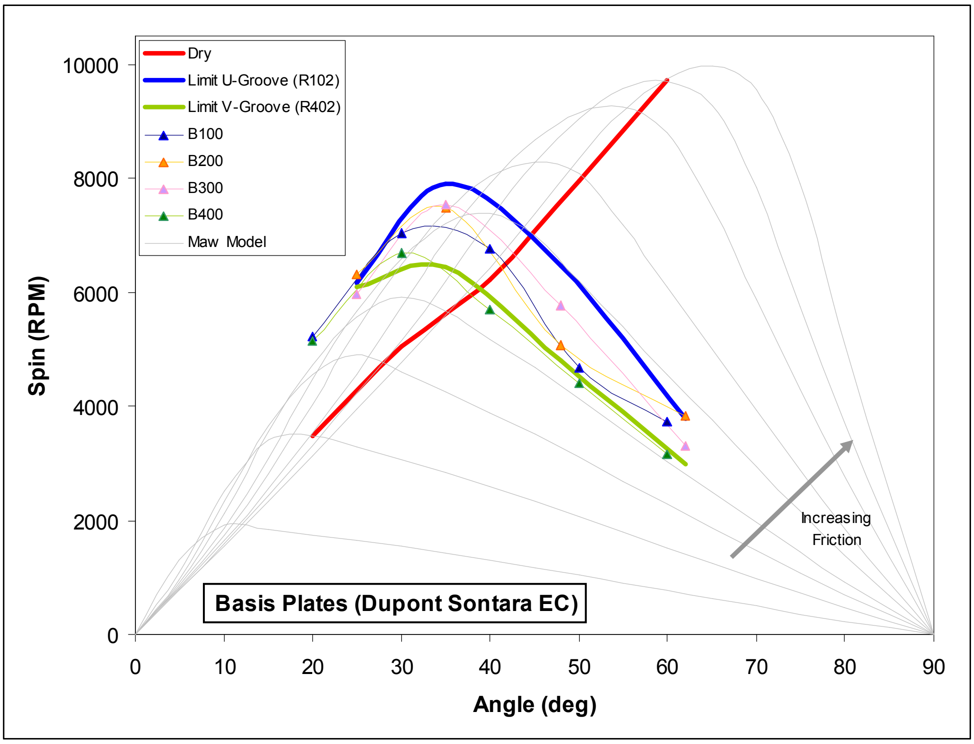


Figure 8.3: Plate testing with Dupont Sontara EC interface

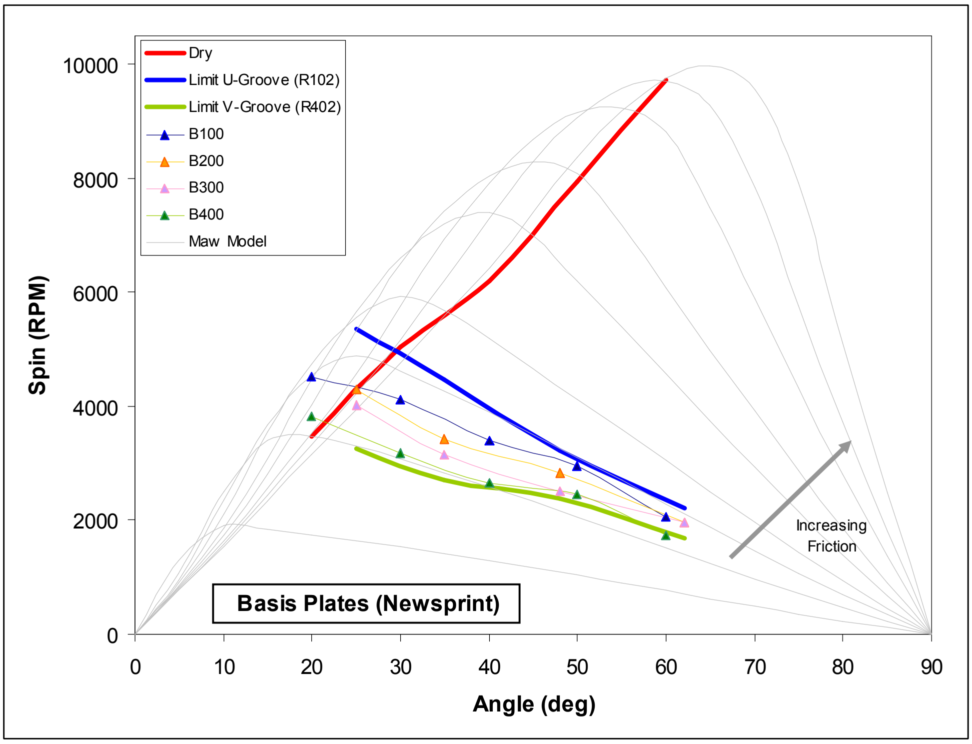


Figure 8.3: Plate testing with standard newsprint interface

A number of observations can be made from the results thus far:

- For both types of interfacial media, the U groove represents a significant performance improvement over the V groove
- For both media, the smaller 0.005" edge radius produces greater spin than the 0.010" radius for the U groove. The edge radius however, makes little or no difference to the V groove
- For all grooves, the Dupont Sontara has higher friction than the newsprint
- Consistent with the model and the player tests, at certain angles, the presence of an interfacial material actually increases spin

9. CONCLUSIONS

Player testing has confirmed that modern groove and face treatment specifications represent a significant performance improvement over more traditional V shaped grooves.

Two materials have been identified as suitable surrogates for grass to be used for laboratory testing on grooved plates. Seventy test plates have been fabricated using wire EDM to accurately efficiently produce the designed range of groove configurations.

The results of the impact performance of these grooved plates, along with trajectory and turf impact behaviour will be considered in the near future. Conclusions on these findings will be confirmed through subsequent player testing.

It is presently anticipated that the bulk of the project will be complete by the Autumn, 2006.

APPENDIX A

TOUR PLAYER TESTING
OF
PRE-1990 AND MODERN CLUB/BALL COMBINATIONS

5th June 2006

INTRODUCTION

The objective of the player testing was to obtain representative launch conditions using equipment representative of today's conformance limits and that of the period prior to the common use of U-grooves. It was a further objective to begin prescribing an experimental surrogate for grass.

Three sets of clubs (comprised of 5, 8 irons and a sand wedge) were produced with grooves representative of the two eras of interest. Balls typical of these two periods were also selected based on a previous study. A third set of irons was used having no grooves (but with typical face roughness) to provide an indication of the practical limit of groove specifications. Impact conditions, determined using high speed video, and the launch conditions, measured by a radar tracking unit, were obtained from a variety of lies, including fairway and light rough as well as a trial wet paper interface.

TEST EQUIPMENT

Three sets of equipment were used in the player testing. Each set contained a 5-iron, an 8-iron and a sand wedge. One set represented a pre-1990 club/ball combination, another modern club/ball combination, while the third set contained grooveless clubs in combination with a modern golf ball. The clubs used in all of the sets were forged muscle-back irons. These clubs were obtained from the manufacturer without grooves in the face. The faces were pocketed using a CNC mill to accept machined face inserts with the desired groove configurations and surface roughness. All sets were matched for length, lie and swingweight.

The pre-1990 set utilised V-grooved irons with wound, liquid centre balata covered golf balls. The Titleist Tour Balata was the golf ball chosen for this combination. It was selected because it had the required performance properties and there was a reasonable quantity on hand to support the testing. The groove configuration for the pre-1990 set was a V-groove with specifications typical of clubs from that era. Figure 1 shows the V-groove configuration.

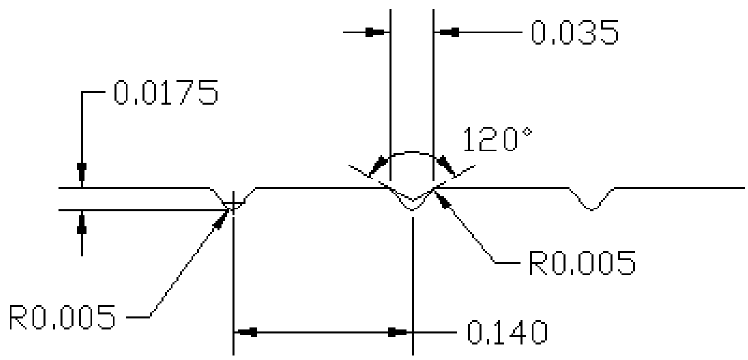


Figure 1 – V-groove Specifications

The modern set utilised U-grooved irons with solid, three piece urethane covered golf balls. The Titleist Pro V1 392 was the golf ball chosen for this combination. The groove configuration for the modern set was a U-groove with specifications at the limits allowed as specified in Appendix II of the Rules of Golf and typical of clubs used by modern Tour players. Figure 2 shows the U-groove configuration.

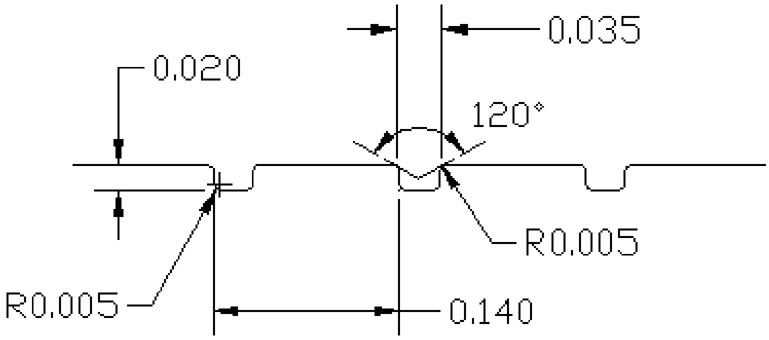


Figure 2 – U-groove Specifications

PLAYER TESTING METHODOLOGY

The testing was performed by six professional golfers. Each player was asked to hit shots from two different lies; one representing a fairway lie (where there is no grass/debris between the clubface and ball, hereafter referred to as the dry condition) and another from light rough (where there is grass between the clubface and ball, hereafter referred to as the wet condition) using each of the three club/ball combination sets. The players were also asked to hit shots using the modern club/ball combination with a wet paper interface on the clubface. The test set-up is shown in Figures 3a and 3b. Figure 4 shows a typical lie in light rough.

Figure 3a –Test Set-up

Figure 3b – Close-up of Test Set-up showing High Speed Video, Radar and Test Equipment

Figure 4 – Typical Lie in Light Rough

The testing was conducted using test conditions designed to randomise as much as possible the test variables while maintaining test efficiency. Table 1 shows an example of the randomised conditions.

Table 1: Sample of Randomised Test Conditions

Test #	Lie	Player	Club	Groove	Ball
1	Fairway	2	8 Iron	U	Pro V1
2	Fairway	1	Sand Wedge	U	Pro V1
3	Fairway	2	5 Iron	V	TB 100
4	Fairway	2	5 Iron	U	Pro V1
5	Fairway	2	8 Iron	V	TB 100
6	Fairway	1	5 Iron	U	Pro V1
7	Fairway	2	Sand Wedge	V	TB 100
8	Fairway	1	5 Iron	V	TB 100
9	Fairway	2	Sand Wedge	U	Pro V1
10	Fairway	1	Sand Wedge	V	TB 100
11	Fairway	1	8 Iron	U	Pro V1
12	Fairway	1	8 Iron	V	TB 100

For each test condition, the following procedure was used:

1. The ball was placed in the listed lie.
2. The player was provided a target (for direction only.)
3. The player struck the ball with the listed club, groove profile and ball type.
4. The radar was used to track the launch and the resulting trajectory.
5. The high speed video, using either a manual or automated trigger, was used to capture the incoming club trajectory and the initial ball launch.

This procedure was repeated for several shots in each condition. In total more than 600 shots were measured and recorded for the six players over two days of testing.

RESULTS - DETERMINATIONOF REPRESENTATIVE LAUNCH CONDITIONS

The measured launch conditions were relatively consistent across the six players, Figure 5. Because of this the average of the six players at each test condition could be used when analysing the data.

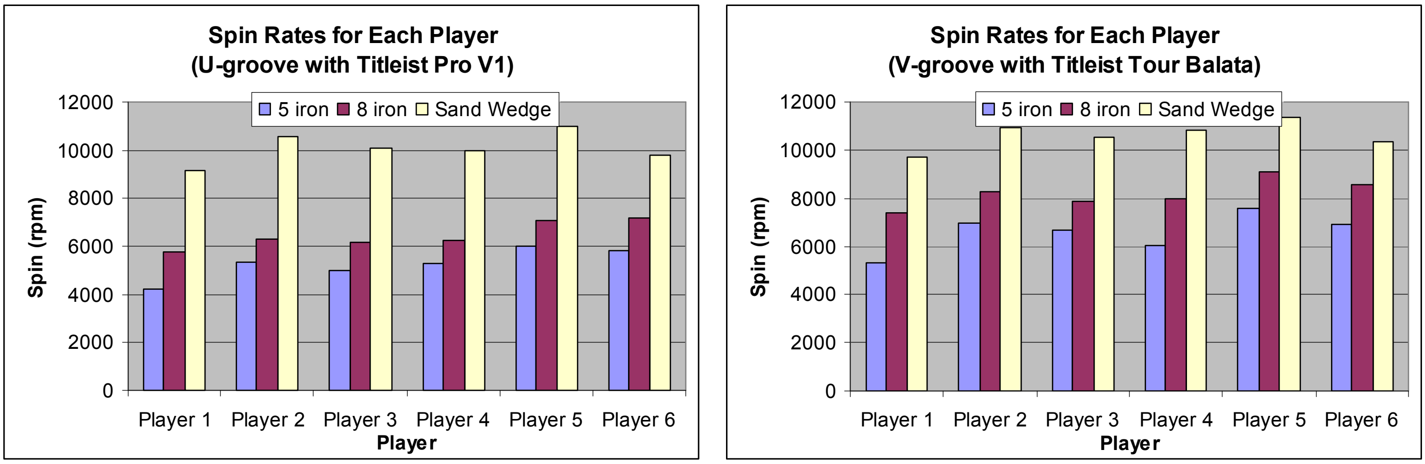


Figure 5 – Sample Player Test Results

Table 2 lists the average impact and launch conditions, as well as the associated confidence intervals, of the shots hit in the dry condition. From the data it can be observed that for both the 5 and 8 irons the V-groove striking the balata covered ball produced greater spins than the modern club/ball combination. This is a function of the multi-layer construction of the modern golf ball. The stiff inner mantle promotes greater reversal of the tangential force thereby reducing spin. Spins from the sand wedges are nearly the same. The reason for this is because at these higher lofts the spin is dominated by friction between the clubface and ball cover. In this instance the thin urethane cover of the modern tour ball is very similar to the balata covered balls of the pre-1990 era.

The average impact and launch conditions, as well as the associated confidence intervals, of the shots hit in the wet condition are presented in Table 3. This data clearly demonstrates the increased effectiveness of modern U-grooves over V-grooves when there is grass or debris between the clubface and ball.

			PLAYER FAIRWAY DATA				
		Deloft	Attack	Club Speed	Ball Speed	Vert. Ang	Spin rate
		[deg]	[deg]	[ft/s]	[ft/s]	[deg]	[rpm]
5U	**mean**	***11.5***	***-8.8***	***137.5***	***189.4***	***15.9***	***5283***
	stdev	*3.0*	*2.2*	*5.7*	*8.1*	*2.3*	*638*
	95%CI	***3.1***	***2.3***	***6.0***	***8.5***	***2.4***	***670***
5V	**mean**	***11.7***	***-8.8***	***137.4***	***188.2***	***13.9***	***6579***
	stdev	*3.5*	*2.5*	*6.6*	*8.5*	*2.4*	*793*
	95%CI	***3.6***	***2.6***	***6.9***	***8.9***	***2.5***	***832***
8U	**mean**	***13.2***	***-10.2***	***130.0***	***171.6***	***19.3***	***6461***
	stdev	*3.6*	*2.5*	*5.3*	*11.1*	*2.3*	*555*
	95%CI	***3.8***	***2.6***	***5.6***	***11.6***	***2.5***	***582***
8V	**mean**	***13.1***	***-10.1***	***129.0***	***168.6***	***18.3***	***8198***
	stdev	*3.7*	*2.4*	*5.1*	*9.6*	*2.4*	*598*
	95%CI	***3.8***	***2.5***	***5.3***	***10.1***	***2.6***	***628***
SWU	**mean**	***13.8***	***-10.7***	***123.1***	***130.5***	***29.2***	***10102***
	stdev	*2.9*	*2.5*	*3.8*	*7.7*	*2.3*	*623*
	95%CI	***3.1***	***2.6***	***4.0***	***8.1***	***2.4***	***654***
SWV	**mean**	***14.8***	***-11.1***	***121.7***	***128.6***	***26.9***	***10619***
	stdev	*2.8*	*2.2*	*3.4*	*9.8*	*2.1*	*563*
	95%CI	***2.9***	***2.3***	***3.5***	***10.3***	***2.3***	***591***

Table 2: Impact and Launch Data (Dry)

			PLAYER ROUGH DATA				
		Deloft	Attack	Club Speed	Ball Speed	Vert. Ang	Spin rate
		[deg]	[deg]	[ft/s]	[ft/s]	[deg]	[rpm]
5U	**mean**	***12.3***	***-8.1***	***137.9***	***180.9***	***14.0***	***6479***
	stdev	*3.8*	*2.8*	*4.9*	*8.7*	*3.4*	*607*
	95%CI	***4.0***	***2.9***	***5.2***	***9.2***	***3.5***	***637***
5V	**mean**	***12.2***	***-8.6***	***138.0***	***177.1***	***15.7***	***3526***
	stdev	*3.1*	*2.6*	*4.9*	*10.0*	*3.0*	*985*
	95%CI	***3.2***	***2.7***	***5.1***	***10.5***	***3.1***	***1034***
8U	**mean**	***13.7***	***-9.8***	***131.4***	***163.0***	***19.0***	***6469***
	stdev	*3.3*	*2.5*	*4.1*	*8.5*	*3.2*	*1055*
	95%CI	***3.4***	***2.6***	***4.3***	***8.9***	***3.3***	***1107***
8V	**mean**	***13.8***	***-9.6***	***129.5***	***154.5***	***22.6***	***3224***
	stdev	*3.3*	*2.7*	*3.8*	*5.9*	*2.9*	*563*
	95%CI	***3.4***	***2.9***	***4.0***	***6.2***	***3.0***	***591***
SWU	**mean**	***15.7***	***-10.5***	***122.9***	***119.0***	***35.0***	***5271***
	stdev	*3.1*	*2.4*	*2.9*	*9.3*	*6.4*	*1579*
	95%CI	***3.3***	***2.5***	***3.0***	***9.8***	***6.7***	***1658***
SWV	**mean**	***15.6***	***-10.8***	***119.1***	***119.2***	***33.8***	***3824***
	stdev	*3.1*	*2.5*	*4.5*	*9.0*	*4.5*	*875*
	95%CI	***3.3***	***2.6***	***4.7***	***9.4***	***4.7***	***918***

Table 3: Impact and Launch Data (Wet)

Figure 6 shows a comparison of the wet and dry conditions for each club in the modern and pre-1990 club/ball equipment sets. The data shows that for the pre-1990 equipment set the spins generated in the dry condition are greater than the spins in the wet condition across all the clubs. This is not true for the modern equipment set. In the modern equipment set the spins generated on shots in the wet condition with the 5 iron are greater than those in the dry condition. For the 8 iron the spins in the wet and dry condition are about the same and for the sand wedge the spin in the dry condition is much greater than the wet condition.

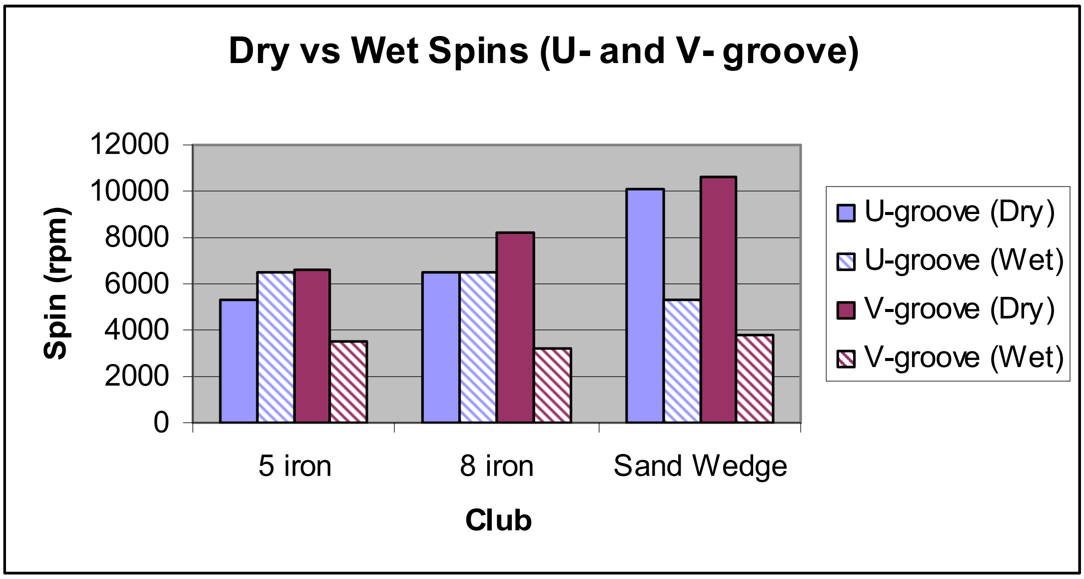


Figure 6 – Dry vs. Wet Spins for Modern and Pre-1990 Equipment Sets

This result agrees with previous simulation and experimental results that suggest that lower frictions can lead to greater spin at lower lofts (less oblique impacts), Figure 7.

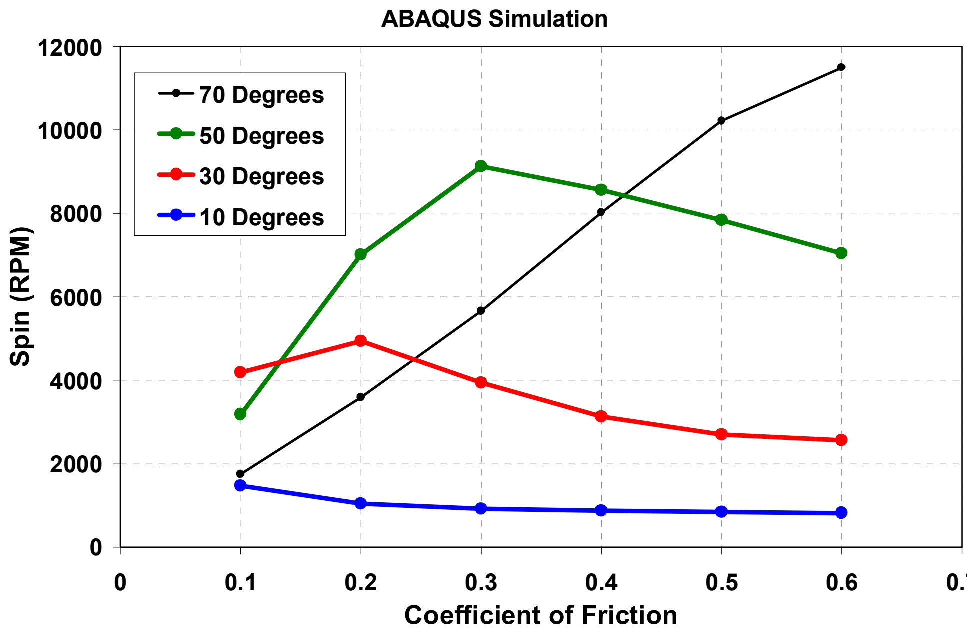


Figure 7– Results of Simulations of Oblique Impacts at Various Friction Levels

As highlighted previously, in addition to the modern and pre-1990 equipment sets, a set of grooveless clubs was also tested in the wet condition. Figure 8 shows a comparison of the modern, pre-1990 and grooveless clubs in the wet condition. As expected the grooveless clubs perform much worse than either of the other two sets when there is grass/debris between the clubface and the ball. However, it can also be seen that the improvement of the U-groove over the V-groove is more than the V-groove compared to no grooves at all.

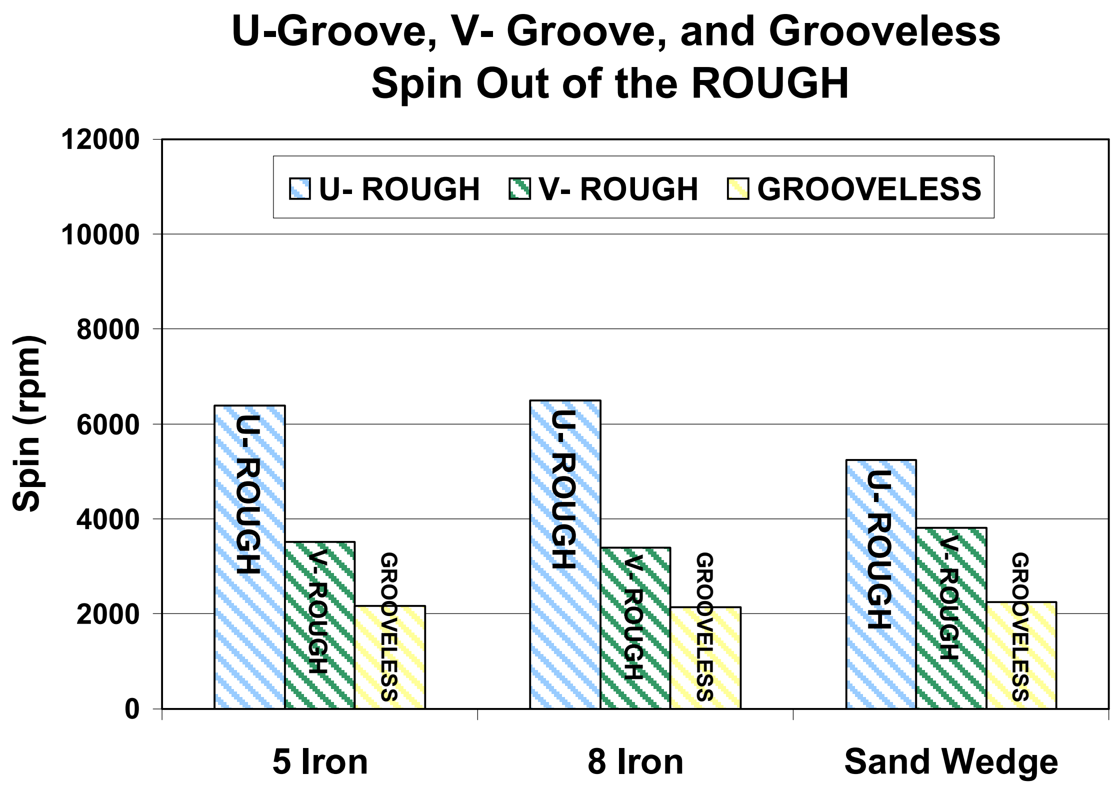


Figure 8– Comparison of Modern, Pre-1990 and Grooveless Irons (Wet)

The results of the player tests are consistent with previous data as well as simulations of oblique impact: The pre-1990 equipment set that consisted of a V-grooved club and wound, liquid-centre balata covered golf ball produced greater spins at lower lofts than the modern equipment set which consisted of U-grooved clubs with a solid, multi-layer urethane covered golf ball. However, in the wet condition, the modern set produced greater spins than the pre-1990 set across all clubs. In fact, for the 8 and 5 irons, the spin from the rough with the modern club actually exceeded that from a clean lie. As expected both modern and pre-1990 equipment sets were superior to the grooveless set for all clubs in the wet condition.

RESULTS – EVALUATION OF A EXPERIMENTAL SURROGATE FOR GRASS

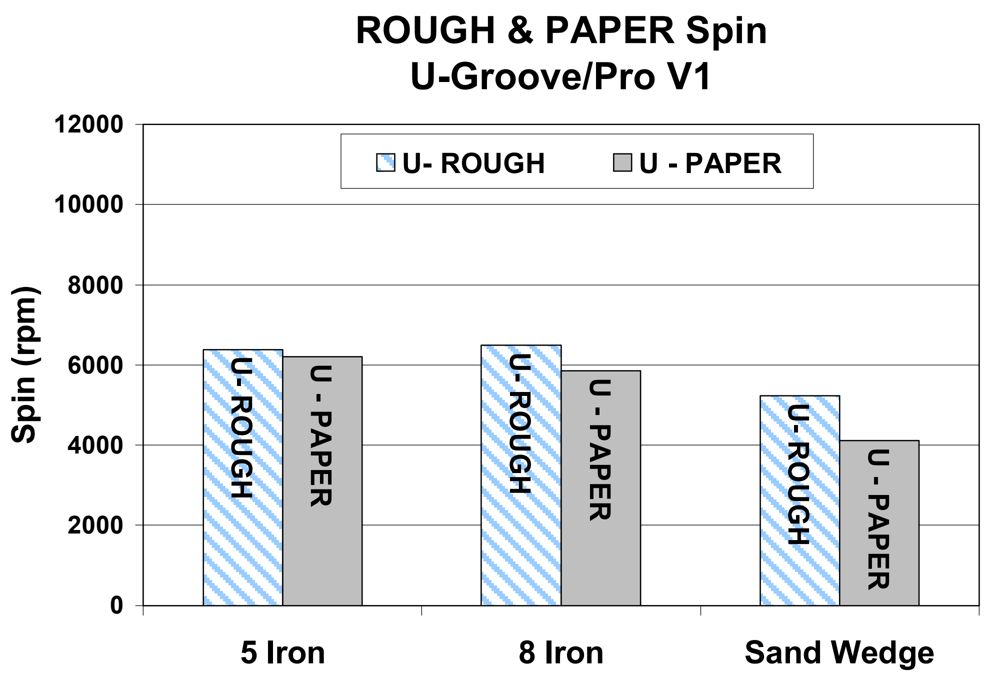


Figure 9– Comparison of Spins with a Wet Paper Interface and from Light Rough

The second objective of this testing was to evaluate a surrogate for grass to facilitate future laboratory testing with impact conditions similar to that of light rough. In this study wet newsprint was selected as the experimental surrogate. For the testing each player was asked to hit shots using the modern equipment set with a piece of wet newsprint adhered to the face of the club. Figure 9 shows the results of this testing compared with actual shots hit from the light rough. The results show that for the 5 iron the wet paper does act as a reasonable surrogate for grass. However at higher lofts, 8 iron and sand wedge, the wet paper is too severe an interface, reducing the spin much more than was observed in actual shots from light rough.

SUMMARY AND CONCLUSIONS

Player testing was performed with six professional golfers. The objective of the player testing was to obtain representative launch conditions using equipment reflective of today's conformance limits and that of the period prior to the common use of U-grooves. It was a further objective to begin prescribing an experimental surrogate for grass.

Each player was asked to hit shots from two different lies; one representing a fairway lie and another from light rough using each of the three club/ball combination sets. Three sets of clubs (comprised of 5, 8 irons and a sand wedge) were produced with grooves representative of the two eras of interest. One set represented pre-1990 club/ball combinations; V-grooved irons and wound, liquid centre balata covered golf balls, another set represented modern club/ball combinations; U-grooved irons and solid, three piece urethane covered golf balls. While a third set of irons was used having no grooves (but with typical face roughness) to provide an indication of the practical limit of groove specifications. The players were also asked to hit shots using the modern club/ball combination with a trial wet paper interface on the clubface. Impact conditions, determined using high speed video, and the launch conditions, measured by a radar tracking unit, were obtained.

The results of the player tests showed that, from a clean lie, the pre-1990 equipment set that consisted of a V-grooved club and wound, liquid centre balata covered golf ball produced greater spins at lower lofts than the modern equipment set which consisted of U-grooved clubs with a solid, multi-layer urethane covered golf ball. However, in the wet condition, the modern set produced greater spins than the pre-1990 set across all clubs. Both the modern and pre-1990 equipment sets were superior to the grooveless set for all clubs in the wet condition.

The results of the tests using a wet paper interface show that for the 5 iron the wet paper does act as a reasonable surrogate for grass. However at higher lofts, 8 iron and sand wedge, the wet paper is too severe an interface, reducing the spin much more than was observed in actual shots from light rough.

The impact and launch conditions obtained will provide the basis for laboratory testing of modified groove and surface conditions to determine their effect on spin. However, prior to any laboratory testing, further study will be necessary to identify a suitable surrogate for grass at higher lofts.

APPENDIX B

ABRASIVE BLASTING
OF STAINLESS STEEL PLATES

22nd March 2006

1. PURPOSE

In order to prepare test plates and club faces for spin testing, it is necessary to apply a uniform surface roughness that is typical of standard club faces. It is also likely that reduced and increased roughness may also be of interest. To that end, an experiment was conducted to study the effect of various abrasive blasting procedures on resulting surface roughness.

Two inch square plates of two grades of stainless steel (304 and 17-4 in their annealed state) were prepared by surface grinding or fly cutting to a uniform initial surface roughness of approximately 35-40 μin. These plates were then subjected to abrasive blasting using four different media and three different blasting periods. The resulting surface roughnesses of the plates were then measured again.

There is a clear relationship between the grit size of the media and the blasting period on the resulting surface roughness. The effect of the material choice appears to be less obvious.

2. PROCEDURE

Plates of 304 stainless steel (Rockwell hardness, $R_c \approx 10$) and 17-4 stainless steel ($R_c \approx 35$) were prepared by flycutting and surface grinding respectively. Both sets of plates, after machining had smooth surfaces with surface roughness of approximately 35 to 40 μin.

An abrasive blasting gun equipped with a gravity feed hopper and a 3/16" ceramic nozzle was situated with the outlet of the nozzle various distances from the target work piece. A distance of 24" ensured that a uniform spray pattern was achieved over the surface of the plate. A schematic diagram of this arrangement is shown in Figure 1.

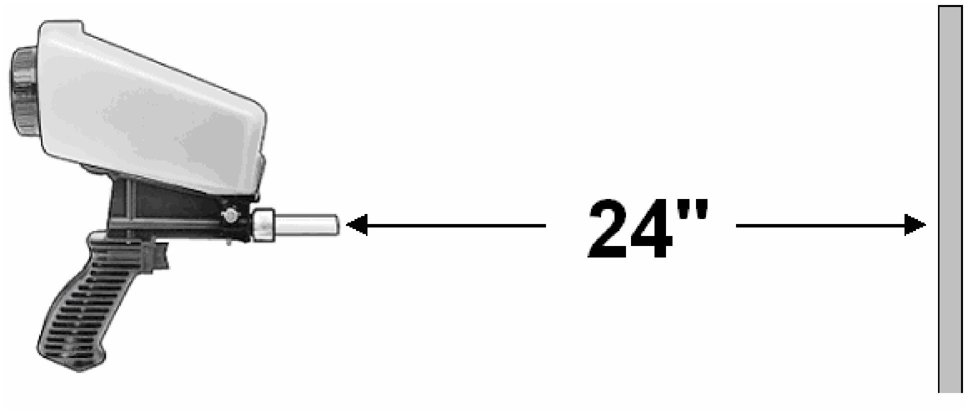


Figure 1: Abrasive blasting schematic

The abrasive grit was loaded into the hopper and the plate mounted to a fixture at the specified distance. Compressed air at 70 psi was supplied to the gun. The plate was then sprayed for the specified period of time. Finally, the surface treatment was measured using the surface roughness machine and the results recorded.

3. RESULTS

Figure 2 shows the results of the media blasting as a function of grit size, media material, plate material and blasting time. It can clearly be seen that the most important variables are the grit size of the media and the blasting time. The plate material had little discernable effect.

4. DISCUSSION

It appears from the data presented in Figure 2 that the grit size of the media is the most important factor in determining the resulting surface roughness. The blasting time is the next most important factor in determining surface roughness. According to Banks et al. (2001), the surface roughness is expected obey Poisson statistics. That is, the Ra roughness is expected increase linearly with the square root of time. In other words, the roughness should develop quickly at first and then more slowly for increasing time.

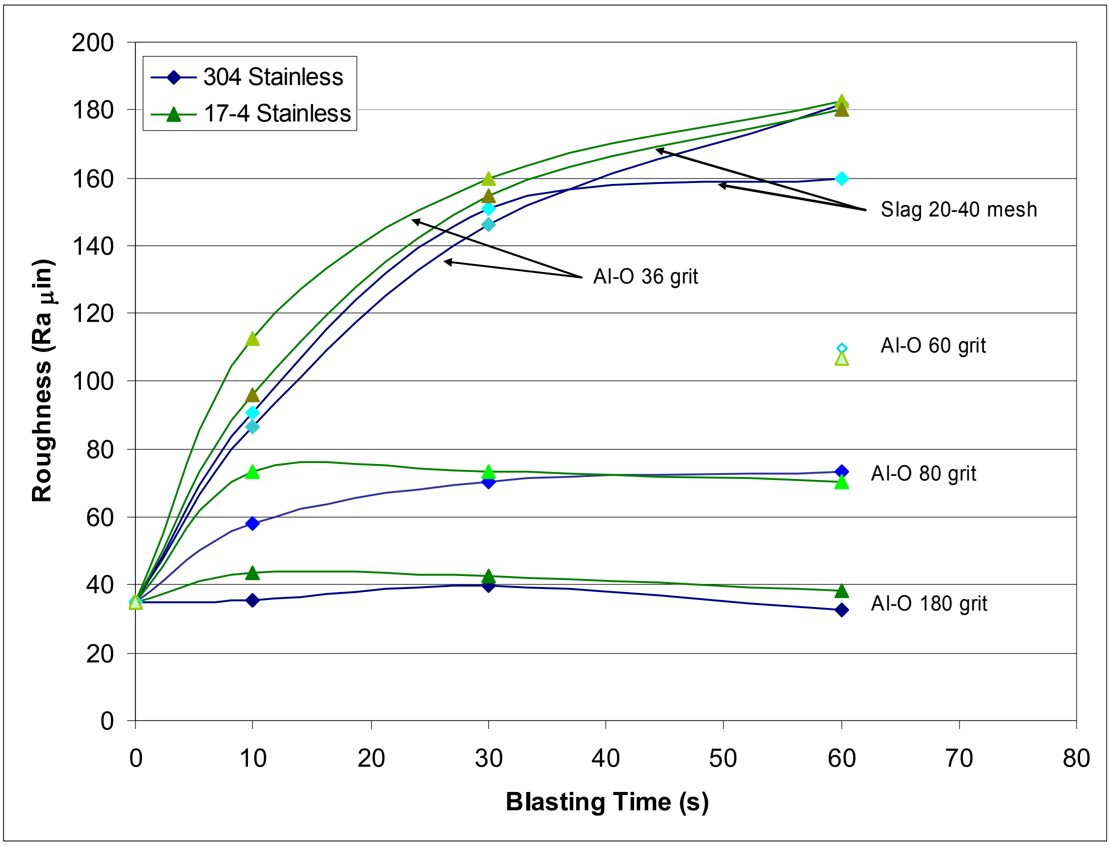


Figure 2: Surface roughness results (◊ - 304 stainless steel, ▲- 17-4 stainless steel)

Although we have only a limited number of discrete blasting times, Figure 2 appears to show this feature. Therefore, since we are most interested in repeatability of surface roughness development, we should use a reasonably long blasting time (since for example the difference in roughness between a 10 and 15 second blasting time is much greater than that between 30 and 35 seconds).

The data is presented in a slightly different manner in Figure 3. The resulting surface roughness is plotted as a function of grit size for the three blasting times. It should be possible to select the desired surface roughness from this chart. It can be seen in Figure 3 that the spray time as the greatest effect when using the most course media.

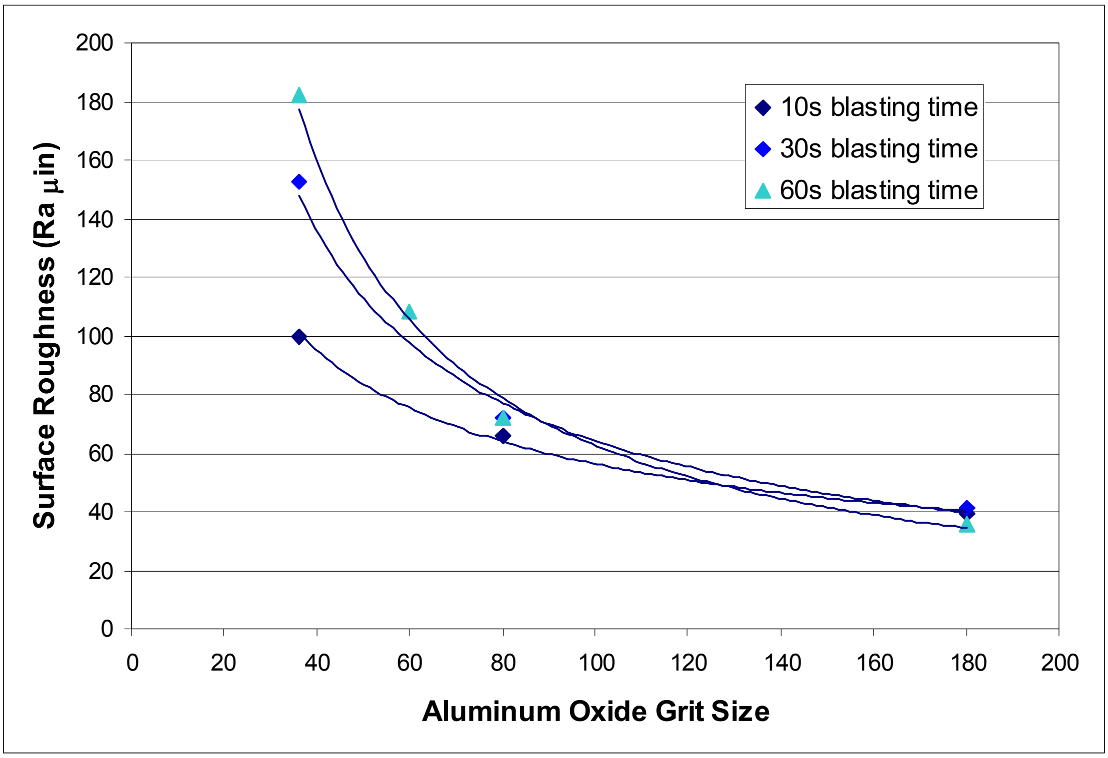


Figure 3: Surface roughness as a function of grit size and spray time.

5. Conclusion

A procedure for generating repeatable, uniform surface at a desired level of roughness for two inch square, stainless steel plates has been developed and tested. Positioning the target plate 24" from the outlet of the spray gun permits a uniform spray over the surface of the plate. The desired level of surface roughness can be achieved by selecting the appropriate grit size and spray time from Figure 3 (for Aluminium Oxide media).

APPENDIX C

INFINITE BARRIER BENCHMARK SPIN TESTING OF PRE-1990 GOLF BALLS

13th April 2006

1. INTRODUCTION

The first step in establishing a benchmark for the level of spin that was achievable before the decade of the 1990s, a series of lab tests were conducted using vintage golf clubs and balls that were first utilised in the USGA's original 1987 Groove Study. This current set of tests focused upon reproducing the original tests conducted using a Wilson U-groove sand wedge and a Wilson V-groove sand wedge in combination with the Titleist 384 Tour and the Spalding Tour Edition golf balls. These tests focused only upon the "dry" testing condition at multiple angles and velocities to determine whether the pre-1990 manufactured balls had maintained a reasonable measure of their original performance and were still suitable for current/future testing. The performance was evaluated in terms of spin and normal coefficient of restitution (e_n).

2. SUMMARY OF 1987 USGA GROOVE STUDY DATA

The original groove study was conducted in two phases. The January 1987 report contains details of Phase I. Table 1 is a small subset of the complete Phase I study and details specifically the Wilson U-groove (WU) and the Wilson V-groove (WV), as well as two grooveless sand wedges with the Titleist Pro Trajectory. One of the grooveless sand wedges is sand blasted (SB) and the other sand wedge was left smooth (SM). Table 1 summarises the spin results for dry impacts conducted at 55 degrees of loft with an impact velocity of 80 feet per second. These clubs were rigidly fixed to an "infinite" mass barrier at the prescribed loft. The full set of balls used in the 1987 Phase I testing were the Titleist Pro Trajectory (PROTRAJ), a wound, balata covered ball, the Pinnacle 384 (PINN384), a solid two piece construction ball with a Surlyn cover, and the Spalding Tour Edition (SPTE), a solid two piece construction ball with a Zinthane cover. The complete set of the pertinent tables for all of the tests is available in the Appendix of this report.

Table 1. Dry Spin Data Summary from January 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI
1987	WU	PROTRAJ	55	80	8400	120
1987	WV	PROTRAJ	55	80	8400	360
1987	SM	PROTRAJ	55	80	8460	120
1987	SB	PROTRAJ	55	80	9000	120
1987	AVG	PROTRAJ	55	80	8460	
1987	SM	PROTRAJ	30	100	7080	120
1987	SB	PROTRAJ	30	100	6900	120
1987	AVG	PROTRAJ	30	100	7440	

Phase II of the Groove Study was reported on in December of 1987. Table 2 is a summary of the spin data for the Wilson U-groove (WU) and Wilson V-groove (WV) clubs tested at a loft of 55 degrees and with an impact velocity of 80 feet per second with the Titleist 384 Tour. The complete set of balls used in Phase II of the Groove Study were the Titleist 384 Tour (TT384), a wound, balata covered ball, the Pinnacle 384 (PINN384), and the Spalding Tour Edition (SPTE). The Titleist 384 Tour used in Phase II of the 1987 groove study replaced the Titleist Pro Trajectory of Phase I. The data for the other balls tested can be found in the Appendix of this report.

Table 2. Dry Spin Data Summary from December 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
1987	WU	TT384	55	80	7860	180	0.860
1987	WV	TT384	55	80	7980	300	0.850
1987	AVG U	TT384	55	80	8100		0.860
1987	AVG V	TT384	55	80	8160		0.870

In Tables 1 and 2 and in subsequent tables, AVG U and AVG V, refer to the average spin data values for all other U-grooved plates in the 1987 300 series plates (301,302,303…) and in the other V-grooved plates of the 200 series (201,202,203…). Plates 201 and 301 are the test plates with the closest groove geometries to the Wilson V and Wilson U respectively. These values were included in these summary tables for comparison purposes and because in each case not every ball/plate/club/loft combination had been tested in 1987. Table 3 is a summary of the spin data taken at other lofts (30, 32.5, and 65 degrees) and velocities (80 and 108 fps) with the Titleist 384 Tour.

Table 3. Dry Spin Data Summary from December 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
1987	WU	TT384	65	80	8580	360	0.810
1987	WV	TT384	65	80	8520	420	0.850
1987	AVG U	TT384	65	80	9180		0.880
1987	AVG V	TT384	65	80	8820		0.890
1987	WU	TT384	30	80	4020	120	0.810
1987	WV*(201)	TT384	30	80	4920	180	0.820
1987	AVG U	TT384	30	80	5040		0.830
1987	AVG V	TT384	30	80	4980		0.820
1987	WU	TT384	32.5	108	8640	300	0.830
1987	WV	TT384	32.5	108	8460	180	0.830
1987	WU*(301)	TT384	32.5	108	7920	180	0.820
1987	WV*(201)	TT384	32.5	108	7740	240	0.810
1987	AVG U	TT384	32.5	108	7800		0.820
1987	AVG V	TT384	32.5	108	7800		0.810

3. Summary Of 2006 Re-Testing of Subsets Of 1987 Groove Study

The subset of tests conducted in 1987 on the Wilson U-groove and Wilson V-groove summarised in the Tables of the above Section 2, were reproduced using both original balls from the Phase II Groove study as well as with the modern Titleist Pro V1 and a mid-1990s Titleist Tour Balata 100. Table 4 is a summary of the spin tests conducted this year at multiple lofts (30, 32.5, 55, 65 degrees) and velocities (80 and 108 fps) with the appropriate balls to reproduce the 1987 testing. Since there were only small populations of the original 1987 test balls (PROTRAJ, TT384, and SPTE) a reasonable surrogate, the Titleist Tour Balata 100 (TB100), was also introduced into the testing where appropriate. The Titleist Tour Balata is also a wound, balata ball and is fortunately still available in relatively large quantities. Tables 5-9 make comparisons between the original 1987 data and the more recent 2006 re-testing of these specific tests. Test results for the SPTE and PINN384 can be found in the Appendix of this report.

Table 4. Dry Spin Data Summary of Test Conducted in 2006.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
2006	WU	TT384	55	80.0	7012	579	0.792
2006	WV	TT384	55	80.1	7277	200	0.830
2006	SB	TT384	55	80.0	7921	261	0.816
2006	WU	TB100	55	79.7	7425	373	0.817
2006	WV	TB100	55	79.6	7442	307	0.833
2006	SB	TB100	55	79.7	7953	359	0.832
2006	WU	PROV1	55	80.1	6982	380	0.855
2006	WV	PROV1	55	80.2	7333	234	0.874
2006	SB	PROV1	55	80.1	7862	214	0.875
2006	WU	TT384	65	80.4	8990	266	0.833
2006	WV	TT384	65	79.9	8908	416	0.861
2006	WU	TB100	65	79.5	8866	417	0.795
2006	WV	TB100	65	80.0	8909	361	0.841
2006	WU	TTT384	30	79.4	3998	238	0.750
2006	WV	TTT384	30	80.0	3847	339	0.754
2006	WU	TB100	30	80.1	4452	341	0.736
2006	WV	TB100	30	80.5	4463	358	0.746
2006	WU	PROV1	30	79.8	3593	260	0.799
2006	WV	PROV1	30	80.0	3500	206	0.811
2006	WU	TT384	32.5	107.8	6075	270	0.737
2006	WV	TT384	32.5	107.9	6031	264	0.739
2006	WU	TB100	32.5	108.1	6586	319	0.741
2006	WV	TB100	32.5	107.6	6595	521	0.748
2006	WU	PROV1	32.5	108.5	5192	261	0.788
2006	WV	PROV1	32.5	107.6	5120	210	0.791

4. COMPARISON OF 1987 GROOVE STUDY DATA WITH 2006 RE-TESTS

The re-testing of the original 1987 Groove Study testing was conducted in order to see if the original testing methods could be reproduced as well as checking to see if the balls used in the original testing had still maintained a reasonable degree of their original impact characteristics. Determining if the balls have maintained a significant degree of their original impact characteristics is key in deciding whether or not they would act as reasonable representatives when used in future player benchmark testing.

Table 5 is a summary of the comparison of the spin data between 1987 and 2006 testing for impact conditions of 55 degrees of loft and 80 feet per second impact velocity for the Titleist 384 Tour and Titleist Tour Balata 100. When making a direct comparison with the TT384 from 1987 to 2006, there was a reduction of 9-11% in spin. When comparing the 1987 TT384 results with the 2006 TB100 results, the Titleist Tour Balata 100 was 6-7% lower in spin than the original 1987 tests conducted with the Titleist 384 Tour.

Table 5. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 55 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	7860	2006	TT384	WU	7012	**-848**	**-11%**
1987	TT384	WV	7980	2006	TT384	WV	7277	**-703**	**-9%**
1987	TT384	WU	7860	2006	TB100	WU	7425	**-435**	**-6%**
1987	TT384	WV	7980	2006	TB100	WV	7442	**-538**	**-7%**

Since the results of the Titleist Tour Balata testing in 2006 were closest to reproducing the 1987 Titleist Tour 384 results (within 7%) for the 55 degree testing, and because the Tour Balata 100 is much more readily available than the Titleist 384 Tour, it was decided to include the Titleist Tour Balata in the remaining tests. The Titleist Tour 384s are still available for testing if deemed necessary; however, there is a very small population which would be too small for significant numbers of lab and player testing.

Table 6 is summary of the comparison of the 1987 Titleist 384 Tour data and the 2006 Titleist Tour Balata tests conducted at a loft of 65 degrees and 80 feet per second. The Titleist 384 Tour had a change of about 5% in spin from the 1987 to the 2006 tests under this set of conditions. It is important to take note that the 2006 data for the TT384 and the TB100 have 4-5% higher spin than the 1987 TT384 test data. Unlike the majority of the other test conditions, under this low speed, highly oblique test condition, there appears to be no decay and a measured increase in spin from 1987 to 2006.

Table 6. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 65 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	8580	2006	TT384	WU	8990	**410**	**5%**
1987	TT384	WV	8520	2006	TT384	WV	8908	**388**	**5%**
1987	TT384	WU	8580	2006	TB100	WU	8910	**330**	**4%**
1987	TT384	WV	8520	2006	TB100	WV	8949	**429**	**5%**

Table 7 is summary of the comparison of the 1987 Titleist 384 Tour and the 2006 Titleist Tour Balata tests conducted at a loft of 30 degrees and 80 feet per second. Since in 1987, the Wilson V-groove was not tested, plates 201 and 301, as well as the average of all V grooved plates is included in the table for comparisons to the 2006 data. The original 1987 test of the Wilson U with the Titleist 384 Tour (4020 rpm) seems to be inconsistent with the other tests (see WU* and WV*) at these conditions in 1987. The Titleist 384 Tour has decreased in spin approximately 22-23% from 1987 to 2006. The Titleist Tour Balata 100 in 2006 is spinning approximately 10-12% below the spin rates of the 1987 Titleist 384 Tour.

Table 7. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 30 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	4020	2006	TT384	WU	3998	**-22**	**-1%**
1987	TT384	WU*(301)	5160	2006	TT384	WU	3988	**-1172**	**-23%**
1987	TT384	WV*(201)	4920	2006	TT384	WV	3847	**-1073**	**-22%**
1987	TT384	AVG U	5040	2006	TT384	WU	3998	**-1042**	**-21%**
1987	TT384	AVG V	4980	2006	TT384	WV	3847	**-1133**	**-23%**
1987	TT384	WU	4020	2006	TB100	WU	4452	**432**	**11%**
1987	TT384	WU*(301)	5160	2006	TB100	WU	4452	**-708**	**-14%**
1987	TT384	WV*(201)	4920	2006	TB100	WV	4463	**-457**	**-9%**
1987	TT384	AVG U	5040	2006	TB100	WU	4452	**-588**	**-12%**
1987	TT384	AVG V	4980	2006	TB100	WV	4463	**-517**	**-10%**

Table 8 is summary of the comparison of the 1987 Titleist Tour 384 data and the 2006 Titleist Tour Balata tests conducted at a loft of 32.5 degrees and 108 feet per second. The 1987 WU and WV data for the Titleist 384 Tour were inconsistent with the other tests of that time period including plates 201 and 301 which closely model the WV and WU. Relative to the 1987 results on plates 201 and 301, the Titleist 384 Tour had a 22-23% reduction in spin from 1987 to 2006. The Titleist Tour Balata 100 2006 data is within 15-17% of the spin rate of the 1987 Titleist 384 Tour when compared with the data on the representative plates 201 and 301.

Table 8. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 32.5 deg 108 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	8640	2006	TT384	WU	6075	**-2565**	**-30%**
1987	TT384	WV	8460	2006	TT384	WV	6031	**-2429**	**-29%**
1987	TT384	WU*(301)	7920	2006	TT384	WU	6075	**-1845**	**-23%**
1987	TT384	WV*(201)	7740	2006	TT384	WV	6031	**-1709**	**-22%**
1987	TT384	WU	8640	2006	TB100	WU	6552	**-2088**	**-24%**
1987	TT384	WV	8460	2006	TB100	WV	6588	**-1872**	**-22%**
1987	TT384	WU*(301)	7920	2006	TB100	WU	6552	**-1368**	**-17%**
1987	TT384	WV*(201)	7740	2006	TB100	WV	6588	**-1152**	**-15%**

In addition to the spin comparisons between the 1987 testing and the current 2006 testing, a comparative evaluation of the normal component of the coefficient of restitution can also be made. Tables 9-12 compare the normal coefficients of restitution for the two testing periods over the same subset of tests as included in the spin data.

Table 9 is summary of the comparison of the 1987 Titleist Tour 384 data and the 2006 Titleist Tour Balata tests conducted at a loft of 55 degrees and 80 feet per second. The direct comparison between the 1987 and 2006 Titleist 384 Tour data show a 2-8% decrease in the normal component of COR (e_n). The comparison of the between the 1987 TT384 and the 2006 testing of the TB100 show a negative 2-5% difference in e_n.

Table 9. Normal COR Data Summary Comparison of 1987 and 2006 Data for 55 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.860	2006	TT384	WU	0.792	**-0.068**	**-8%**
1987	TT384	WV	0.850	2006	TT384	WV	0.830	**-0.020**	**-2%**
1987	TT384	WU	0.860	2006	TB100	WU	0.817	**-0.043**	**-5%**
1987	TT384	WV	0.850	2006	TB100	WV	0.833	**-0.017**	**-2%**

Table 10 is summary of the normal coefficient of restitution comparison of the 1987 Titleist Tour 384 data and the 2006 Titleist Tour Balata tests conducted at a loft of 65 degrees of loft and 80 feet per second. The Titleist 384 Tour shows a slight increase in the e_n from 1987 to 2006. The comparison of the 1987 Titleist 384 Tour and the 2006 Titleist Tour Balata 100 data reveal a 0-2% reduction in e_n.

Table 10. Normal COR Data Summary Comparison of 1987 and 2006 Data for 65 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.810	2006	TT384	WU	0.833	**0.023**	**3%**
1987	TT384	WV	0.850	2006	TT384	WV	0.861	**0.011**	**1%**
1987	TT384	WU	0.810	2006	TB100	WU	0.792	**-0.018**	**-2%**
1987	TT384	WV	0.850	2006	TB100	WV	0.853	**0.003**	**0%**

Table 11 is summary of the normal coefficient of restitution comparison of the 1987 Titleist 384 Tour data and the 2006 Titleist Tour Balata tests conducted at a loft of 30 degrees and 80 feet per second. The direct comparison of the 1987 and 2006 Titleist 384 Tour data show a 7-8% decrease in the spin rate. The comparison of the 1987 TT384 and the 2006 TB100 data show a negative 9% difference in e_n.

Table 11. Normal COR Data Summary Comparison of 1987 and 2006 Data for 30 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.810	2006	TT384	WU	0.750	**-0.060**	**-7%**
1987	TT384	WV*(201)	0.820	2006	TT384	WV	0.754	**-0.066**	**-8%**
1987	TT384	AVG U	0.830	2006	TT384	WU	0.750	**-0.080**	**-10%**
1987	TT384	AVG V	0.820	2006	TT384	WV	0.754	**-0.066**	**-8%**
1987	TT384	WU	0.810	2006	TB100	WU	0.736	**-0.074**	**-9%**
1987	TT384	WV*(201)	0.820	2006	TB100	WV	0.748	**-0.072**	**-9%**
1987	TT384	AVG U	0.830	2006	TB100	WU	0.736	**-0.094**	**-11%**
1987	TT384	AVG V	0.820	2006	TB100	WV	0.748	**-0.072**	**-9%**

Table 12 is summary of the comparison of the 1987 Titleist Tour 384 data and the 2006 Titleist Tour Balata tests conducted at a loft of 32.5 degrees and 108 feet per second. The comparison of the 1987 and 2006 Titleist 384 Tour data revealed an 11% decrease in normal coefficient of restitution. There is a 10-11% difference in e_n between the 2006 testing of the Titleist Tour Balata 100 and the 1987 testing of the Titleist 384 Tour.

Table 12. Normal COR Data Summary Comparison of 1987 and 2006 Data for 32.5 deg 108 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.830	2006	TT384	WU	0.737	**-0.093**	**-11%**
1987	TT384	WV	0.830	2006	TT384	WV	0.739	**-0.091**	**-11%**
1987	TT384	WU	0.830	2006	TB100	WU	0.740	**-0.090**	**-11%**
1987	TT384	WV	0.830	2006	TB100	WV	0.748	**-0.082**	**-10%**

5. CONCLUSIONS

The tests that made direct comparisons between the results from the original 1987 study and the re-testing in 2006 for the most part demonstrated some decrease in both the magnitude of spin as well as normal coefficient of restitution, e_n. The degree, in which these direct decreases could be measured, showed sensitivity to the degree of obliqueness and impact velocity. The higher lofted impacts of 55 degrees and lower speed of 80 fps, show the least amount of reduction of spin and normal coefficient of restitution. The lower loft of 32.5 degrees and higher impact velocity of 108 feet per second showed the largest decreases in both spin and normal coefficient of restitution. The most highly lofted tests conducted at 65 degrees and 80 feet per second showed a slight increase in both spin and e_n.

The Titleist Tour Balata 100 is the best ball tested that could represent the original balls used in the 1987 Groove Study. The introduction of the Titleist Tour Balata 100 as a benchmark ball does help to reclaim some of the reduced spin and normal coefficient of restitution performance that was lost in the original Titleist Pro Trajectory and Titleist 384 Tour. These test results reclaim some of the reduced spin from the PROTRAJ and Titleist 384 Tour at the most oblique angles and slow velocities. At the higher impact velocities and closer to normal impacts, the reduced spin and e_n seem to be experienced by all of the balls included in the test. Based on these series of test included in this report, it is recommended that the Titleist Tour Balata 100 be used in subsequent player tests to represent the pre-1990 performance benchmark ball.

APPENDIX C.2

Table 1. Dry Spin Data Summary from January 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI
1987	WU	PROTRAJ	55	80	8400	120
1987	WV	PROTRAJ	55	80	8400	360
1987	SM	PROTRAJ	55	80	8460	120
1987	SB	PROTRAJ	55	80	9000	120
1987	AVG	PROTRAJ	55	80	8460	
1987	WU	PINN	55	80	4440	360
1987	WV	PINN	55	80	5040	780
1987	SM	PINN	55	80	6480	720
1987	SB	PINN	55	80	5040	300
1987	WU	SPTE	55	80	8880	300
1987	WV	SPTE	55	80	8760	240
1987	AVG	SPTE	55	80	8760	
1987	SM	PROTRAJ	30	100	7080	120
1987	SB	PROTRAJ	30	100	6900	120
1987	AVG	PROTRAJ	30	100	7440	

Table 2. Dry Spin Data Summary from December 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
1987	WU	TT384	55	80	7860	180	0.860
1987	WV	TT384	55	80	7980	300	0.850
1987	AVG U	TT384	55	80	8100		0.860
1987	AVG V	TT384	55	80	8160		0.870
1987	WU	SPTE	55	80	8520	300	0.800
1987	WV	SPTE	55	80	8940	180	0.840
1987	AVG U	SPTE	55	80	8940		0.860
1987	AVG V	SPTE	55	80	8880		0.860
1987	WU	PINN	55	80	4380	540	0.820
1987	WV	PINN	55	80	5700	420	0.820
1987	AVG U	PINN	55	80	7860		0.860
1987	AVG V	PINN	55	80	7920		0.870

Table 3. Dry Spin Data Summary from December 1987 USGA Groove Study Report.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
1987	WU	TT384	65	80	8580	360	0.810
1987	WV	TT384	65	80	8520	420	0.850
1987	AVG U	TT384	65	80	9180		0.880
1987	AVG V	TT384	65	80	8820		0.890
1987	WU	PINN	65	80	3600	180	0.890
1987	WV	PINN	65	80	3840	300	0.890
1987	AVG U	PINN	65	80	5940		0.920
1987	AVG V	PINN	65	80	5820		0.930
1987	WU	TT384	30	80	4020	120	0.810
1987	WV*(201)	TT384	30	80	4920	180	0.820
1987	AVG U	TT384	30	80	5040		0.830
1987	AVG V	TT384	30	80	4980		0.820
1987	WU*(301)	SPTE	30	80	6180	180	0.800
1987	WV*(201)	SPTE	30	80	6180	180	0.800
1987	AVG U	SPTE	30	80	6180		0.800
1987	AVG V	SPTE	30	80	6240		0.800
1987	WU*(301)	PINN	30	80	4920	240	0.820
1987	WV*(201)	PINN	30	80	4980	120	0.820
1987	AVG U	PINN	30	80	4980		0.820
1987	AVG V	PINN	30	80	5160		0.820
1987	WU	TT384	32.5	108	8640	300	0.830
1987	WV	TT384	32.5	108	8460	180	0.830
1987	WU*(301)	TT384	32.5	108	7920	180	0.820
1987	WV*(201)	TT384	32.5	108	7740	240	0.810
1987	AVG U	TT384	32.5	108	7800		0.820
1987	AVG V	TT384	32.5	108	7800		0.810

Table 4. Dry Spin Data Summary of Test Conducted in 2006.

Test Date	Club	Ball	Angle (deg)	Velocity (fps)	Spin (rpm)	95% CI	e_n
2006	WU	TT384	55	80.0	7012	579	0.792
2006	WV	TT384	55	80.1	7277	200	0.830
2006	SB	TT384	55	80.0	7921	261	0.816
2006	WU	SPTE	55	79.9	7871	735	0.786
2006	WV	SPTE	55	80.0	8045	524	0.821
2006	SB	SPTE	55	80.3	7631	1192	0.816
2006	WU	PINN384	55	80.1	4819	405	0.819
2006	WV	PINN384	55	80.0	5219	419	0.852
2006	SB	PINN384	55	79.8	4359	527	0.836
2006	WU	TB100	55	79.7	7425	373	0.817
2006	WV	TB100	55	79.6	7442	307	0.833
2006	SB	TB100	55	79.7	7953	359	0.832
2006	WU	PROV1	55	80.1	6982	380	0.855
2006	WV	PROV1	55	80.2	7333	234	0.874
2006	SB	PROV1	55	80.1	7862	214	0.875
2006	WU	PINN	55	79.6	4879	381	0.840
2006	WV	PINN	55	80.0	4986	796	0.843
2006	SB	PINN	55	79.8	4853	721	0.829
2006	WU	TT384	65	80.4	8990	266	0.833
2006	WV	TT384	65	79.9	8908	416	0.861
2006	WU	SPTE	65	81.1	5158	602	0.803
2006	WV	SPTE	65	79.1	5238	878	0.837
2006	WU	TB100	65	79.5	8866	417	0.795
2006	WV	TB100	65	80.0	8909	361	0.841
2006	WU	PROV1	65	80.2	8801	349	0.885
2006	WV	PROV1	65	80.0	9027	320	0.918
2006	WU	TTT384	30	79.4	3998	238	0.750
2006	WV	TTT384	30	80.0	3847	339	0.754
2006	WU	SPTE	30	79.4	4601	185	0.736
2006	WV	SPTE	30	79.4	4572	333	0.755
2006	WU	TB100	30	80.1	4452	341	0.736
2006	WV	TB100	30	80.5	4463	358	0.746
2006	WU	PROV1	30	79.8	3593	260	0.799
2006	WV	PROV1	30	80.0	3500	206	0.811
2006	WU	TT384	32.5	107.8	6075	270	0.737
2006	WV	TT384	32.5	107.9	6031	264	0.739
2006	WU	SPTE	32.5	107.5	6690	569	0.725
2006	WV	SPTE	32.5	107.3	6530	301	0.731
2006	WU	TB100	32.5	108.1	6586	319	0.741
2006	WV	TB100	32.5	107.6	6595	521	0.748
2006	WU	PROV1	32.5	108.5	5192	261	0.788
2006	WV	PROV1	32.5	107.6	5120	210	0.791

Table 5. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 55 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	PROTRAJ	WU	8400	2006	TT384	WU	6935	**-1465**	**-17%**
1987	PROTRAJ	WV	8400	2006	TT384	WV	7254	**-1146**	**-14%**
1987	PROTRAJ	SB	9000	2006	TT384	SB	7962	**-1038**	**-12%**
1987	PROTRAJ	WU	8400	2006	TB100	WU	7404	**-996**	**-12%**
1987	PROTRAJ	WV	8400	2006	TB100	WV	7488	**-912**	**-11%**
1987	PROTRAJ	SB	9000	2006	TB100	SB	7896	**-1104**	**-12%**

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	7860	2006	TT384	WU	6935	**-925**	**-12%**
1987	TT384	WV	7980	2006	TT384	WV	7254	**-726**	**-9%**
1987	TT384	WU	7860	2006	TB100	WU	7404	**-456**	**-6%**
1987	TT384	WV	7980	2006	TB100	WV	7488	**-492**	**-6%**

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	SPTE	WU	8520	2006	SPTE	WU	7937	**-583**	**-7%**
1987	SPTE	WV	8940	2006	SPTE	WV	8007	**-933**	**-10%**
1987	SPTE	WU	8520	2006	TB100	WU	7404	**-1116**	**-13%**
1987	SPTE	WV	8940	2006	TB100	WV	7488	**-1452**	**-16%**

Table 6. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 65 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	8580	2006	TT384	WU	8990	**410**	**5%**
1987	TT384	WV	8520	2006	TT384	WV	8908	**388**	**5%**
1987	TT384	WU	8580	2006	TB100	WU	8910	**330**	**4%**
1987	TT384	WV	8520	2006	TB100	WV	8949	**429**	**5%**

Table 7. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 30 deg 80 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	4020	2006	TT384	WU	3998	**-22**	**-1%**
1987	TT384	WU*(301)	5160	2006	TT384	WU	3988	**-1172**	**-23%**
1987	TT384	WV*(201)	4920	2006	TT384	WV	3847	**-1073**	**-22%**
1987	TT384	AVG U	5040	2006	TT384	WU	3998	**-1042**	**-21%**
1987	TT384	AVG V	4980	2006	TT384	WV	3847	**-1133**	**-23%**
1987	TT384	WU	4020	2006	TB100	WU	4452	**432**	**11%**
1987	TT384	WU*(301)	5160	2006	TB100	WU	4452	**-708**	**-14%**
1987	TT384	WV*(201)	4920	2006	TB100	WV	4463	**-457**	**-9%**
1987	TT384	AVG U	5040	2006	TB100	WU	4452	**-588**	**-12%**
1987	TT384	AVG V	4980	2006	TB100	WV	4463	**-517**	**-10%**
1987	SPTE	WU*(301)	6180	2006	SPTE	WU	4601	**-1579**	**-26%**
1987	SPTE	WV*(201)	6180	2006	SPTE	WV	4572	**-1608**	**-26%**
1987	SPTE	AVG U	6180	2006	SPTE	WU	4601	**-1579**	**-26%**
1987	SPTE	AVG V	6240	2006	SPTE	WV	4572	**-1668**	**-27%**

Table 8. Dry Spin Data Summary Comparison of 1987 and 2006 Data for 32.5 deg 108 fps.

Test Date	Ball	Club	Spin (rpm)	Test Date	Ball	Club	Spin (rpm)	delta (rpm)	delta %
1987	TT384	WU	8640	2006	TT384	WU	6075	**-2565**	**-30%**
1987	TT384	WV	8460	2006	TT384	WV	6031	**-2429**	**-29%**
1987	TT384	WU*(301)	7920	2006	TT384	WU	6075	**-1845**	**-23%**
1987	TT384	WV*(201)	7740	2006	TT384	WV	6031	**-1709**	**-22%**
1987	TT384	WU	8640	2006	TB100	WU	6552	**-2088**	**-24%**
1987	TT384	WV	8460	2006	TB100	WV	6588	**-1872**	**-22%**
1987	TT384	WU*(301)	7920	2006	TB100	WU	6552	**-1368**	**-17%**
1987	TT384	WV*(201)	7740	2006	TB100	WV	6588	**-1152**	**-15%**

Table 9. Normal COR Data Summary Comparison of 1987 and 2006 Data for 55 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.860	2006	TT384	WU	0.792	**-0.068**	**-8%**
1987	TT384	WV	0.850	2006	TT384	WV	0.830	**-0.020**	**-2%**
1987	TT384	WU	0.860	2006	TB100	WU	0.817	**-0.043**	**-5%**
1987	TT384	WV	0.850	2006	TB100	WV	0.833	**-0.017**	**-2%**
Test Date	**Ball**	**Club**	**COR**	**Test Date**	**Ball**	**Club**	**COR**	**delta (COR)**	**delta %**
1987	SPTE	WU	0.800	2006	SPTE	WU	0.786	**-0.014**	**-2%**
1987	SPTE	WV	0.840	2006	SPTE	WV	0.821	**-0.019**	**-2%**
1987	SPTE	WU	0.800	2006	TB100	WU	0.817	**0.017**	**2%**
1987	SPTE	WV	0.840	2006	TB100	WV	0.833	**-0.007**	**-1%**

Table 10. Normal COR Data Summary Comparison of 1987 and 2006 Data for 65 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.810	2006	TT384	WU	0.833	**0.023**	**3%**
1987	TT384	WV	0.850	2006	TT384	WV	0.861	**0.011**	**1%**
1987	TT384	WU	0.810	2006	TB100	WU	0.792	**-0.018**	**-2%**
1987	TT384	WV	0.850	2006	TB100	WV	0.853	**0.003**	**0%**

Table 11. Normal COR Data Summary Comparison of 1987 and 2006 Data for 30 deg 80 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.810	2006	TT384	WU	0.750	**-0.060**	**-7%**
1987	TT384	WV*(201)	0.820	2006	TT384	WV	0.754	**-0.066**	**-8%**
1987	TT384	AVG U	0.830	2006	TT384	WU	0.750	**-0.080**	**-10%**
1987	TT384	AVG V	0.820	2006	TT384	WV	0.754	**-0.066**	**-8%**
1987	TT384	WU	0.810	2006	TB100	WU	0.736	**-0.074**	**-9%**
1987	TT384	WV*(201)	0.820	2006	TB100	WV	0.748	**-0.072**	**-9%**
1987	TT384	AVG U	0.830	2006	TB100	WU	0.736	**-0.094**	**-11%**
1987	TT384	AVG V	0.820	2006	TB100	WV	0.748	**-0.072**	**-9%**
1987	SPTE	WU*(301)	0.800	2006	SPTE	WU	0.738	**-0.062**	**-8%**
1987	SPTE	WV*(201)	0.8	2006	SPTE	WV	0.762	**-0.038**	**-5%**
1987	SPTE	AVG U	0.800	2006	SPTE	WU	0.738	**-0.062**	**-8%**
1987	SPTE	AVG V	0.800	2006	SPTE	WV	0.762	**-0.038**	**-5%**

Table 12. Normal COR Data Summary Comparison of 1987 and 2006 Data for 32.5 deg 108 fps.

Test Date	Ball	Club	COR	Test Date	Ball	Club	COR	delta (COR)	delta %
1987	TT384	WU	0.830	2006	TT384	WU	0.737	**-0.093**	**-11%**
1987	TT384	WV	0.830	2006	TT384	WV	0.739	**-0.091**	**-11%**
1987	TT384	WU	0.830	2006	TB100	WU	0.740	**-0.090**	**-11%**
1987	TT384	WV	0.830	2006	TB100	WV	0.748	**-0.082**	**-10%**
1987	TT384	WU	0.830	2006	SPTE	WU	0.726	**-0.104**	**-13%**
1987	TT384	WV	0.830	2006	SPTE	WV	0.731	**-0.099**	**-12%**

APPENDIX D

IDENTIFICATION AND CHARACTERISATION OF EXPERIMENTAL SURROGATES FOR GRASS

22nd June 2006

INTRODUCTION

Appendix A describes player testing that was conducted to obtain representative launch conditions from lies in the fairway and in light rough using equipment typical of today's conformance limits and that of the period prior to the common use of U-grooves under conditions representing lies. One of the further objectives of this testing was to provide the baseline spin rates for the identification and characterisation of one or more experimental surrogates for grass.

Laboratory tests were conducted by firing golf balls from air cannon at clubs from the sets used in the player testing with a variety of materials placed in the interface between the club and ball. The resulting spin was measured and the values were compared to the measured spins from the player testing to determine the applicability of the interface materials as a surrogate for grass.

TEST EQUIPMENT

Two sets of equipment were used in the laboratory testing. Each set contained a 5-iron, an 8-iron and a sand wedge. One set represented a pre-1990 club/ball combination, another modern club/ball combination. The pre-1990 set utilised V-grooved irons with the Titleist Tour Balata, a wound, liquid centre balata covered golf ball. The modern set utilised U-grooved irons with the Titleist Pro V1 392, a solid, three piece urethane covered golf ball.

For the testing, the shafted test club was mounted in a test fixture (Figure 1) that held the club at the grip. During set-up for each club, the fixture was rotated to the correct lie angle. In addition the fixture was pivoted to obtain the impact loft angle that was measured for each club during player testing (including de-lofting). The appropriate golf balls were fired at the fixtured clubs at impact speeds equivalent to those measured for each club during player testing. The pre- and post- impact ball speed, angle and spin were measured and recorded for each shot. Figure 2 shows the spin test set-up.

Figure 1 – Club Test Fixture

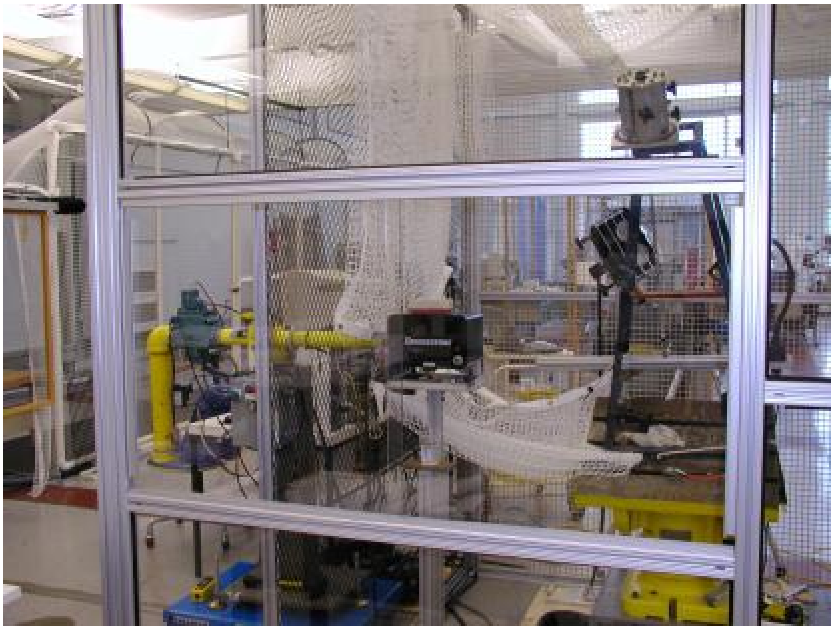


Figure 2 – Spin Test Set-up

A variety of papers and fabric with varying moisture levels were applied to the club face prior to impact. More than a dozen different materials/configurations went through an initial screening process. Through the screening process the number of viable candidate surrogates was narrowed to seven. The seven candidate grass surrogates include three different materials, two different moisture levels as well as a configuration with slits intended to mimic the blades of grass. These are listed in Table 1 and shown in Figure 3.

Table 1: Candidate Grass Surrogates

Candidate Surrogate Material	***Description***
Wet Newsprint	Standard newsprint soaked in water
Wet Fabric	Dupont Sontara EC (PR821) spunlaced fabric soaked in water
Wet Tissue	Tissue paper soaked in water
Wet Slitted Newsprint	Standard newsprint with a series of 3/16" wide slits soaked in water
Slitted Wet Fabric	Dupont Sontara EC (PR821) spunlaced fabric with a series of 3/16" wide slits soaked in water
2 Drop Slitted Newsprint	Standard newsprint with a series of 3/16" wide slits moistened with two drops of water
2 Drop Tissue	Tissue paper moistened with two drops of water

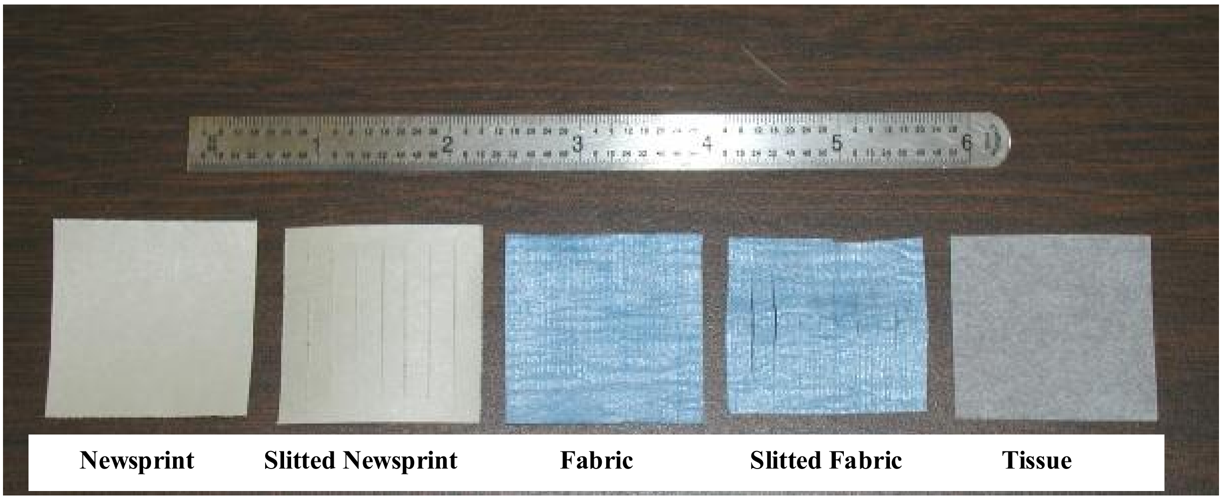


Figure 3 – Candidate Grass Surrogates

RESULTS

The graph in Figure 4 shows the measured spin rates of the seven candidate grass surrogates for each club tested. Also presented in the graph are the average player spin rates that were measured during the player testing for the shots from light rough.

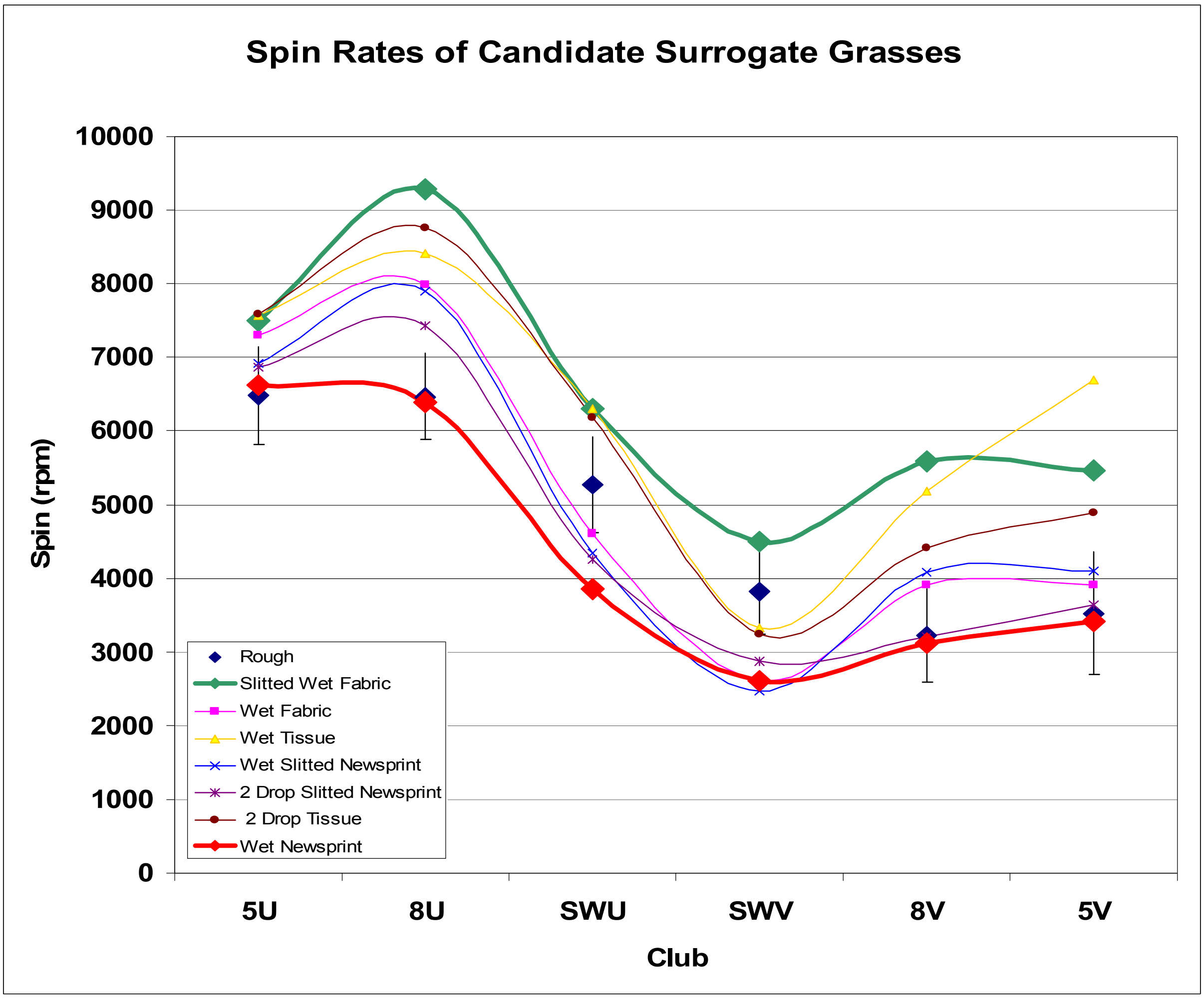


Figure 4 – Spin Test Results for Candidate Grass Surrogates

The results indicate that none of the candidate surrogates performs exactly like grass for all clubs. With the exception of two of the candidate surrogates all of the candidate surrogates showed similar trends when compared to the player test results; tending to reduce spin too much for the sand wedge and too little for the 5- and 8- irons.

One exception to this was the wet newsprint. For the 5- and 8- irons with both the U- and V-grooved clubs, the wet newsprint produced nearly identical spin rates in the lab testing to those measured during the player testing. However, for the sand wedge, the wet newsprint had too severe an effect; producing spin rates that were more than 1000 rpm less than measured during the player testing. The other exception was the wet, slitted fabric, which reduced the spin rates less than those measured during the player testing for all clubs. It can also be observed that the spins produced using wet newsprint and those produced using wet, slitted fabric bracket the spins measured during the player testing across all clubs.

SUMMARY AND CONCLUSIONS

Laboratory tests were conducted by firing golf balls from air cannon at clubs from the sets used in the player testing with a variety of materials placed in the interface between the club and ball. The resulting spin was measured and the values were compared to the measured spins from the player testing to determine the applicability of the interface materials as a surrogate for grass.

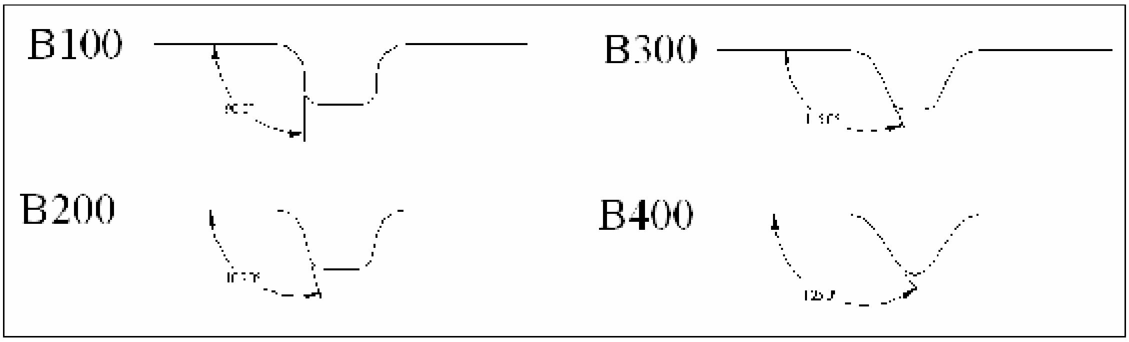
Seven candidate grass surrogates including three different materials, two different moisture levels as well as a configuration with slits intended to mimic the blades of grass were tested. None of the candidate surrogates performed exactly like grass for all clubs. However the spins produced using two of the surrogate candidates, wet newsprint and wet, slitted fabric, envelope the spins measured during the player testing across all clubs.

Based on these results it is recommended that the plate testing of various groove configurations be conducted using both the wet newsprint and the wet, slitted fabric as surrogates. Using such an approach would provide a conservative estimate of how each groove configuration would perform in rough conditions like that observed during the initial player testing.

APPENDIX E

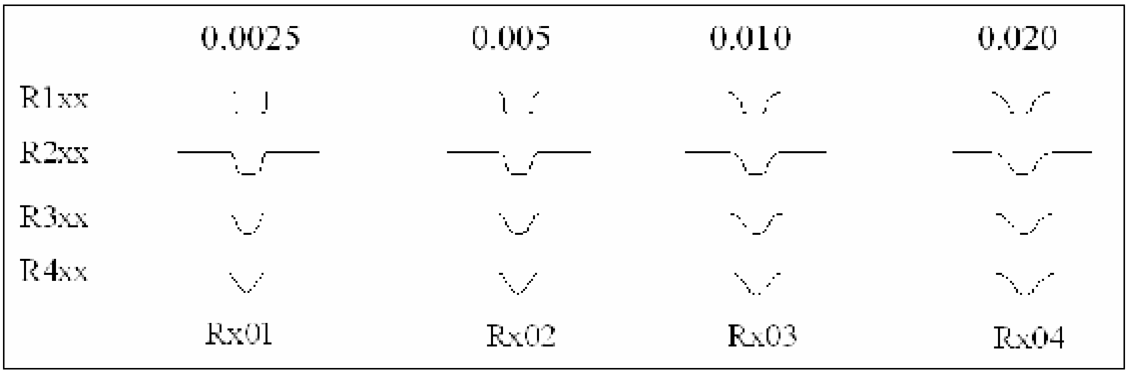
BASIS PLATES (B-SERIES)

Groove Width:	0.035”	Groove Depth:	0.020”
Edge Radius:	0.010”	Groove Spacing:	0.140”
Surface Roughness (Ra):	100 µin		



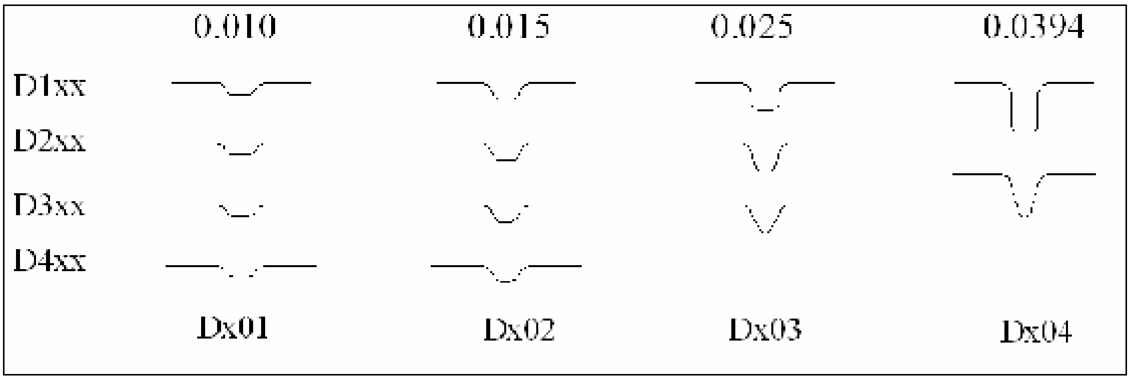
EDGE RADIUS PLATES (R-SERIES)

Groove Width:	0.035”	Groove Depth:	0.020”
Edge Radius:	As Shown	Groove Spacing:	0.140”
Surface Roughness (Ra):	100 µin		



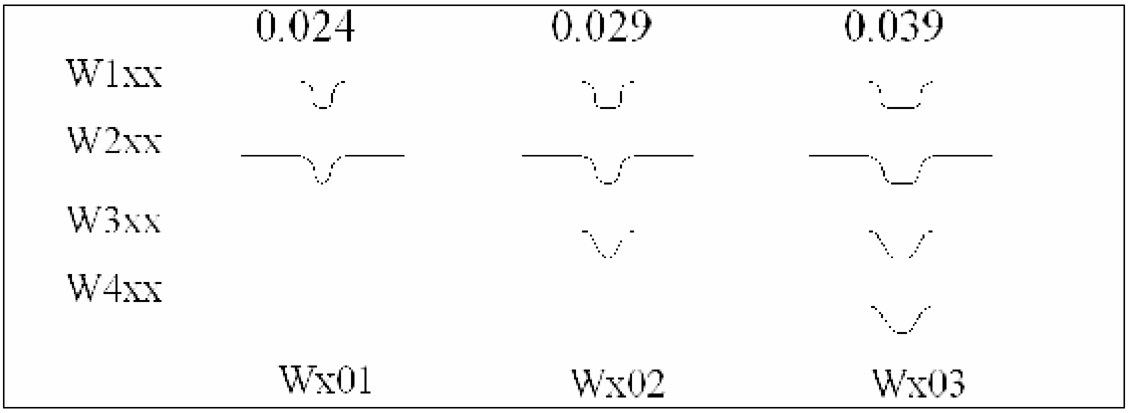
DEPTH PLATES (D-SERIES)

Groove Width:	0.035”	Groove Depth:	As Shown
Edge Radius:	0.010	Groove Spacing:	0.140”
Surface Roughness (Ra):	100 µin		



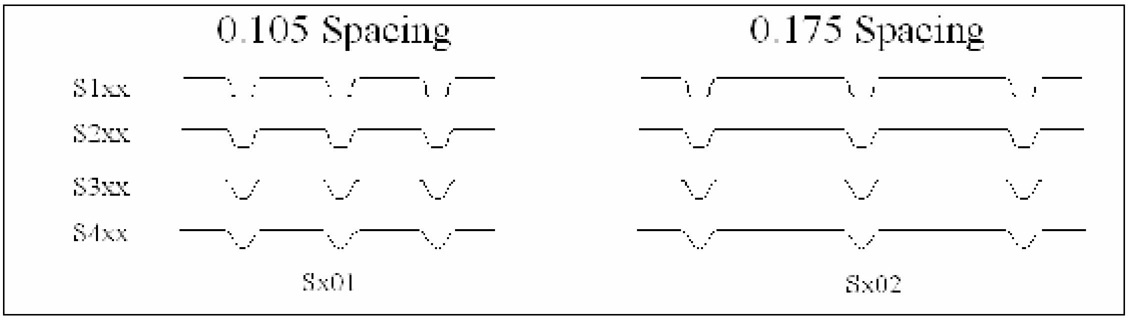
WIDTH PLATES (W-SERIES)

Groove Width:	As Shown	Groove Depth:	0.020”
Edge Radius:	0.010	Groove Spacing:	0.140”
Surface Roughness (Ra):	100 µin		



SPACING PLATES (S-SERIES)

Groove Width:	0.035”	Groove Depth:	0.020”
Edge Radius:	0.010	Groove Spacing:	As Shown
Surface Roughness (Ra):	100 µin		

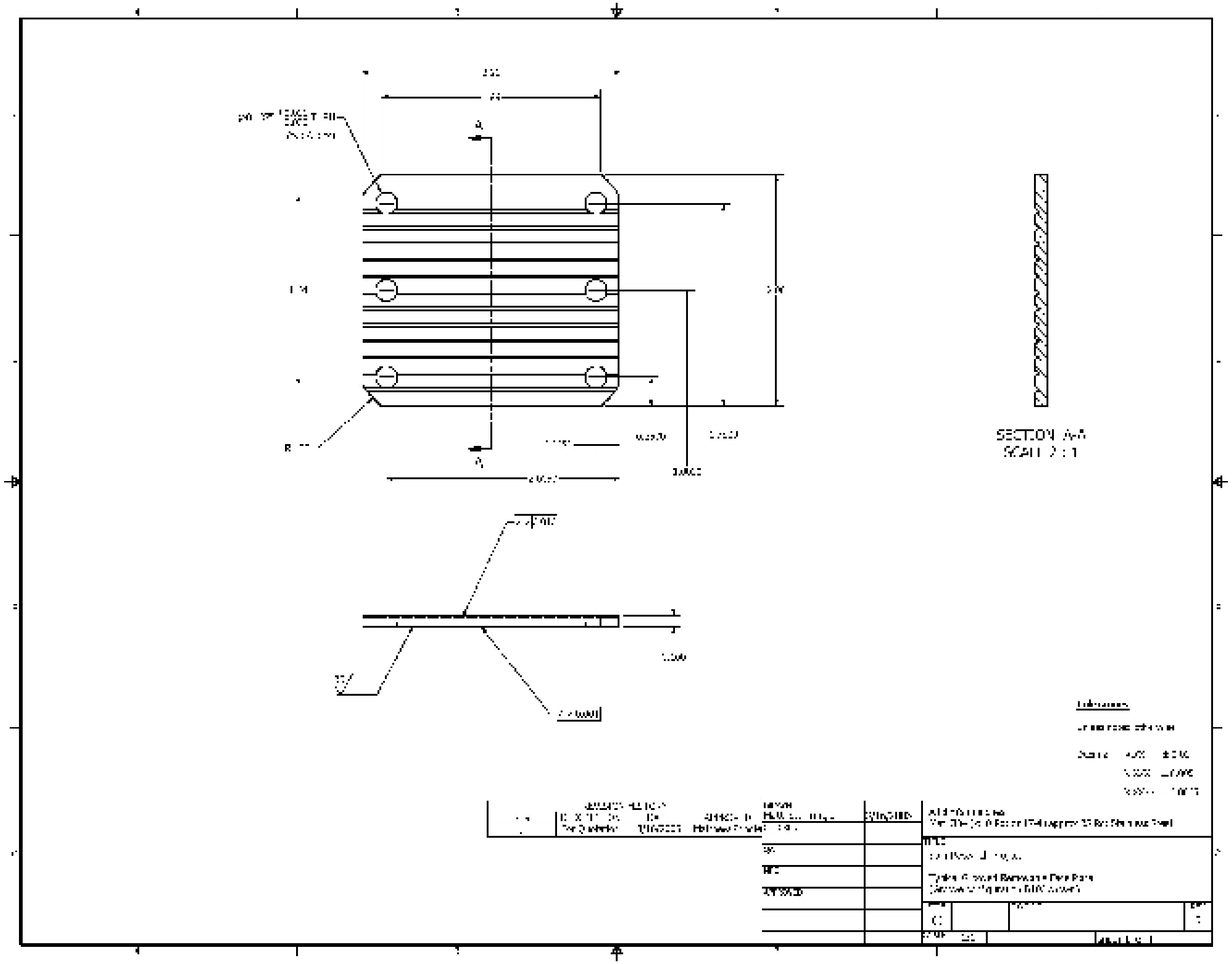


SURFACE ROUGHNESS PLATES (SR-SERIES)

Groove Width:	0.035”	Groove Depth:	0.020”
Edge Radius:	0.010	Groove Spacing:	0.140”
Surface Roughness (Ra):	Abrasive blasting and milling specifications to be determined		

APPENDIX F

Test Plate Dimensions



APPENDIX G

PROCEDURE TO STUDY THE EFFECT OF GROOVE SPECIFICATIONS ON LAUNCH CONDITIONS

23rd June 2006

PURPOSE

To measure the effect of groove configuration and surface treatments on the rebound of a golf ball.

EQUIPMENT REQUIRED

Kistler load triaxial load cell Test plates ProV1 balls

Two launch monitors (to measure inbound and outbound ball conditions)

PC with 12-bit Pico scope and two serial ports to retrieve launch monitor data.

SELECTION OF SPEED AND ANGLE SETTINGS

As has been discussed in a previous report, with laboratory testing, we have only two variables to manipulate, (i) ball speed and (ii) target angle. Therefore, it is not possible to match three launch conditions precisely. We have elected for this study to have experimental settings that are representative of the **ball spin rate** and **launch velocity** observed for the dry condition player testing.

Figure 1 shows the relationship between the dynamic loft of the club (that is the static loft minus the observed deloft and the angle of attack) and the resulting ball speed and spin rate.

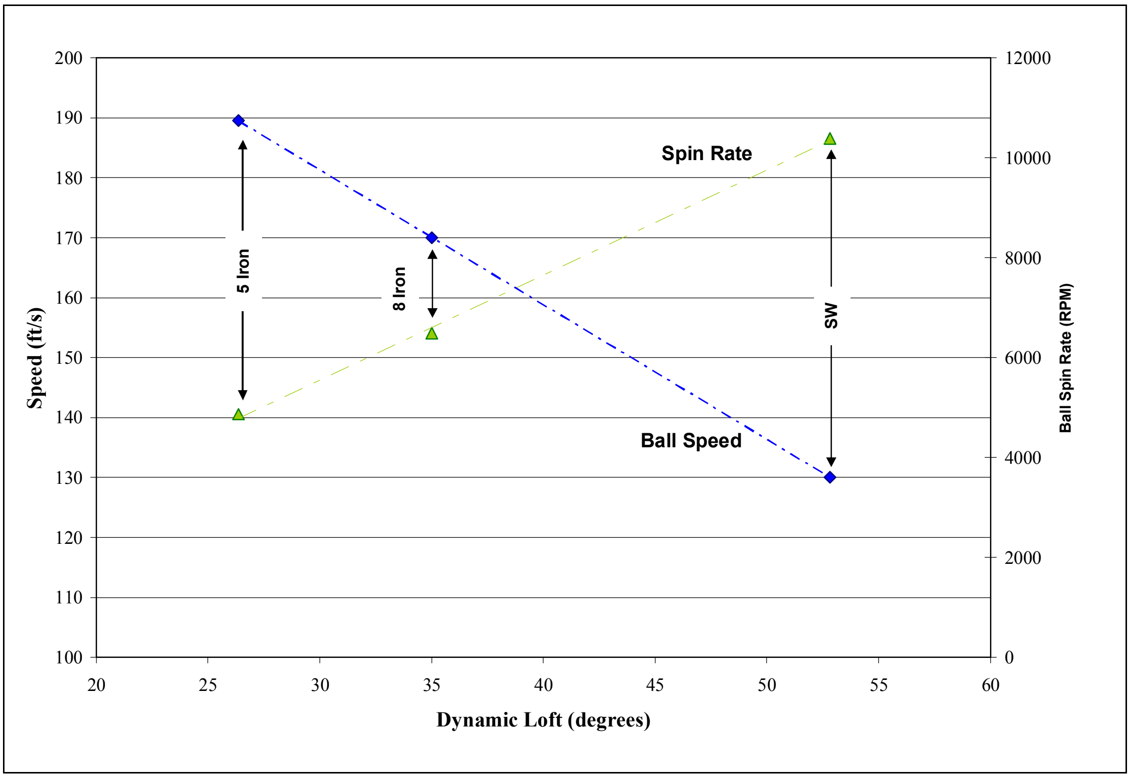


Figure 1: Ball speed and spin as a function of dynamic loft

Rather than attempting to experimentally determine the inbound ball speed and angle for the range of irons, a lumped parameter model due to Maw has been used to predict these settings. The model prediction was checked at one setting and it is expected that reasonable results will be observed at the other angles. The result of this model is shown in Figure 2. For example, if we want to simulate a 7 iron (static loft of 35 degrees) the infinite mass ball speed would be 112.3 ft/s and the plate angle would be 31.4 degrees. It is expected that, in the dry conditions, this will result in a net ball speed of 179 ft/s and a spin rate of 6100 RPM.

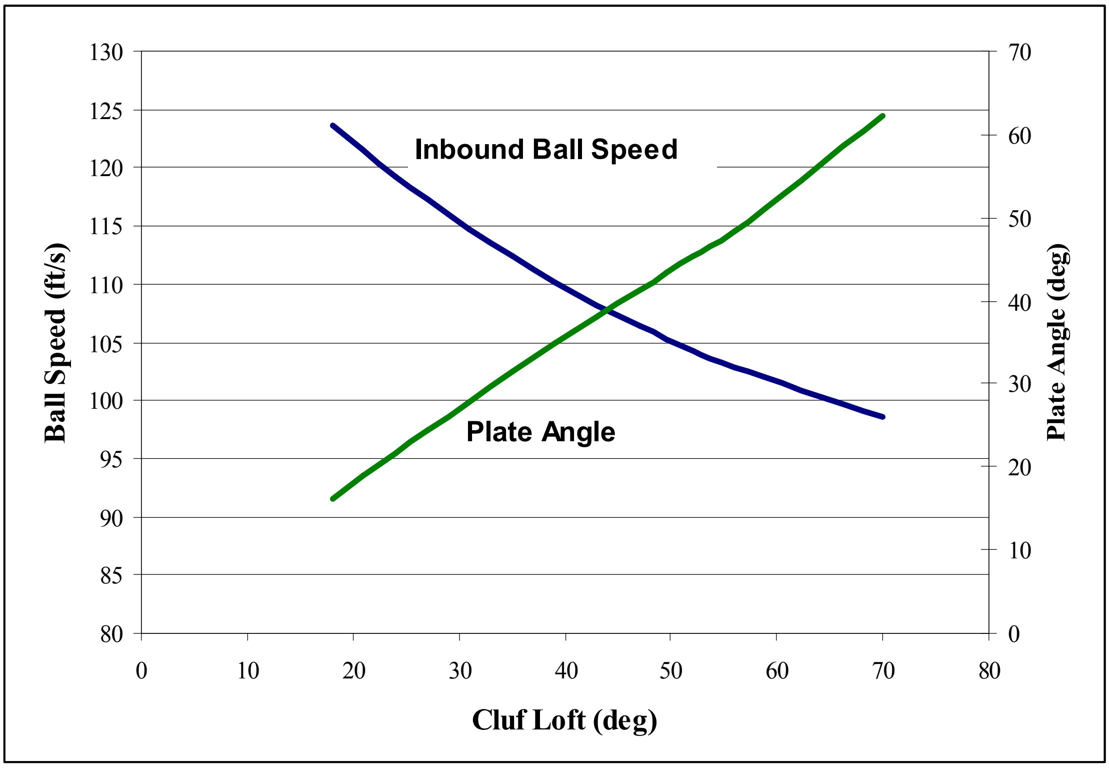


Figure 2: Infinite Mass settings as a function of simulated club loft

Testing Overview

In order to establish a good reference, both the base U and V plates will be tested at plate angles of 20 to 60 degrees in 10 degree increments (with the appropriate ball speed as shown in Figure 2). These two plates will be tested dry and wet with both paper types. Following this, the plates will be tested wet with both papers (but not dry conditions) at 25, 35, 48 and 62 degrees which represent 5, 8, SW and flop shots; where possible, non-productive testing will be eliminated.

Procedure

Figure 3 shows the test set up including the massive block housing the triaxial load cell and the outbound launch monitor.

Figure 3: Grooved test plate oblique impact test setup

Base U and V Plate Testing

The objective of this portion of the testing is to establish a set of baseline performances for both the current groove specification (U) and the target groove specification (V) in the dry and with both paper types across a wide range of impact angles.

The test conditions for this portion of the procedure are given in Table 1 in the appendix at the end of the document.

1) Mount plate B100 (base U groove) on the Kistler base plate
2) Rotate the block to the first angle given in Table 1 and adjust ball speed to the speed given in Table 1. Ball speed tolerance is 1.5 ft/s.
3) Ensure that the impact location is as centred on the plate as practical.
4) Adjust the position of the outbound BFA to capture the outbound ball.

5) Open the c:\impact station data\Kistler BFA Master.xls data recording spreadsheet. Be sure to record the outbound BFA angle.
6) Save the spreadsheet using the naming convention provided in Table 1.
7) Launch balls into the plate in dry conditions and record the inbound and outbound results from the BFA. Also record the first impact from the Kistler transducer.
8) Repeat step 6 until the confidence interval is less than 5 RPS.
9) Save and close the spreadsheet.
10) Repeat steps 4 through 9 for the remaining conditions given in Table 1.
11) Repeat steps 1 through 10 with plate B400 (base V groove)

Remaining Plates

The test procedure for the remaining plates is similar to that for the base U and V plates except that (i) the dry condition is not tested and (ii) there are not as many angles. The procedure is as listed above following the settings listed in Table 2.

Table 1: Base Plate Testing

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
B1	B100	20	120	•		
B2	B100	20	120		•	
B3	B100	20	120			•
B4	B100	30	114	•		
B5	B100	30	114		•	
B6	B100	30	114			•
B7	B100	40	107	•		
B8	B100	40	107		•	
B9	B100	40	107			•
B10	B100	50	101	•		
B11	B100	50	101		•	
B12	B100	50	101			•
B13	B100	60	94	•		
B14	B100	60	94		•	
B15	B100	60	94			•
B16	B400	20	120	•		
B17	B400	20	120		•	
B18	B400	20	120			•
B19	B400	30	114	•		
B20	B400	30	114		•	
B21	B400	30	114			•
B22	B400	40	107	•		
B23	B400	40	107		•	
B24	B400	40	107			•
B25	B400	50	101	•		
B26	B400	50	101		•	
B27	B400	50	101			•
B28	B400	60	94	•		
B29	B400	60	94		•	
B30	B400	60	94			•

Table 2: Plate Testing Schedule

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
B31	B200	25	117		•	
B32	B200	25	117			•
B33	B200	35	111		•	
B34	B200	35	111			•
B35	B200	48	102		•	
B36	B200	48	102			•
B37	B200	62	94		•	
B38	B200	62	94			•
B39	B300	25	117		•	
B40	B300	25	117			•
B41	B300	35	111		•	
B42	B300	35	111			•
B43	B300	48	102		•	
B44	B300	48	102			•
B45	B300	62	94		•	
B46	B300	62	94			•
S1	S101	25	117		•	
S2	S101	25	117			•
S3	S101	35	111		•	
S4	S101	35	111			•
S5	S101	48	102		•	
S6	S101	48	102			•
S7	S101	62	94		•	
S8	S101	62	94			•
S9	S102	25	117		•	
S10	S102	25	117			•
S11	S102	35	111		•	
S12	S102	35	111			•
S13	S102	48	102		•	
S14	S102	48	102			•
S15	S102	62	94		•	
S16	S102	62	94			•
S17	S401	25	117		•	
S18	S401	25	117			•
S19	S401	35	111		•	
S20	S401	35	111			•
S21	S401	48	102		•	
S22	S401	48	102			•
S23	S401	62	94		•	
S24	S401	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
S25	S402	25	117		•	
S26	S402	25	117			•
S27	S402	35	111		•	
S28	S402	35	111			•
S29	S402	48	102		•	
S30	S402	48	102			•
S31	S402	62	94		•	
S32	S402	62	94			•
S33	S201	25	117		•	
S34	S201	25	117			•
S35	S201	35	111		•	
S36	S201	35	111			•
S37	S201	48	102		•	
S38	S201	48	102			•
S39	S201	62	94		•	
S40	S201	62	94			•
S41	S202	25	117		•	
S42	S202	25	117			•
S43	S202	35	111		•	
S44	S202	35	111			•
S45	S202	48	102		•	
S46	S202	48	102			•
S47	S202	62	94		•	
S48	S202	62	94			•
S49	S301	25	117		•	
S50	S301	25	117			•
S51	S301	35	111		•	
S52	S301	35	111			•
S53	S301	48	102		•	
S54	S301	48	102			•
S55	S301	62	94		•	
S56	S301	62	94			•
S57	S302	25	117		•	
S58	S302	25	117			•
S59	S302	35	111		•	
S60	S302	35	111			•
S61	S302	48	102		•	
S62	S302	48	102			•
S63	S302	62	94		•	
S64	S302	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
D1	D101	25	117		•	
D2	D101	25	117			•
D3	D101	35	111		•	
D4	D101	35	111			•
D5	D101	48	102		•	
D6	D101	48	102			•
D7	D101	62	94		•	
D8	D101	62	94			•
D9	D102	25	117		•	
D10	D102	25	117			•
D11	D102	35	111		•	
D12	D102	35	111			•
D13	D102	48	102		•	
D14	D102	48	102			•
D15	D102	62	94		•	
D16	D102	62	94			•
D17	D103	25	117		•	
D18	D103	25	117			•
D19	D103	35	111		•	
D20	D103	35	111			•
D21	D103	48	102		•	
D22	D103	48	102			•
D23	D103	62	94		•	
D24	D103	62	94			•
D25	D104	25	117		•	
D26	D104	25	117			•
D27	D104	35	111		•	
D28	D104	35	111			•
D29	D104	48	102		•	
D30	D104	48	102			•
D31	D104	62	94		•	
D32	D104	62	94			•
D33	D201	25	117		•	
D34	D201	25	117			•
D35	D201	35	111		•	
D36	D201	35	111			•
D37	D201	48	102		•	
D38	D201	48	102			•
D39	D201	62	94		•	
D40	D201	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
D41	D202	25	117		•	
D42	D202	25	117			•
D43	D202	35	111		•	
D44	D202	35	111			•
D45	D202	48	102		•	
D46	D202	48	102			•
D47	D202	62	94		•	
D48	D202	62	94			•
D49	D203	25	117		•	
D50	D203	25	117			•
D51	D203	35	111		•	
D52	D203	35	111			•
D53	D203	48	102		•	
D54	D203	48	102			•
D55	D203	62	94		•	
D56	D203	62	94			•
D57	D204	25	117		•	
D58	D204	25	117			•
D59	D204	35	111		•	
D60	D204	35	111			•
D61	D204	48	102		•	
D62	D204	48	102			•
D63	D204	62	94		•	
D64	D204	62	94			•
D65	D301	25	117		•	
D66	D301	25	117			•
D67	D301	35	111		•	
D68	D301	35	111			•
D69	D301	48	102		•	
D70	D301	48	102			•
D71	D301	62	94		•	
D72	D301	62	94			•
D73	D302	25	117		•	
D74	D302	25	117			•
D75	D302	35	111		•	
D76	D302	35	111			•
D77	D302	48	102		•	
D78	D302	48	102			•
D79	D302	62	94		•	
D80	D302	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
D81	D303	25	117		•	
D82	D303	25	117			•
D83	D303	35	111		•	
D84	D303	35	111			•
D85	D303	48	102		•	
D86	D303	48	102			•
D87	D303	62	94		•	
D88	D303	62	94			•
D89	D304	25	117		•	
D90	D304	25	117			•
D91	D304	35	111		•	
D92	D304	35	111			•
D93	D304	48	102		•	
D94	D304	48	102			•
D95	D304	62	94		•	
D96	D304	62	94			•
D97	D401	25	117		•	
D98	D401	25	117			•
D99	D401	35	111		•	
D100	D401	35	111			•
D101	D401	48	102		•	
D102	D401	48	102			•
D103	D401	62	94		•	
D104	D401	62	94			•
D105	D402	25	117		•	
D106	D402	25	117			•
D107	D402	35	111		•	
D108	D402	35	111			•
D109	D402	48	102		•	
D110	D402	48	102			•
D111	D402	62	94		•	
D112	D402	62	94			•
R1	R101	25	117		•	
R2	R101	25	117			•
R3	R101	35	111		•	
R4	R101	35	111			•
R5	R101	48	102		•	
R6	R101	48	102			•
R7	R101	62	94		•	
R8	R101	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
R9	R102	25	117		•	
R10	R102	25	117			•
R11	R102	35	111		•	
R12	R102	35	111			•
R13	R102	48	102		•	
R14	R102	48	102			•
R15	R102	62	94		•	
R16	R102	62	94			•
R17	R103	25	117		•	
R18	R103	25	117			•
R19	R103	35	111		•	
R20	R103	35	111			•
R21	R103	48	102		•	
R22	R103	48	102			•
R23	R103	62	94		•	
R24	R103	62	94			•
R25	R104	25	117		•	
R26	R104	25	117			•
R27	R104	35	111		•	
R28	R104	35	111			•
R29	R104	48	102		•	
R30	R104	48	102			•
R31	R104	62	94		•	
R32	R104	62	94			•
R33	R201	25	117		•	
R34	R201	25	117			•
R35	R201	35	111		•	
R36	R201	35	111			•
R37	R201	48	102		•	
R38	R201	48	102			•
R39	R201	62	94		•	
R40	R201	62	94			•
R41	R202	25	117		•	
R42	R202	25	117			•
R43	R202	35	111		•	
R44	R202	35	111			•
R45	R202	48	102		•	
R46	R202	48	102			•
R47	R202	62	94		•	
R48	R202	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
R49	R203	25	117		•	
R50	R203	25	117			•
R51	R203	35	111		•	
R52	R203	35	111			•
R53	R203	48	102		•	
R54	R203	48	102			•
R55	R203	62	94		•	
R56	R203	62	94			•
R57	R204	25	117		•	
R58	R204	25	117			•
R59	R204	35	111		•	
R60	R204	35	111			•
R61	R204	48	102		•	
R62	R204	48	102			•
R63	R204	62	94		•	
R64	R204	62	94			•
R65	R301	25	117		•	
R66	R301	25	117			•
R67	R301	35	111		•	
R68	R301	35	111			•
R69	R301	48	102		•	
R70	R301	48	102			•
R71	R301	62	94		•	
R72	R301	62	94			•
R73	R302	25	117		•	
R74	R302	25	117			•
R75	R302	35	111		•	
R76	R302	35	111			•
R77	R302	48	102		•	
R78	R302	48	102			•
R79	R302	62	94		•	
R80	R302	62	94			•
R81	R303	25	117		•	
R82	R303	25	117			•
R83	R303	35	111		•	
R84	R303	35	111			•
R85	R303	48	102		•	
R86	R303	48	102			•
R87	R303	62	94		•	
R88	R303	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
R89	R304	25	117		•	
R90	R304	25	117			•
R91	R304	35	111		•	
R92	R304	35	111			•
R93	R304	48	102		•	
R94	R304	48	102			•
R95	R304	62	94		•	
R96	R304	62	94			•
R97	R401	25	117		•	
R98	R401	25	117			•
R99	R401	35	111		•	
R100	R401	35	111			•
R101	R401	48	102		•	
R102	R401	48	102			•
R103	R401	62	94		•	
R104	R401	62	94			•
R105	R402	25	117		•	
R106	R402	25	117			•
R107	R402	35	111		•	
R108	R402	35	111			•
R109	R402	48	102		•	
R110	R402	48	102			•
R111	R402	62	94		•	
R112	R402	62	94			•
R113	R403	25	117		•	
R114	R403	25	117			•
R115	R403	35	111		•	
R116	R403	35	111			•
R117	R403	48	102		•	
R118	R403	48	102			•
R119	R403	62	94		•	
R120	R403	62	94			•
R121	R404	25	117		•	
R122	R404	25	117			•
R123	R404	35	111		•	
R124	R404	35	111			•
R125	R404	48	102		•	
R126	R404	48	102			•
R127	R404	62	94		•	
R128	R404	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
W1	W101	25	117		•	
W2	W101	25	117			•
W3	W101	35	111		•	
W4	W101	35	111			•
W5	W101	48	102		•	
W6	W101	48	102			•
W7	W101	62	94		•	
W8	W101	62	94			•
W9	W102	25	117		•	
W10	W102	25	117			•
W11	W102	35	111		•	
W12	W102	35	111			•
W13	W102	48	102		•	
W14	W102	48	102			•
W15	W102	62	94		•	
W16	W102	62	94			•
W17	W103	25	117		•	
W18	W103	25	117			•
W19	W103	35	111		•	
W20	W103	35	111			•
W21	W103	48	102		•	
W22	W103	48	102			•
W23	W103	62	94		•	
W24	W103	62	94			•
W25	W201	25	117		•	
W26	W201	25	117			•
W27	W201	35	111		•	
W28	W201	35	111			•
W29	W201	48	102		•	
W30	W201	48	102			•
W31	W201	62	94		•	
W32	W201	62	94			•
W33	W202	25	117		•	
W34	W202	25	117			•
W35	W202	35	111		•	
W36	W202	35	111			•
W37	W202	48	102		•	
W38	W202	48	102			•
W39	W202	62	94		•	
W40	W202	62	94			•

Test #	Plate	Angle (from vertical)	Ball Speed (ft/s)	Dry	Wet Newsprint	Wet Slitted Blue Cloth
W41	W203	25	117		•	
W42	W203	25	117			•
W43	W203	35	111		•	
W44	W203	35	111			•
W45	W203	48	102		•	
W46	W203	48	102			•
W47	W203	62	94		•	
W48	W203	62	94			•
W49	W302	25	117		•	
W50	W302	25	117			•
W51	W302	35	111		•	
W52	W302	35	111			•
W53	W302	48	102		•	
W54	W302	48	102			•
W55	W302	62	94		•	
W56	W302	62	94			•
W57	W303	25	117		•	
W58	W303	25	117			•
W59	W303	35	111		•	
W60	W303	35	111			•
W61	W303	48	102		•	
W62	W303	48	102			•
W63	W303	62	94		•	
W64	W303	62	94			•
W65	W403	25	117		•	
W66	W403	25	117			•
W67	W403	35	111		•	
W68	W403	35	111			•
W69	W403	48	102		•	
W70	W403	48	102			•
W71	W403	62	94		•	
W72	W403	62	94			•

APPENDIX H

FUNDAMENTAL MECHANICS OF OBLIQUE IMPACT (PART II: HOMOGENOUS ELASTIC SPHERE)

3rd March 2005

SUMMARY

It was shown in a previous report **[1]** that a substantial portion of the behaviour of golf balls in oblique impact can be described by the dynamics of rigid spheres. However, some of the behaviour was not as well captured by this model. A recommendation of this report was to investigate alternative analytic and finite element models in order to better understand oblique impact behaviour. It was a further recommendation of this report that additional experimental data be gathered. This report summarises an oblique impact model proposed by Maw, Barber and Fawcett **[2]** and its subsequent comparison to a wide range of experimental conditions tested.

Although a substantial amount of experimental data will be presented in this report, a subsequent report will be generated with a more thorough description of the experimental method and results.

1. MODELLING OBLIQUE CONTACT OF HOMOGENEOUS ELASTIC BODIES

1.1 NORMAL CONTACT

The mechanics of normal contact between two solids of revolution is well documented and is attributed to Hertz. Derivation of this description of contact is beyond the scope of this report (see Johnson **[3]** for details). However, it is useful to review some important results of this description. Figure 1 shows the collision between two collinear spheres. Each sphere is homogenous, isotropic, and elastic. At the start of the collision, contact is made at a point with an infinitesimally small mutual force between them. As the collision progresses, the centres of the spheres become closer, and the force between the two increases. Commensurate with this, is an increase in the area of the (circular) contact region. The mutual force between the two slows the approach velocity. Eventually, the spheres will reverse their approach velocity and begin separating.

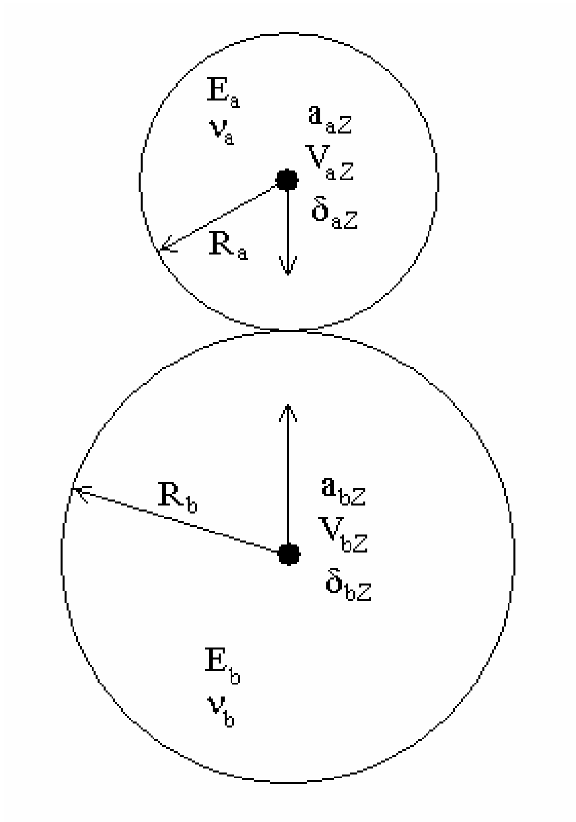


Figure 1: Normal contact of elastic spheres

Hertz, in the later portion of the nineteenth century, derived expressions for the mutual force between the two bodies as a function of their mutual approach. These expressions remain valid today, and will be used to describe the normal contact between the golf ball and the target surface. The force between the two bodies as a function of the distance of mutual approach (δ_z) is given by **[3]**:

$$P = \frac{4}{3} R^{1/2} E \delta_Z^{3/2} = K \delta_Z^{3/2} \tag{1.1}$$

where *R*, the equivalent radius of curvature is given by:

$$\frac{1}{R} = \frac{1}{R_a} + \frac{1}{R_b} \tag{1.2}$$

and the equivalent elastic modulus by:

$$\frac{1}{E}=\frac{(1-\nu_a)}{E_a}+\frac{(1-\nu_b)}{E_b} \tag{1.3}$$

The ordinary differential equation therefore for the impact of two elastic spheres is:

$$m\frac{d^2\delta_Z}{dt^2}=-K\delta_Z^{3/2} \tag{1.4}$$

where *m* is the equivalent mass of the spheres:

$$\frac{1}{m}=\frac{1}{m_a}+\frac{1}{m_b} \tag{1.5}$$

Additionally, the radius of the circular contact area, *b*, may be found from the mutual approach distance, δ_z:

$$b=(R\delta_Z)^{1/2} \tag{1.6}$$

1.2 TANGENTIAL CONTACT

Analogous to the quantifiable force/displacement relationship in the normal direction, the deformation of an elastic sphere in response to tangential force may be calculated. The tangential loading of elastic spheres was considered initially by Mindlin **[4]** and Mindlin and Deresiewicz **[5]**. It is from this work that Maw, et al. **[2]** derives expressions for the tangential compliance. It is beyond the scope of this paper to discuss the formulation of Maw et al. much less the tangential compliance derivations of Mindlin and Mindlin and Deresiewicz. However a very brief review of the important relations will be presented.

It is assumed that the tangential traction on the contact area is of the form:

$$f(r)\propto\left(1-\frac{r^2}{b^2}\right)^{1/2} \tag{1.7}$$

(Note that the distribution of normal pressure is ***[3]****:*

$$p(r)=p(0)\left(1-\frac{r^2}{b^2}\right)^{1/2} \tag{1.8}$$

If the frictional behaviour is assumed to be Newtonian (that is, the maximum tangential friction force is proportional to the normal force), and the entire contact surface is in slip then the origin of (1.7) is clear. However, if a certain region of the contact area is stuck to the target surface, it would appear to the author that the distribution of tractions is statically indeterminate and hence the justification of (1.7) is unclear. However, we will proceed unhindered and explore the distribution of tangential traction question at a later date.)

Given (1.7), the work of Mindlin **[4]** and some simplifying assumptions discussed by Maw et al. **[2]**, the tangential displacement in the direction of the gross velocity of the ball is:

$$u_x = \frac{\pi}{16Gb}\left[2(2-\nu)\left(2b^2 - r^2\right)\right], \quad 0 \le r \le b \\ = 0, \qquad r > b \tag{1.9}$$

Equations (1.7) and (1.9) therefore provide a basis for a tangential force/displacement relationship that are inserted into the equations of motion (both linear and rotational) and solved numerically for the duration of the contact.

A Matlab® program based on the original FORTRAN code of Maw et al. has been written to solve the equations of motion in the normal and tangential directions.

2. Oblique Impact Simulation

2.1 System Definition and Initial Conditions

A useful benefit of the equations of motion when cast in non-dimensional form is that the properties of the sphere can be characterised by a single parameter:

$$\chi = \frac{\kappa m}{2m^*} \tag{2.1}$$

where:

$$m_i^* = \frac{m_i}{\left(1 + \frac{R_i^2}{k_i^2}\right)}, \qquad \frac{1}{m^*} = \frac{1}{m_a^*} + \frac{1}{m_b^*} \tag{2.2}$$

(*k* being the radius of gyration of the sphere) and:

$$\frac{1}{\kappa} \equiv \frac{\dfrac{1-\nu_a/2}{G_a} + \dfrac{1-\nu_b/2}{G_b}}{\dfrac{1-\nu_a}{G_a} + \dfrac{1-\nu_b}{G_b}} \tag{2.3}$$

and the initial conditions are also defined by a single non-dimensional parameter:

$$\psi = \frac{2(1-\nu)}{\mu(2-\nu)} \cdot \frac{V_x}{V_{z0}} \tag{2.4}$$

where μ is the coefficient of friction (assumed to be the same for static and dynamic conditions), V_x is the relative tangential velocity that is normalised by the initial relative normal velocity.

3.1 Generalised Impact Behaviour Against a Rigid Barrier

3.1.1 Sliding Contact

As discussed in Part I of this series of reports **[1]**, when there is insufficient friction for a given collision condition, the ball will slide throughout the entire impact. Due to the sliding, the force between the ball and the barrier in the tangential direction will be (i) proportional to the normal force and (ii) generated throughout the entire impact regardless of whether the ball is rigid or flexible. Hence, the final spin will be independent of the elastic behaviour of the sphere.

3.1.2 "Rolling" Contact

For a rigid sphere, a tangential force will be applied when contact commences. This force will both increase the spin and decrease the tangential velocity until, at some point in the collision, the relative tangential speed between the surface of the ball and the barrier becomes zero. At this point, a rigid sphere would be rolling on the surface of the barrier. Since the sphere is rolling, there is no longer any tangential force between the two bodies. The spin generated therefore is a function only of the initial relative velocity and mass properties of the sphere. Provided there is sufficient friction to achieve this rolling contact *at any time during the impact*, the final spin and tangential velocity will be the same.

The presence of flexibility of the ball significantly changes the tangential response. The flexibility may be thought of as a spring which, when coupled with the mass properties of the ball results in an oscillatory system. Unlike the rigid sphere, tangential forces applied to the flexible ball do not instantaneously increase spin. Increased spin is delayed through the spring action of the flexible ball. This delay permits the tangential force to be applied for a longer time than that of a rigid ball, potentially resulting in significantly higher spin. However, this spring action can also result in a reversing of the oscillation of the system such that the tangential force acts to reduce spin as the impact progresses.

For example, Figure 2 shows the predicted force-time history for a one-piece rubber golf ball against a thirty degree barrier. Superimposed on this is the force-time history for a tangentially rigid sphere of similar mass properties.

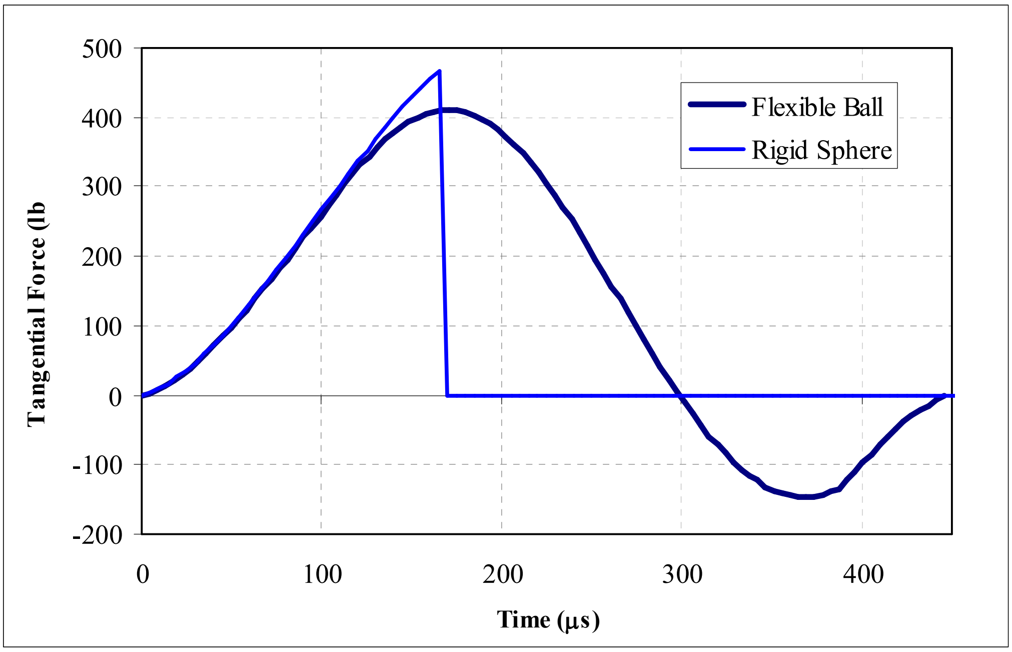


Figure 2: Tangential force history for tangentially flexible and rigid spheres (30° barrier, 80 ft/s, =0.3)

It may be seen in Figure 2 that initially, the two time histories are coincident. This corresponds to slipping contact in both models. It can also be seen that at approximately 170 μs, the rigid model predicts a sudden drop in the tangential force as sliding transitions to rolling contact. However, this behaviour is inconsistent with experimental observations for golf balls. Focusing therefore on the flexible ball model, it may be seen that the tangential force continues to be generated well after sliding has ceased. After 300 μs, the force has finally reduced to zero. However, due to the oscillatory nature of the flexible model, the force then reverses and actually reduces the final tangential impulse, and by extension, the spin. This force reversal is a key component in understanding the nature of the oblique impact. Capturing this feature is a powerful addition to the analytical model.

3.2 Ball Parameter

The tangential force reversal, which is fundamental to oblique impact, depends on the timing of the tangential oscillation of the ball relative to the total contact time. That is, the behaviour of the force reversal will depend on the natural frequency of the ball in the tangential direction relative to that in the normal direction. Since the ball is characterised by only one parameter (χ) in the model, it is not surprising that the ratio of natural frequencies is a function of χ . According to Maw et al. **[5]**:

$$\frac{\omega_T}{\omega_N} = \sqrt{2\chi} \tag{2.5}$$

Therefore, if more force reversal is desired, the tangential frequency (and hence stiffness) should be increased relative to the normal direction and vice-versa. In practice, χ for a homogenous ball can only be varied within a small range. For example, a rubber sphere has a value of 1.17 and a steel sphere is 1.44. This results in a natural frequency ratio of 1.53 to 1.7. In the case of golf balls made of rubber or other polymers, the range for homogenous construction is even lower. However, golf balls need not be constructed homogenously, and by combining various layers, it is practical to achieve properties outside of that achievable with only one layer.

In order to explore the effect of the natural frequency ratio on the impact response, the variable χ was allowed to vary beyond that which is attainable for a homogenous sphere (from 0.6 to 17). The results are given in Figure 3, again for a thirty degree impact. The bold blue trace is that of a homogenous rubber ball. As χ is increased, the tangential force reversal occurs earlier reducing the final tangential impulse (and spin). As the tangential stiffness increases even more, the tangential force will begin to go through multiple oscillations. Initially this may seem physically unrealistic. However Cross **[6]**, presented experimental force measurements for a basketball oblique impact (as well as other ball types) that displayed three complete cycles of tangential force. This may be explained by the fact that the normal stiffness of an inflated basketball is quite low. (*Note: this also suggests that the oblique impact behaviour of inflatables may be quite sensitive to inflation pressure*).

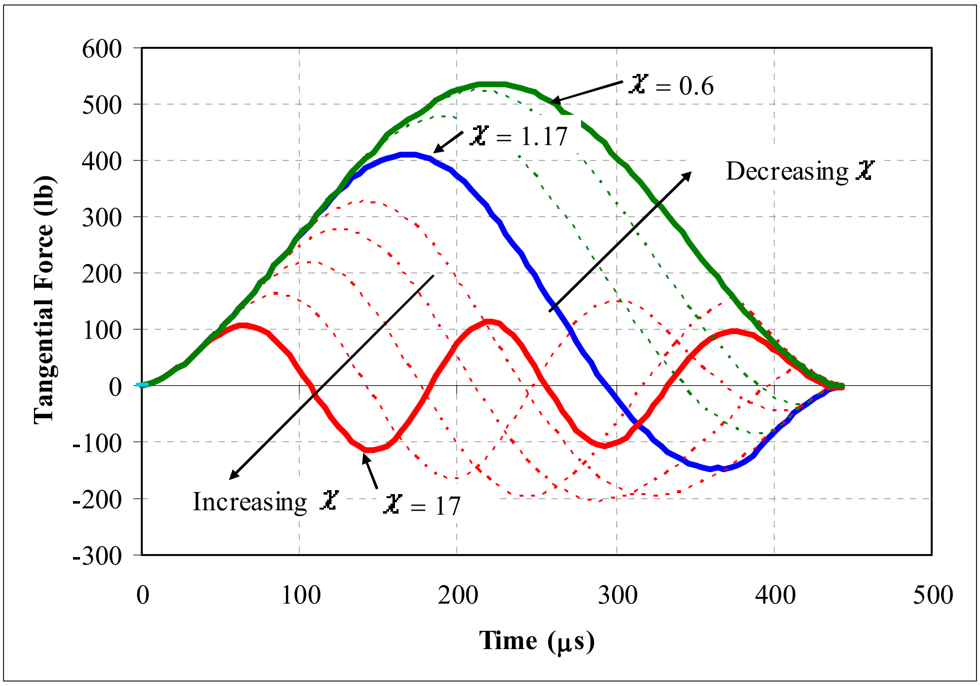


Figure 3: Effect of tangential stiffness on tangential force history (30° barrier, 80 ft/s, =0.3)

Conversely, by decreasing χ, the force reversal is delayed, and the final tangential impulse is greater. Eventually, if the tangential stiffness is reduced sufficiently, a friction limit on the tangential force will be met, and no further change will occur. This suggests a physical limit on the maximum spin that can be created for a given sphere and inbound condition. This limit corresponds to the slip limit discussed in Section 2.2.1. Figure 4 shows the progression of spin rate for a ball having the mass properties of a golf ball but with varying tangential flexibility.

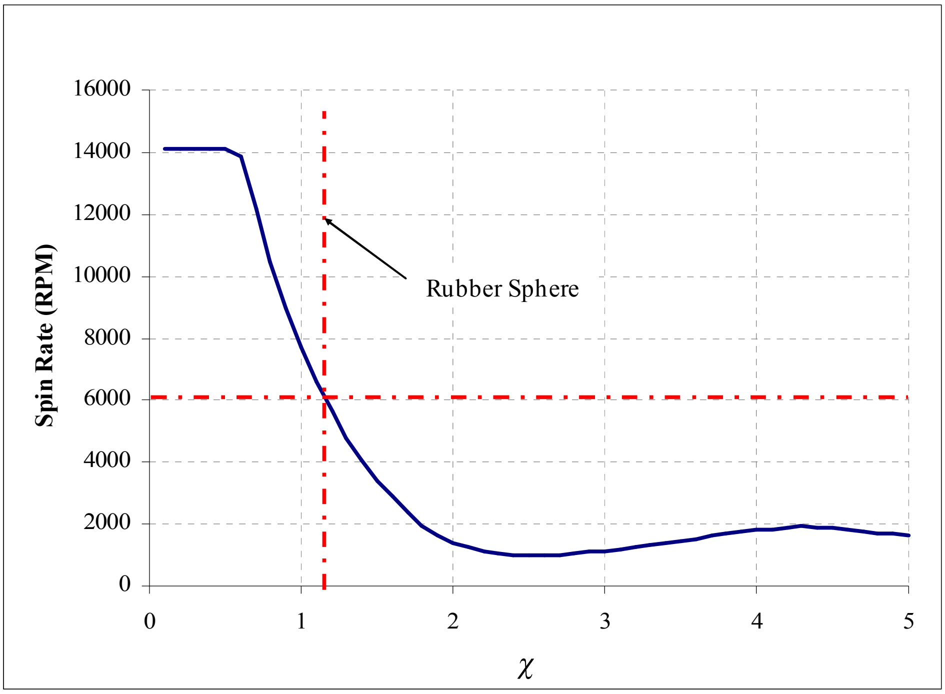


Figure 4: Effect of tangential stiffness on spin rate (30° barrier, 80 ft/s, =0.3)

3.3 Initial Condition

It was pointed out in the first report in this series, that the final spin rate is a function of (i) the maximum possible tangential impulse and (ii) the mass properties of the sphere. The maximum possible tangential impulse is the product of the coefficient of friction and the normal impulse (which itself is proportional to the normal direction velocity change of the sphere):

$$\Delta G^T = \mu \Delta G^N = \mu m_b \left(V_b^{N'} - V_{b0}^N \right) \tag{2.6}$$

Therefore, the maximum possible spin may be increased by increasing the maximum possible tangential impulse. This can be achieved either by increasing the coefficient of friction or the normal direction velocity change. Figure 5 shows the effect of varying the impact angle. The lower the angle, the higher the change in normal velocity and hence the greater the maximum tangential impulse. As noted, changing the coefficient of friction would also change the maximum tangential impulse, so it should be no surprise that the initial condition parameter, ψ (equation 2.4), includes the ratio of coefficient of friction to impact angle. Also note that no matter what the tangential flexibility of the sphere, the maximum impulse limitation corresponding to sliding contact will still apply. This limitation may be seen in the spin plateaus shown in Figure 5.

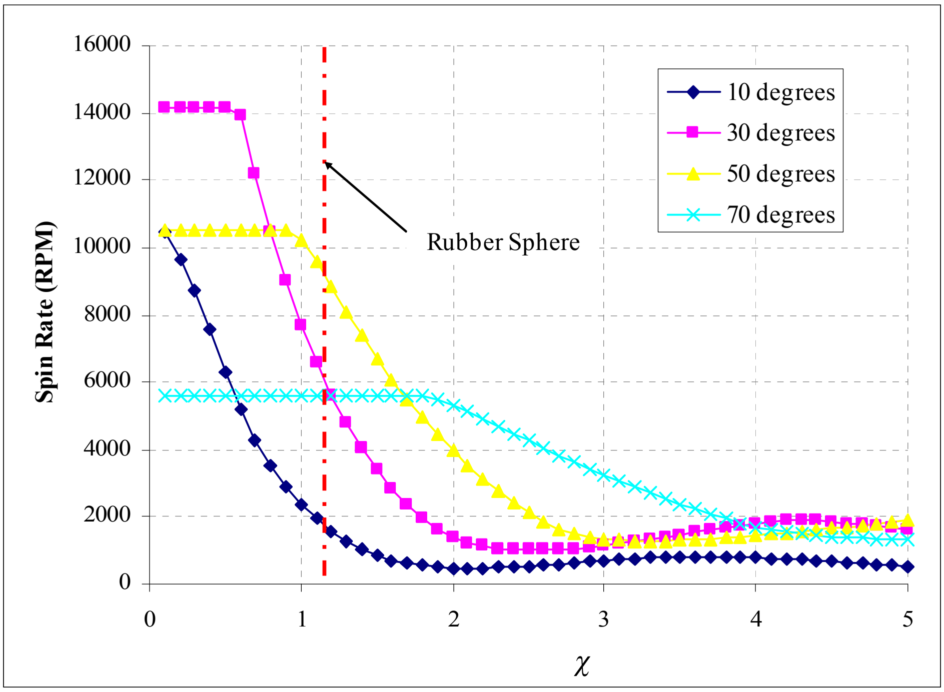


Figure 5: Effect of tangential stiffness and impact angle on spin rate (80 ft/s, μ=0.3)

4 Comparison to Experimental Data

Oblique impact experiments were conducted with a variety of golf balls against rigid barriers set at a series of angles with different frictional surfaces. A report on the collection of the data and a more thorough tabulation of the results will be compiled in the near future. However, it is useful to test the improved analytical model against the data.

4.1 Model Parameters

Generally speaking, the model input parameters are well defined. However, there are three variables that will be tuned for the various ball/barrier systems. Additionally, an adjustment to the initial velocity is made to account for inelasticity.

4.1.1 Coefficient of Friction

At high impact angles, sliding will take place throughout most or all of the impact. During sliding, the tangential force will be a more or less constant ratio of the normal force, i.e.:

$$F^T = \mu F^N \tag{3.1}$$

Therefore, the coefficient of friction for a given ball/barrier surface combination will be estimated using a seventy degree impact. Figure 6 shows a typical plot of the ratio of tangential to normal forces during the impact and the estimated coefficient of friction (0.26 for a Pinnacle ball against a clean, dry Aluminium plate).

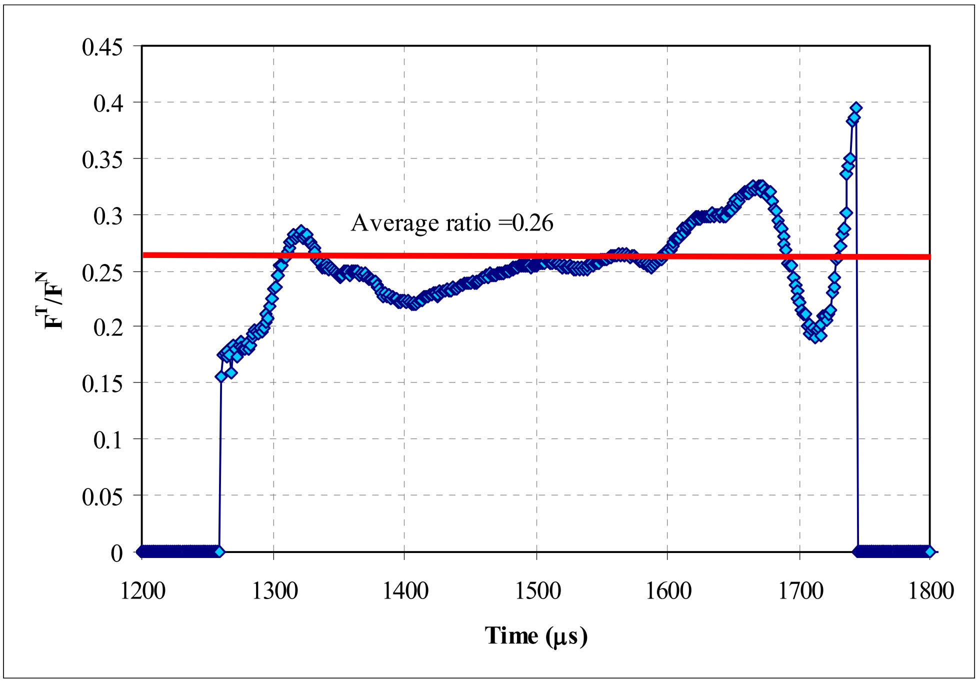


Figure 6: Typical force ratio time history

4.1.2 Elastic Modulus

The elastic modulus, mass of the ball and normal direction velocity determine the total contact time. The contact time is straightforward to determine directly from the normal force/time history. Since the mass of the ball and the normal direction ball velocity are directly measured, this leaves only the elastic modulus to vary to achieve the correct contact time.

4.1.3 Tangential Stiffness Correction

The value of χ calculated from equations 2.1 – 2.3 is for a homogenous sphere. We know however that the golf ball is not homogenous. It is therefore justifiable to adjust the value of χ. The most desirable procedure would be to adjust χ until the experimental and model tangential force time histories coincide. However, the tangential force measurement contains noise components that likely shift the force timing. Therefore, χ will be adjusted to match the spin rate for the thirty degree impact against a clean dry Aluminium surface for each ball type.

4.2 Test Conditions

Pinnacle Gold and Titleist Pro V1 balls were tested across a broad range of angles and surface conditions. Tables 1-3 summarises the model inputs for the various conditions

Table 1: Coefficients of Friction

	Pinnacle Gold	**Titleist Pro V1**
Clean Dry Aluminium	0.31	0.48
Wet Paper Interface	0.03	0.03
ABS Plastic	0.06	0.07-0.14*
Sand Paper	0.40	0.63

** Erratic friction observed experimentally, average value of 0.10 used in simulations*

Table 2: Elastic Modulus

	Pinnacle Gold	**Titleist Pro V1**
Elastic Modulus	160 MPa	115 MPa

Table 3: Corrected χ (Rubber Sphere = 1.17)

	Pinnacle Gold	**Titleist Pro V1**
Corrected χ	1.37	1.26

4.3 RESULTS

Figures 7 and 8 show the plots of the experimental data points and the model simulations. It can be seen that there is generally excellent agreement between the two for both the Pinnacle and the Pro V1 balls.

A non-intuitive result is that for all ball/surface combinations, there exists an angle of maximum spin. Impacts at angles beyond this point result in less spin. This result is due to the fact that as the angle increases, the normal direction velocity change, and hence the maximum tangential impulse, decreases. For slippery surfaces, the peak spin occurs at a low angle. As the friction increases, the peak spin angle also increases.

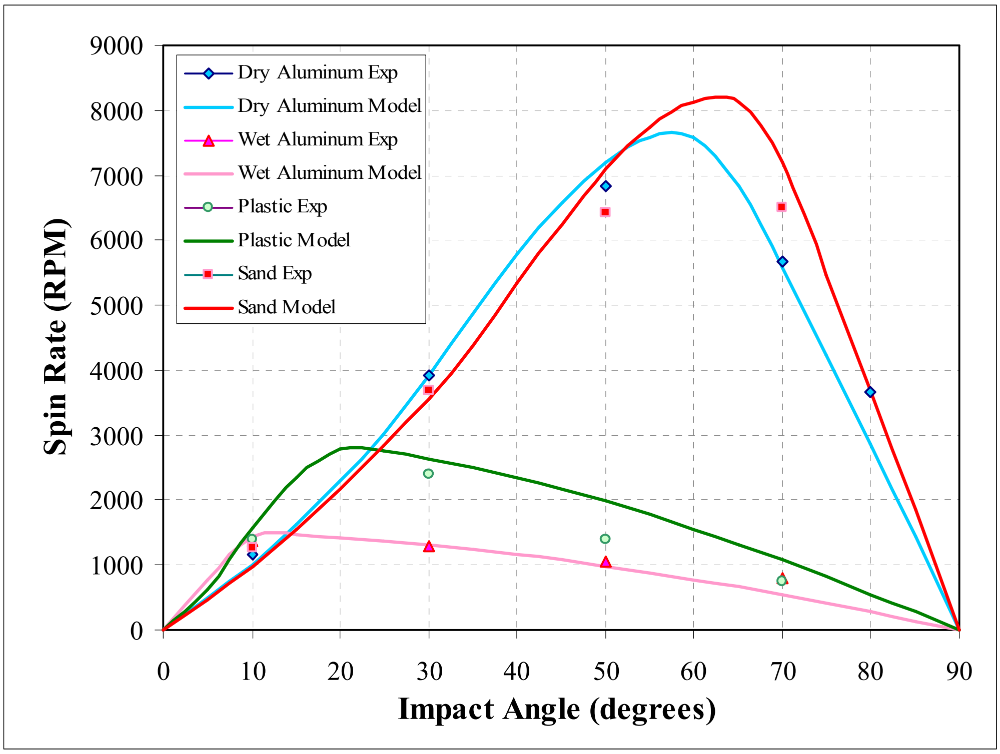


Figure 7: Experimental and simulation results for Pinnacle Gold (80 ft/s impact speed)

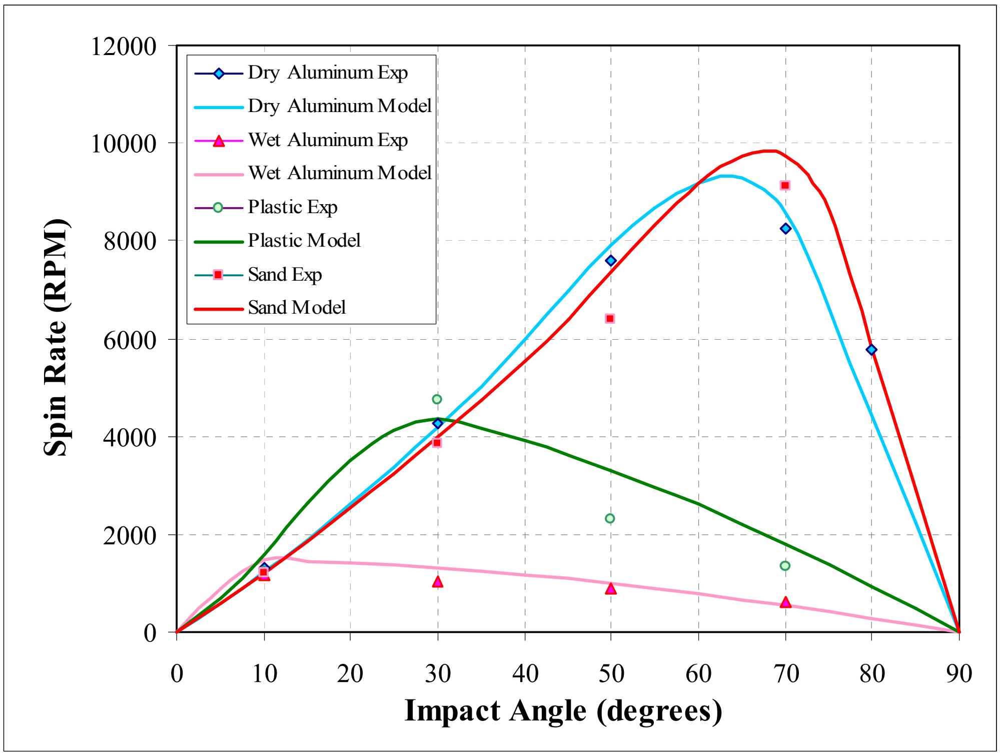


Figure 8: Experimental and simulation results for Pro V1 (80 ft/s impact speed)

5 Interesting Model Results

It appears that the improved analytical model is capable of simulating the spin resulting from the oblique impact of golf balls (at least of typical construction). It is therefore educational to use the model to explore this behaviour and some of the ramifications this may have on research and conformance testing.

5.1 Frictional Effects

It can be seen in Figures 7 and 8 that the friction plays a strong role in effect of the impact angle on spin. A more uniform distribution of friction coefficients has been simulated using the model (for the model Pinnacle Gold) and the results are plotted in Figure 9. Also plotted in this figure is the "Kinematically Limited Spin" curve presented in **[1]**. It may be recalled that for rigid body impact, spin above this line is impossible and spin below this line represented sliding contact throughout impact. Figure 9 demonstrates that tangential flexibility can allow spin somewhat higher or lower than the simpler model predicts. For sliding contact throughout impact, both models predict identical spin.

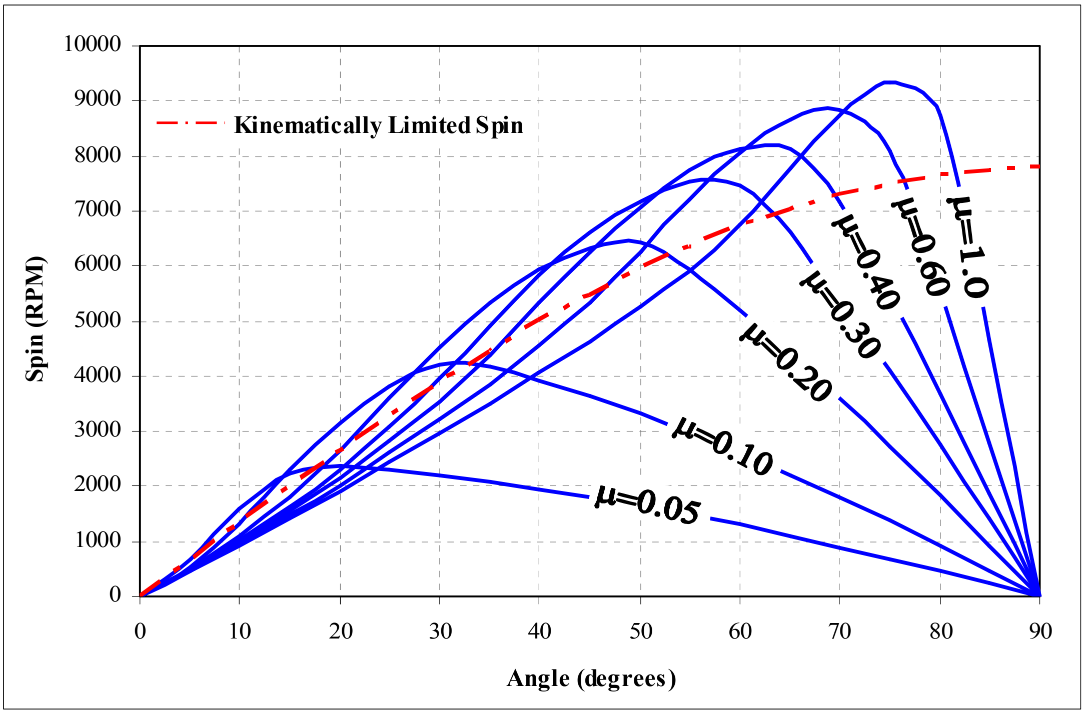


Figure 9: Effect of loft on model results for Pinnacle Gold (80 ft/s impact speed)

The same results have been plotted in Figure 10, but in a slightly different format. The effect of friction on spin at a variety of lofts has been presented. Several interesting features may be seen in Figure 10. First, for all lofts except 70 and 80 degrees, the maximum spin point can be reached and exceeded for the coefficients of friction typically seen in conforming club/ball combinations. In fact, for moderate lofts (20° - 40°), less friction would result in significantly higher spin than would occur, for example, with a normal iron and a Titleist Pro V1.

Next, it can be seen that at 50°, spin is relatively constant across the range of typical frictional conditions. As has been noted in previous reports, if spin is to be used as an indicator of dry condition friction, 70° impact is much more suitable than 50° since spin increases monotonically with friction at this higher loft.

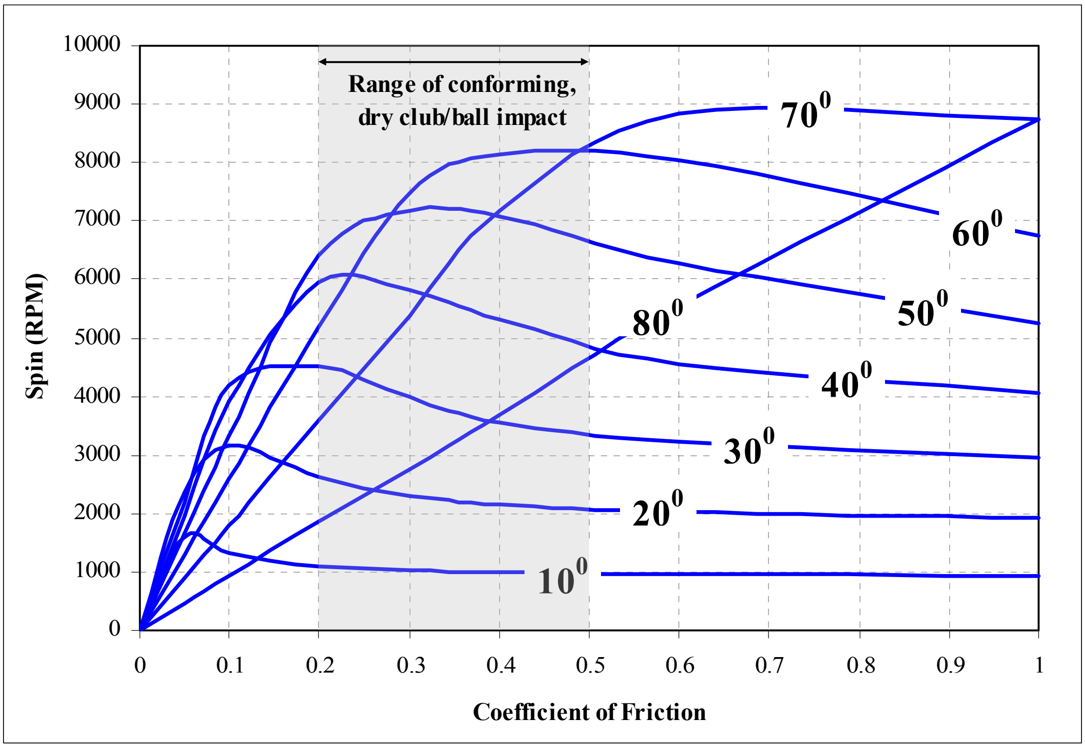


Figure 10: Effect of friction on model results for Pinnacle Gold (80 ft/s impact speed)

5.2 Driver Spin Vs. Wedge Spin

The performance of a golf ball at low angles of impact in comparison to that at high angles of impact is also of interest. The model was used to determine whether the ratio of wedge spin to driver spin could be changed significantly from the performance of balls currently used. Figure 11 shows this ratio for a variety of friction coefficients over a wide range of χ .

It can be seen in Figure 11 that for balls of today, and coefficients of friction in the range of 0.3 to 0.5, the ratio of wedge spin to driver spin is approximately 3 to 4.5. If a ball could be designed with values of χ approaching 1.7, the spin ratio could be increased to 5 or 6. It should be noted however that such a change would result in an overall reduction in spin at both lofts.

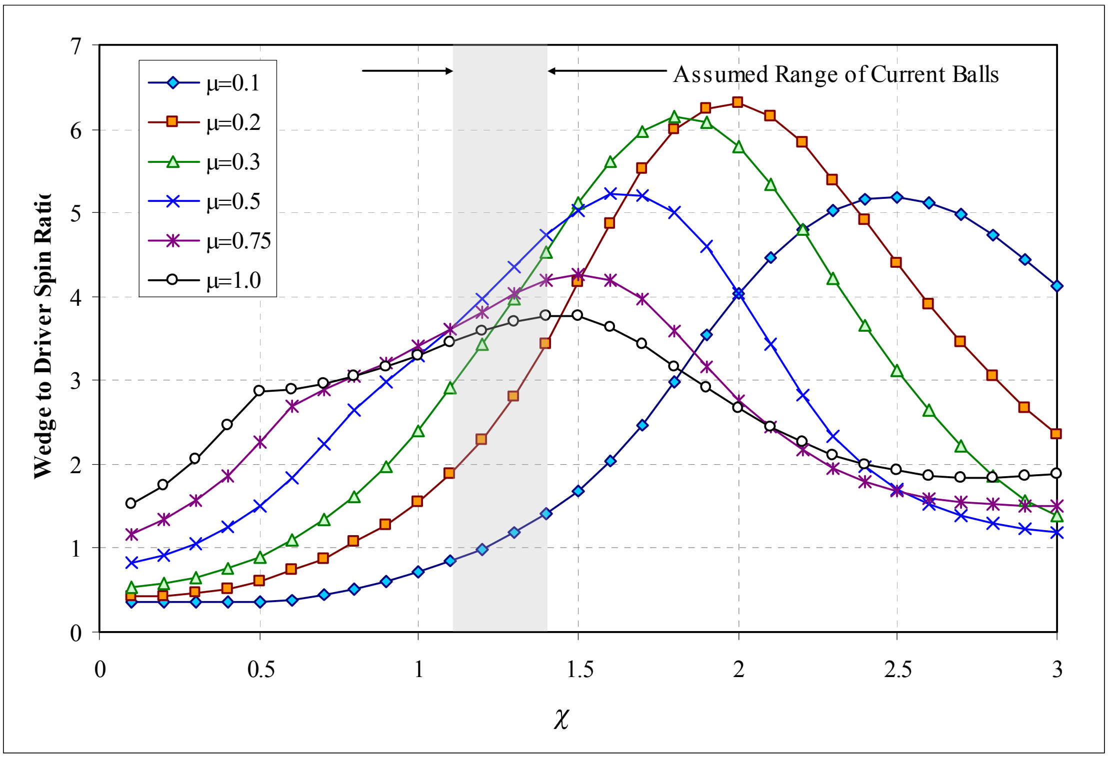


Figure 11: Effect of tangential flexibility on wedge/driver spin ratio

5.3 Effect of Flexible Clubface

Much of the attention of this report has been the effect of varying the tangential stiffness properties of a ball without modifying the normal direction behaviour. Since the oblique response however is related to the ratio of the tangential to normal stiffness, changing the normal stiffness whilst maintaining the tangential properties would achieve similar results. This can be achieved by reducing the club normal stiffness via a thin faced club, for example. This would increase the tangential frequency in relation to the normal, and spin would in general be therefore lowered.

6 Conclusions and Recommendations

This report has discussed the role of tangential flexibility on oblique impact response. It has been demonstrated that significant variations from the response predicted by the rigid body model can occur due to this flexibility. The model of Maw et al appears to adequately capture the response of oblique impacts for golf balls. The model was then used to demonstrate some interesting and important features about the oblique impact properties of balls and clubs that exist today and what features may be desirable to designers for the future. These include:

- the importance of tangential force oscillations on the resulting spin
- ball construction can significantly change the tangential force oscillation during impact
- ball construction changes could lead to impact behaviour significantly different than balls of today
- the counterintuitive result that increased friction can in lead to lower spin and vice-versa.
- The equally counterintuitive result that increased loft can lead to lower spin
- flexible club faces provide a mechanism for reduced spin

Several improvements to the model would increase its usefulness:

- The current model as written simulates impacts with rigid barriers only. It would be useful to extend this model to finite mass clubs with face flexibility.
- The construction of the ball can only be represented by the averaged parameters of the model. Extending the model to explicitly solve for multiple layer construction would be beneficial

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