An Investigation into Ball-Turf Impact Characteristics

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Abstract

A modified baseball pitching machine has been utilised to conduct an initial investigation into the effects of different types of simulated golf shots impacting with different types of turf. A dependency of ball cover material on shot results has been demonstrated for a sand wedge type shot impacting with green turf. Differences in shot result for driver, 5 iron and sand wedge shots have been demonstrated for different types of turf characterised using the USGA TruFirm device. These differences appear to relate most closely to the stiffness values attained from the device with an increased stiffness resulting in a ball leaving the turf faster, at a shallower angle and generally with less spin (or even top spin) than an equivalent impact on less stiff turf although insufficient data has been collected in this initial study to definitively characterise these relationships.

Introduction

An investigation has been recently undertaken into better understanding the interactions between the golf ball and the turf that it strikes on impact with either the fairway or the green. The investigation also gave the opportunity to determine if there is a correlation between a golf ball's physical interactions with the turf and the readings of the USGA TruFirm testing device.

Experimental Method

A baseball pitching machine has been purchased by The R&A and has been modified to allow it to fire golf balls, Figure 1. The modifications included decreasing the space between the launcher wheels to accommodate the reduced diameter of the golf ball, incorporating a chute to allow better control of the presentation of the ball to the spinning wheels and incorporation of a laser trigger to be broken as the ball exits the machine which is suitable for triggering the high speed camera or other measurement apparatus.

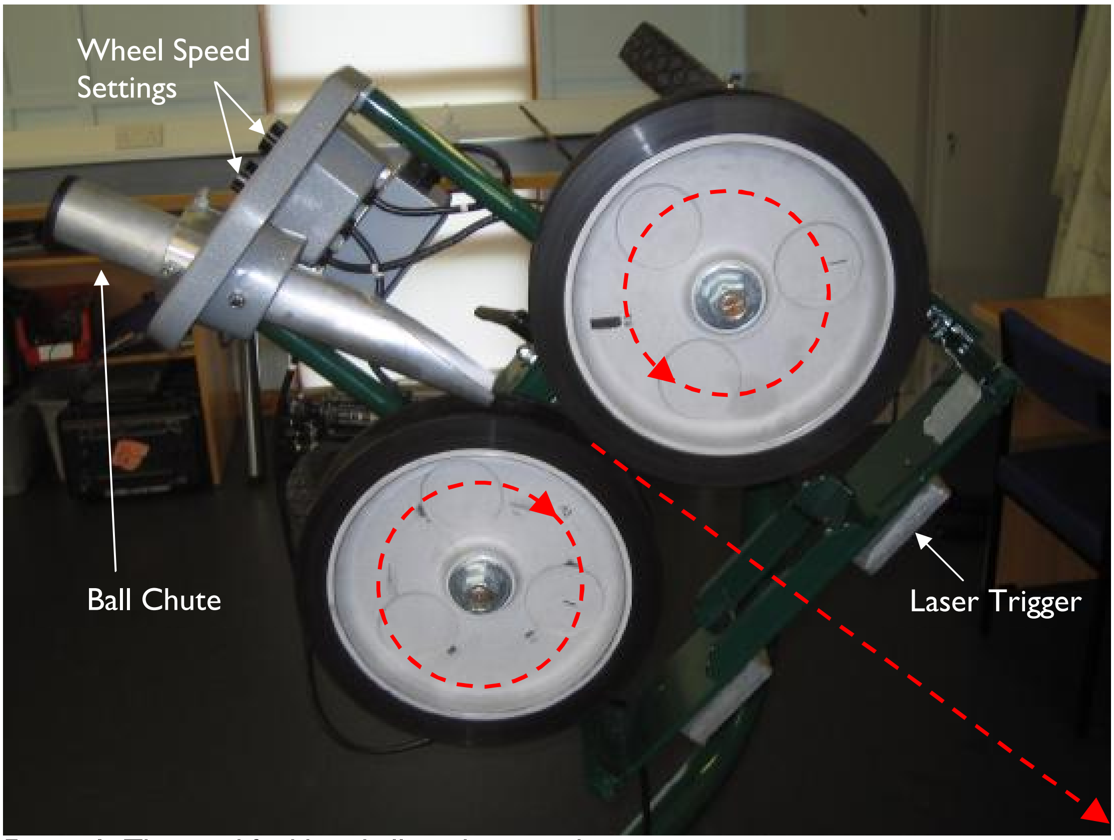

Figure 1. The modified baseball pitching machine.

The pitching machine comprises two spinning rubber wheels, the speeds of which are independently controlled. The ball passes between the wheels and leaves with a speed which is dependent on the average speed of the wheels and an amount of spin dependent on the differential speed between the wheels (i.e. having one wheel spinning at a higher speed than the other will impart more spin on the ball than if the wheels are spinning at similar speeds). The pitching machine was calibrated using one of The R&A's launch monitors (The Callaway Performance Analysis System – CPAS) to ascertain which wheel speed settings would be required to replicate specific ball speeds and spins (the calibration of angle was not as important at this stage since the machine can be physically rotated to change the impact angle independent of changes to speed and/or spin).

The R&A's high speed camera was used to record the impact of each shot with the turf. The recording of each shot was triggered by the ball breaking the beam of the laser trigger mounted on the pitching machine. Verification work was undertaken prior to taking the machine into the field, comparing the accuracy of the measurements taken from the high speed camera under laboratory conditions against those attained using the proven technology of the CPAS.

The camera was set up a suitable distance from the impact to ensure that the field of view was sufficient to capture an adequate amount of the ball flight to accurately measure speed, angle and spin both pre and post impact with the turf. A calibration fixture was utilised for each shot to calibrate distances within the field of view and define angles relative to the ground at the point of impact.

A composite of several frames both pre and post impact, Figure 2, shows the typical field of view for a 5 iron shot impacting with the turf. The coordinates of the edges of the line of the ball and how they change relative to each other between frames (illustrated by the different colours of the crosses) were utilised to calculate speed, spin and angle pre and post impact with the turf.

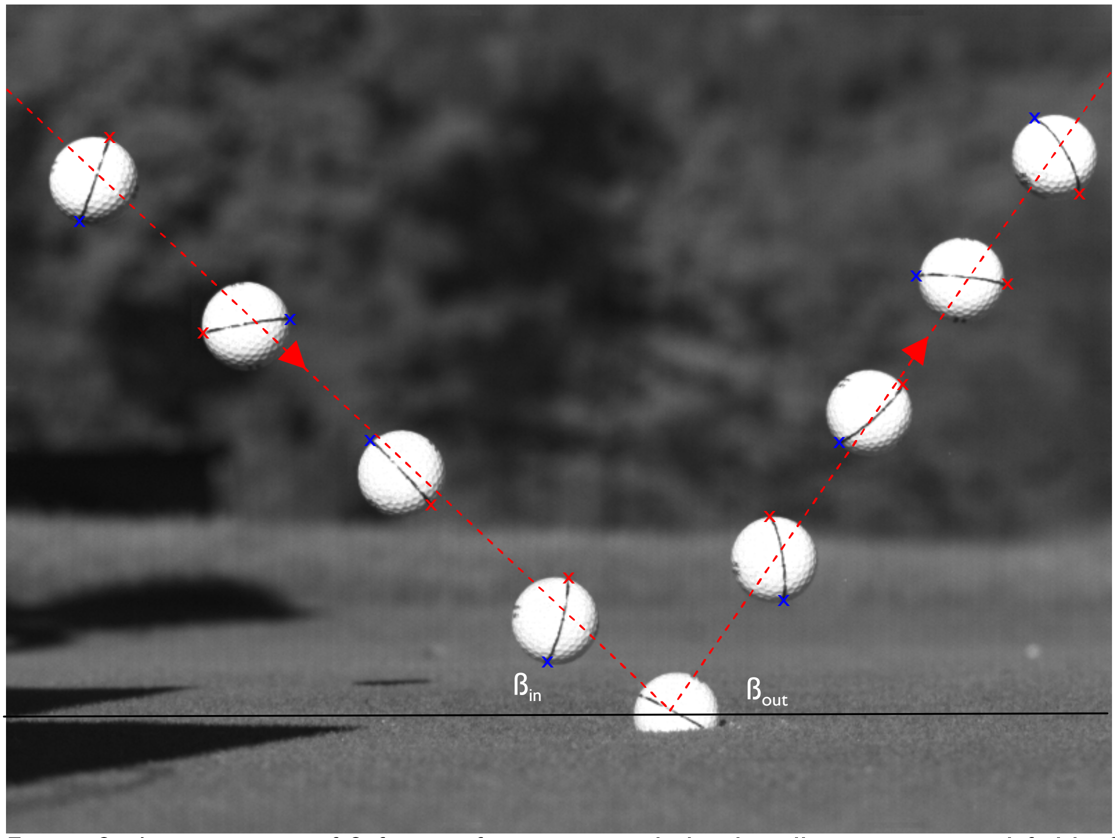

Figure 2. A composite of 9 frames from a recorded video illustrating typical field of view and also how pre- and post- speed, spin and angle can be calculated.

Laser measuring equipment (as used for our drive measuring studies) was used to measure the bounce and roll of the ball from where it impacted on the green/fairway. Figure 3 shows the layout and set up of the equipment on one of the test greens.

Figure 3. The testing set up comprising the modified pitching machine, high speed camera and distance measuring laser equipment.

Testing was conducted at two different sites in St Andrews both on fairway type turf and on practice greens. Furthermore, four golf courses, each identified as having different turf conditions have been visited for testing these are:

a) Ladybank Golf Club

b) Loch Lomond Golf Club

c) The Northumberland Golf Club

d) The Renaissance Golf Club

At each venue, two sites were tested, one representing turf of fairway condition and one representing green condition. The landing conditions utilised on the fairway were designed to be akin to those of a ball landing on the fairway after being struck with a driver whilst those shots fired at the green were designed to replicate firstly 5 iron landing conditions and secondly sand wedge landing conditions from shots struck by those clubs by elite golfers. These landing conditions were selected to cover the speeds/spins/angles most likely encountered on each surface within the time constraints associated with testing at each venue.

The target 5 iron and sand wedge landing conditions were those measured by the USGA and utilised for the bounce and roll investigation forming part of the recent Spin Studies whilst the target landing conditions for the driver were attained by use of the USGA Indoor Test Range simulation software for a drive struck with typical elite golfer launch conditions (180 mph ball speed, 10 degrees launch angle and 2520 rpm launch spin – the default launch angle and spin for the Overall Distance Standard for golf balls).

The target landing conditions for the three clubs are detailed in Table 1 below:

Table 1. Target landing conditions selected for the Ball/Turf impact interaction study.

Club	Speed (MPH)	Angle (Degrees)	Spin (RPM)
Driver	66	36	1950
5 Iron	56	44	4440
Sand Wedge	49	51	9060

In practice, the range of achievable impact conditions on the pitching machine was limited by the discrete nature of the speed setting dials. Changing one dial by the smallest achievable amount could result in a change to the impact conditions of a few hundred RPM or a couple of MPH impact speed. Consequentially, the exact target impact conditions were not achievable and in some cases near estimates were utilised instead, Table 2. Whilst these are not exactly those that were targeted, they would most likely be within the range of typical landing conditions for these clubs as struck by Elite golfers (for example, range of landing speeds measured for 5 iron shots at the 2008 Open Championship on the 12th hole ranged from 45 to 64 MPH) so the small differences from the target landing conditions in this study are not deemed problematic.

Table 2. Achieved landing conditions for the Ball/Turf impact interaction study.

Club	Speed (MPH)	Angle (Degrees)	Spin (RPM)
Driver	64	36	2250
5 Iron	56.5	44	4550
Sand Wedge	52.5	51	9000

For each landing condition, 20 shots were fired from the pitching machine – 10 each with a USGA/R&A Calibration Ball and a Titleist Pro V1. The USGA/R&A Calibration Ball has a Surlyn cover whereas the Titleist Pro V1 has a polyurethane cover. It is important to note that the ball launcher was moved slightly between shots to ensure that all impacts were on turf that had not previously been impacted as part of this study.

Finally, the turf at each test site was characterised. The USGA TruFirm testing device was used to test the mechanical characteristics of the turf along with taking measurements of the moisture content at each site. Soil core samples were taken, separated into four depth ranges of 20mm (0-20mm, 20-40mm, 40-60mm, 60-80mm) and processed for calculation of the organic matter content. To calculate the organic mater content, the samples were dessicated, weighed and then burnt. The organic matter content is related to the percentage of the dessicated mass that is lost upon ignition of the sample, with a higher percentage relating to a higher organic matter content in the sample.

Results

Outliers

Inclement weather at two of the test sites resulted in water being deposited onto the wheels during testing. This caused a considerable amount of variability to the impact conditions, in particular to the spin of the ball. Consequentially, to maintain the integrity of the data set, shots with an inbound spin more than 480 rpm higher or (more usually) lower than the achieved inbound spins for each shot type as listed previously in Table 2 were removed from the final data set. The level of filtering was decided at 480 rpm since this is 3x the typical standard deviation of 160 rpm which was achieved for a set of 10 shots when measured in dry conditions which was deemed a reasonable test for an outlier. This resulted in 31 shots being removed from the overall data set of 330 shots.

Inter Site Variability

USGA TruFirm Characterisation

The USGA TruFirm device was used to measure the characteristics of the turf at each test site producing 5 characteristic parameters of the turf:

Stiffness: The resistance of a body to deflection by an applied force. The stiffness k of an elastic body that deflects a distance d under an applied force F is $k = F/d$. Stiffness is the scientifically correct term for the property most golfers would refer to as 'firm'.

Resilience: In physics and engineering, resilience is defined as the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered. The resilience is given as a number between 0 and 1 with a higher number seeing a greater proportion of the energy stored in the system being recovered.

Penetration: This is the depth of maximum penetration.

Recovery: This is the depth to which the turf recovers before the USGA TruFirm device leaves contact with the turf.

Moisture: The percentage of moisture within the turf.

The results for each site, Table 3, show that the turf conditions investigated in this study had stiffnesses ranging from 2.2 to 8.7 MPa, resilience values from 0.12 to 0.34, penetration from 8.8 to 15.4 mm with recovery values from 0.7 to over 3 mm. These represent a good range of turf characteristics on which to conduct the investigation.

Table 3. The USGA TruFirm results measured at each of the test sites

	Site	Stiffness (MPa)	Resilience	Penetration (mm)	Recovery (mm)	Moisture (%)
Fairway	Practice Centre	4.7	0.27	11.5	2.3	22%
	Renaissance	8.2	0.18	8.9	1.1	27%
	Northumberland	2.2	0.28	15.4	2.1	22%
	Ladybank	4.2	0.34	11.5	3.1	15%
	Loch Lomond	3.0	0.20	13.7	1.6	22%
Green	Practice Centre	5.7	0.24	10.5	1.8	50%
	Balgove	7.8	0.18	9.1	1.1	40%
	Renaissance	8.7	0.17	8.8	0.9	47%
	Northumberland	2.4	0.19	14.3	1.5	35%
	Ladybank	4.5	0.24	11.2	1.9	47%
	Loch Lomond	5.3	0.12	10.8	0.7	26%

Organic Matter Content Determination

The soil core samples from each site were processed to determine the organic matter content. These data are presented graphically in Figure 4 for the fairway sites and Figure 5 for the green sites. For greens, the ideal range in the top 60 mm is 4-6%, which should then show a reduction at the 60-80 mm layer. Because of their young age the St Andrews Practice Centre, Balgove green, St Andrews Practice Centre 'fairway', Loch Lomond green and Renaissance Club green and fairway have values well below this range. The Ladybank green is almost perfect, the Northumberland green has slightly excessive organic matter. The Ladybank fairway is very high due to its fibrous thatch but the Northumberland fairway is off the scale because of its excessively dense thatch.

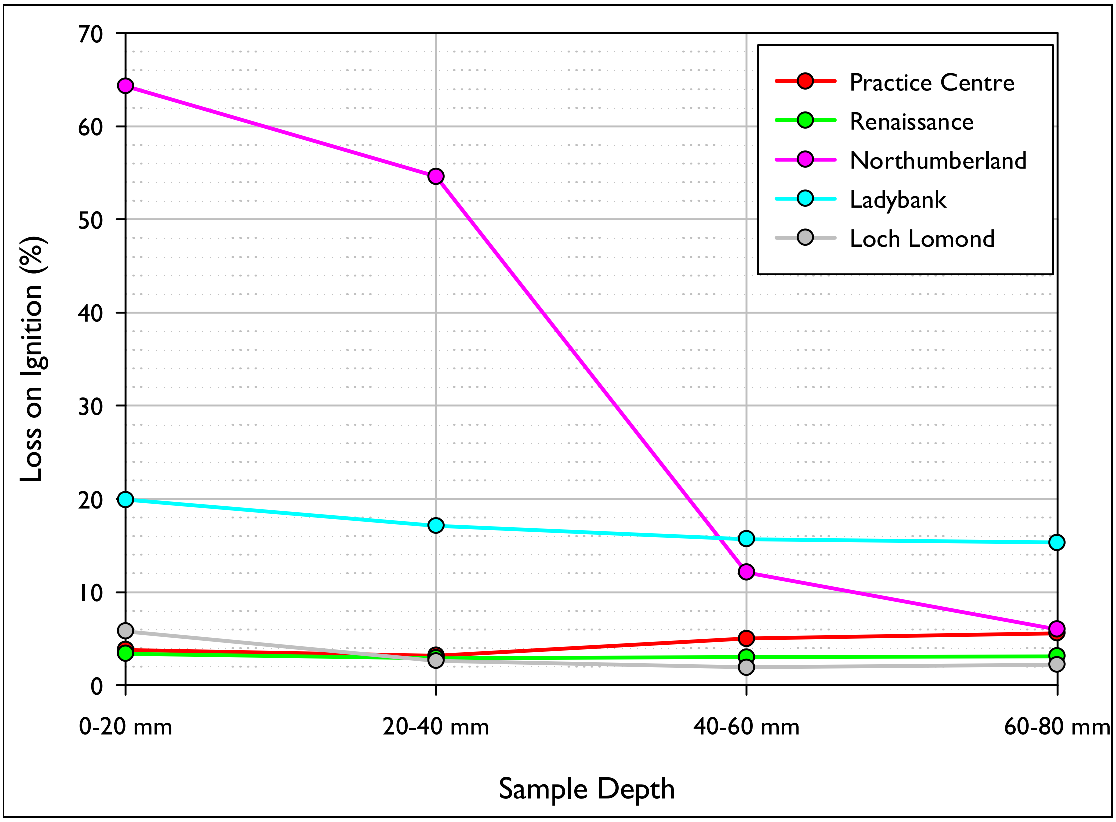

Figure 4. The percentage organic matter content at different depths for the fairway sites tested.

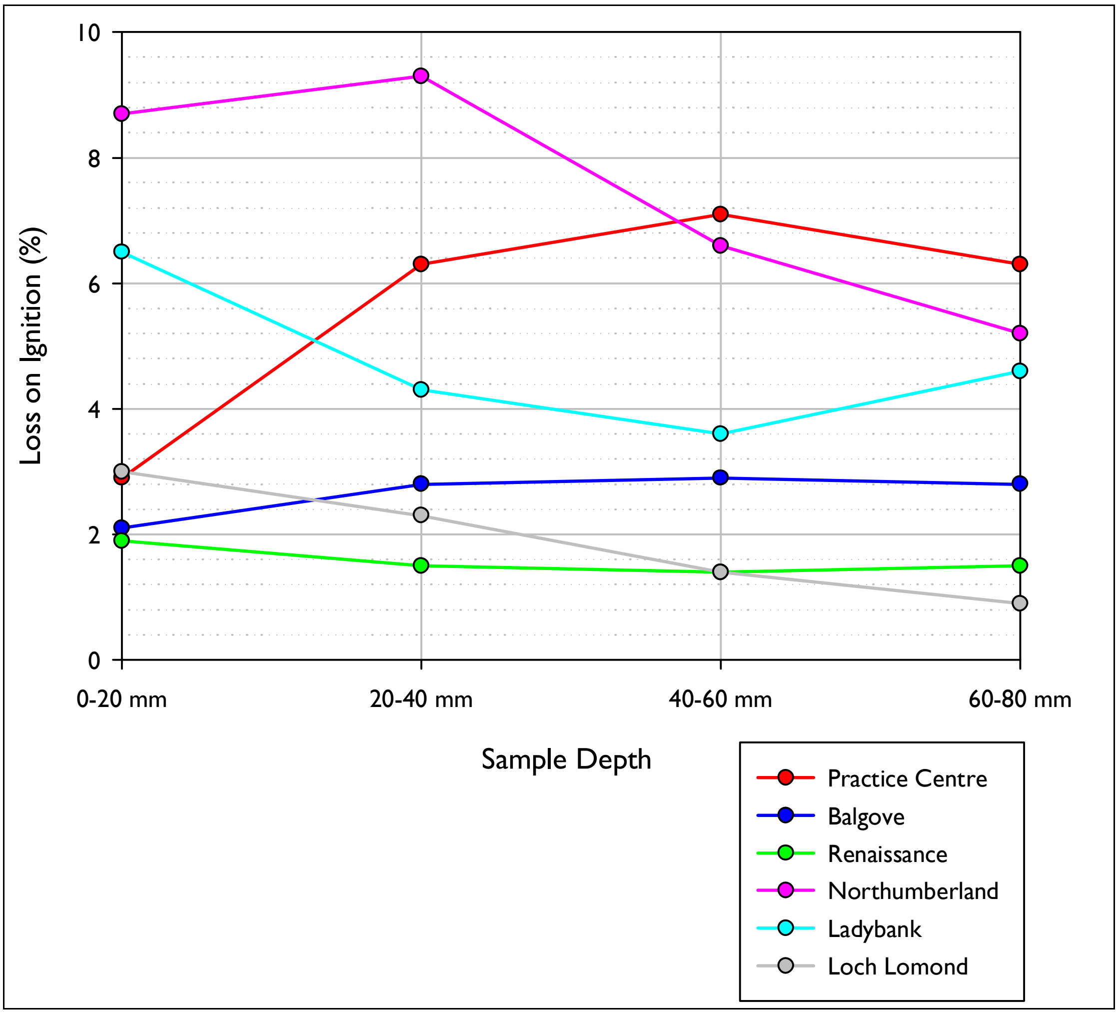

Figure 5. The percentage organic matter content at different depths for the green sites tested.

It is not simply the quantity of organic matter that may impact on ball/turf reaction but also the texture and distribution of it through the tested layers. For example, the organic matter content results for the Balgove and Loch Lomond greens appear to be similar as shown in Figure 5 although when comparing profiles from the greens, Figure 6 it can be seen that there is a variation in texture and distribution of the organic matter density which is not picked up when analysing 20 mm layers.

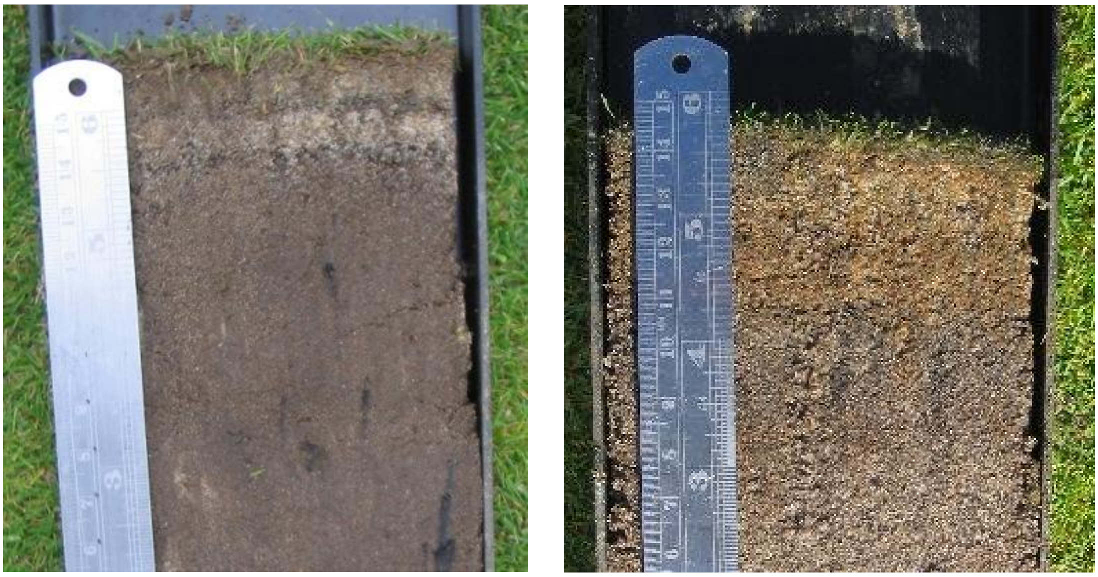

Figure 6. Turf Profiles from the Balgove (left) and Loch Lomond (right) greens.

Inter-ball type variability

For each impact condition at each test site, 5 measured parameters of the ball/turf interactions were compared for the two ball types to determine whether there were any differences which were statistically significant. The 5 parameters compared were:

a) The outbound speed of the ball after impact (Vout)

b) The outbound angle of the ball after impact

c) The difference between the inbound spin and the outbound spin

d) The Coefficient of Restitution (CoR) of the impact (this is the ratio of the vertical component of the outbound speed to the vertical component of the inbound speed)

e) The measured bounce and roll from where the ball pitches to its final resting position

Two-sample T tests were used to determine whether differences observed between the sets of data relating to the two ball types for each parameter for each test (site & 'club') were statistically significant. The results for these tests, Table 4, show that there were only two parameters (out of 25) which showed a difference of statistical significance between the two ball types when fired using the driver inbound condition. For the 5 iron, there were no differences of statistical significance observed between the two ball types. For the sand wedge though, there were considerably more differences observed between the two ball types. In total, there were 13 parameters out of a possible 30 which showed statistically significant differences between ball types. Of the 6 sites on which the sand wedge impact condition was tested, only one, the green at the St Andrews Links Trust practice centre showed differences for all 5 parameters. The practice putting green on the Balgove course showed a difference in 3 of 5 parameters whilst the practice greens at The Renaissance and Loch Lomond showed differences for 2 parameters each. In fact the only course not to show a statistically significant difference between ball types for any parameter was the practice chipping green at Ladybank Golf Club. The most prevalent parameter for showing a change was measured bounce and roll with a difference being observed at 4 of 6 test sites whilst differences in the outbound angle and the change in spin through impact were significantly significant at 3 sites each.

Table 4. Results of Statistical Analysis to determine which of the 5 parameters showed a statistically significant difference (✓) between the Calibration ball and the Pro V1 for each test site and impact condition.

	Site	Vout	ΔAngle	ΔSpin	CoR	Bounce /Roll
Driver	Practice Centre	✘	✘	✘	✘	✓
	Renaissance	✘	✘	✘	✘	✘
	Northumberland	✘	✘	✓	✘	✘
	Ladybank	✘	✘	✘	✘	✘
	Loch Lomond	✘	✘	✘	✘	✘
5 Iron	Balgove	✘	✘	✘	✘	✘
	Renaissance	✘	✘	✘	✘	✘
	Northumberland	✘	✘	✘	✘	✘
	Ladybank	✘	✘	✘	✘	✘
	Loch Lomond	✘	✘	✘	✘	✘
Sand Wedge	Practice Centre	✓	✓	✓	✓	✓
	Balgove	✓	✓	✘	✘	✓
	Renaissance	✘	✘	✓	✘	✓
	Northumberland	✘	✓	✘	✘	✘
	Ladybank	✘	✘	✘	✘	✘
	Loch Lomond	✘	✘	✓	✘	✓

Of particular interest is the comparison between the sand wedge data at the St Andrews Practice Centre and Ladybank. The USGA TruFirm data from both sites, Table 3, are similar for both sites but when considering the ball comparison data, Table 4, there are statistically significant differences between ball types for each of the parameters investigated whilst at Ladybank, there are no parameters showing statistically significant differences which may seem counter-intuitive. The differences in speed and angle can be illustrated by comparing Figure 7 and Figure 8 which show the outbound velocity vectors for the individual sand wedge shots with the two different ball types at Ladybank and the St Andrews Practice Ground respectively. It can be seen that whilst there are variations between individual shots at Ladybank, Figure 7, the population data for the calibration ball (red) and the Pro V1 (blue) overlay each other. Conversely, at the St Andrews Practice Centre, Figure 8, there is again variability in the shots and a small amount of overlap between the two populations but generally, the calibration ball shots (red) leave the turf at a steeper angle with a lower speed (shorter lines) than the Pro V1 balls. The calibration balls also were spinning on average 1,000 rpm less than the Pro V1 ball after impact, yet finished over half a yard closer to where the ball pitched than the Pro V1.

A possible explanation of the differences between two sites with nominally the same USGA TruFirm readings may lie in the species of grass present at each site. The green at the Practice Centre has a sward comprising approximately equal amounts of browntop bent and fescue, whilst the green at Ladybank is a blend of browntop bent and annual meadow-grass, with the latter grass being more dominant.

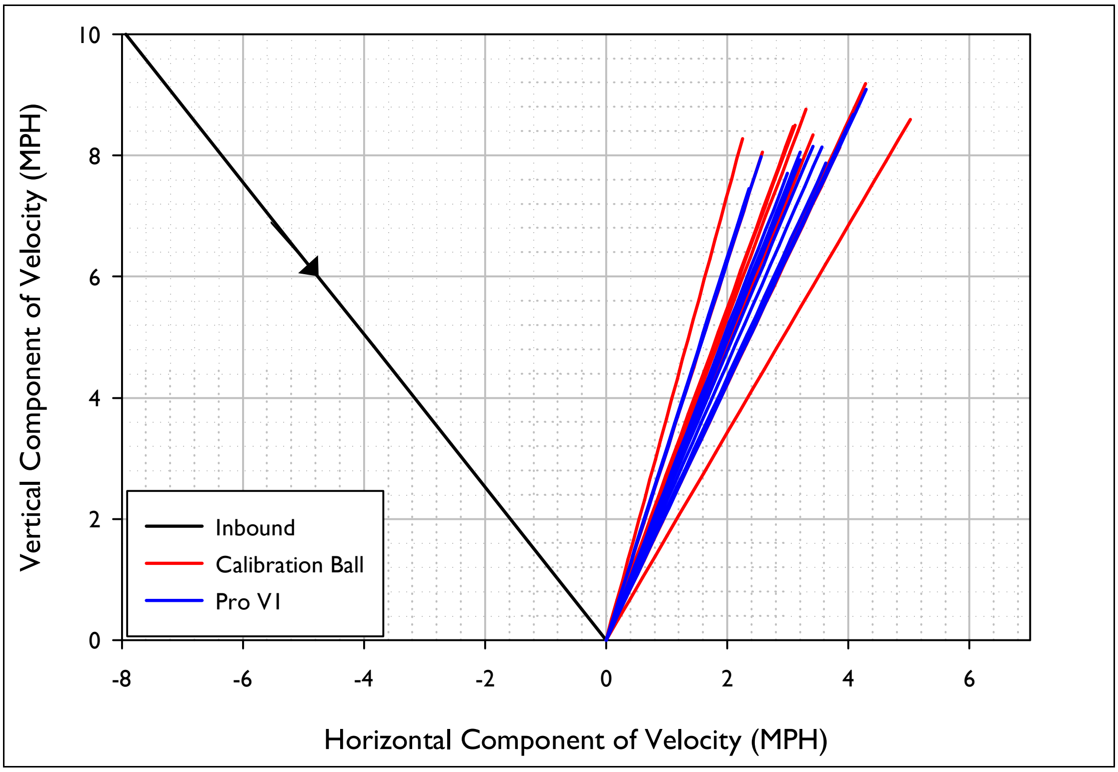

Figure 7. Outbound velocity vectors for the individual sand wedge shots at Ladybank

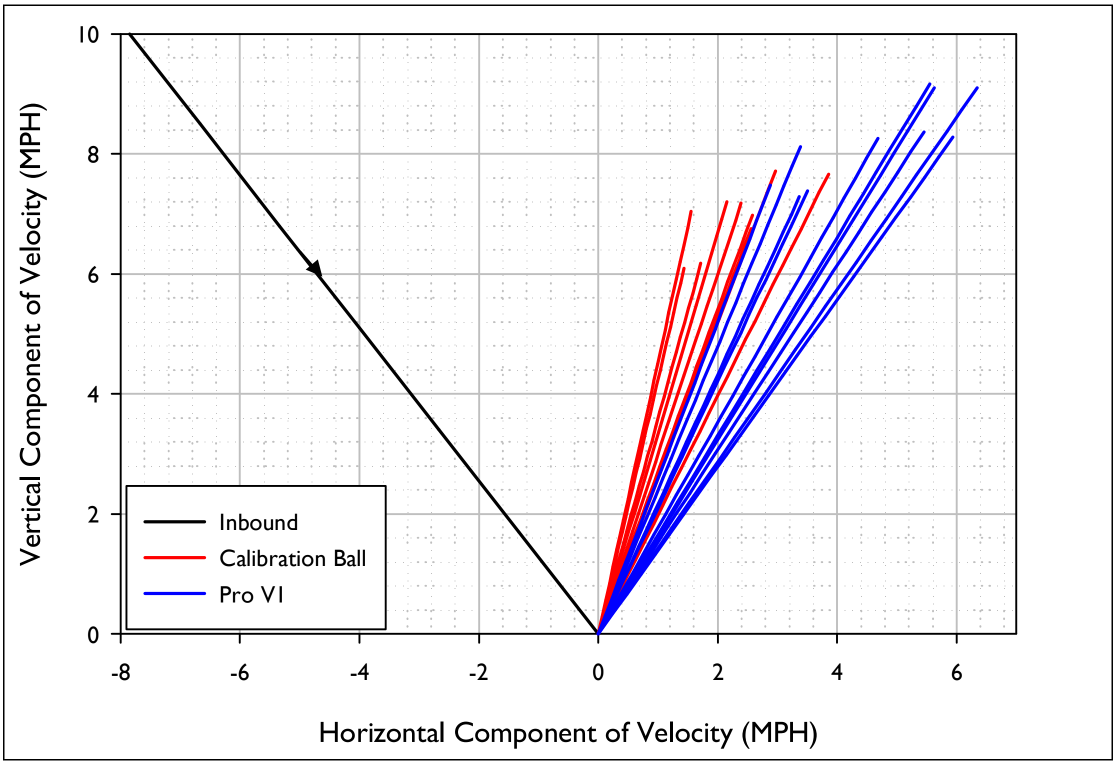

Figure 8. Outbound velocity vectors for the individual sand wedge shots at the St Andrews Practice Centre.

In summary when considering inter- ball type variability, there appears to be evidence to suggest a dependency of certain parameters on the ball type, at least when considering shots with typical sand wedge impact conditions. Furthermore, there is a suggestion that the grass species present at the test sites contribute to this dependency. There is very limited evidence of a dependency on ball type for the driver impact condition and no evidence from these tests that there is a statistically significant dependency on ball type when considering the 5 iron impact condition. It is worth noting that different ball types will lead to different launch conditions on impact with the golf club and as such will lead to different inbound conditions for impact with the turf.

Comparison of Ball-Turf Interaction Parameters to Turf Parameters

Given that the three different sets of impact conditions utilised for this study are significantly different from each other in terms of speed, spin and inbound angle, it is appropriate at this point to consider the evidence of any trends relating measured impact parameters to characteristic turf parameters individually. Two turf parameters measured using the USGA TruFirm device were selected for comparison to the ball impact parameters, stiffness and resilience. Stiffness and penetration are generally interdependent when considering ball/turf interactions so trends observed with stiffness would be expected for penetration as well. Also, whilst not always the case, there was a very good correlation between resilience and recovery for the sites investigated in this study such that trends observed with differences in resilience would similarly be expected for differences in recovery. The Appendix contains graphs comparing the parameters not considered in the main body of this report.

Driver

Initially, the shots for the driver impact condition with the fairway are considered. Figure 9 below is a composite image of 9 frames taken from a typical driver impact. It is useful to note that the time interval between the frames pre and post impact is different with the spacing post impact being 1.85x that pre impact (since the ball is moving much slower after impact).

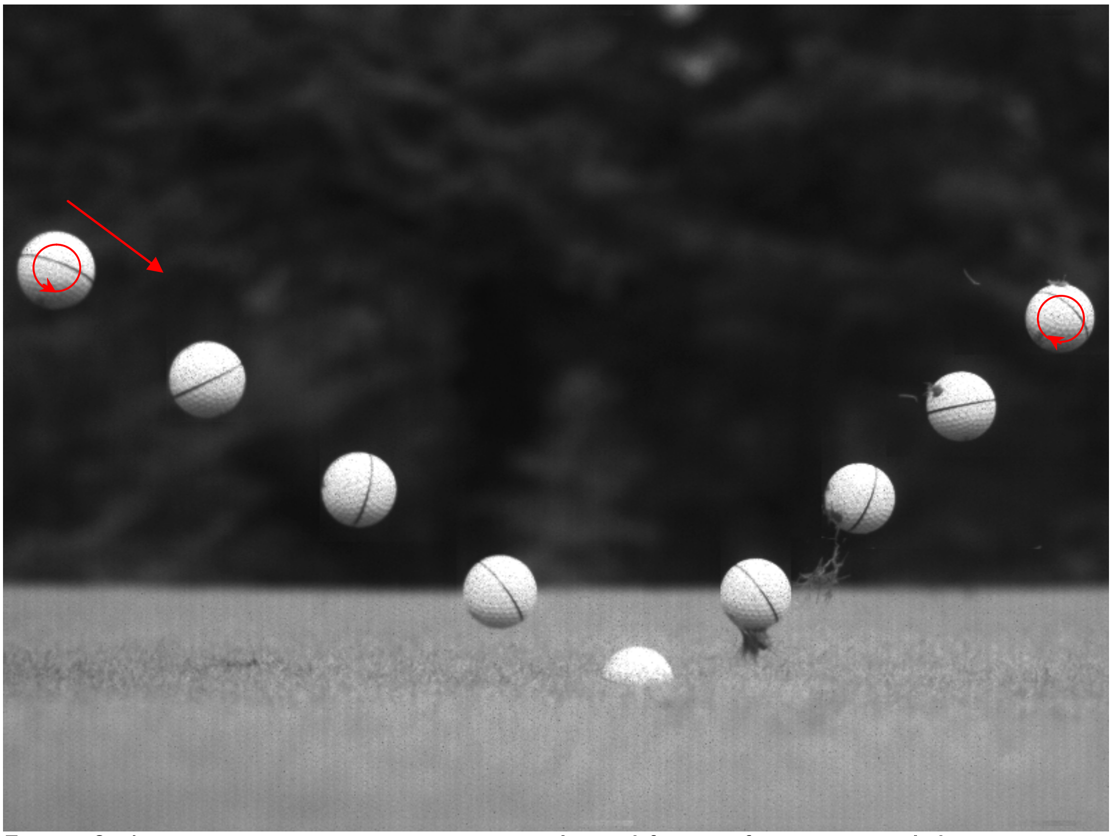

Figure 9. A composite image comprising selected frames from a typical driver impact.

To further illustrate the differences in speed (and angle) before and after impact, Figure 10 shows the velocity (speed and direction) of the calibration ball before and after impact for the different venues. It can be seen that the velocity vector for the average inbound condition is considerably longer (and hence faster) than the outbound conditions at each of the venues. It can also be seen that whilst the outbound angle for three of the courses is similar, Northumberland and Loch Lomond have a higher outbound angle – in fact Loch Lomond not only has the steepest outbound angle but also the lowest outbound speed (which would lead to an expected lower bounce and roll at Loch Lomond than the other venues).

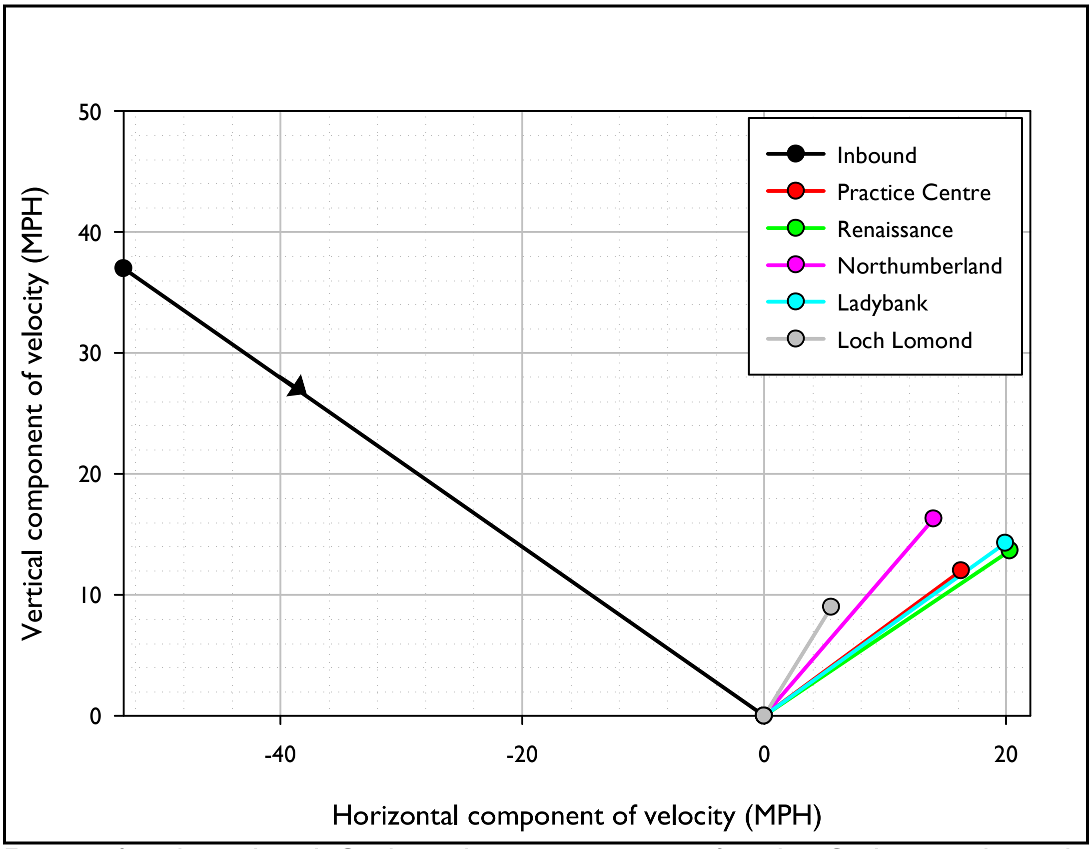

Figure 10. Inbound and Outbound velocity vectors for the Calibration ball when launched with Driver impact conditions.

If the outbound speeds of the ball (Vout) are considered against the stiffness of the turf at each site, Figure 11, it can be seen that whilst not definitive, there is certainly a reasonable indication of a positive correlation between stiffness and Vout – i.e. as stiffness increases then so does the outbound speed of the ball. Similarly, when comparing Vout to the resilience measured at each site, Figure 12, it can be seen that with the exception of one site (The Renaissance, circled in blue on both graphs), there appears to be a very good relationship between the outbound speed of the impact and the resilience of the fairway. A higher ball speed after impact would result in the ball travelling further which would suggest that the trends observed would agree with the perceived logic that the ball would be expected to bounce/roll further on stiff, resilient (bouncy) fairways.

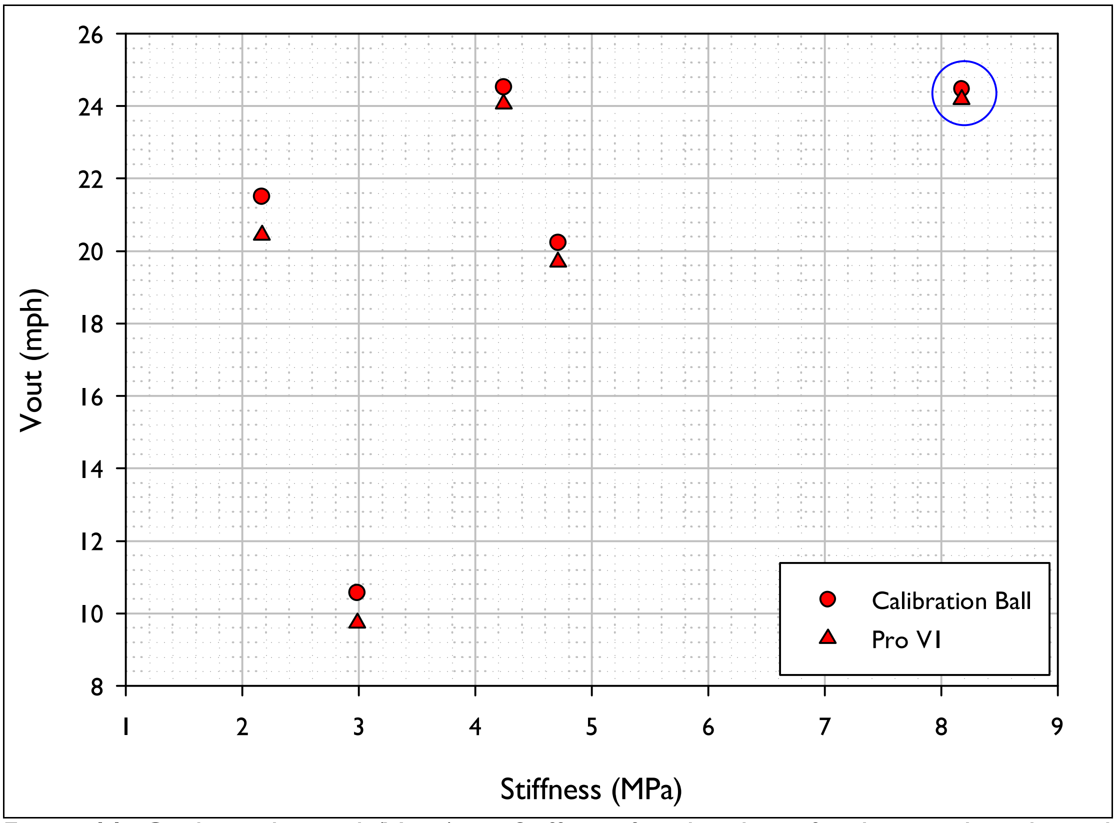

Figure 11. Outbound speed (Vout) vs. Stiffness for the shots fired using the inbound conditions akin to those for a Driver.

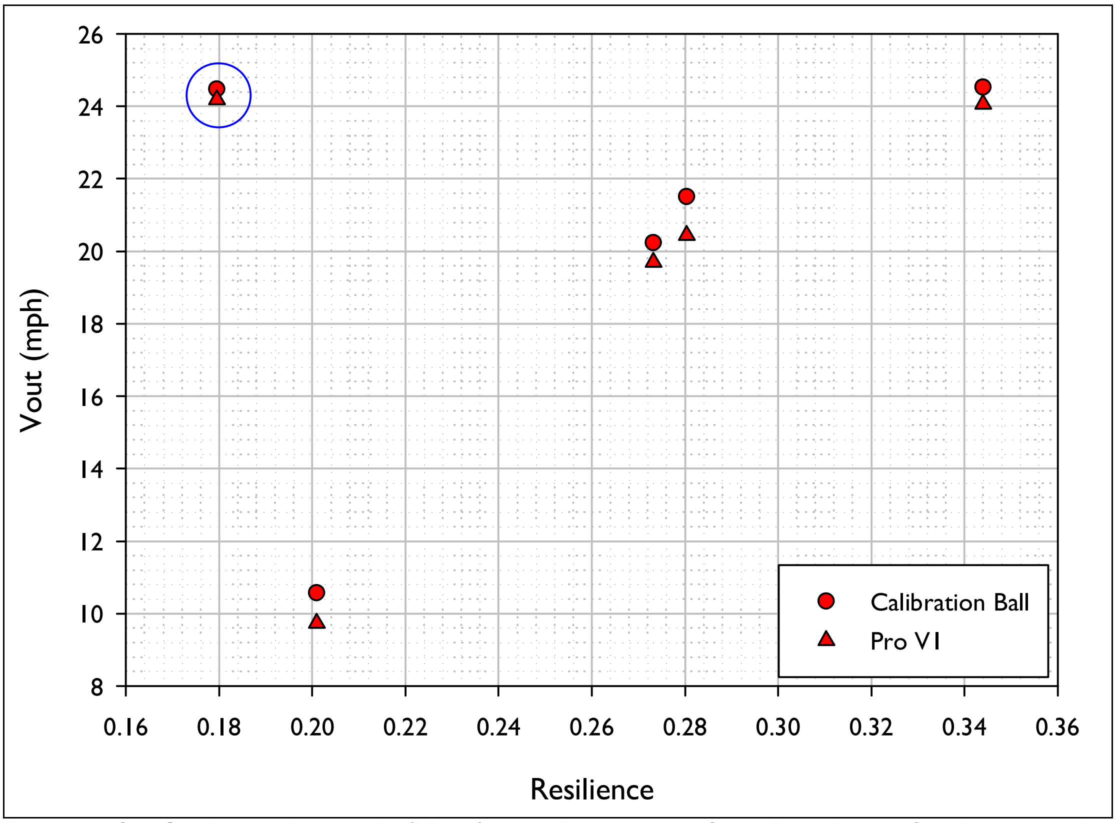

Figure 12. Outbound speed (Vout) vs. Resilience for the shots fired using the inbound conditions akin to those for a Driver.

Figure 13 and Figure 14 show the changes in outbound angle after impact with stiffness and resilience respectively. It can be seen that when comparing the outbound angle against stiffness, that the outbound angle decreases as the stiffness of the turf increases. A decrease in outbound angle is also observed with increasing the resilience of the turf, Figure 14, again with the exception of the resilience observed at The Renaissance (circled in blue) which was considerably lower than would have been expected to fit with the trend exhibited by the other courses. A ball which exits the turf at a shallower angle would (within reason) be expected to bounce/roll further than the equivalent ball exiting the turf with a higher angle. Assuming this to be the case, the trends observed would be consistent with the ball being expected to bounce and roll further on a stiff, resilient fairway.

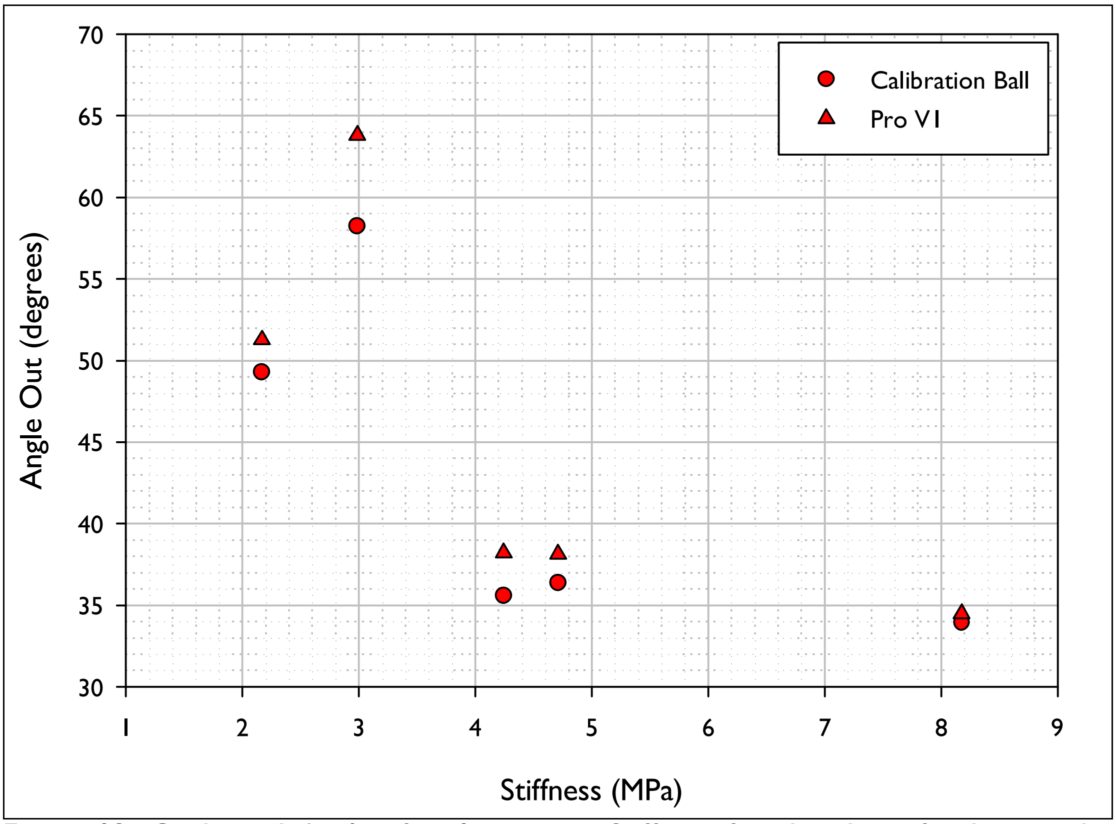

Figure 13. Outbound Angle after Impact vs. Stiffness for the shots fired using the inbound conditions akin to those for a Driver.

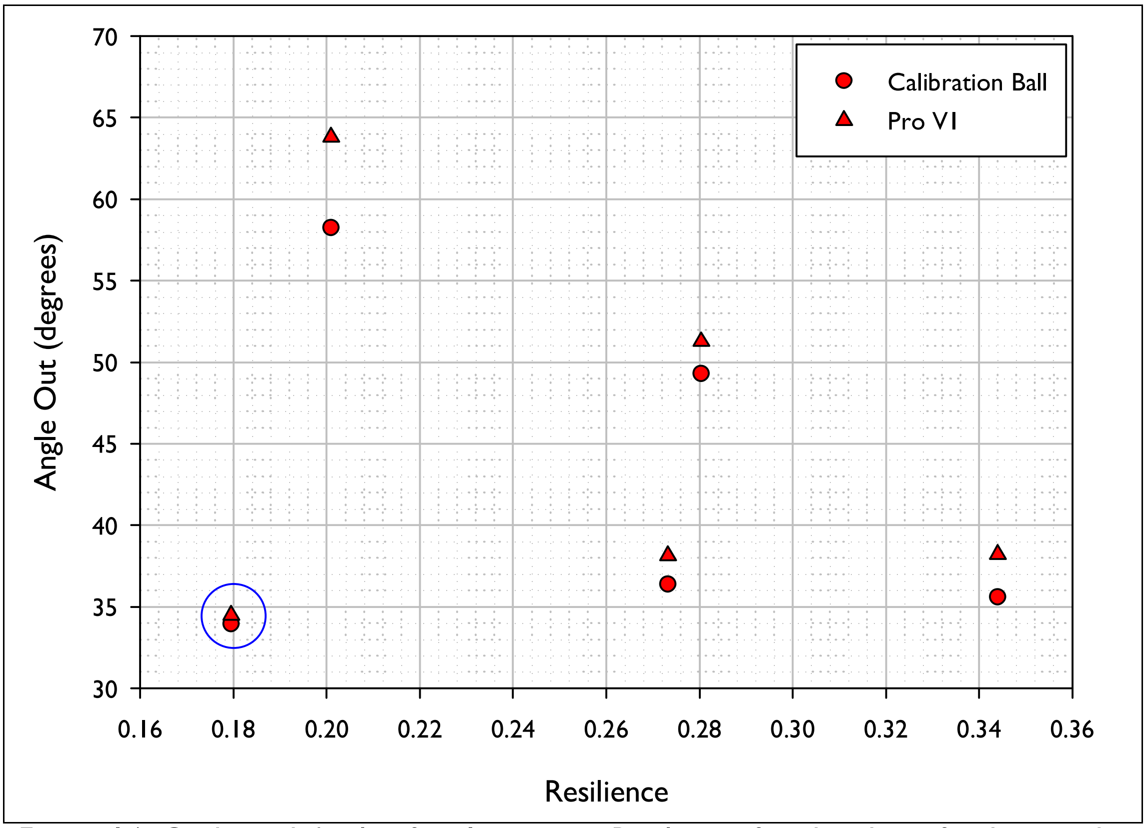

Figure 14. Outbound Angle after Impact vs. Resilience for the shots fired using the inbound conditions akin to those for a Driver.

When considering the change in spin through the impact with stiffness, Figure 15, it can be seen that generally, as stiffness of the turf increases, so does the change in spin between the inbound and outbound conditions. Given that the average inbound spin for the driver condition shots was approximately 2250 RPM, it can be seen that all of the average outbound conditions had a reversal in the direction of spin (i.e. the change in spin was greater than 2250 RPM), leaving the ground with 'topspin'. This would lead the ball to roll further than a shot with lower spin or even maintaining backspin (assuming the other outbound conditions are consistent between shots). However, when the change in spin is compared to the resilience of the turf, Figure 16, the data are sufficiently spread out to make the determination of any particular trends difficult to discern.

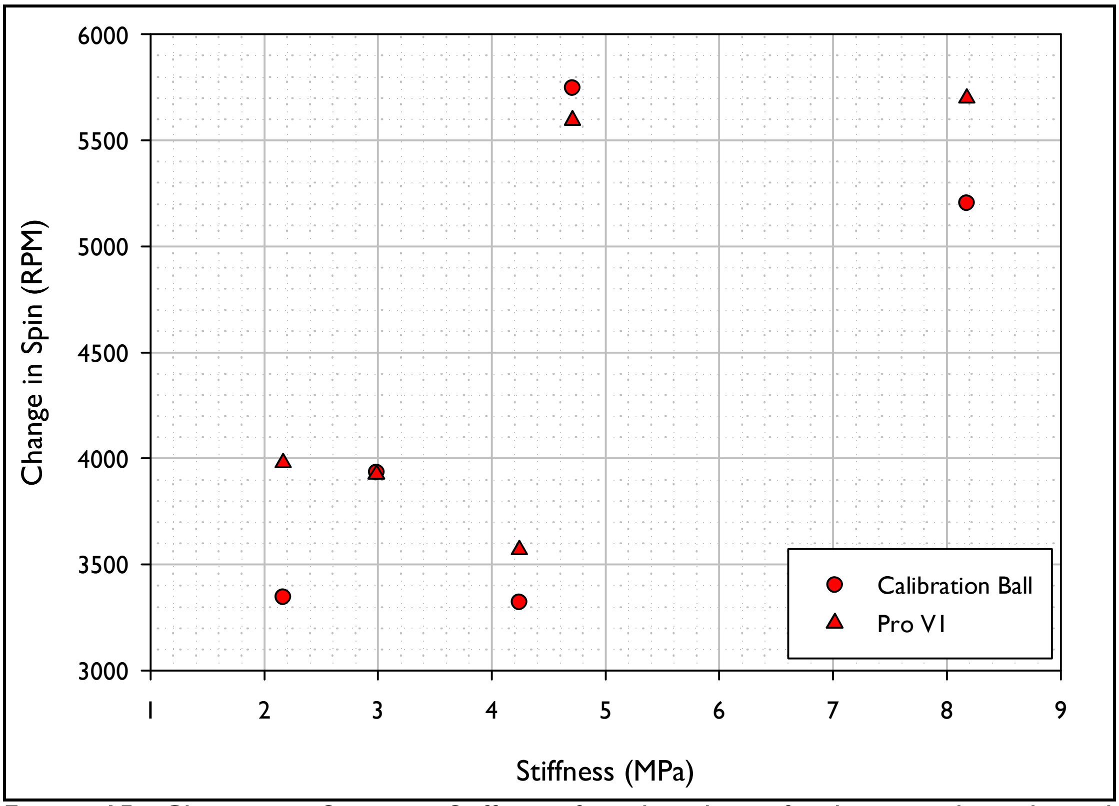

Figure 15. Change in Spin vs. Stiffness for the shots fired using the inbound conditions akin to those for a Driver.

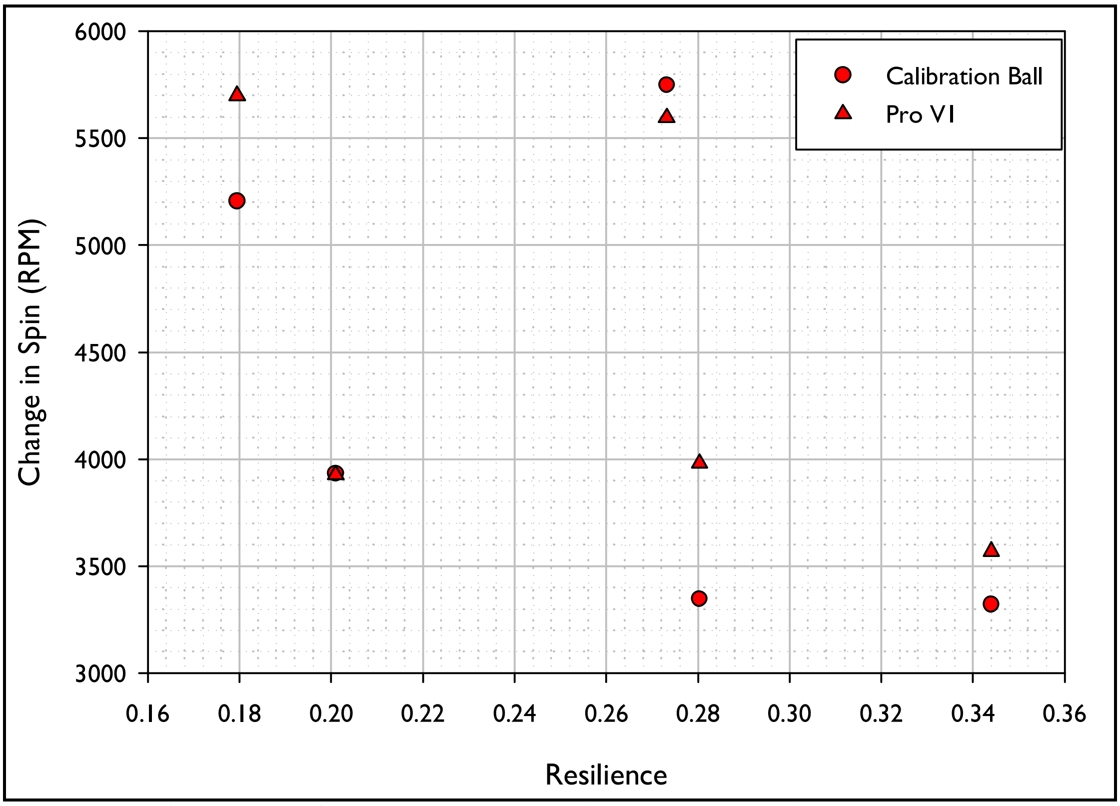

Figure 16. Change in Spin vs. Resilience for the shots fired using the inbound conditions akin to those for a Driver.

A comparison of the bounce and roll values to the stiffness of the turf, Figure 17, shows that as stiffness increases so the distance travelled between the impact position of the ball and its final resting position increases. This increased bounce and roll is due to the cumulative effect of the increased exit speed of the ball with a shallower outbound angle and higher value of 'topspin' associated with a stiffer fairway as measured and presented previously. When considering the relationship between bounce and roll and the resilience of the turf, Figure 18, it can again be seen that as resilience increases then so bounce and roll increases although the seemingly anomalous data point from The Renaissance (circled in blue) is omnipresent.

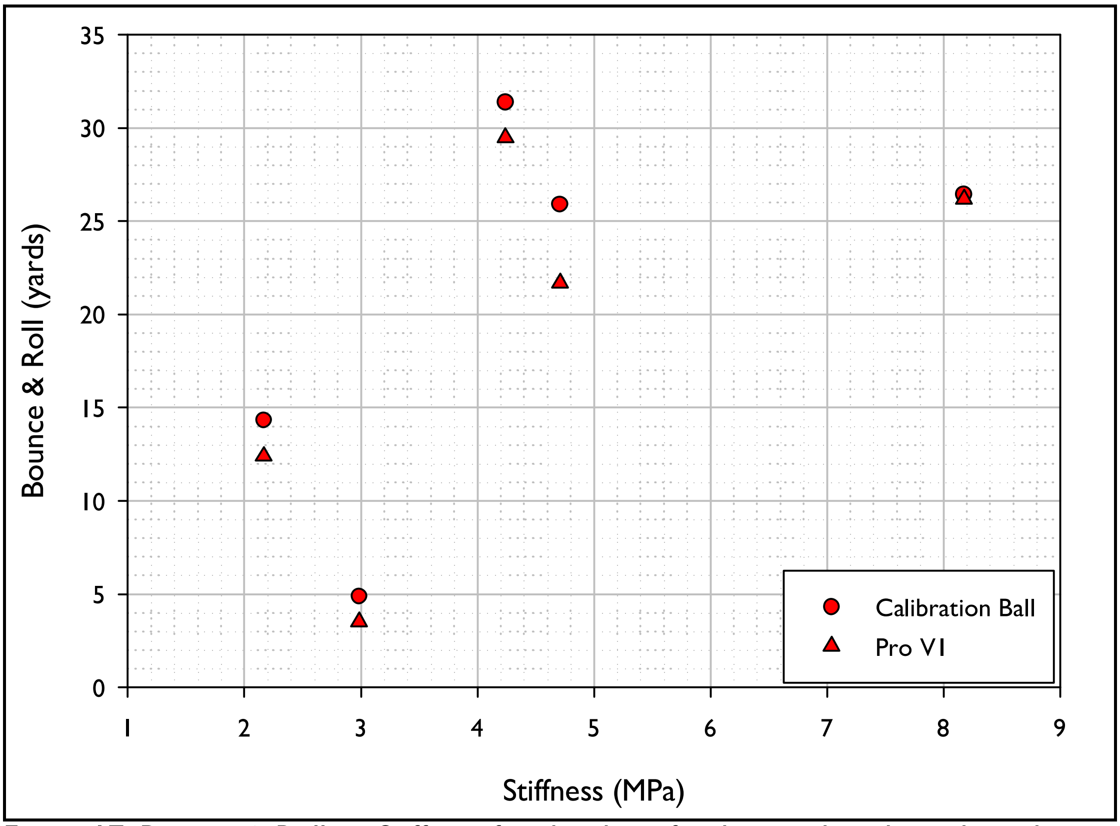

Figure 17. Bounce & Roll vs. Stiffness for the shots fired using the inbound conditions akin to those for a Driver.

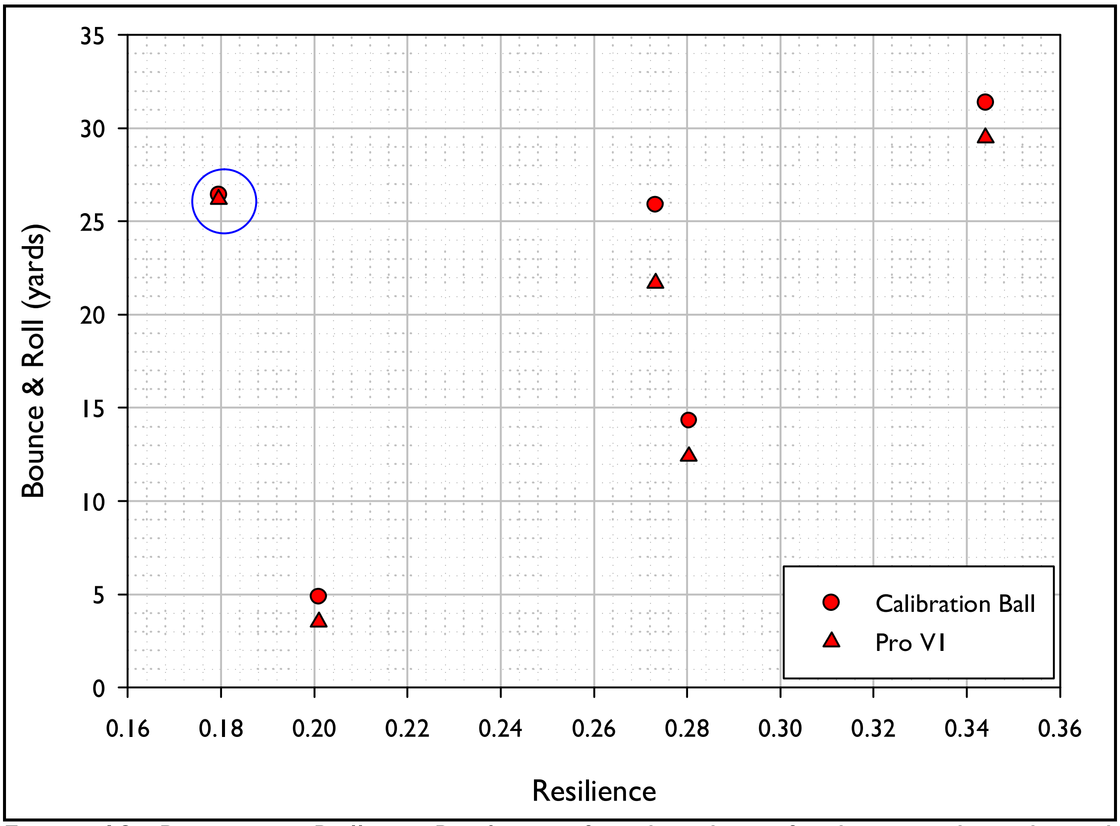

Figure 18. Bounce & Roll vs. Resilience for the shots fired using the inbound conditions akin to those for a Driver.

Finally, the Coefficient of Restitution (CoR) of the ball/turf impacts is considered against the stiffness and resilience of the turf, Figure 19 and Figure 20 respectively. It can be seen from Figure 19 that the spread in CoR values for the less stiff fairways is sufficient to prevent the determination of a correlation between CoR and stiffness. However, if the CoR is considered as a function of resilience, Figure 20, it can be seen that is reasonable evidence of an increase in CoR as the resilience of the turf increases. This is not unexpected since the CoR of the ball/turf impact is the most comparable interaction to that of the USGA TruFirm device with the turf (although it is important to note that there will be a significant difference in strain rates during the interaction with the turf due the significantly different impact speeds of the ball compared to the USGA TruFirm device – the normal impact speed of the ball is approaching 40 mph whilst the impact speed of the USGA TruFirm device is around 2-3 mph).

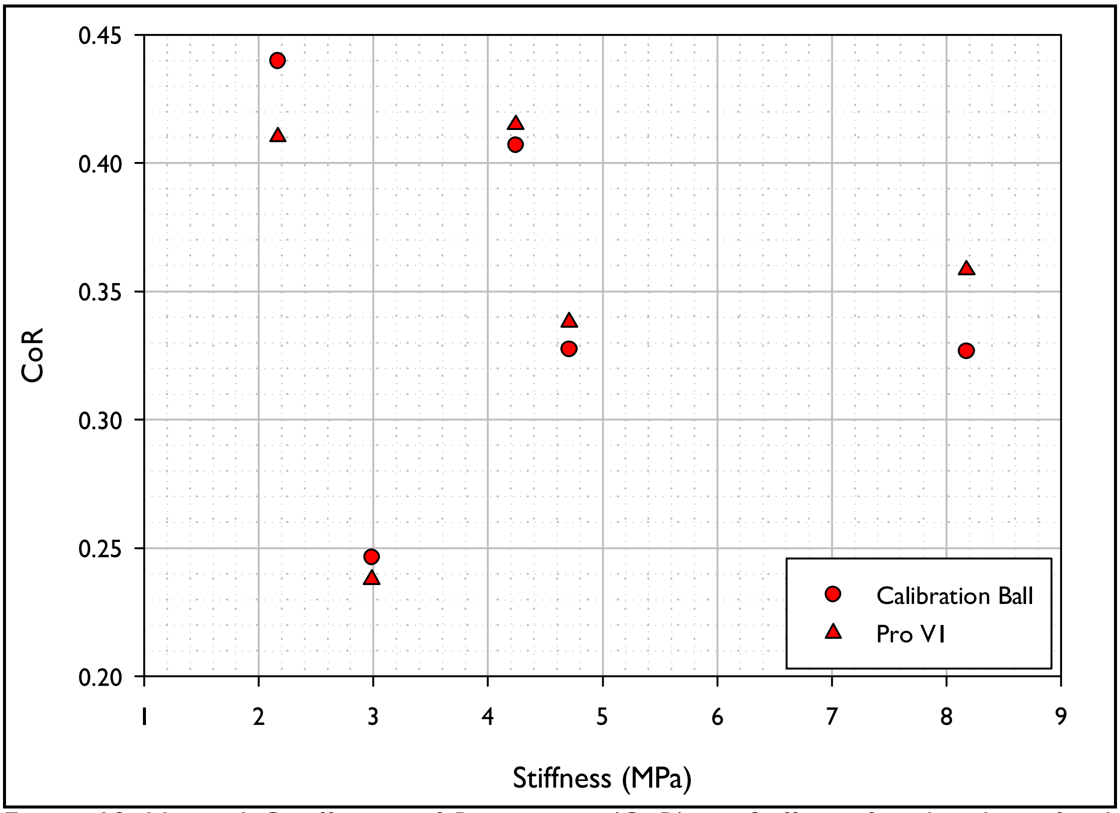

Figure 19. Vertical Coefficient of Restitution (CoR) vs. Stiffness for the shots fired using the inbound conditions akin to those for a Driver.

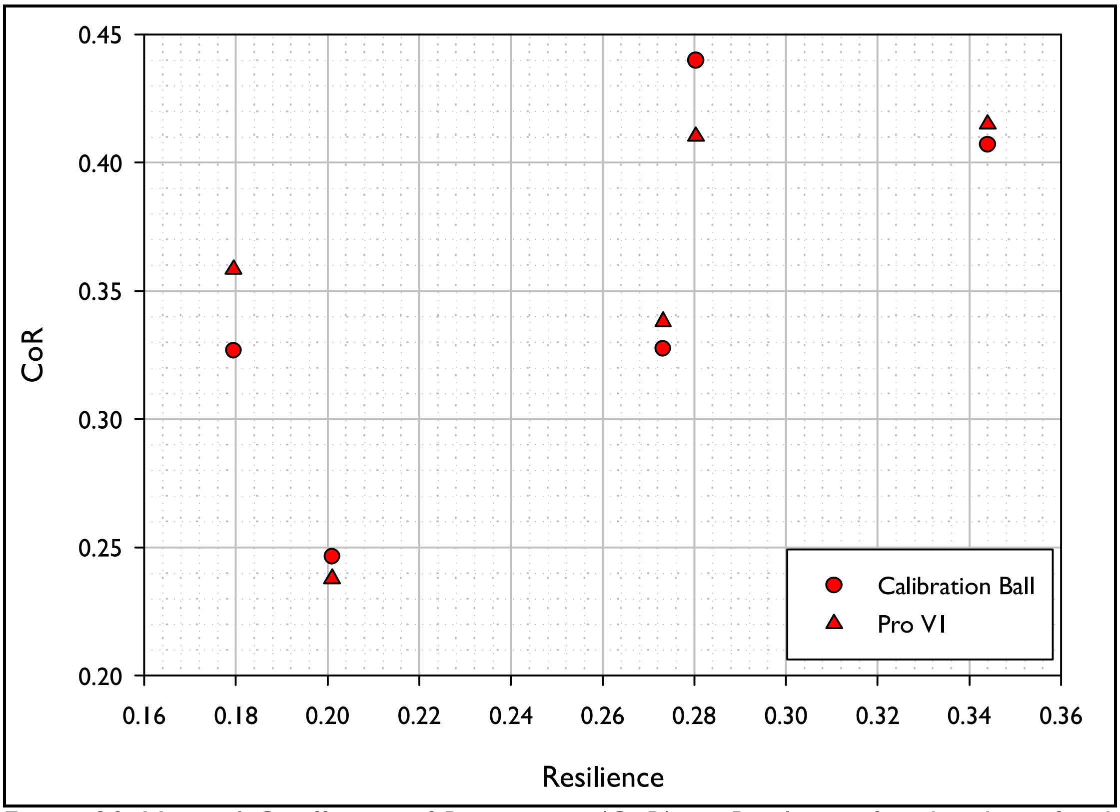

Figure 20. Vertical Coefficient of Restitution (CoR) vs. Resilience for the shots fired using the inbound conditions akin to those for a Driver.

In summary, when considering the shots with inbound conditions similar to those expected for a driver, it can be seen that as stiffness increases then the outbound speed of the ball after impact with the turf increases whilst the outbound angle of the ball decreases. The change in spin achieved during impact also increases, resulting in the ball having more ‘topspin’. This faster, shallower trajectory with a greater amount of ‘topspin’ results in the ball travelling further through bounce and roll before coming to rest.

An increase in resilience similarly suggests an increase in the post impact speed of the ball along with a decrease in the outbound angle through impact, resulting in a generally higher bounce and roll distance. However, the evidence of an apparent anomalous result would suggest that the relationship between these parameters and the resilience of the turf may not be as simple as would appear to be for stiffness (when considering these sites). Additionally, the vertical CoR of the impact appears to increase with the resilience of the turf as measured using the USGA TruFirm device.

5 Iron

Following the consideration of the shots struck with the inbound conditions of a driver impacting with turf of fairway condition, those shots with the inbound conditions akin to those of a 5 iron when impacting with turf of green type conditions are considered. Figure 21 shows a composite image of 9 frames taken from a typical 5 iron impact. The time between the frames taken pre and post impact are such that the post impact frames are 7.9x the time spacing of the pre impact frames.

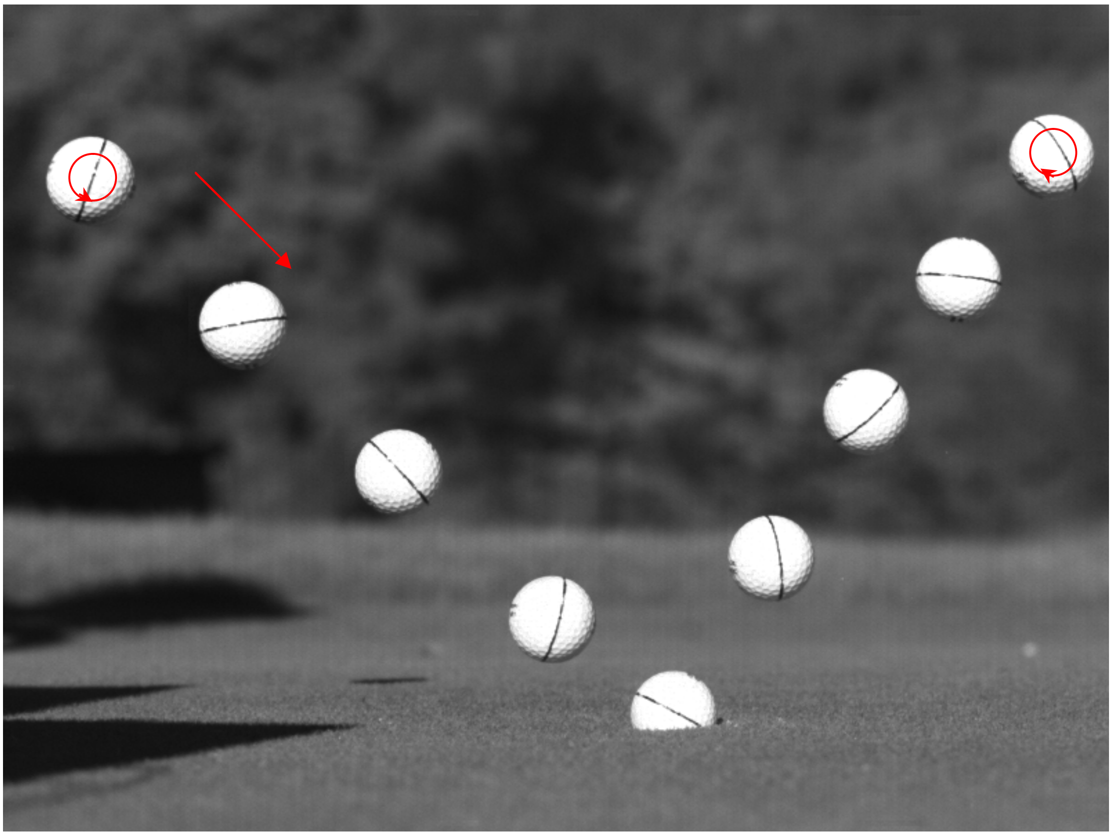

Figure 21. Selected frames from a typical 5 iron impact.

The velocity vector (speed and angle) of the average calibration ball prior to and after impact with the different turf conditions is shown in Figure 22. It can be seen that the outbound velocities for these impacts are considerably lower than the inbound velocities. It can be seen that the two sites at St Andrews – the Practice Centre green and the Balgove practice green have very similar outbound velocities. Similarly, with the exception of The Northumberland which has the slowest outbound speed coming off the green very close to vertically, the other (three) sites have similar outbound angles. It is also interesting to note at this stage that whilst the inbound speed of the 5 iron shot is lower than that observed for the driver previously, the difference in inbound angle results in the vertical component of the velocity being higher than that of the driver (approximately 42 mph compared to 38 mph for the driver).

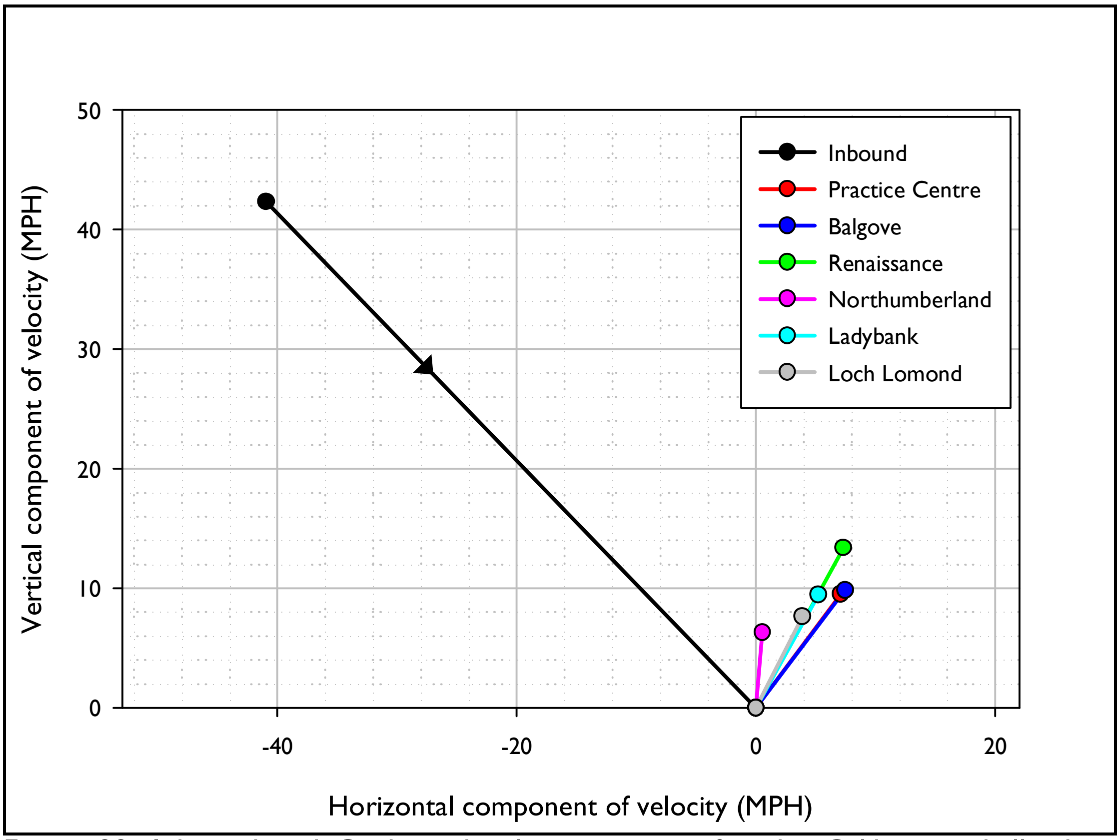

Figure 22. Inbound and Outbound velocity vectors for the Calibration ball when launched with 5 iron impact conditions.

If the outbound speeds of the ball (Vout) are considered against the stiffness of the turf at each site, Figure 23, it can be seen that as the stiffness of the turf increases, the outbound speed of the ball increases as well. On comparing the outbound speeds of the ball to the resilience measured at each site, Figure 24, the trend is not as well established. If the data from The Northumberland (circled in blue) which has a very low outbound speed were not considered then there is a suggestion of an increase of resilience relating to a slight increase in outbound speed although this is not as clear as the observed trend between outbound speed and stiffness and it would be equivalently justified to suggest a negligible increase in ball speed with increasing resilience.

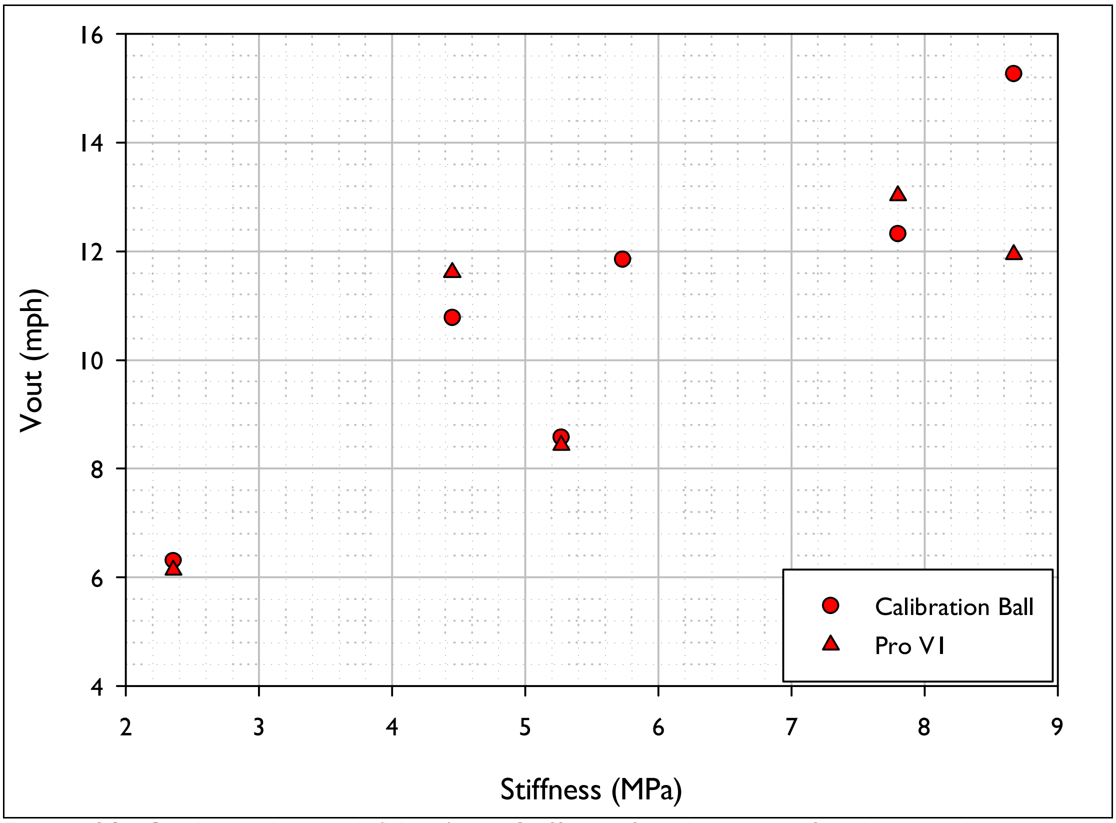

Figure 23. Outbound speed (Vout) vs. Stiffness for the shots fired using the inbound conditions akin to those for a 5 Iron.

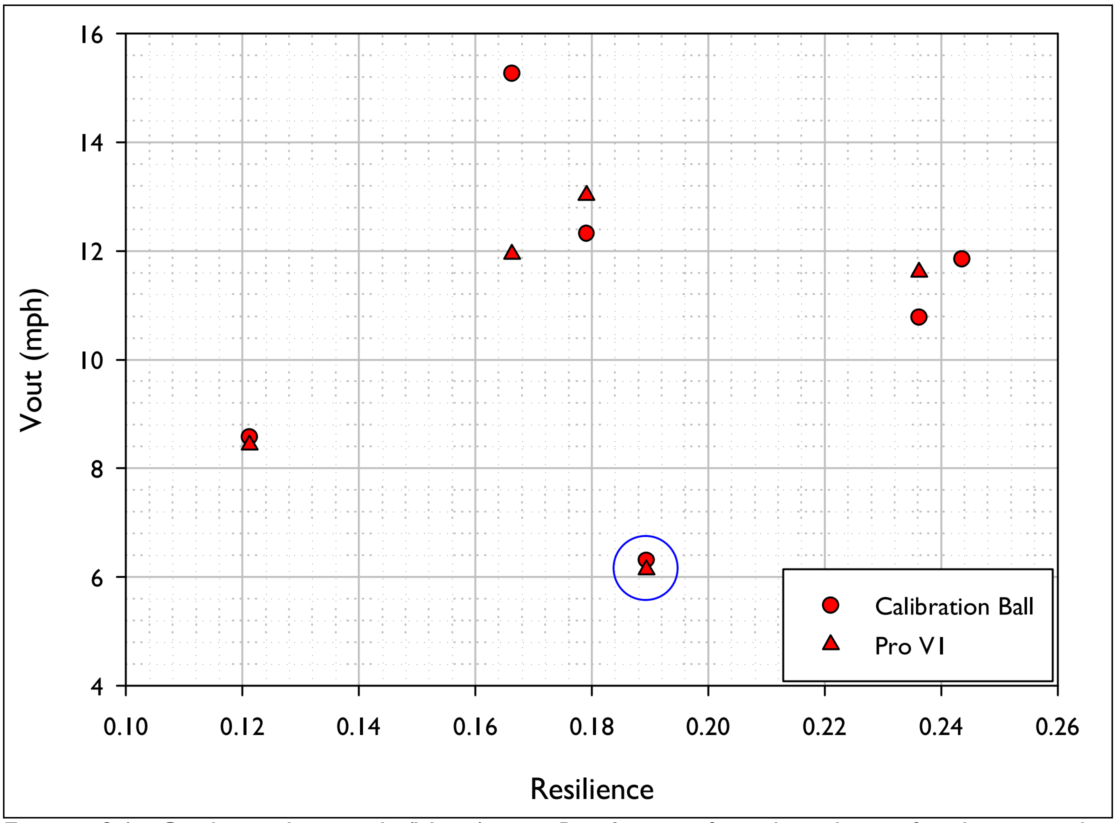

Figure 24. Outbound speed (Vout) vs. Resilience for the shots fired using the inbound conditions akin to those for a 5 Iron.

On considering the outbound angle against the stiffness of the greens, Figure 25, it can be seen that as previously observed for the Driver shots, an increase in stiffness leads to a decrease in the outbound angle post impact. As for the Vout data, the outbound angle vs. resilience data, Figure 26, does not appear to show any definitive trend, even without considering the data from The Northumberland (circled in blue)

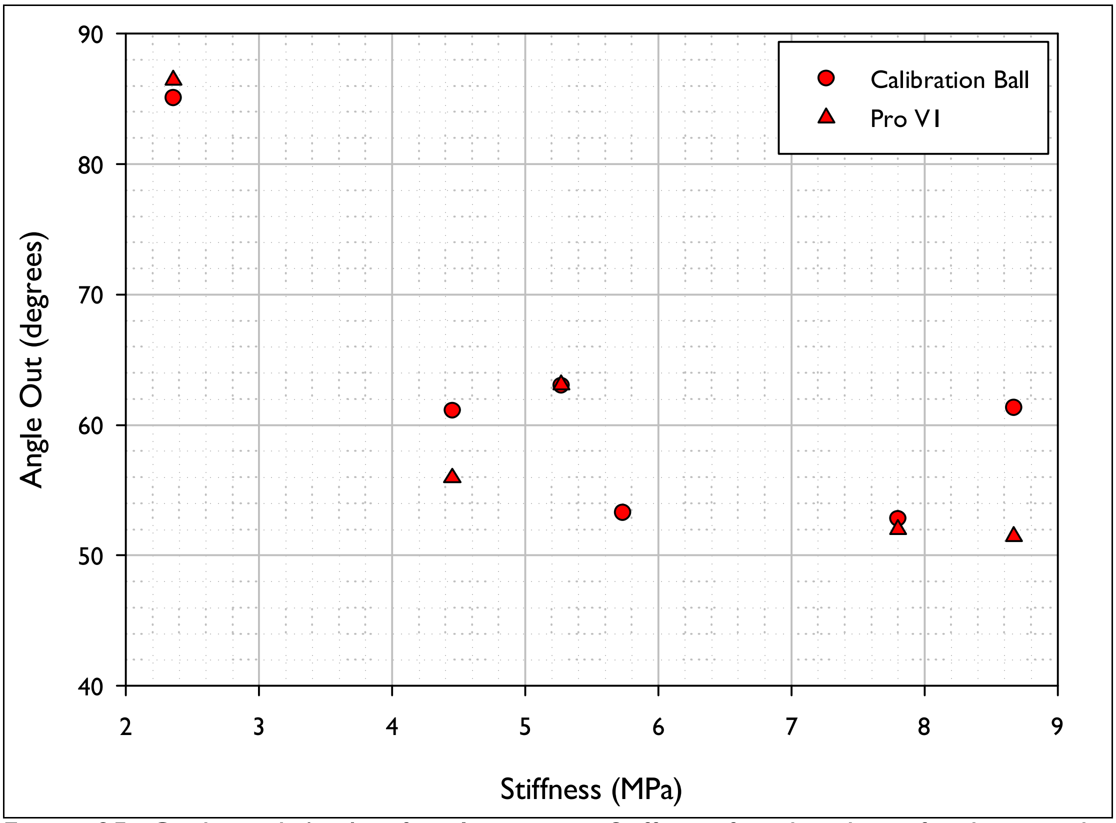

Figure 25. Outbound Angle after Impact vs. Stiffness for the shots fired using the inbound conditions akin to those for a 5 Iron.

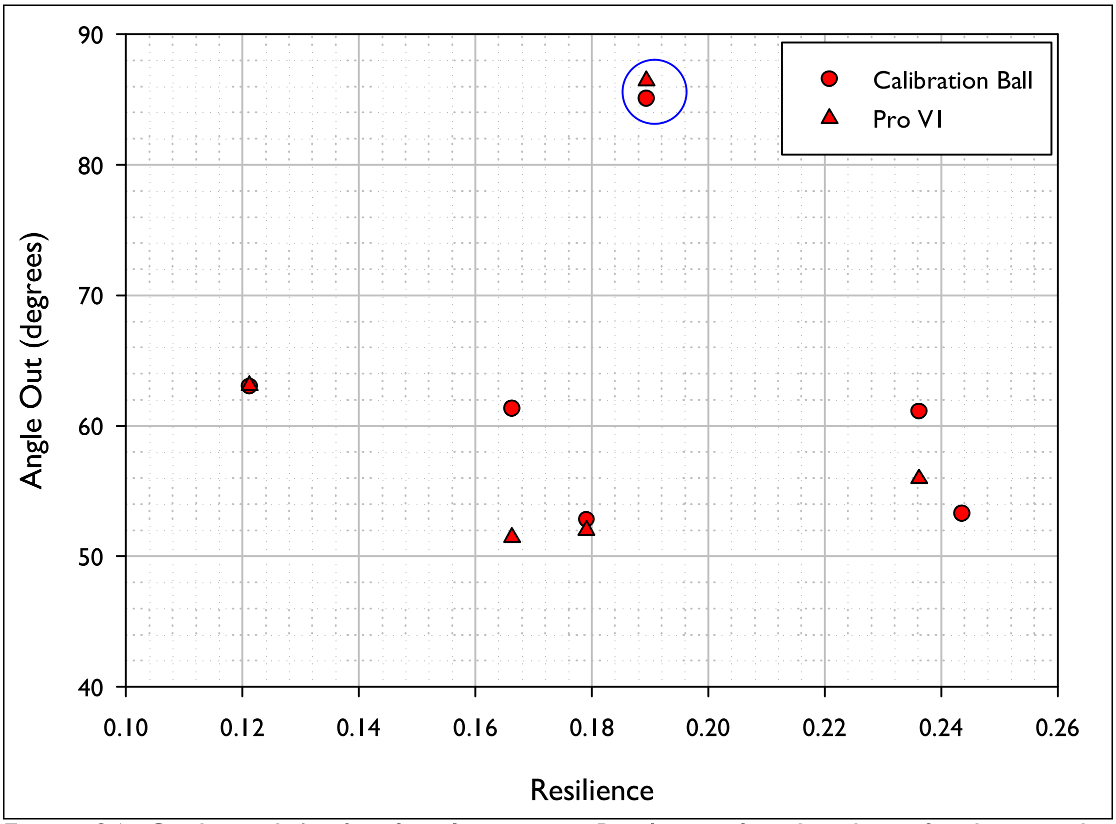

Figure 26. Outbound Angle after Impact vs. Resilience for the shots fired using the inbound conditions akin to those for a 5 Iron.

Moving on to consider the change in spin as a function of stiffness, Figure 27, it can be seen that again there appears to be a reasonable trend whereby an increase in stiffness will lead to an increase in the change of spin. Given that the average inbound spin was 4550 RPM, it can be seen that in all cases, the inbound backspin has been translated to 'topspin' after impact.

If the change in spin is considered as a function of resilience instead of stiffness, Figure 28, there is insufficient evidence to suggest a meaningful trend between these two parameters.

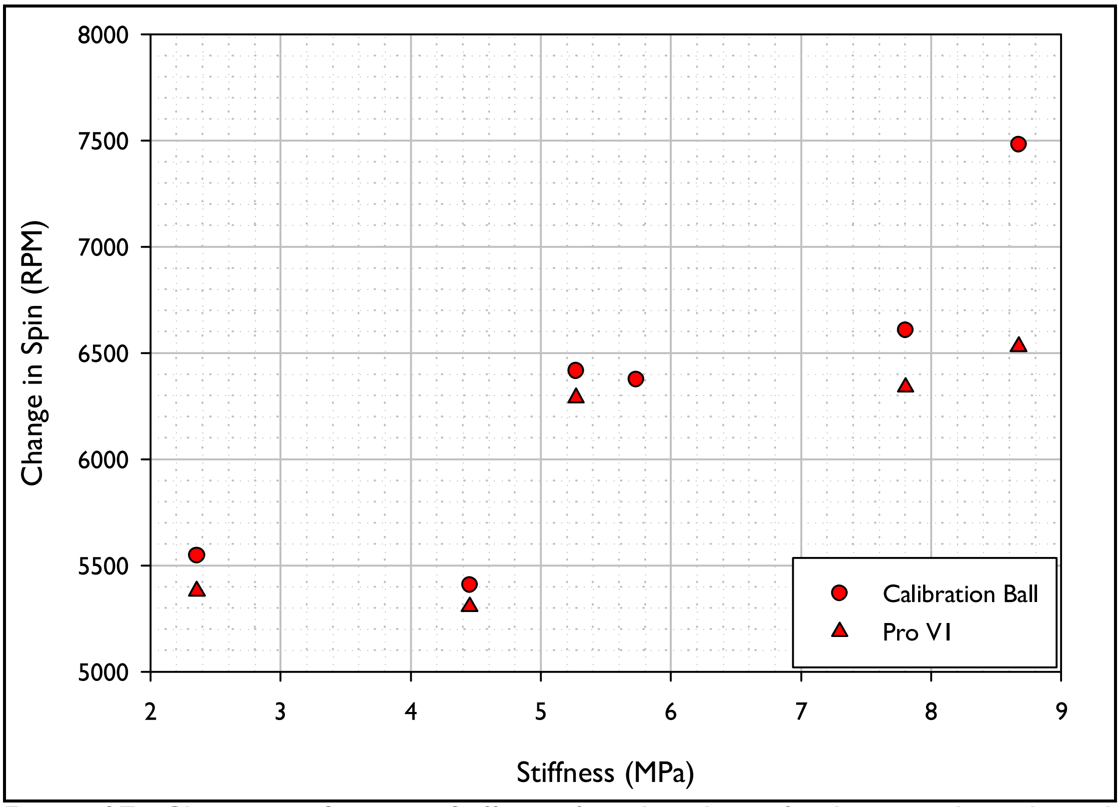

Figure 27. Change in Spin vs. Stiffness for the shots fired using the inbound conditions akin to those for a 5 Iron.

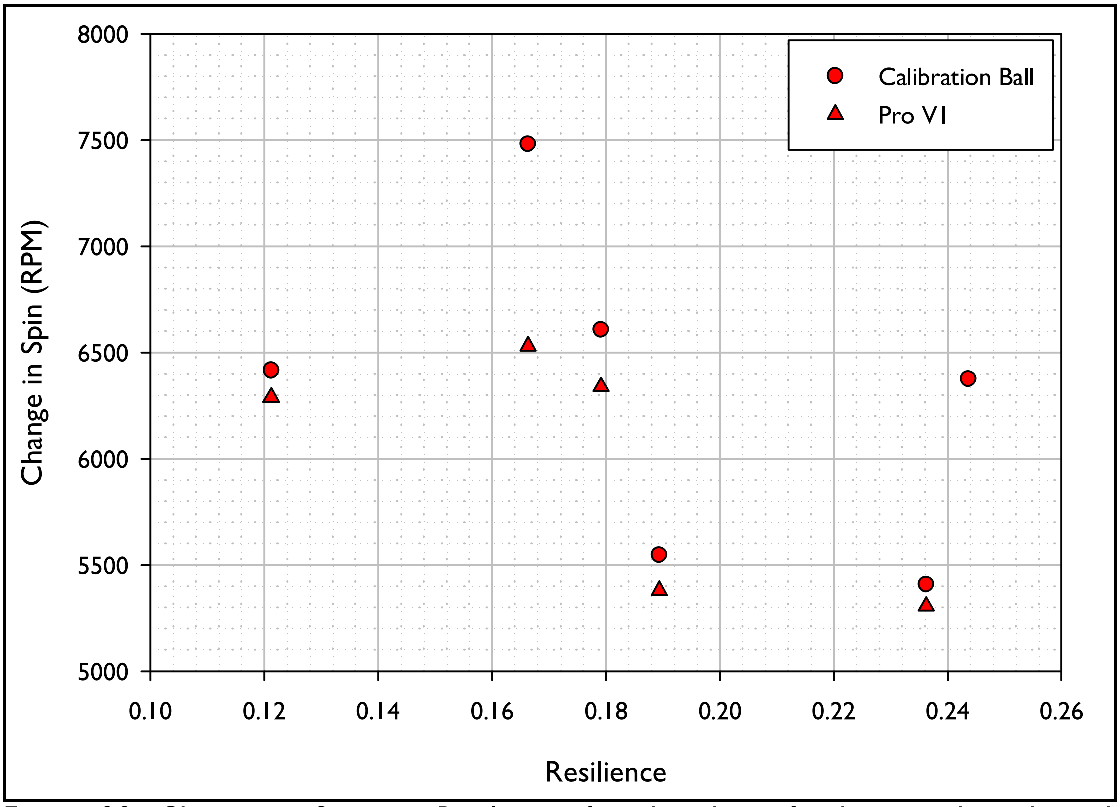

Figure 28. Change in Spin vs. Resilience for the shots fired using the inbound conditions akin to those for a 5 Iron.

The Bounce and Roll of the balls were considered as a function of stiffness, Figure 29. It can be seen that the distance between the ball pitching and its final position increases as stiffness increases. This is not unexpected since previously it has been established that a stiffer green causes the ball to leave the surface post impact moving faster, at a shallower angle with more 'topspin' – a combination of changes which would logically result in more bounce and roll.

The Bounce and Roll data were then plotted against the resilience, Figure 30, showing no evidence of a definitive trend between the two parameters.

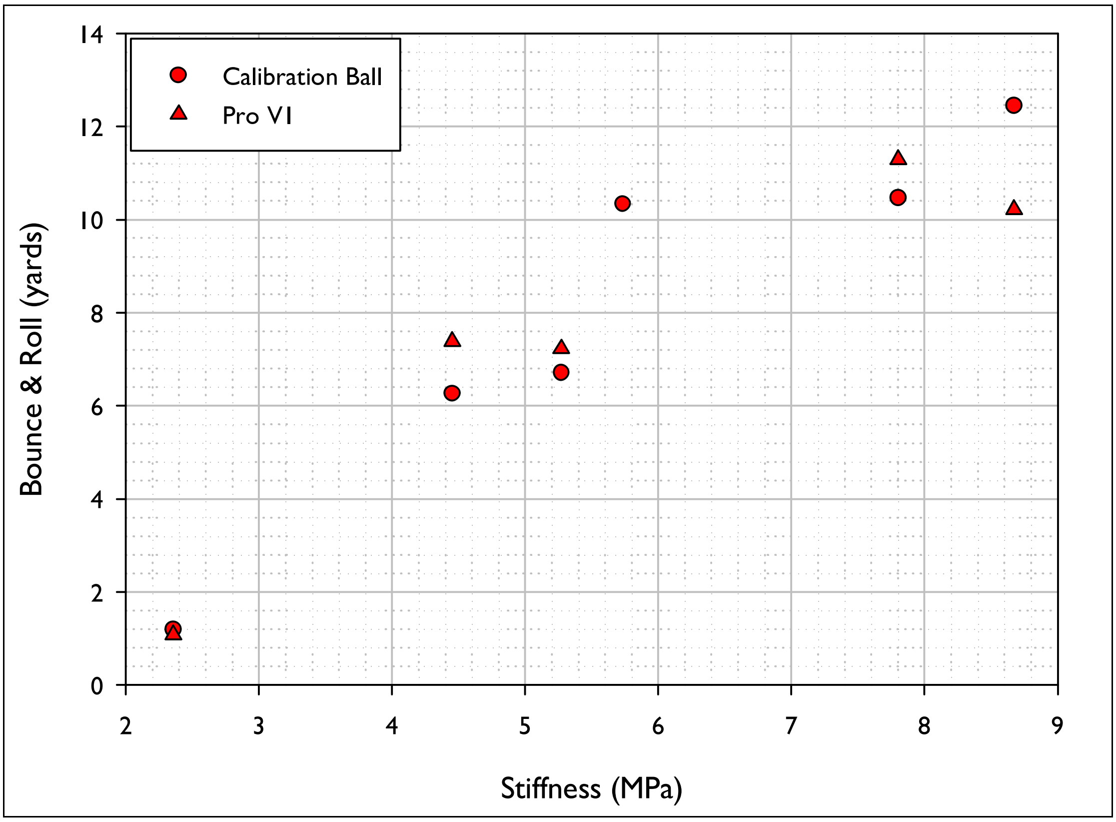

Figure 29. Bounce & Roll vs. Stiffness for the shots fired using the inbound conditions akin to those for a 5 Iron.

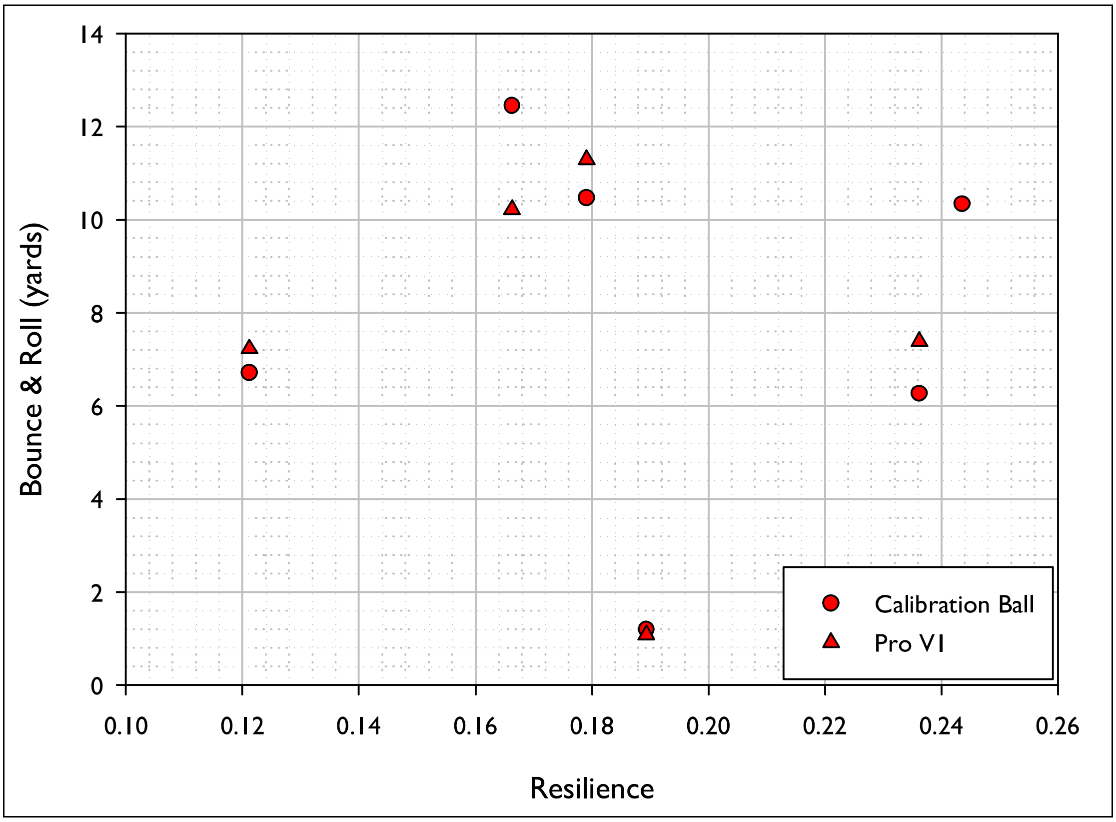

Figure 30. Bounce & Roll vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

Finally, as for the driver, the Coefficient of Restitution data for the ball impacting with the turf were plotted against the stiffness and resilience values, Figure 31 and Figure 32 respectively. It can be seen that in contrast to the driver data presented previously, there would appear to be a reasonable trend between CoR and stiffness such that as stiffness increased then so did CoR. This trend is not particularly evident for the resilience data, Figure 32, even with the removal of the seemingly anomalous data from The Northumberland, circled in blue.

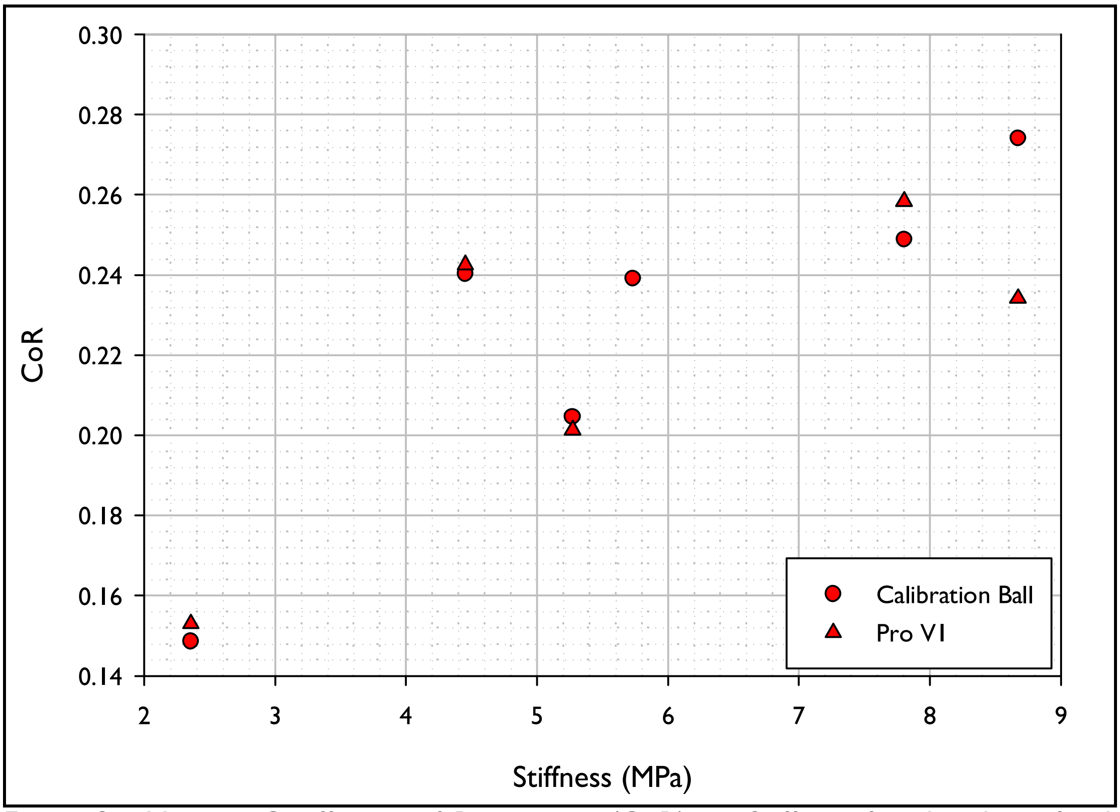

Figure 31. Vertical Coefficient of Restitution (CoR) vs. Stiffness for the shots fired using the inbound conditions akin to those for a 5 Iron.

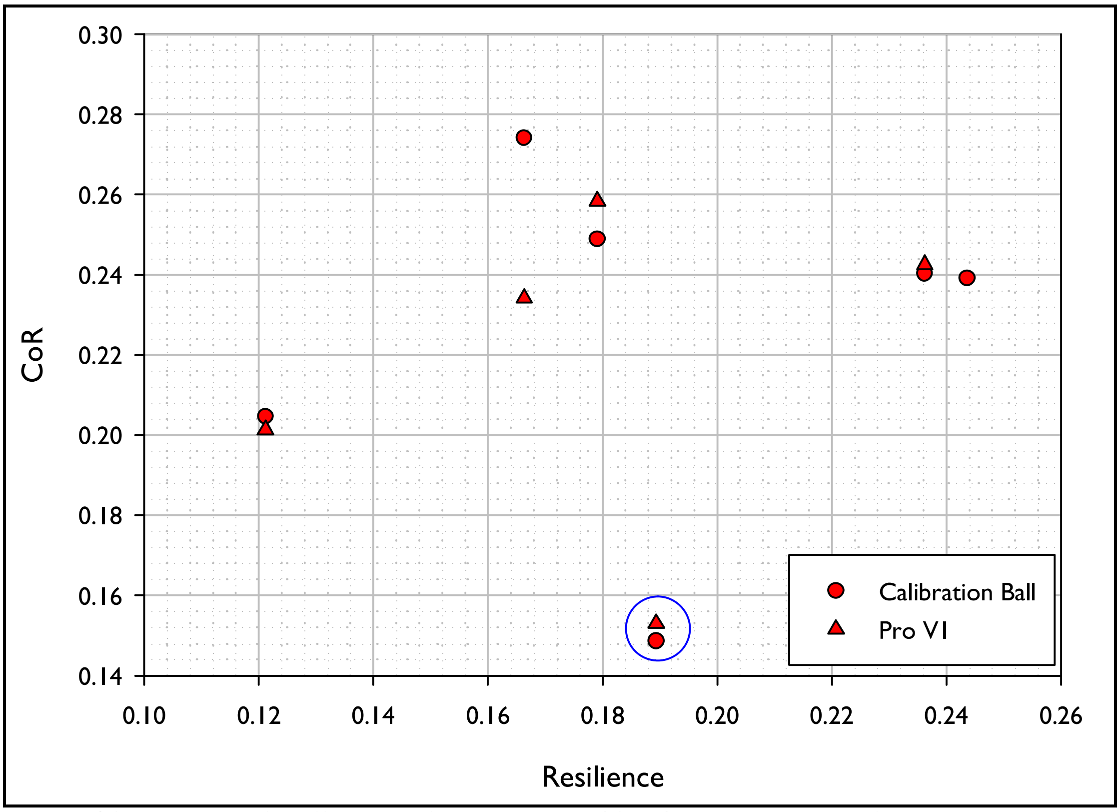

Figure 32. Vertical Coefficient of Restitution (CoR) vs. Resilience for the shots fired using the inbound conditions akin to those for a 5 Iron.

In summary, when considering the shots with inbound conditions similar to those expected for a 5 iron, it can be seen that there are reasonable trends evident between the stiffness and all of the investigated parameters. As stiffness increases, the outbound speed of the ball after impact increases with the ball leaving at a shallower angle and more 'topspin'. These outbound conditions result in a greater distance between the impact position of the ball and its final resting position. There is also evidence of a dependence of stiffness on the vertical CoR of the ball as well.

Conversely, when considering the resilience data, there is sufficient variability to prevent establishing convincing trends between the measured resilience of the green and any of the measured parameters.

Sand Wedge

The third set of impact conditions for consideration was those akin to the impact conditions expected for a sand wedge. A composite image of 9 images taken from the high speed video of a typical sand wedge shot, Figure 33, shows outbound images taken at 8.5x the time interval of the inbound images.

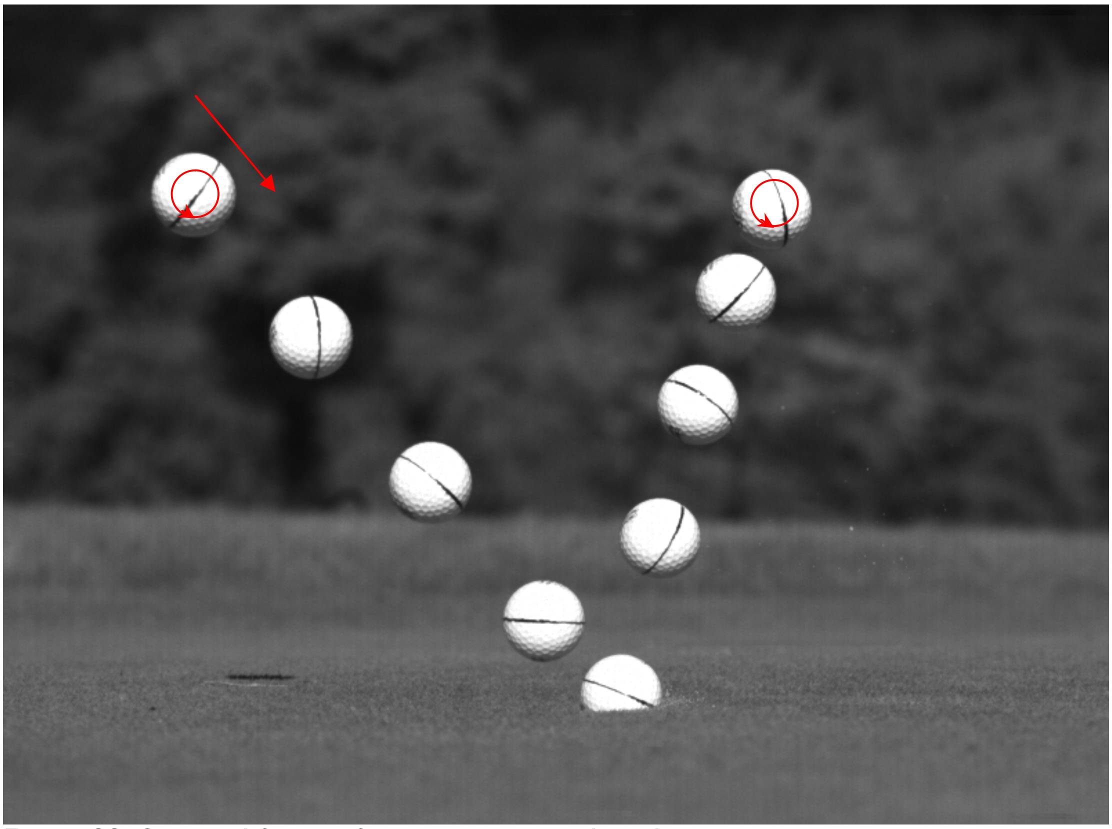

Figure 33. Selected frames from a typical sand wedge impact.

The velocity vector (speed and angle) of the average calibration ball prior to and after impact with the different turf conditions is shown in Figure 34. It can be seen that the outbound velocities for these impacts are again considerably lower than the inbound velocities and unsurprisingly the lowest out of any of the impact conditions investigated in this study. The outbound angles are also steeper than observed for the other clubs, with the average post impact shot at The Northumberland rebounding at an angle of greater than 90 degrees – i.e. back towards the ball launcher. Again, whilst the inbound speed of the sand wedge shot is the lowest of the three clubs, the vertical component of the impact velocity is of a comparable order of magnitude to that of the 5 iron, due to the difference in inbound velocity between the clubs.

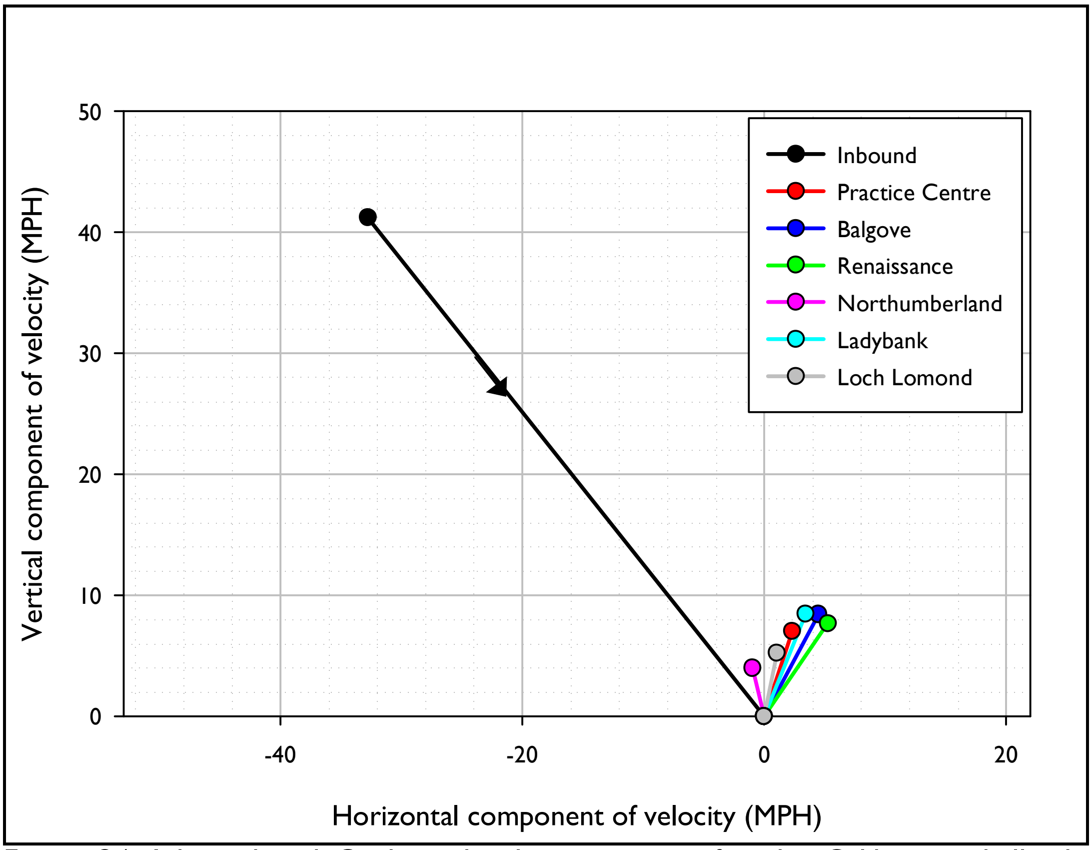

Figure 34. Inbound and Outbound velocity vectors for the Calibration ball when launched with sand wedge impact conditions.

On considering the outbound speed of the ball after impact with the different stiffness values of the turfs, Figure 35, it can be seen that again an increase in the stiffness of the turf leads to an increase in the outbound speed of the ball.

Considering the outbound speed of the ball against the resilience of the different turfs, Figure 36, it can be seen that generally, there is an increase of ball speed with increasing resilience of the turf. This trend however is not as prominent as previously exhibited for stiffness and the data from The Northumberland (circled in blue) looks to fall outwith any trend amongst the other data points.

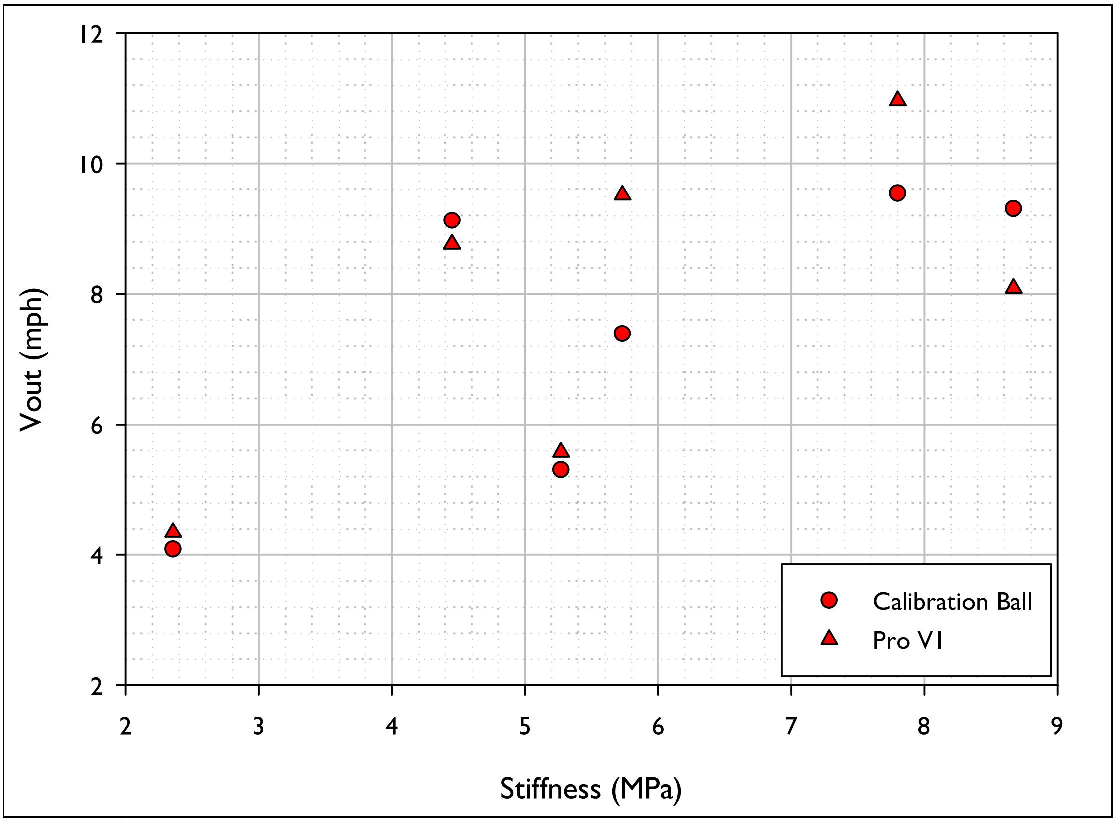

Figure 35. Outbound speed (Vout) vs. Stiffness for the shots fired using the inbound conditions akin to those for a sand wedge.

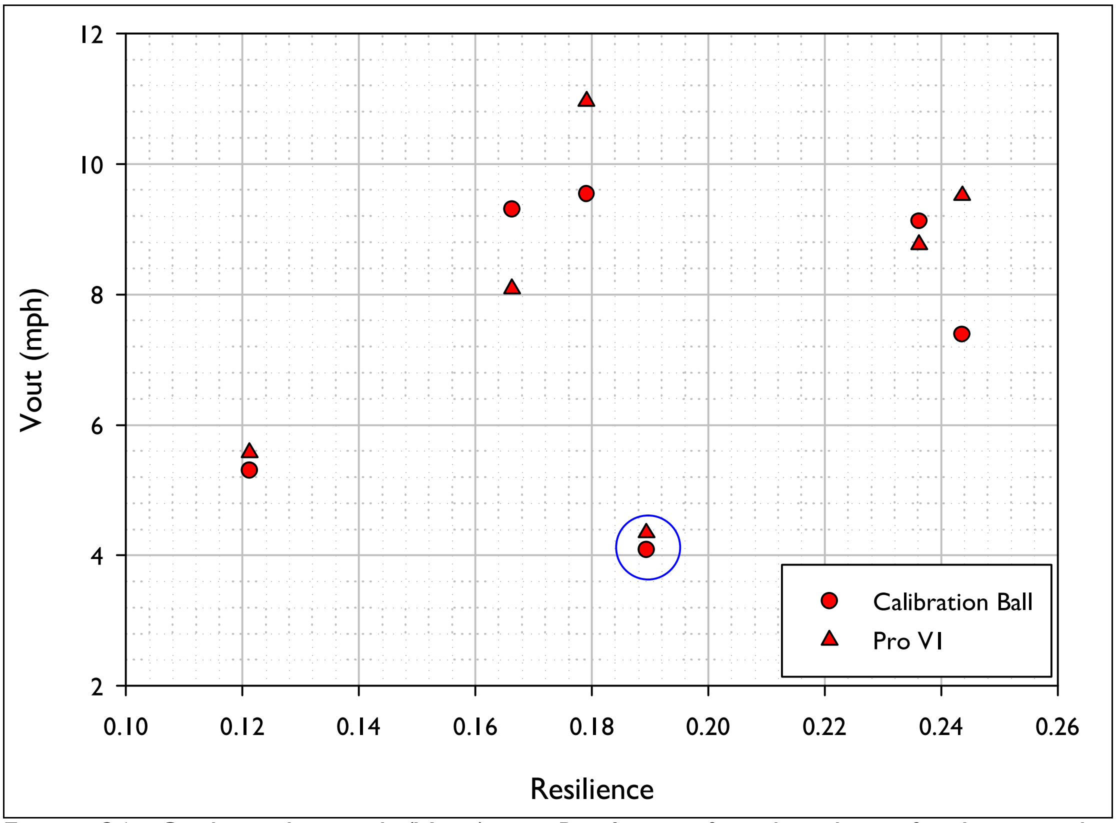

Figure 36. Outbound speed (Vout) vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

The outbound angle after impact also decreases with stiffness, Figure 37. This trend is consistent with both of the other clubs which show a decrease in outbound angle with increasing stiffness.

Looking at the resilience data, Figure 38, it would appear that there may be an decrease in the outbound angle after impact with increasing resilience but again as with the Vout data for this ‘club’, the data from The Northumberland (again circled in blue) appears to not follow the trend that may be exhibited by the other data.

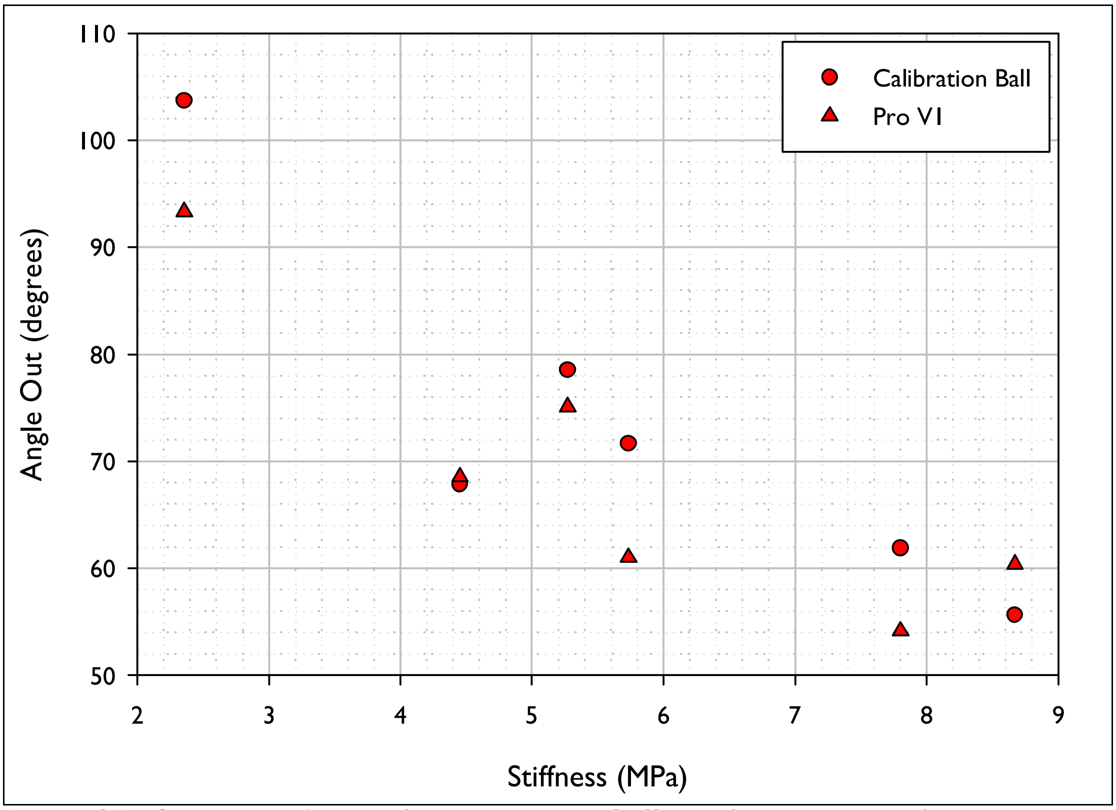

Figure 37. Outbound Angle after Impact vs. Stiffness for the shots fired using the inbound conditions akin to those for a sand wedge.

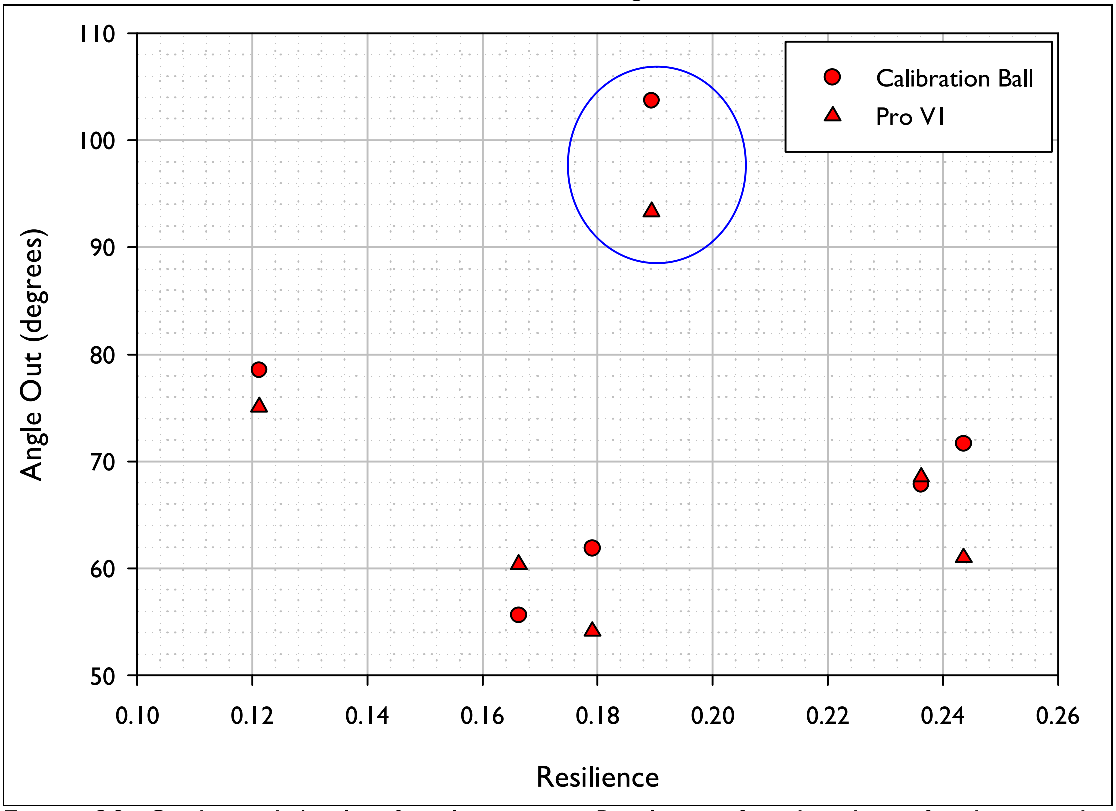

Figure 38. Outbound Angle after Impact vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

If the change in spin through impact is considered as a function of stiffness, Figure 39, it can be seen that there is suitable variation through the sites to not present any particular trends within these data. It is however interesting to note that the largest change in spin exhibited for any site was just over 7,000 RPM which was lower than the 9,000 RPM impact spin for this 'club'. This means that in every case for this impact set up, the ball retained an amount of backspin after the impact which is contrary to both of the previous clubs where the ball left the turf with topspin.

On considering the change in spin vs. resilience, Figure 40, it can be seen that there may be evidence for a decrease in the change of spin as the resilience increases, although there is still considerable scatter on these data so the trend is questionable at best.

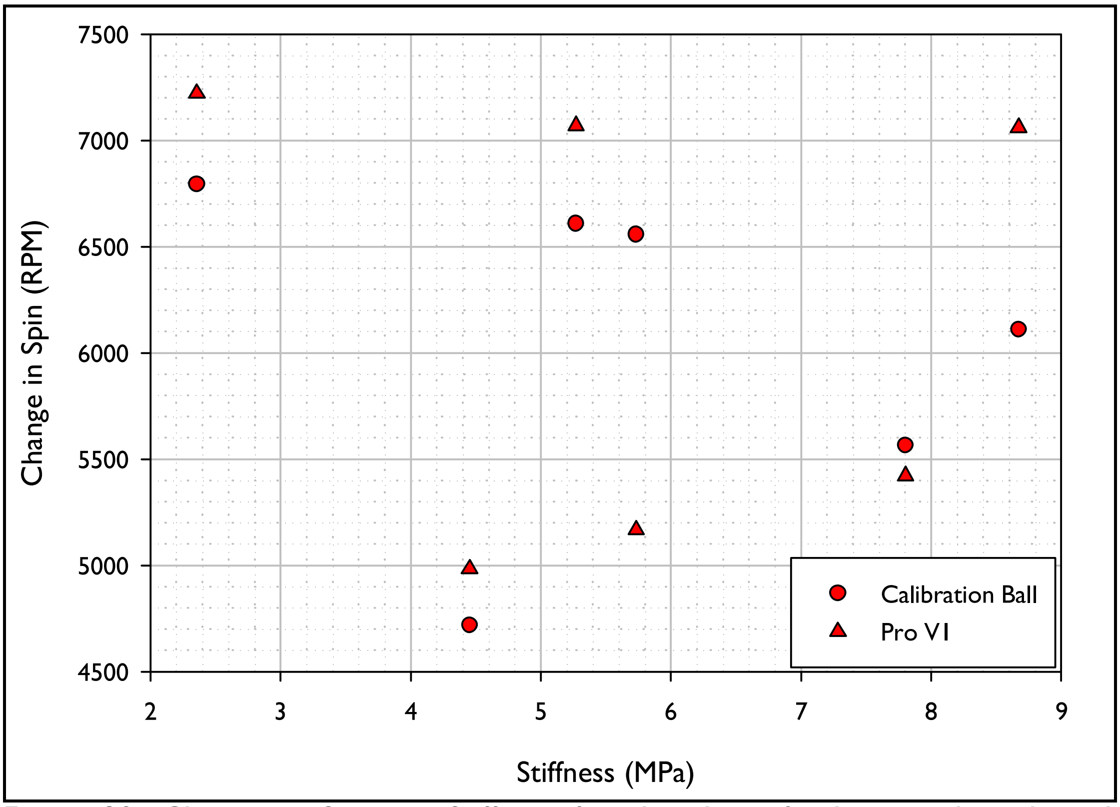

Figure 39. Change in Spin vs. Stiffness for the shots fired using the inbound conditions akin to those for a sand wedge.

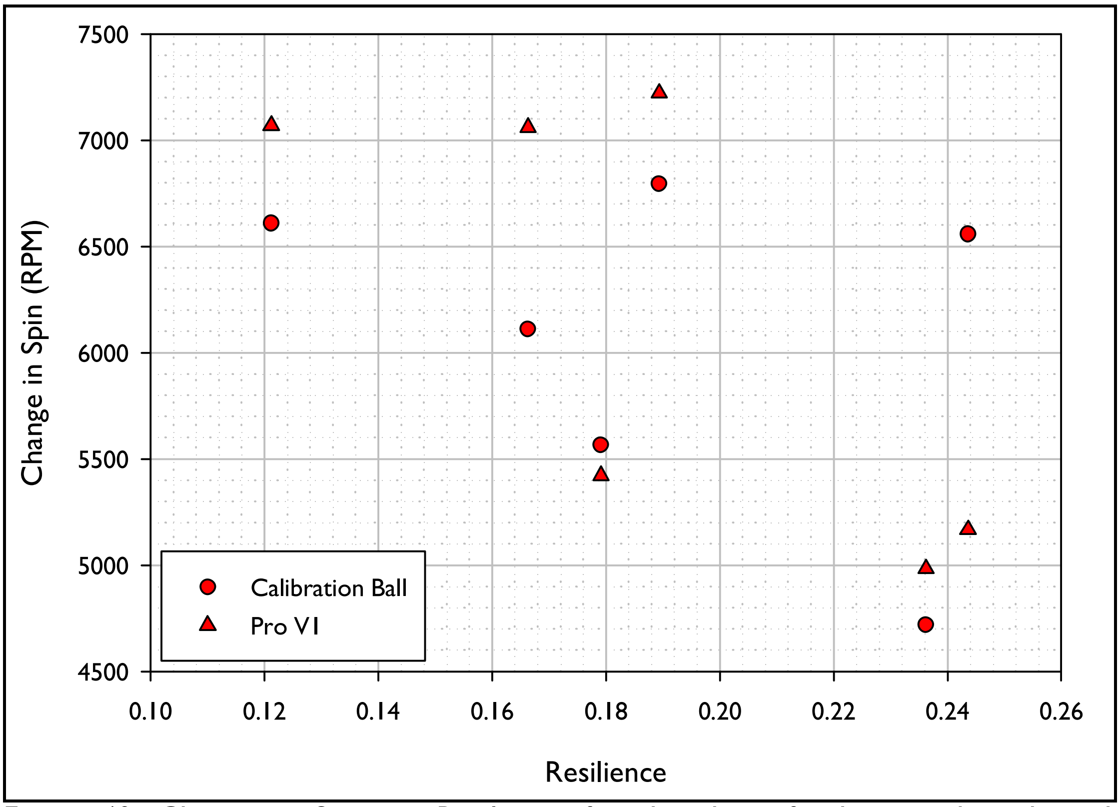

Figure 40. Change in Spin vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

The bounce and roll distances of the balls after impact simulating a sand wedge shot were considerably lower than observed for the other sites, with negative bounce and roll distances being recorded for three ball/site combinations (a negative value means that the ball has spun back to finish closer to the pitching machine than where the ball impacted with the turf).

When considering the bounce and roll of the shots as a function of stiffness, Figure 41, it can be seen that again there is good evidence of bounce and roll increasing as stiffness increases. It is also important to note at this point that with the differences in bounce and roll between the two ball types for all sites tested with stiffness higher than 5 MPa were statistically significant (as established previously).

If the bounce and roll of the shots is considered as a function of resilience, Figure 42, the relationship is not as clearly evident. There is some suggestion that if the data from The Northumberland (circled in blue) is discounted then bounce and roll increases as resilience increases but this is not nearly as clearly evident as when considering the stiffness of the turf at these sites.

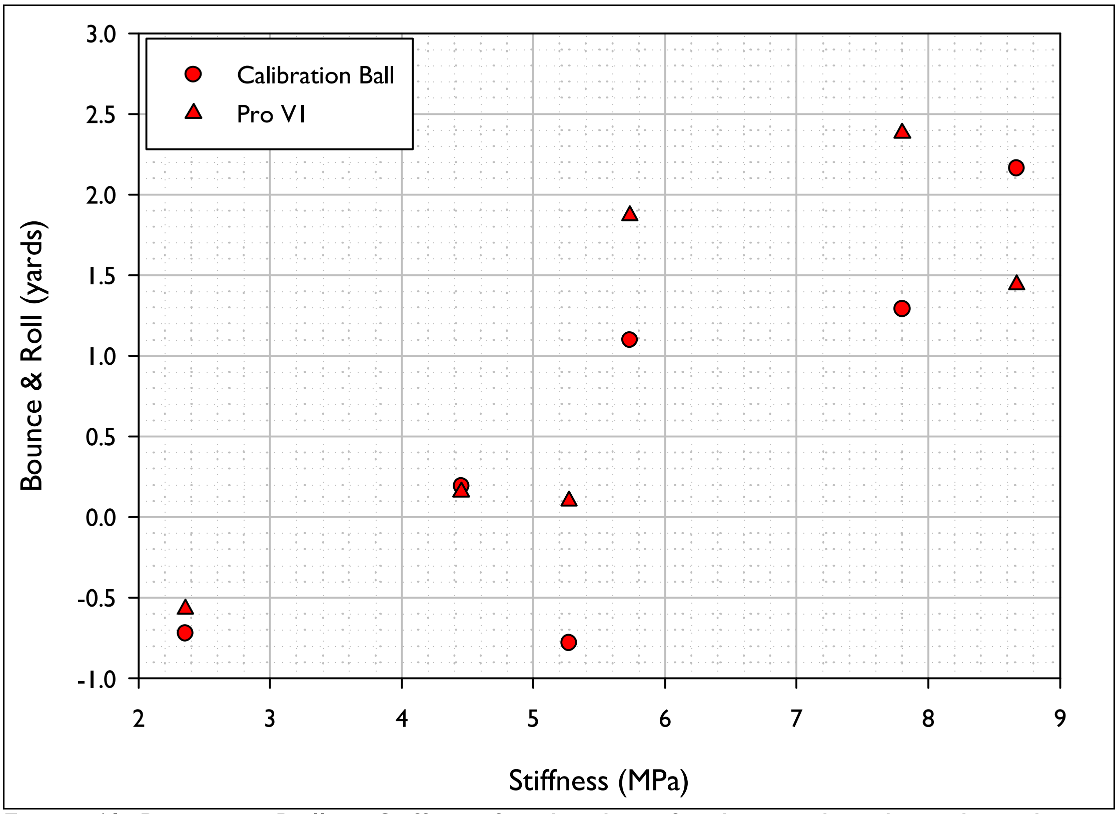

Figure 41. Bounce & Roll vs. Stiffness for the shots fired using the inbound conditions akin to those for a sand wedge.

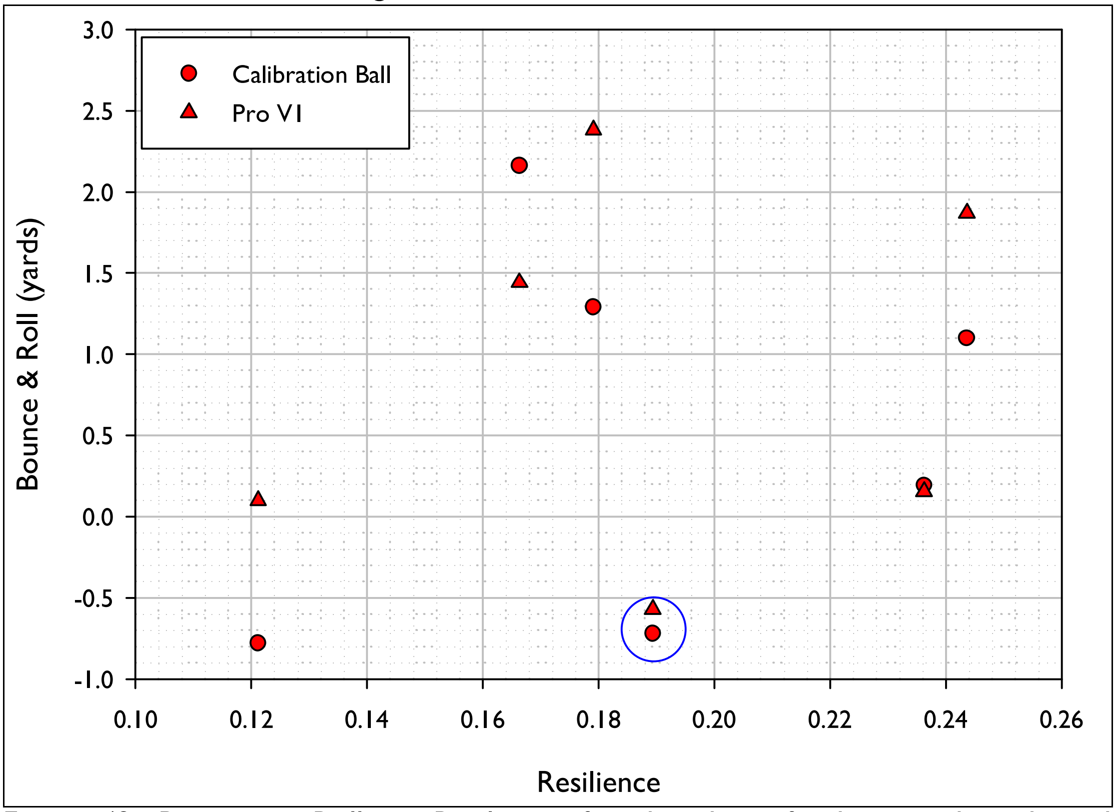

Figure 42. Bounce & Roll vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

When considering the CoR of these shots as functions of stiffness and resilience, Figure 43 and Figure 44 respectively, it can be seen that there is some evidence of CoR increasing with stiffness and also that CoR will increase with Resilience, although again this is more evident if the data from The Northumberland is discounted.

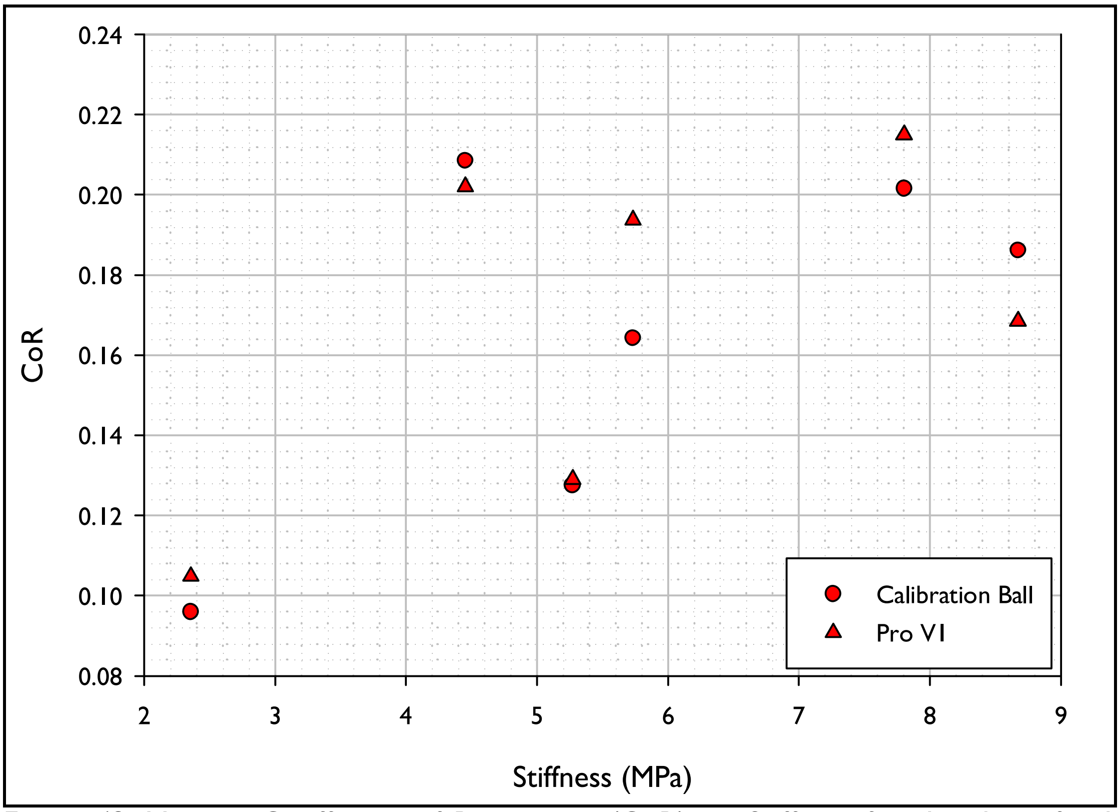

Figure 43. Vertical Coefficient of Restitution (CoR) vs. Stiffness for the shots fired using the inbound conditions akin to those for a sand wedge.

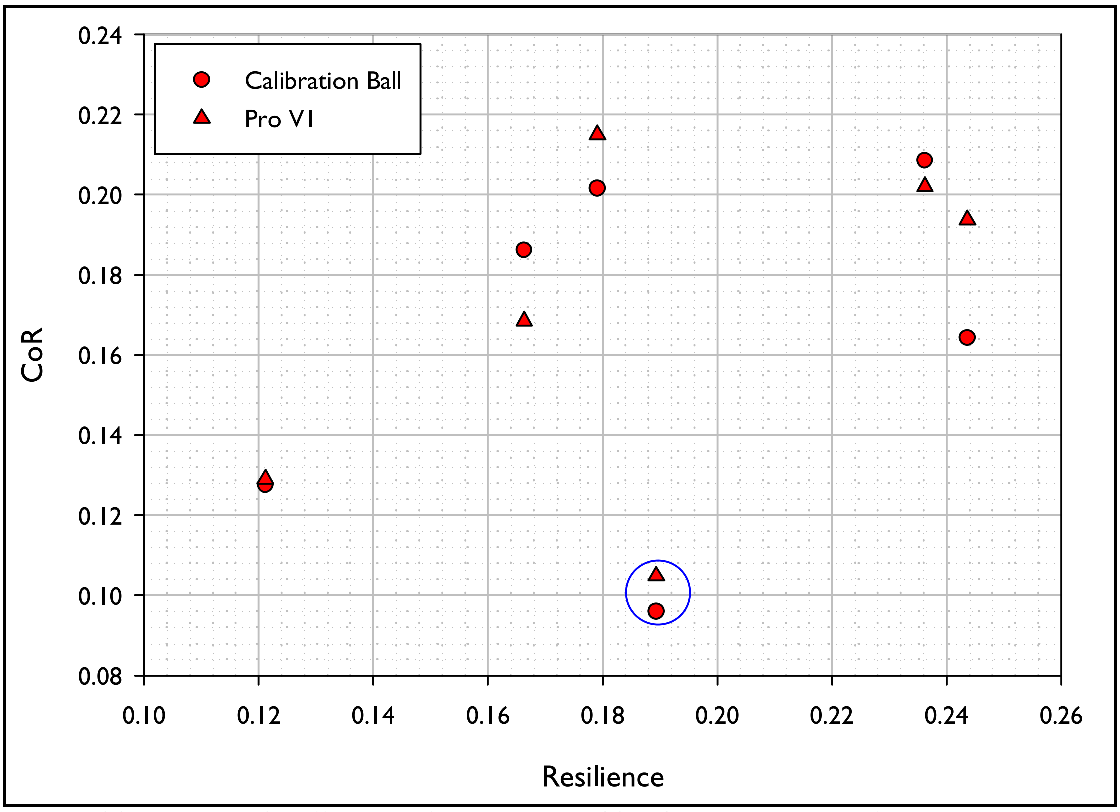

Figure 44. Vertical Coefficient of Restitution (CoR) vs. Resilience for the shots fired using the inbound conditions akin to those for a sand wedge.

In summary, when considering the shots with inbound conditions similar to those expected for a sand wedge, it can be seen that there are reasonable trends again evident between the stiffness and most of the investigated parameters. As the stiffness increases, the outbound speed of the ball after impact increases with the ball leaving at a shallower angle. These outbound conditions result in greater distance being achieved between the impact position of the ball on the turf and its final resting position. One significant difference between these data and those for the other club impact conditions considered earlier is that if the stiffness of the test site is sufficiently low then the conditions would appear to be conducive to the ball spinning back to a resting position closer to the pitching machine than where the ball impacted with the turf. There is also evidence of a dependence of stiffness on the vertical CoR of the ball as well.

When considering the resilience data, there is evidence of a dependence of the Vout, outbound angle, change in spin and bounce and roll on the resilience although, as previously observed for the driver data, the strength of the evidence is limited by the presence of a seemingly anomalous test site, in this case it was the data from The Northumberland.

Conclusions and Future Work

Statistically significant differences in turf/ball impact parameters have been observed between the polyurethane covered Titleist Pro V1 golf ball and the ionomer (Surlyn) covered USGA/R&A Calibration ball. These differences manifest themselves almost exclusively for the sand wedge impact condition with very limited evidence of any ball type dependency for the driver and no evidence for any differences for the 5 iron impact condition. Within the sand wedge data, the most prevalent difference of significance is in the measured bounce and roll of the balls, followed by the outbound angle and the change in spin. Only one site shows statistically significant differences between ball types for all 5 measured parameters (Speed, change in spin, outbound angle after impact, vertical CoR and bounce & roll) whilst only one site shows no differences of significance between any of the parameters. The USGA TruFirm data from these two sites is similar indicating that the measured differences are at least in part due to the difference in grass species present at the two sites.

When investigating trends between the ball/turf impact parameters and the turf parameters as measured using the USGA TruFirm device, evidence has been observed for a reasonable correlation between the outbound parameters of the ball after impacting with the turf and the stiffness of the same turf. Generally, for all three impact conditions (driver/fairway, 5 iron/green & sand wedge/green), as the stiffness of the turf increases then the outbound speed of the ball increases. The outbound angle after impact decreases with increasing stiffness for all three impact conditions, resulting in a shot that leaves the turf at a shallower angle. There also appears to be an increase in the change of spin (resulting in the ball leaving the turf with less spin or even top spin) as stiffness increases although whilst the data is insufficient to confirm this trend for the sand wedge impact condition, it is certainly apparent for the driver and 5 iron impact conditions. These trends in outbound speed, outbound angle and (for the most part) spin explain the increase in bounce & roll distance observed as turf stiffness increases. Furthermore, for the 5 iron and the sand wedge impact conditions show a reasonable dependence of vertical Coefficient of Restitution to the turf stiffness, although the scatter of the data points for the driver make the determination of any trends difficult.

When considering the resilience of the turf, it is more difficult to discern trends from the data attained during this investigation. For each impact condition the data from one site appears anomalous when considered in the context of any trends involving the other data points. In the case of the driver data The Renaissance appears to have a resilience which is considerably lower than might be expected given the resilience of the other sites which produced similar results. In the case of the iron data, The Northumberland had a resilience which was much higher than might have been expected given the data presented at the other sites. In both cases, it may be suggested that the relationship between resilience and these impact parameters is more complicated than that relating them to stiffness.

Both of the key areas of investigation in this study have yielded positive results. There is reasonable evidence to suggest that the cover material selected for a golf ball will have a significant effect on how that ball interacts with the turf under specific turf and impact conditions. There is also strong evidence that the USGA TruFirm device can be used to indicate the interaction between ball and turf. However, for both areas of investigation, the data collected is insufficient to categorically define the trends observed. There are a multitude of further areas of research that would be useful as means of enhancing this research including (but not limited to):

- The testing of further inbound parameters. Some of the trends observed have been demonstrated for particular inbound conditions but not for others (for example the statistical significance of ball cover material is apparent for sand wedge impact conditions but not for 5 iron impact conditions). It would be of interest to expand the testing matrix both with a view to identifying the onset of such trends in the context of predescribed impact conditions (6 iron, 7 iron etc) and also to investigate the effect of individual impact parameters, for instance maintain impact speed and angle constant whilst varying only the level of spin for the impact.

- The testing of further sites to enhance the dataset and ideally allow the isolation of a particular USGA TruFirm parameter – for example a multitude of sites with similar USGA TruFirm parameters with the exception of different stiffness readings should allow the isolation of trends relating to stiffness.

- An investigation into the effect of moisture on outbound parameters. Previous research utilising the USGA TruFirm device has shown negligible effects of precipitation on USGA TruFirm readings. It would be useful to investigate the effect of moisture on post impact ball parameters – e.g. test the same site before and after application of water.

- The evidence suggesting a grass species/cover material dependency on outbound ball parameters (at least for the sand wedge) merits further investigation into the effect of grass species on outbound ball parameters.

- The texture, density and distribution of organic matter to the base of the turf and the soil profile, to a depth of 80 mm, may have an effect on outbound parameters and moisture retention. There would be merit for further investigation into the influence of organic matter content.

- The testing of fairways and greens at the Open Championship venues giving a wider range of turf characteristics to investigate.

Appendix

Contained within the appendix to this report are the graphs showing each of the 5 parameters measured from the ball impact with the turf (Vout, outbound angle, change in spin, bounce & roll and vertical Coefficient of Restitution) plotted against the three parameters from the USGA TruFirm turf characterisation which were not considered during the main body of this report (penetration, recovery and moisture). As previously discussed, penetration and stiffness are interdependent and (whilst not always the case) for these sites investigated, recovery and resilience are interdependent. As such, the trends exhibited for the impact parameters as functions of stiffness and/or resilience would also be expected for penetration and/or recovery respectively. As previously, these data for each type of simulated golf shot are presented separately.

Driver Shots

A. Penetration

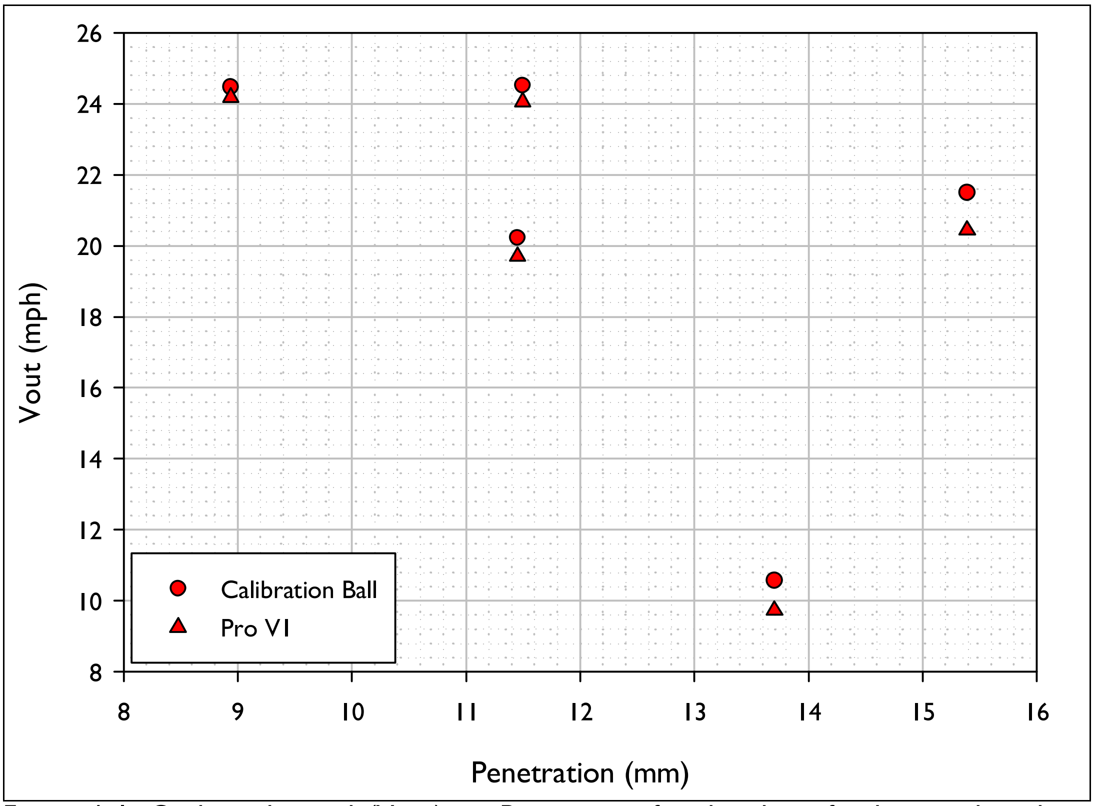

Figure A.1. Outbound speed (Vout) vs. Penetration for the shots fired using the inbound conditions akin to those for a Driver.

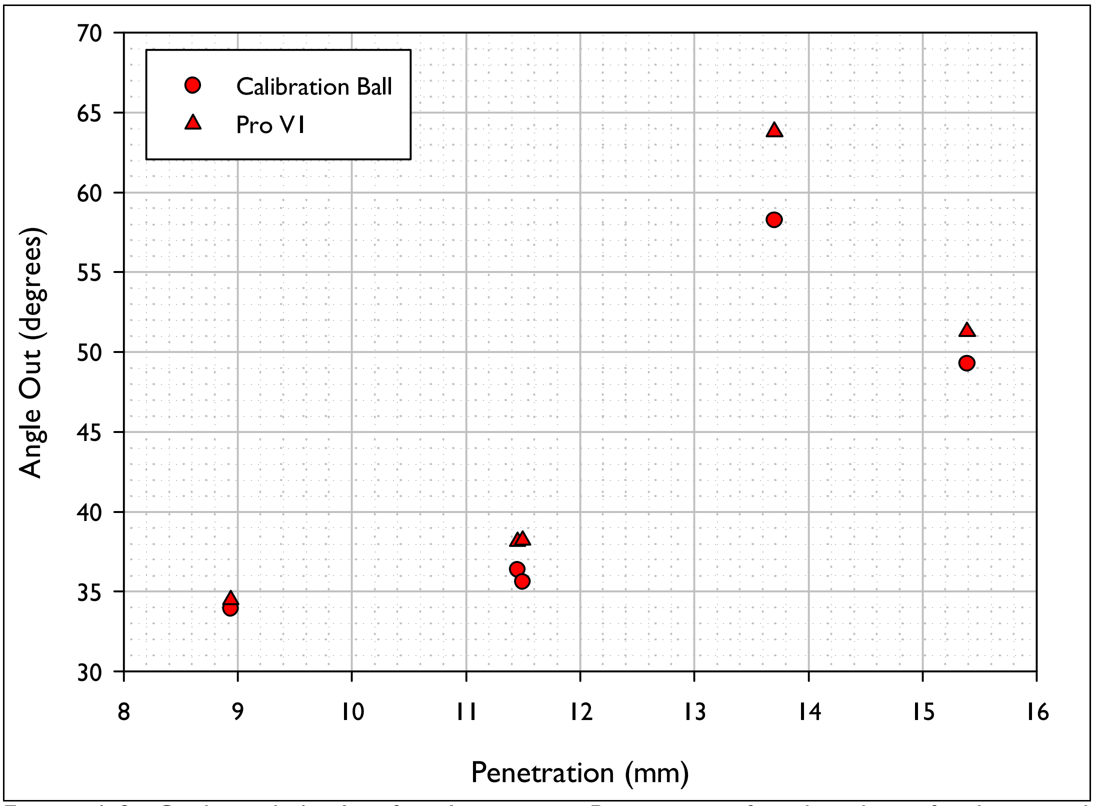

Figure A.2. Outbound Angle after Impact vs. Penetration for the shots fired using the inbound conditions akin to those for a Driver.

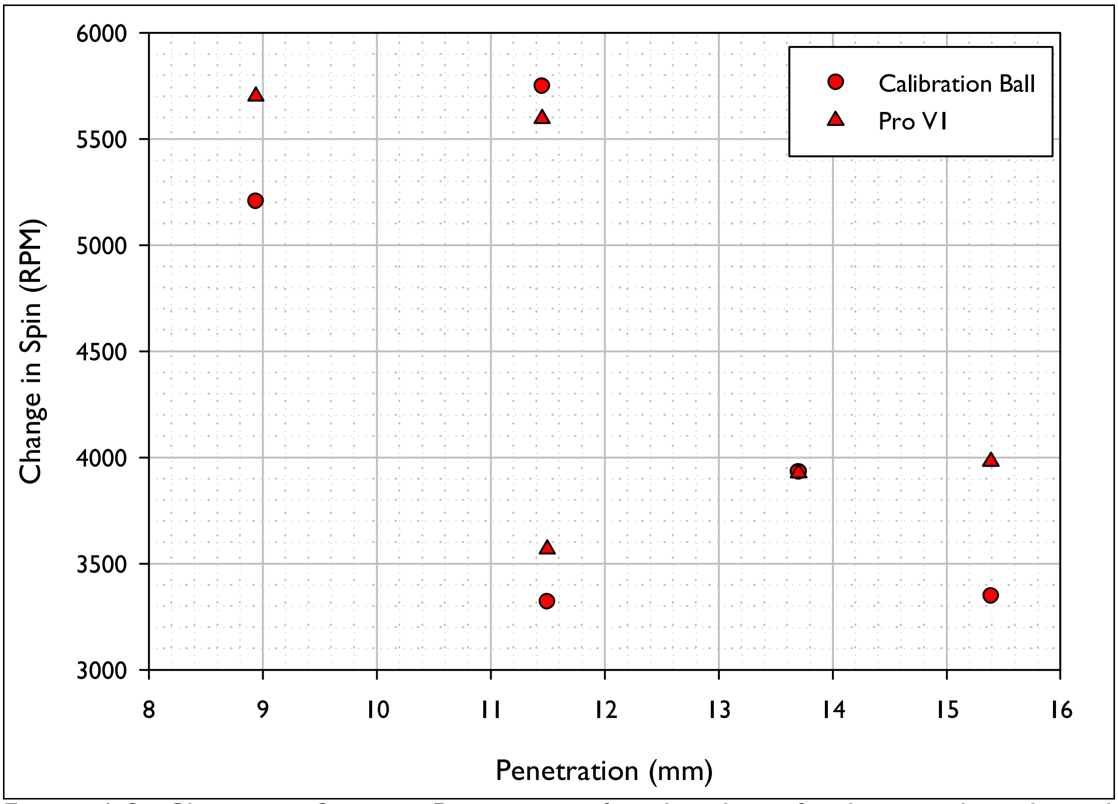

Figure A.3. Change in Spin vs. Penetration for the shots fired using the inbound conditions akin to those for a Driver.

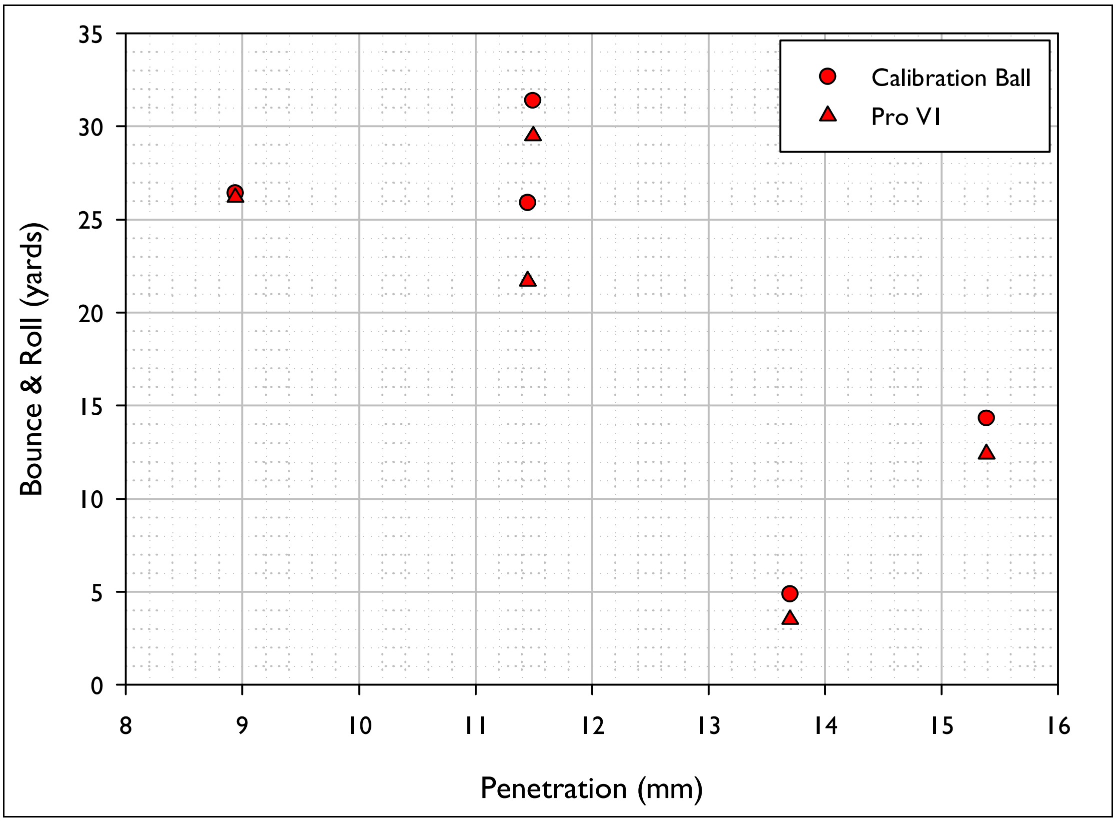

Figure A.4. Bounce & Roll vs. Penetration for the shots fired using the inbound conditions akin to those for a Driver.

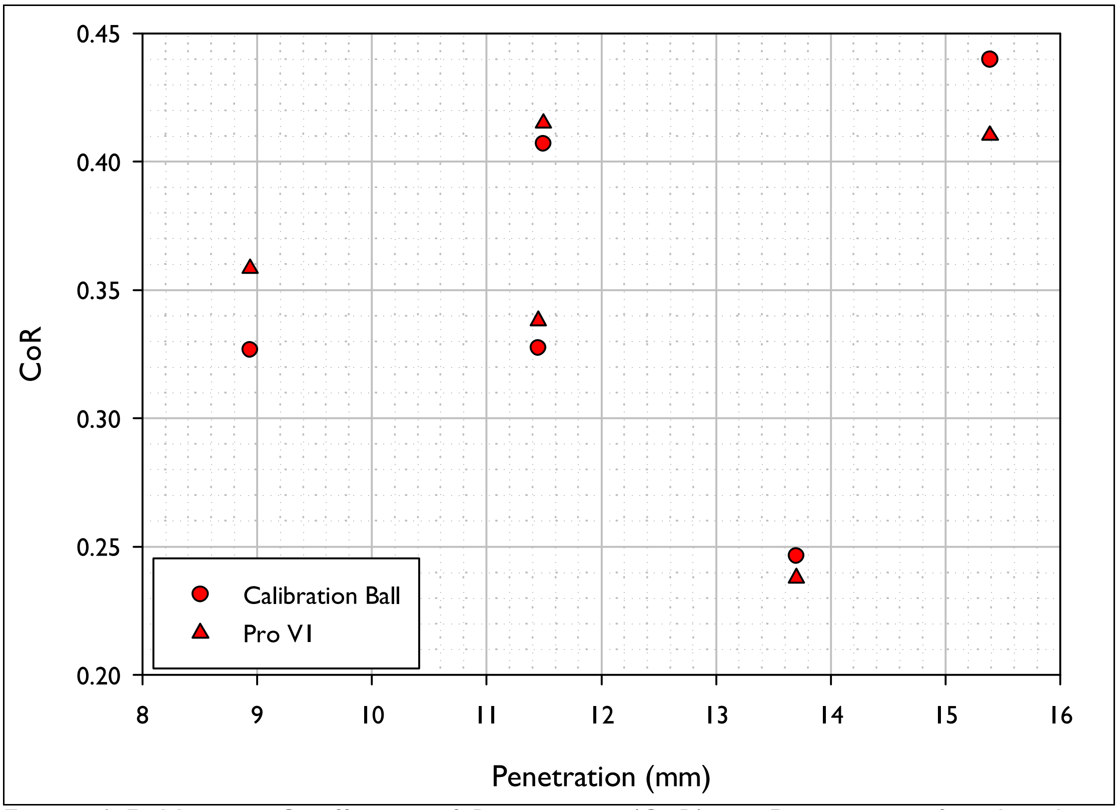

Figure A.5. Vertical Coefficient of Restitution (CoR) vs. Penetration for the shots fired using the inbound conditions akin to those for a Driver.

B. Recovery

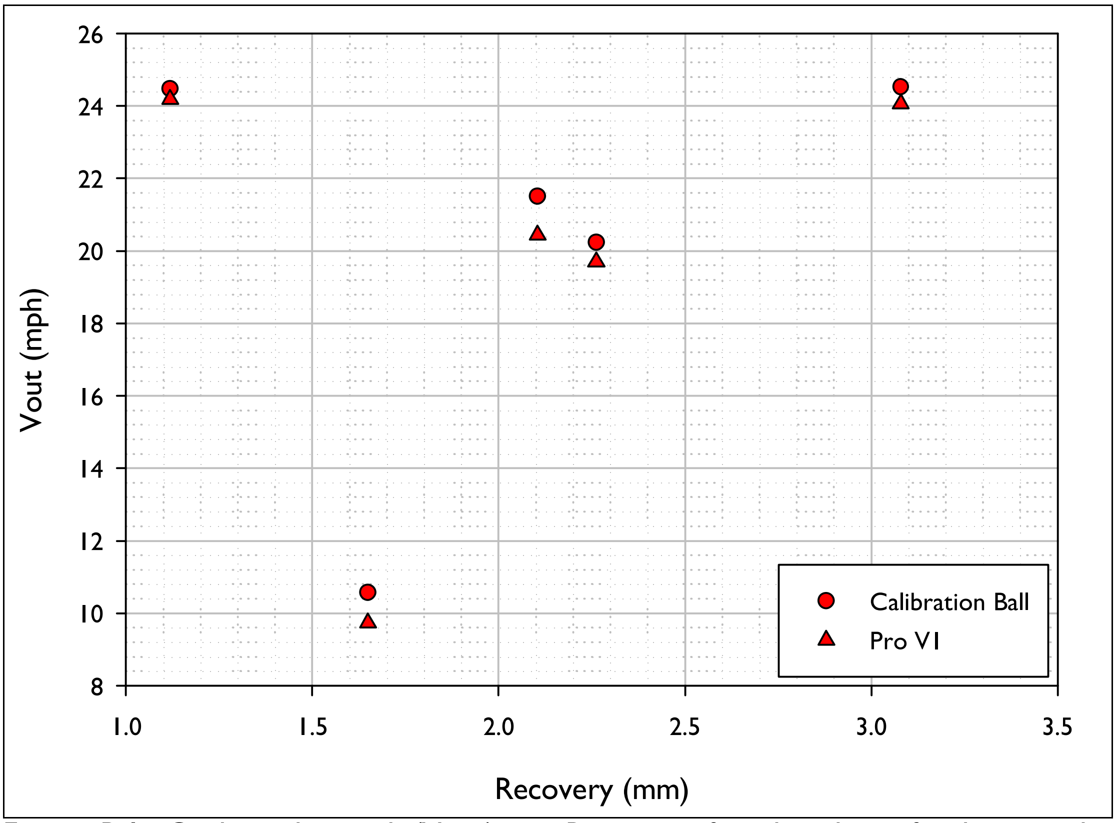

Figure B.1. Outbound speed (Vout) vs. Recovery for the shots fired using the inbound conditions akin to those for a Driver.

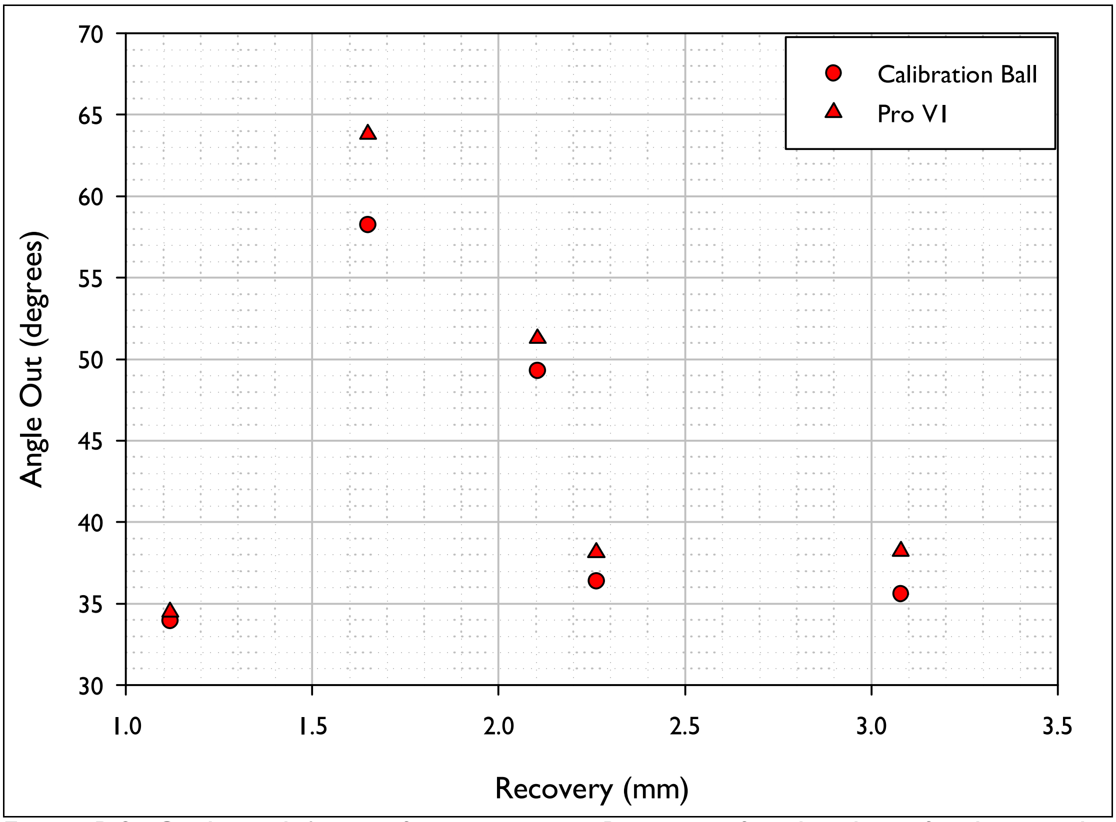

Figure B.2. Outbound Angle after Impact vs. Recovery for the shots fired using the inbound conditions akin to those for a Driver.

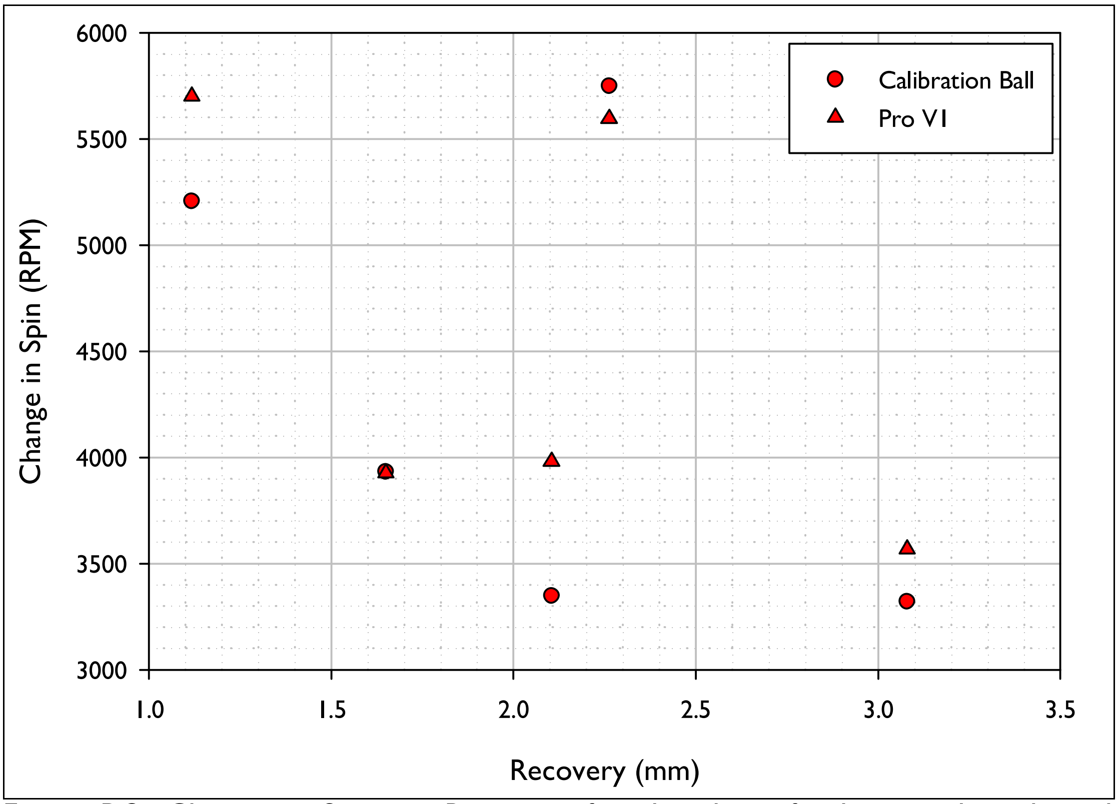

Figure B.3. Change in Spin vs. Recovery for the shots fired using the inbound conditions akin to those for a Driver.

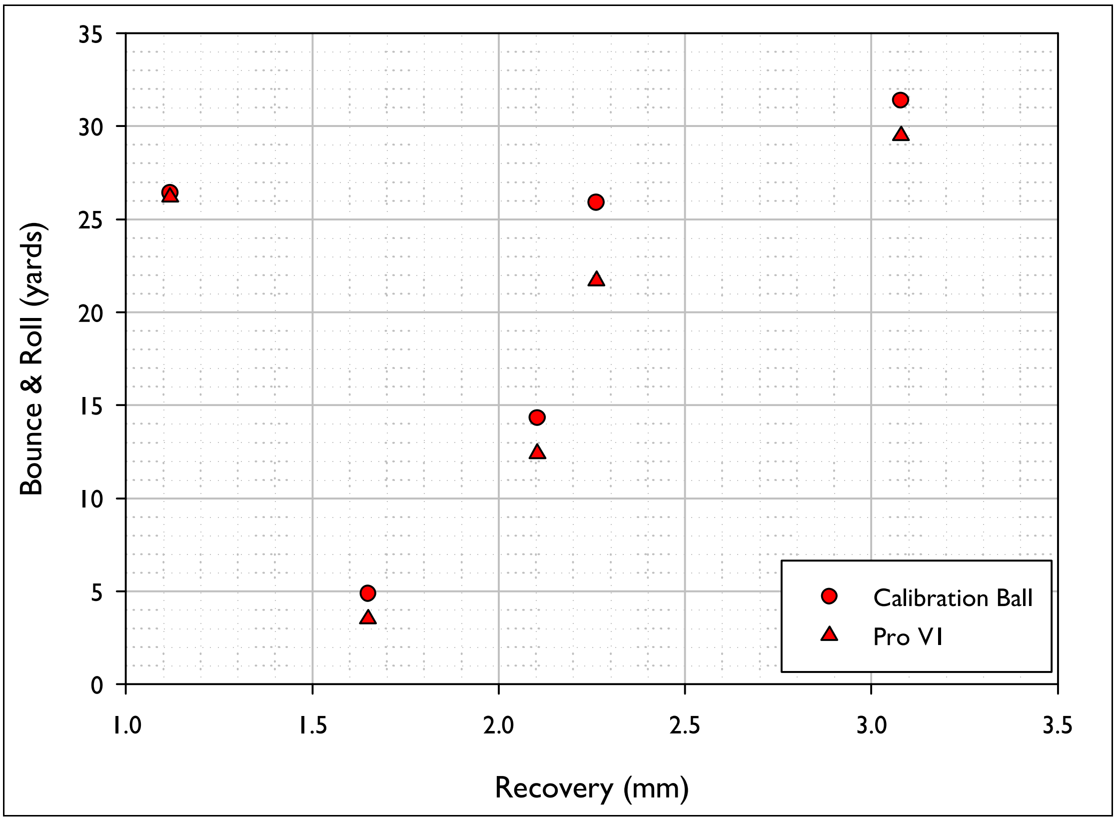

Figure B.4. Bounce & Roll vs. Recovery for the shots fired using the inbound conditions akin to those for a Driver.

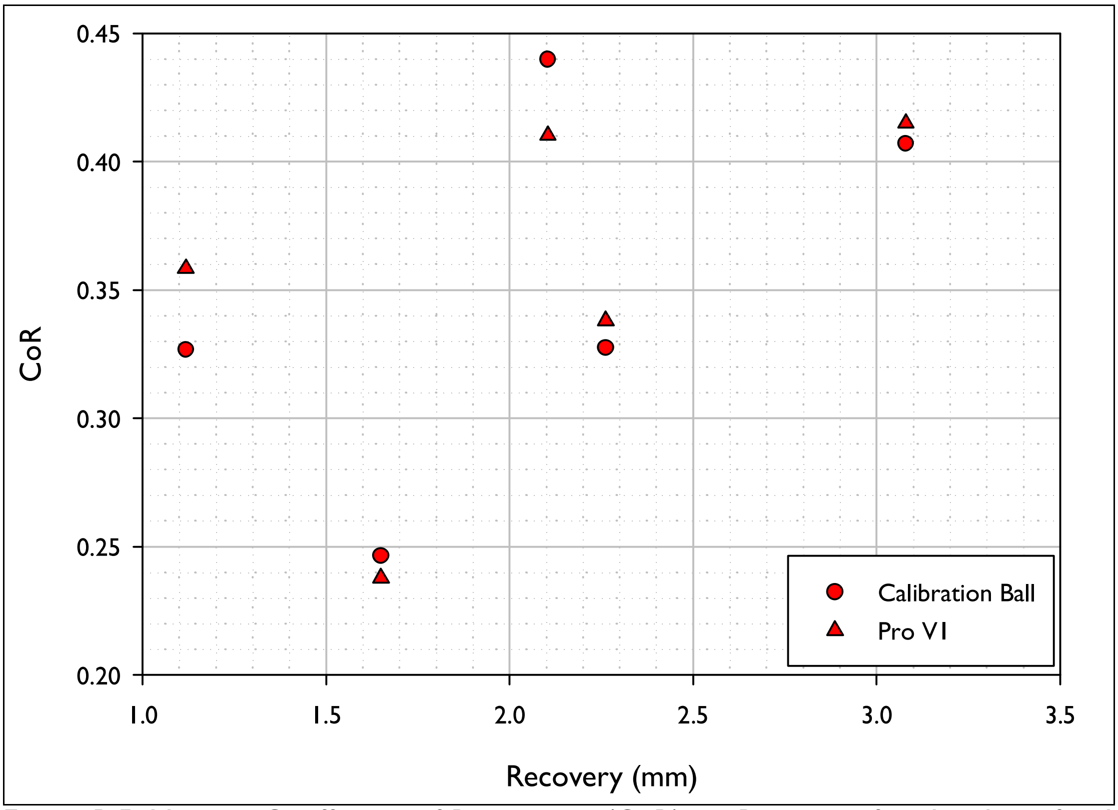

Figure B.5. Vertical Coefficient of Restitution (CoR) vs. Recovery for the shots fired using the inbound conditions akin to those for a Driver.

C. Moisture

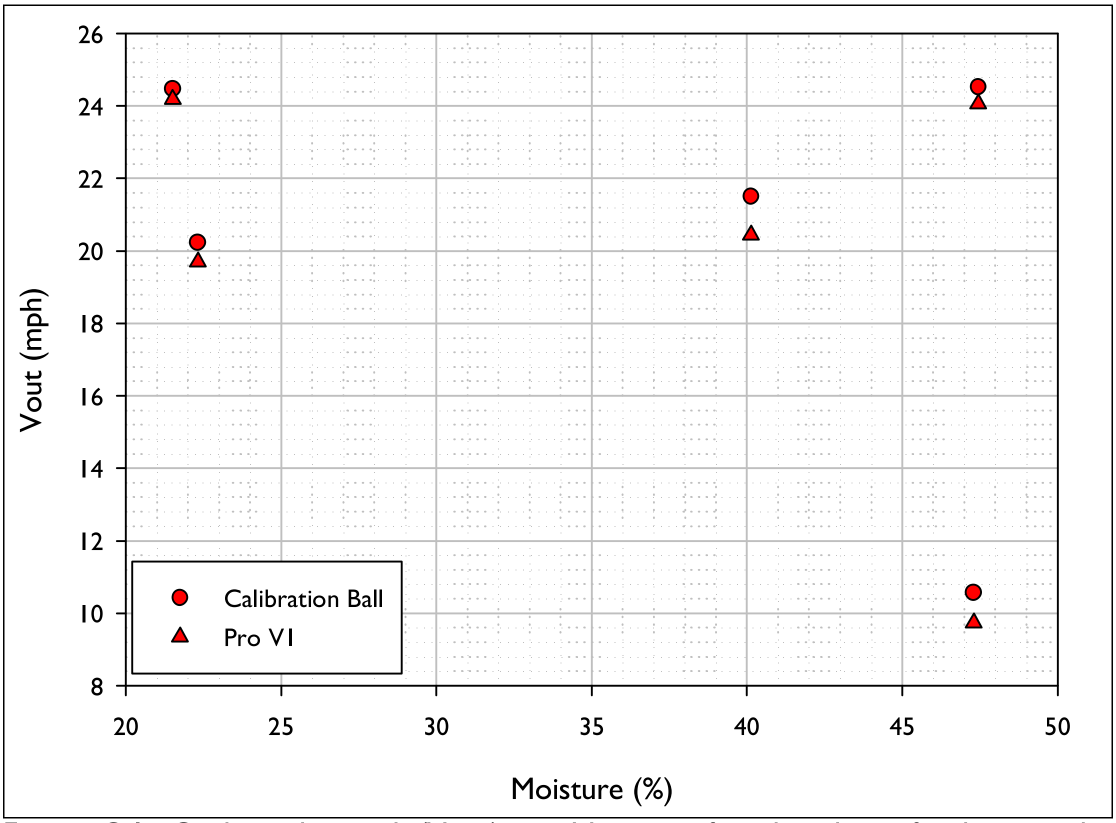

Figure C.1. Outbound speed (Vout) vs. Moisture for the shots fired using the inbound conditions akin to those for a Driver.

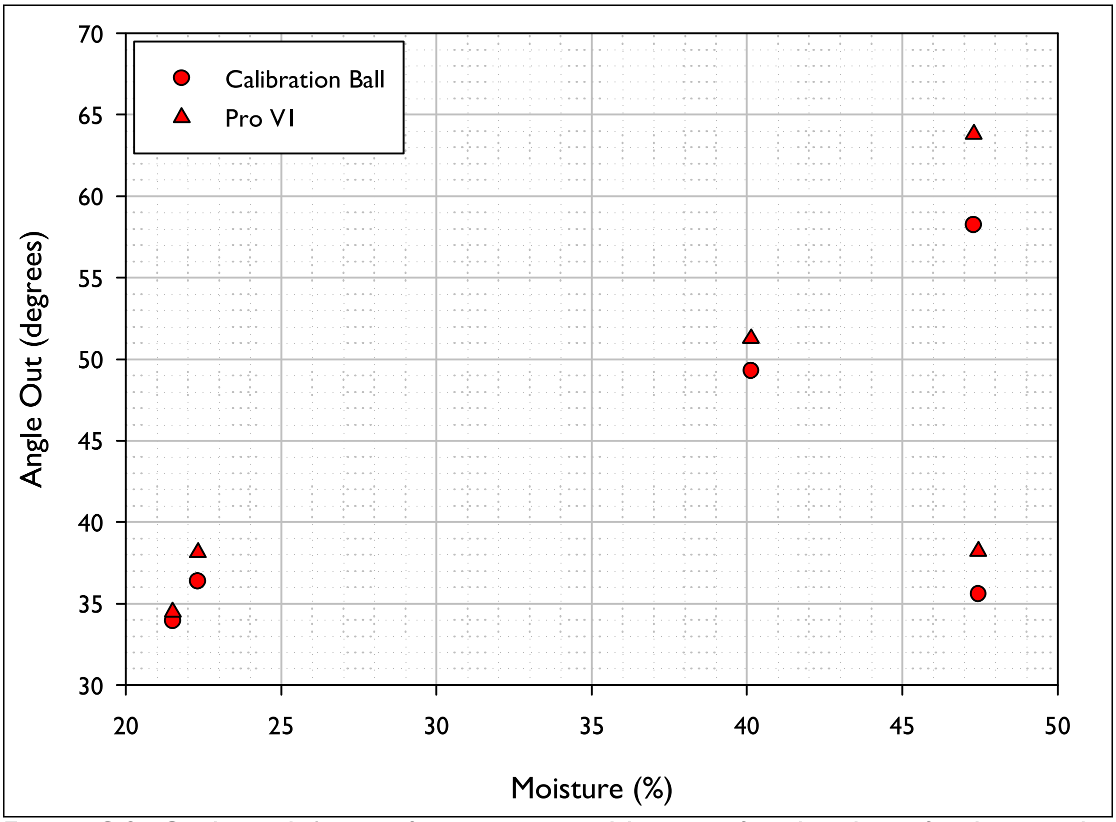

Figure C.2. Outbound Angle after Impact vs. Moisture for the shots fired using the inbound conditions akin to those for a Driver.

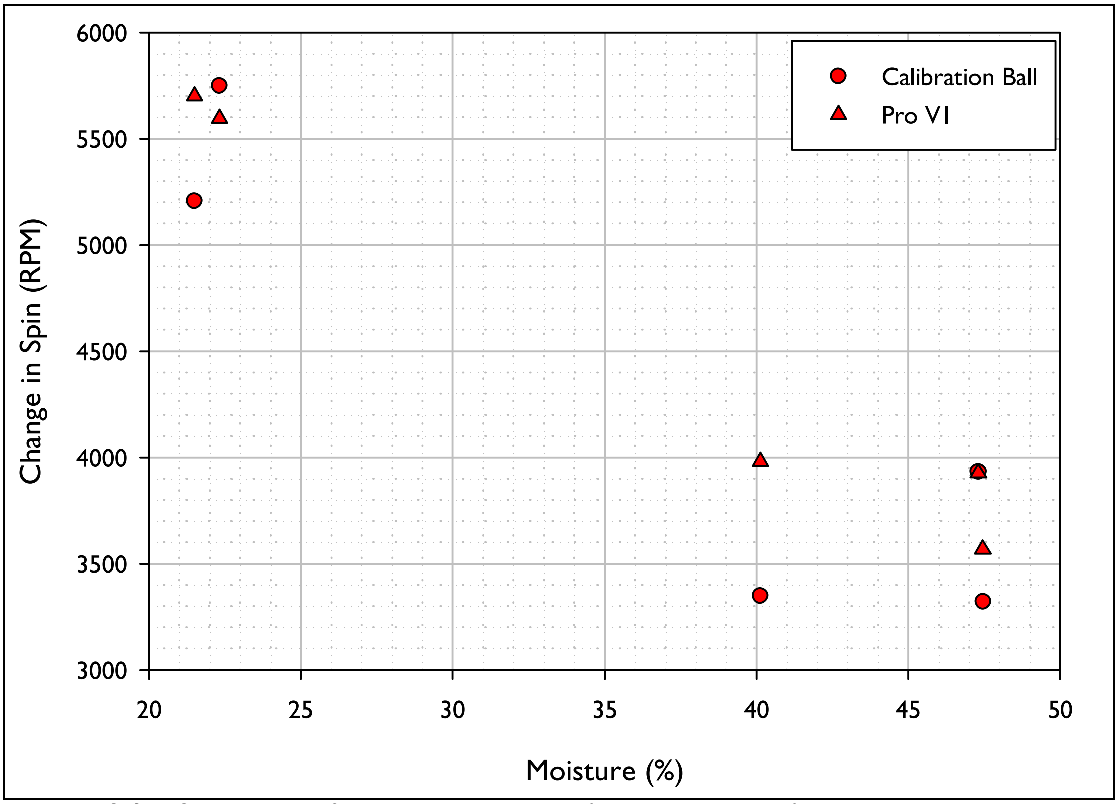

Figure C.3. Change in Spin vs. Moisture for the shots fired using the inbound conditions akin to those for a Driver.

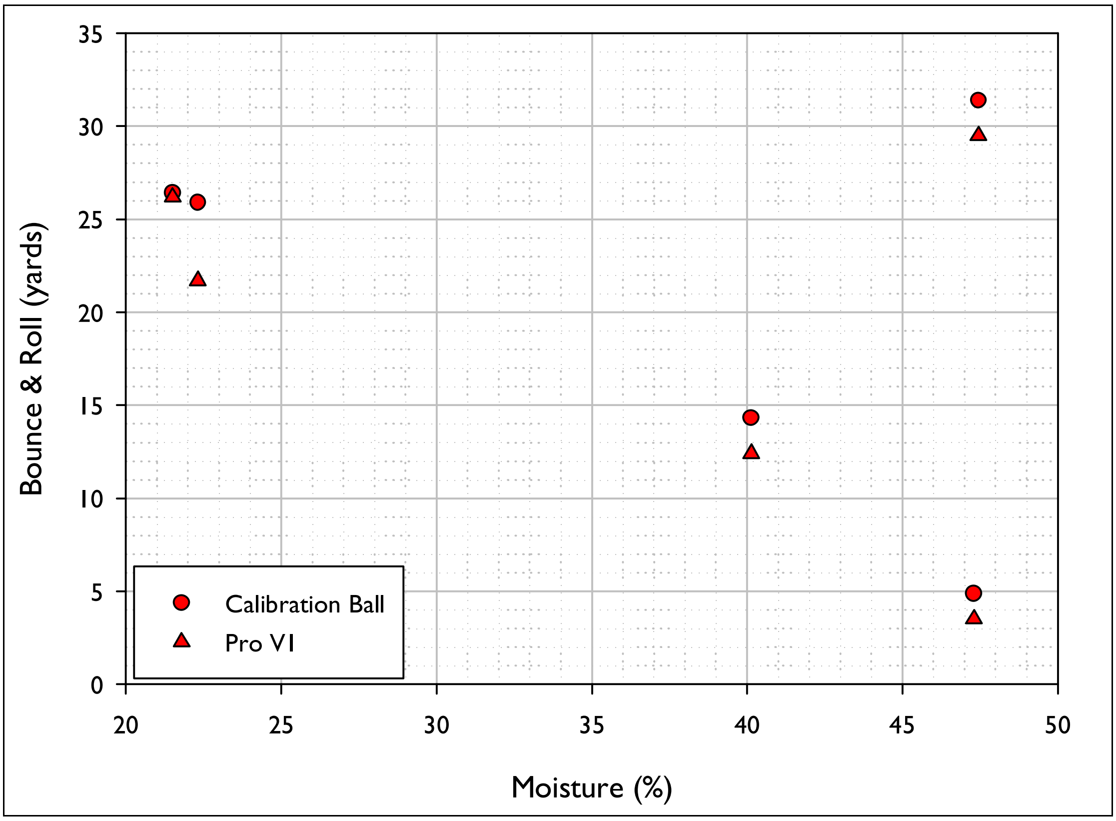

Figure C.4. Bounce & Roll vs. Moisture for the shots fired using the inbound conditions akin to those for a Driver.

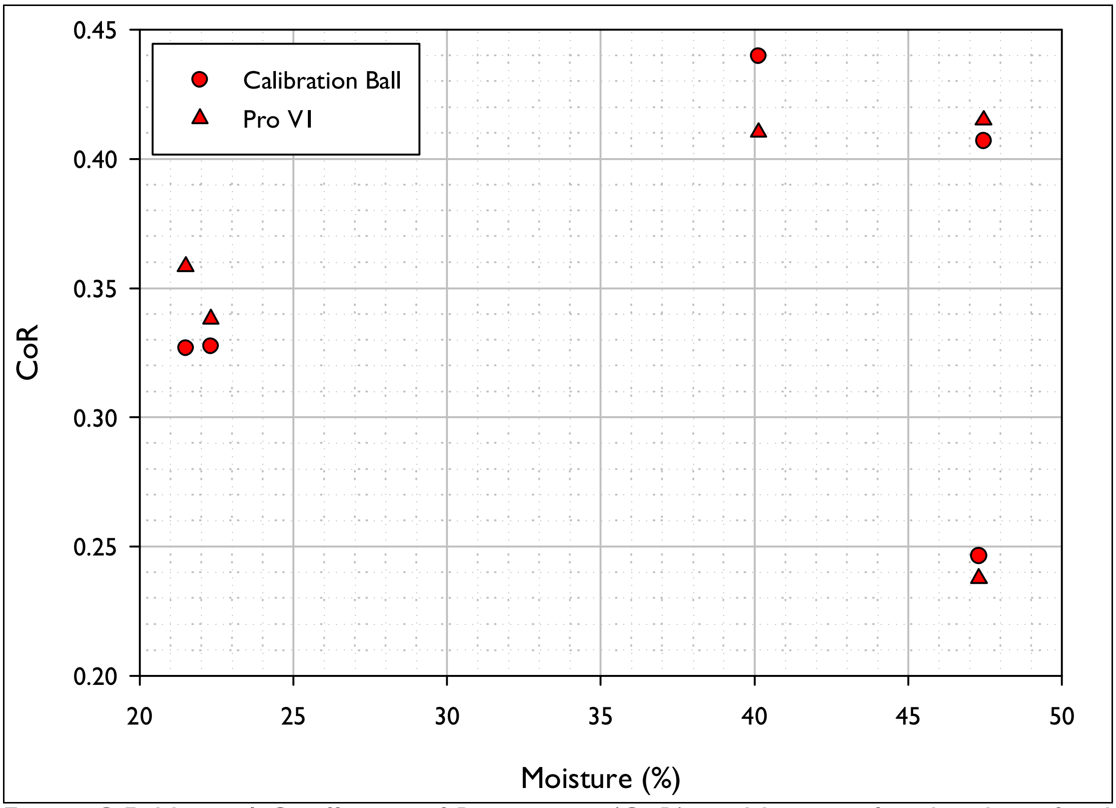

Figure C.5. Vertical Coefficient of Restitution (CoR) vs. Moisture for the shots fired using the inbound conditions akin to those for a Driver.

5 Iron

D. Penetration

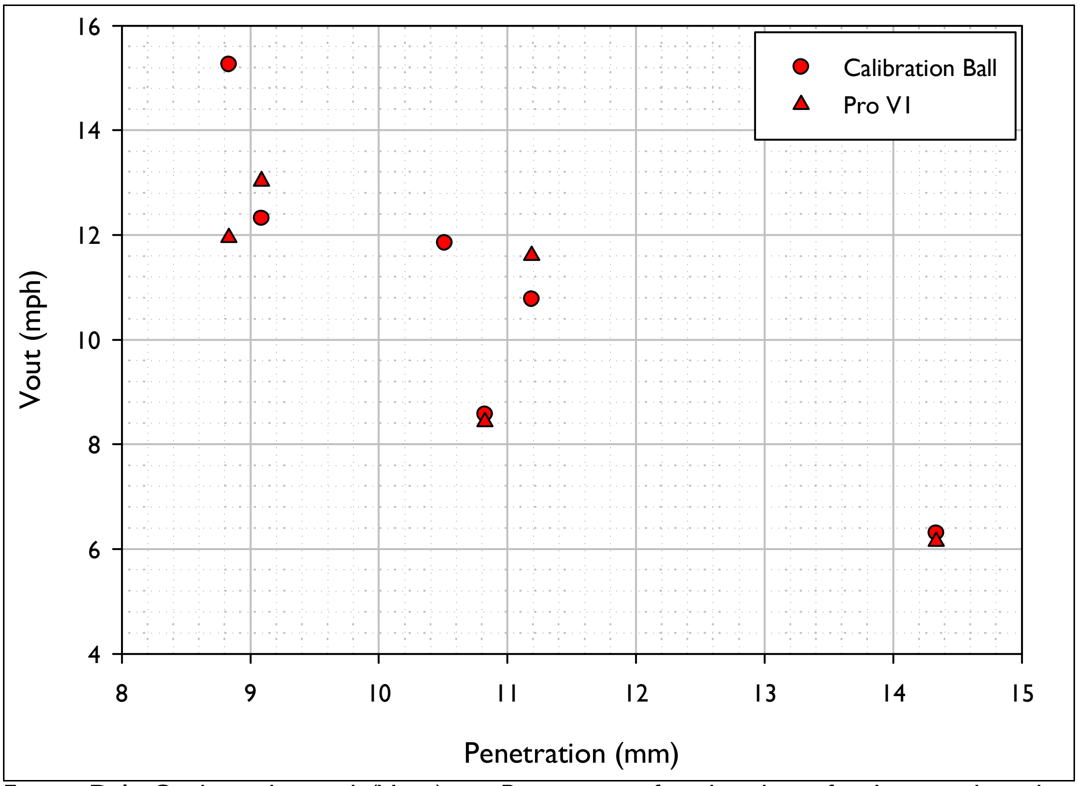

Figure D.1. Outbound speed (Vout) vs. Penetration for the shots fired using the inbound conditions akin to those for a 5 Iron.

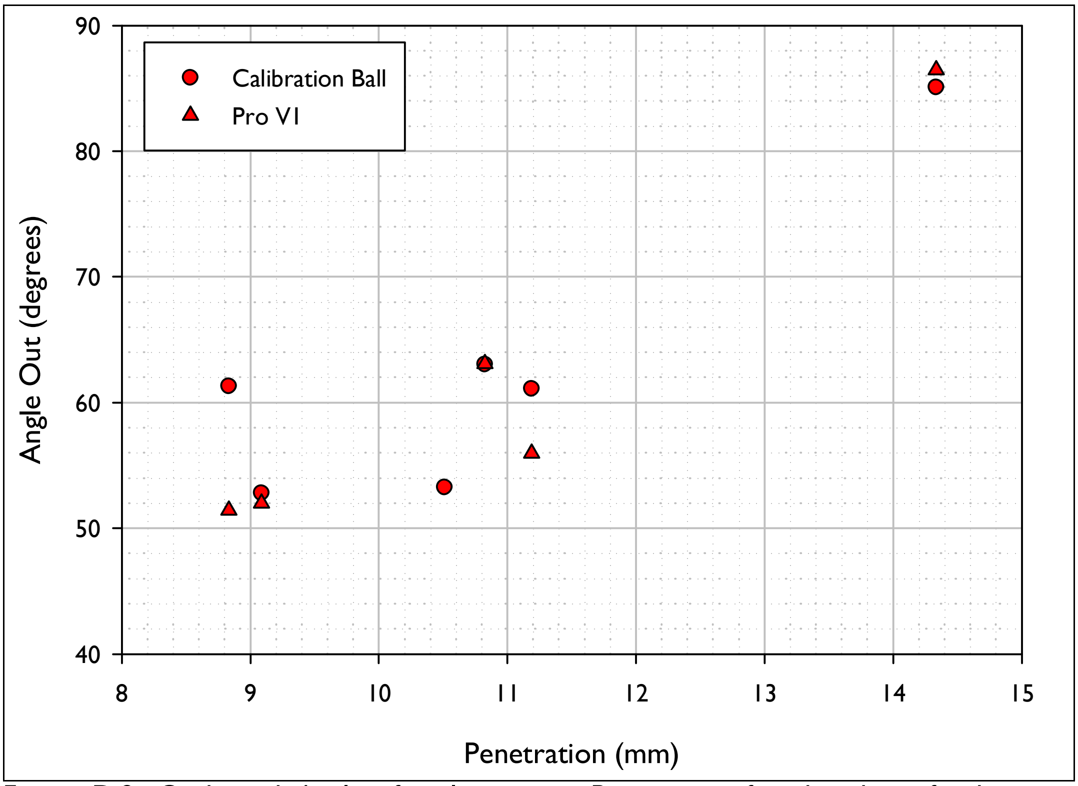

Figure D.2. Outbound Angle after Impact vs. Penetration for the shots fired using the inbound conditions akin to those for a 5 Iron.

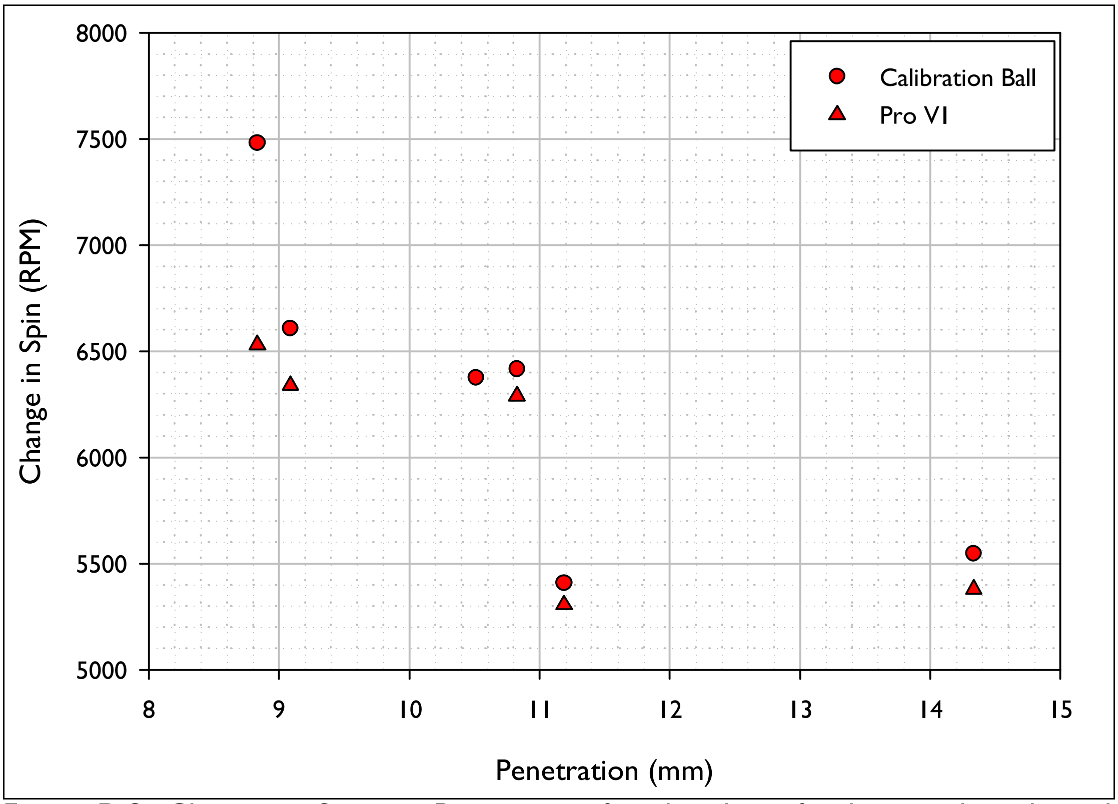

Figure D.3. Change in Spin vs. Penetration for the shots fired using the inbound conditions akin to those for a 5 Iron.

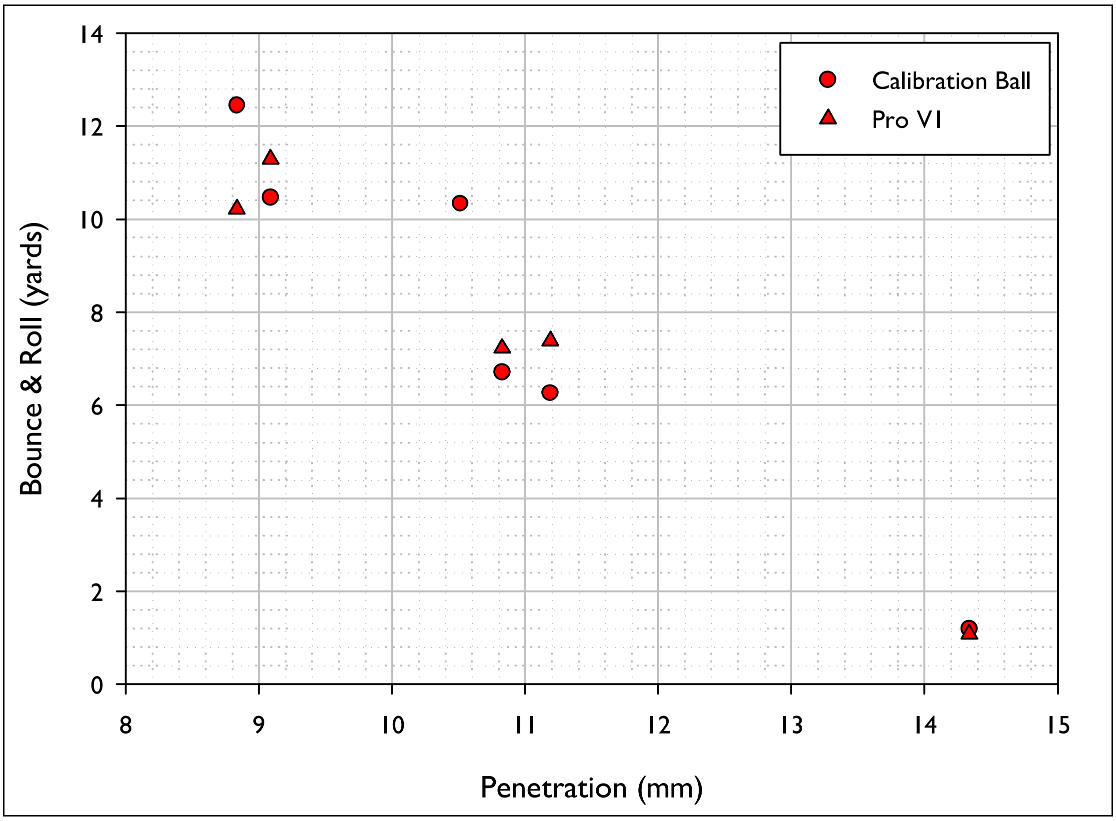

Figure D.4. Bounce & Roll vs. Penetration for the shots fired using the inbound conditions akin to those for a 5 Iron.

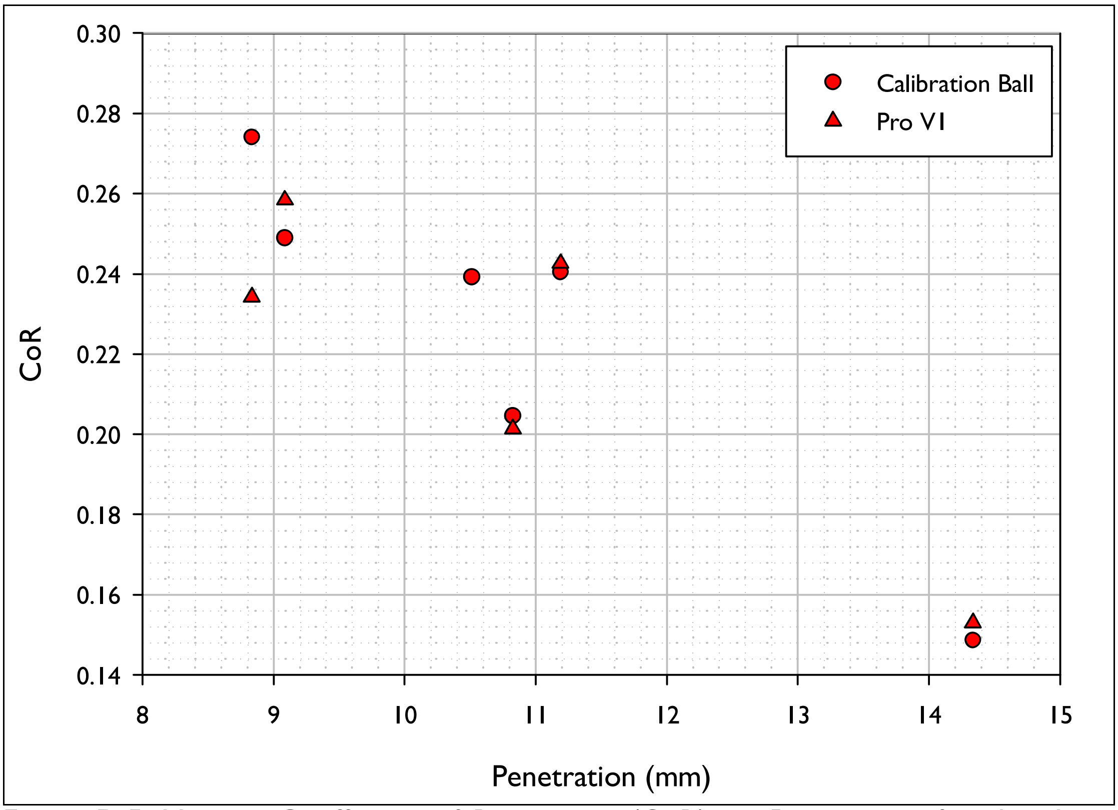

Figure D.5. Vertical Coefficient of Restitution (CoR) vs. Penetration for the shots fired using the inbound conditions akin to those for a 5 Iron.

E. Recovery

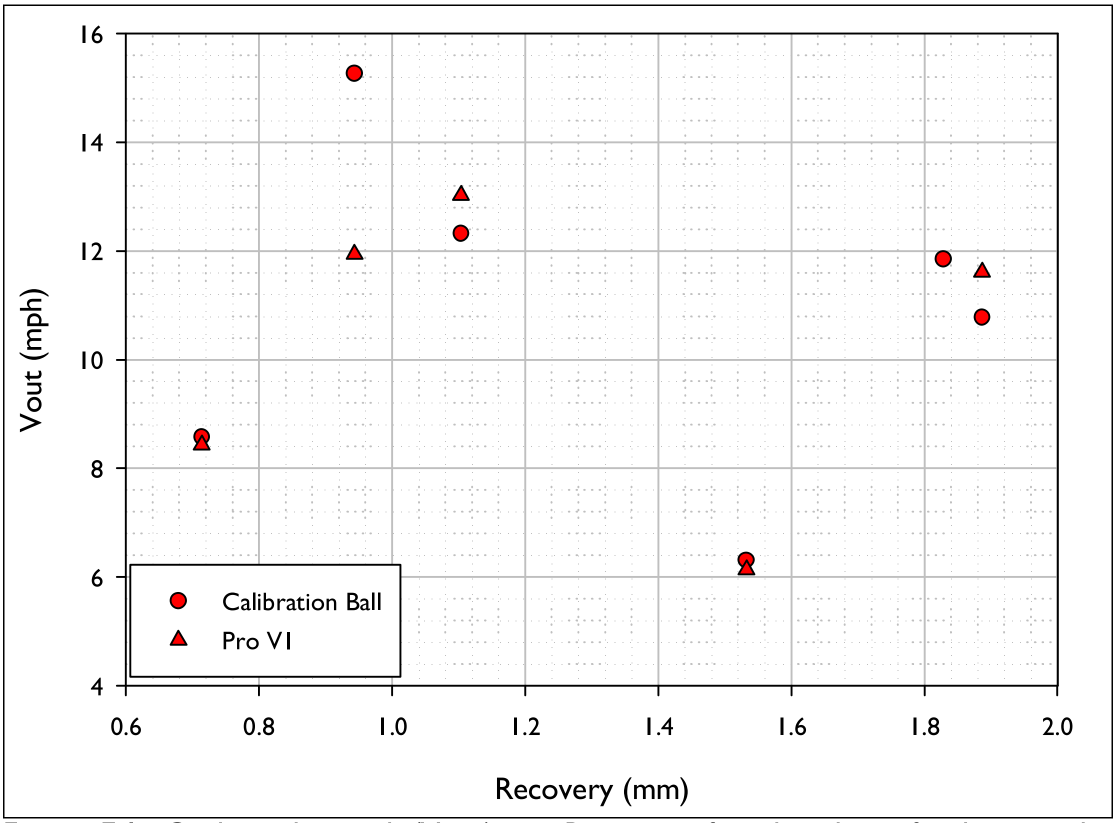

Figure E.1. Outbound speed (Vout) vs. Recovery for the shots fired using the inbound conditions akin to those for a 5 Iron.

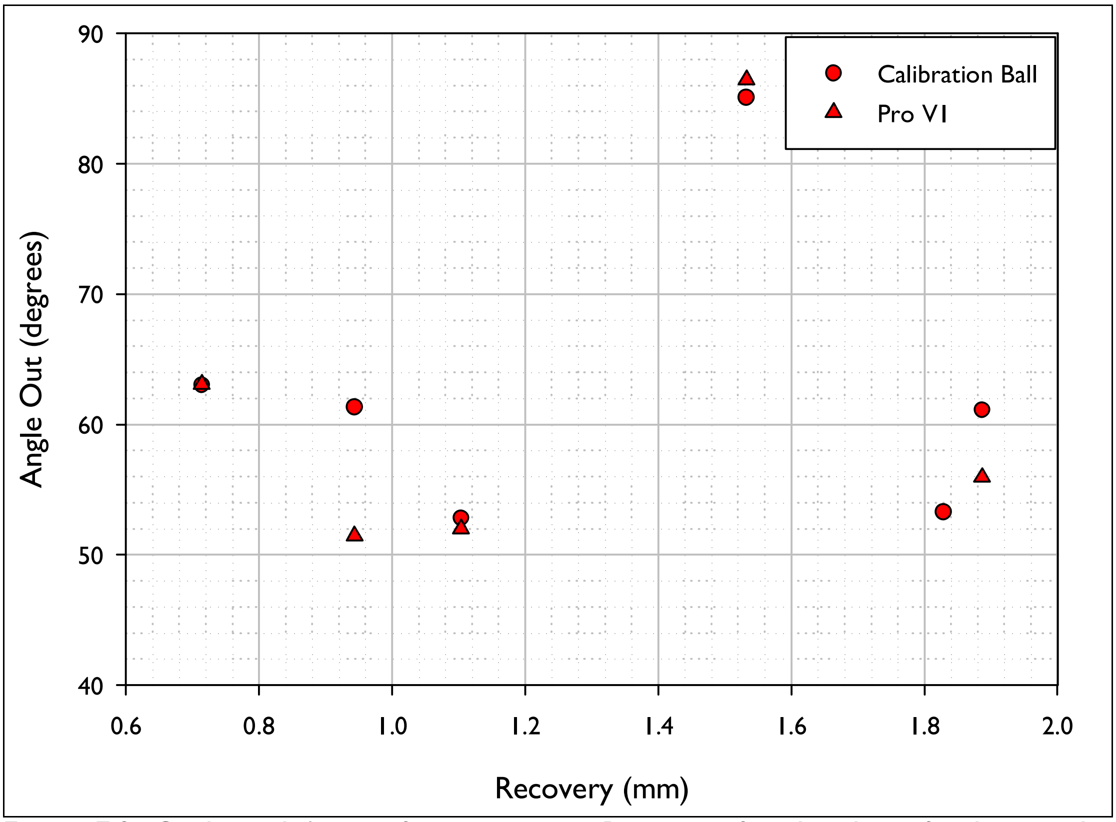

Figure E.2. Outbound Angle after Impact vs. Recovery for the shots fired using the inbound conditions akin to those for a 5 Iron.

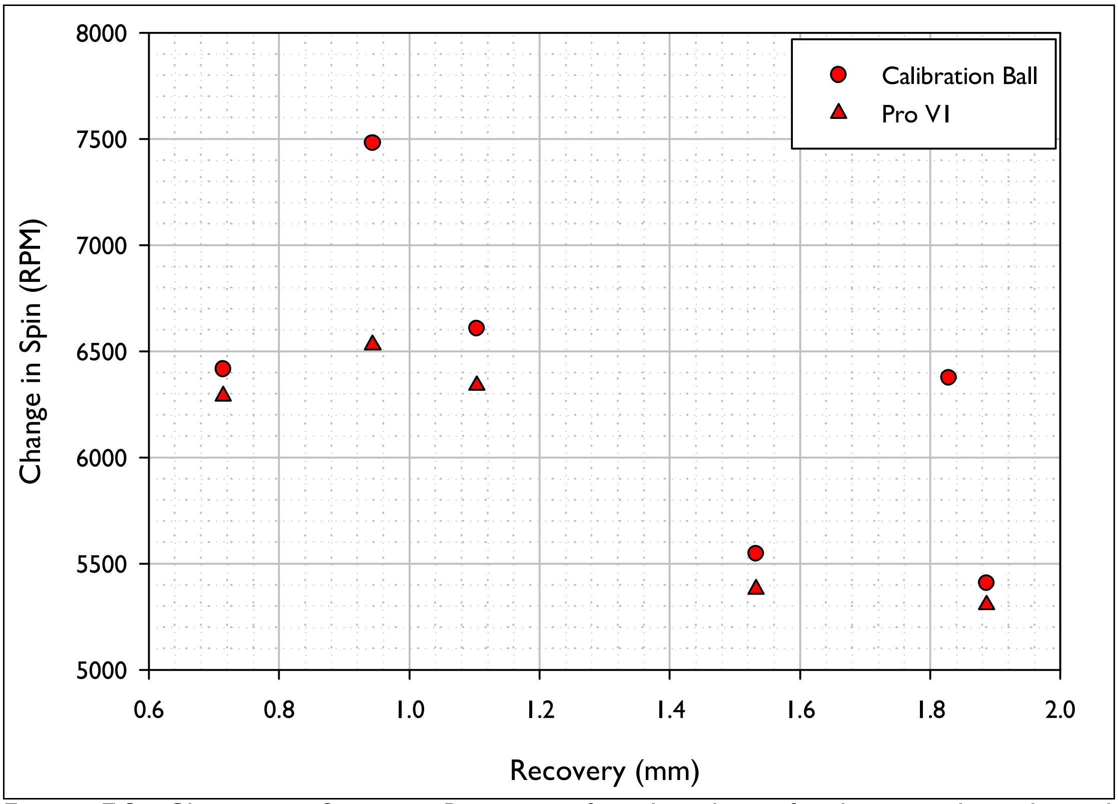

Figure E.3. Change in Spin vs. Recovery for the shots fired using the inbound conditions akin to those for a 5 Iron.

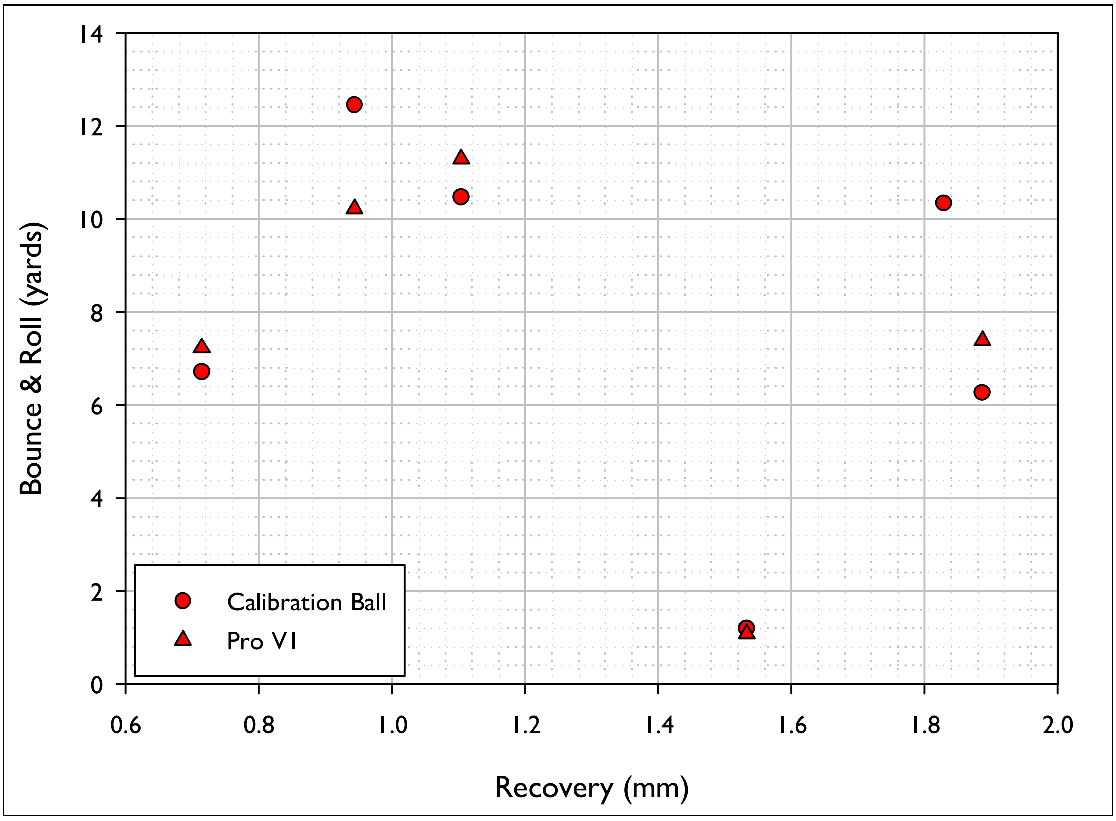

Figure E.4. Bounce & Roll vs. Recovery for the shots fired using the inbound conditions akin to those for a 5 Iron.

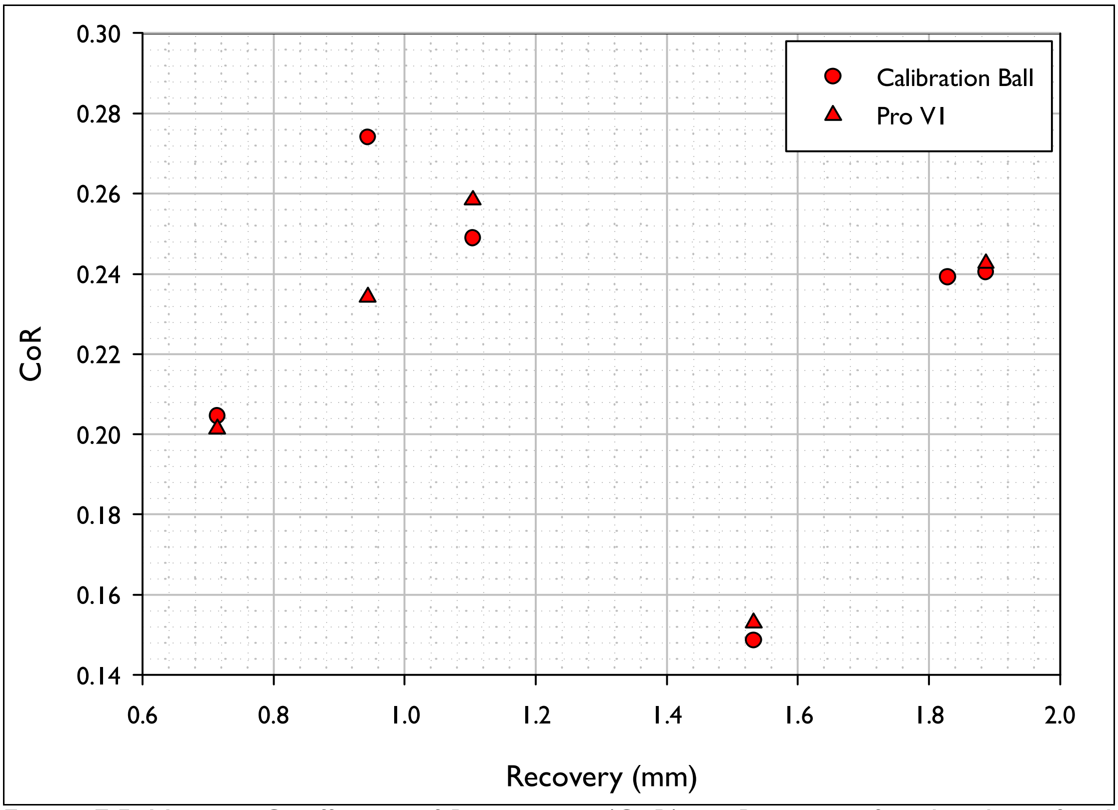

Figure E.5. Vertical Coefficient of Restitution (CoR) vs. Recovery for the shots fired using the inbound conditions akin to those for a 5 Iron.

F. Moisture

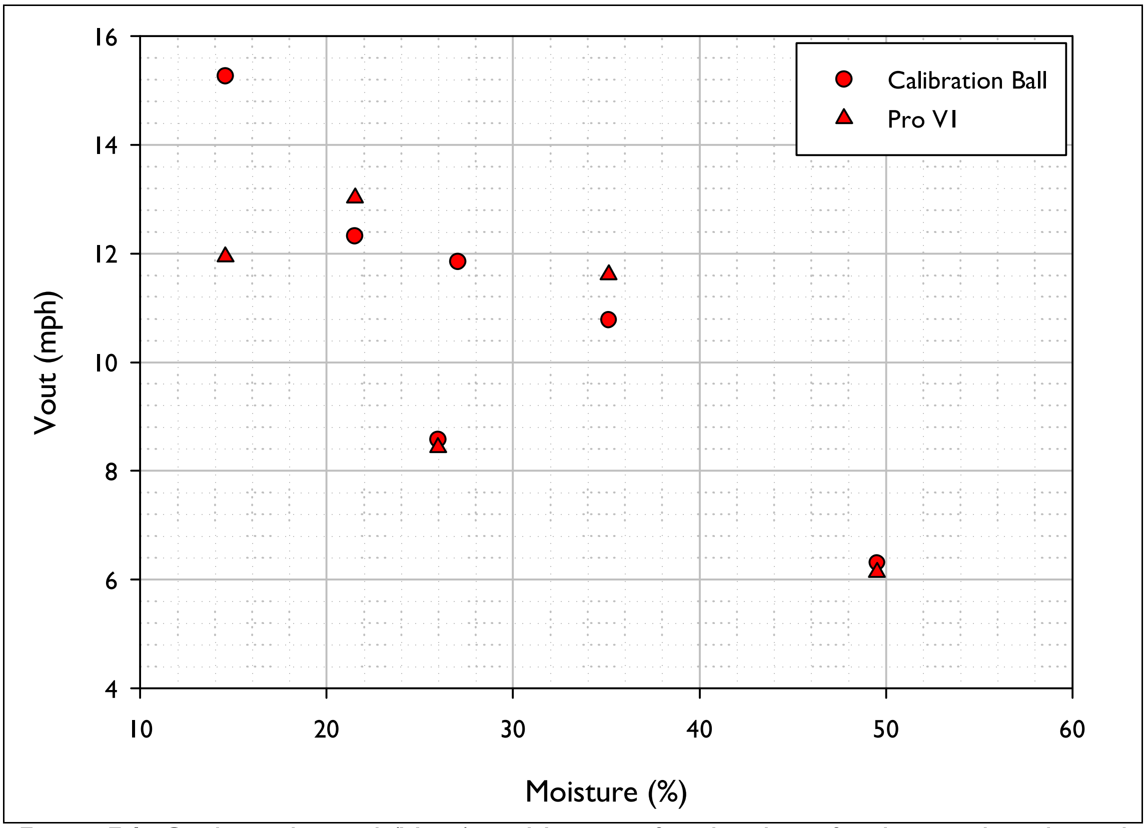

Figure F.1. Outbound speed (Vout) vs. Moisture for the shots fired using the inbound conditions akin to those for a 5 Iron.

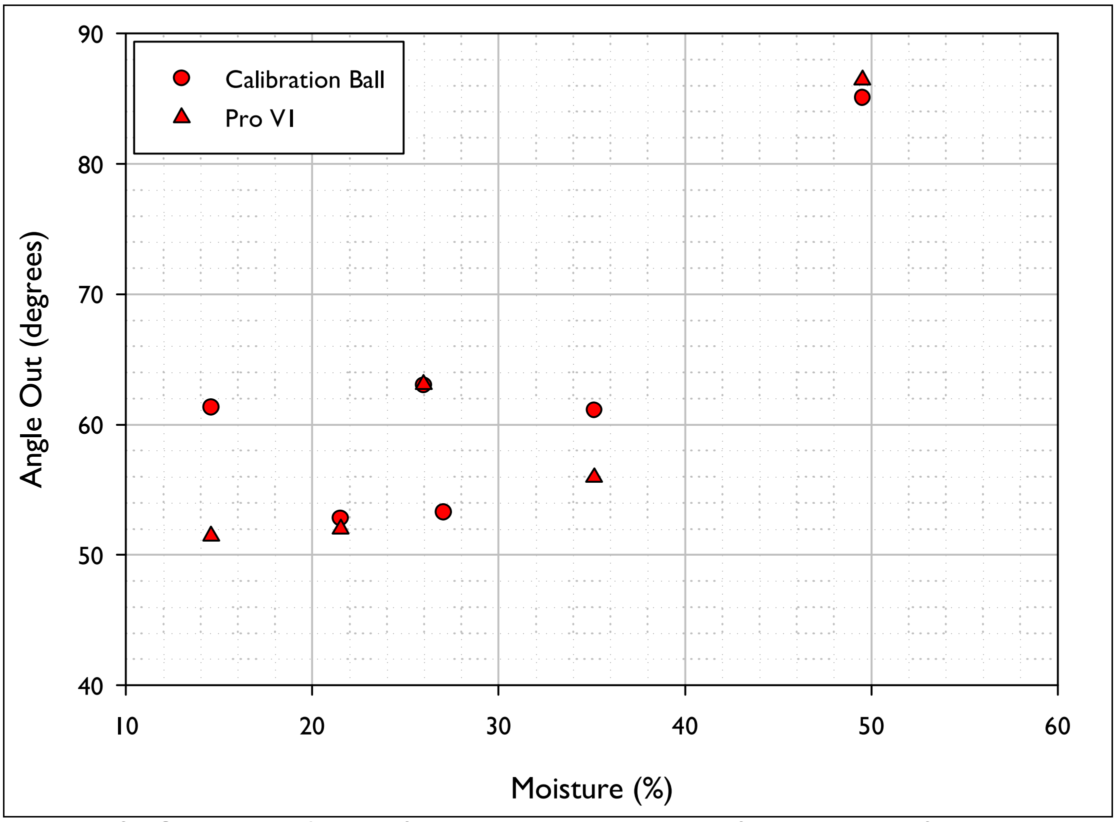

Figure F.2. Outbound Angle after Impact vs. Moisture for the shots fired using the inbound conditions akin to those for a 5 Iron.

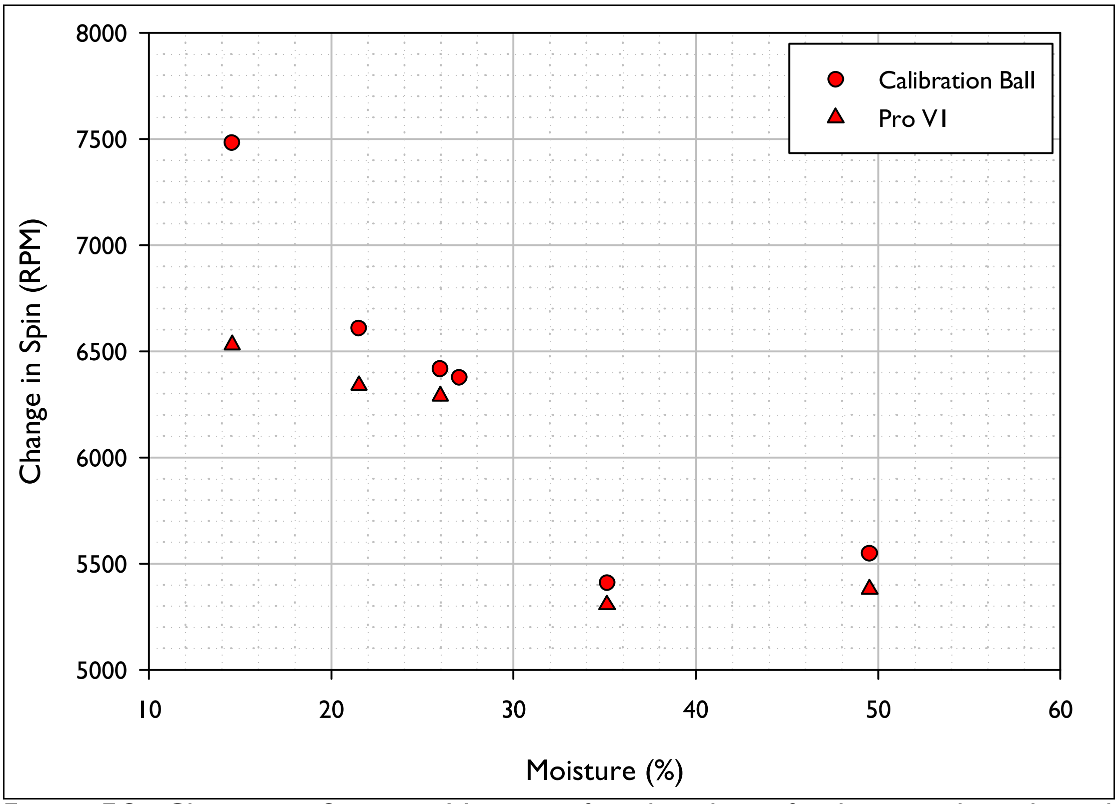

Figure F.3. Change in Spin vs. Moisture for the shots fired using the inbound conditions akin to those for a 5 Iron.

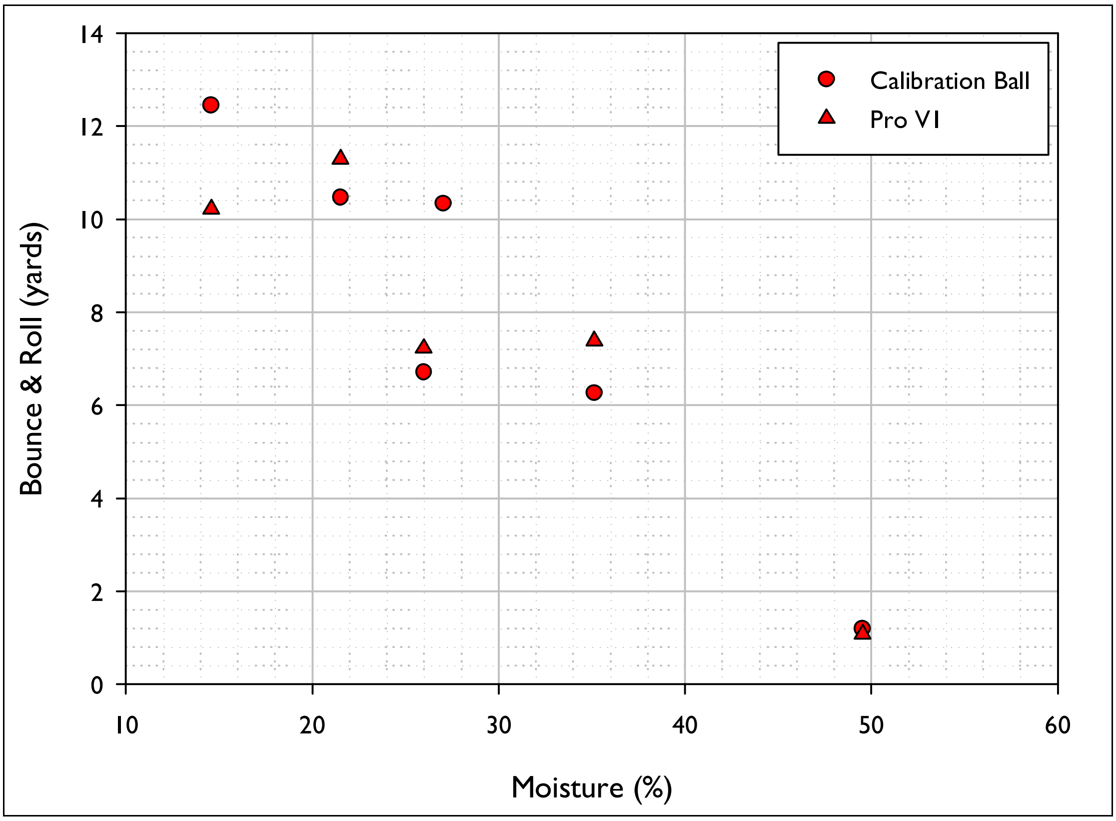

Figure F.4. Bounce & Roll vs. Moisture for the shots fired using the inbound conditions akin to those for a 5 Iron.

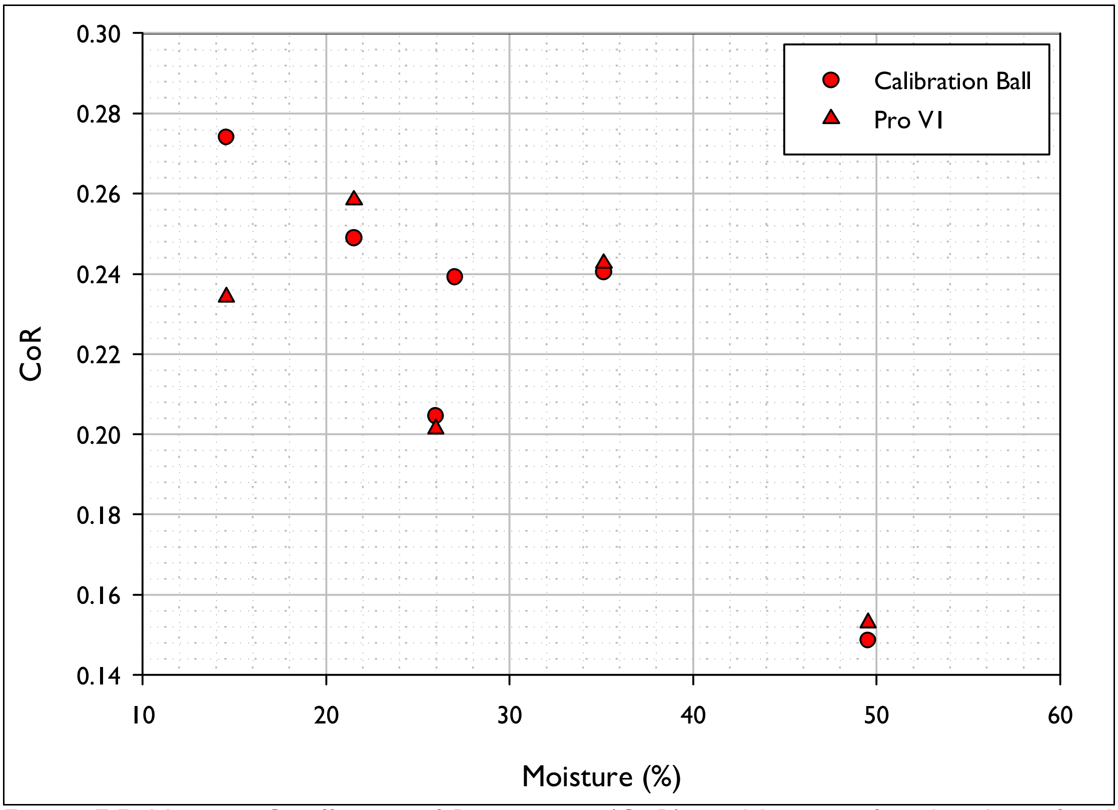

Figure F.5. Vertical Coefficient of Restitution (CoR) vs. Moisture for the shots fired using the inbound conditions akin to those for a 5 Iron.

Sand Wedge

G. Penetration

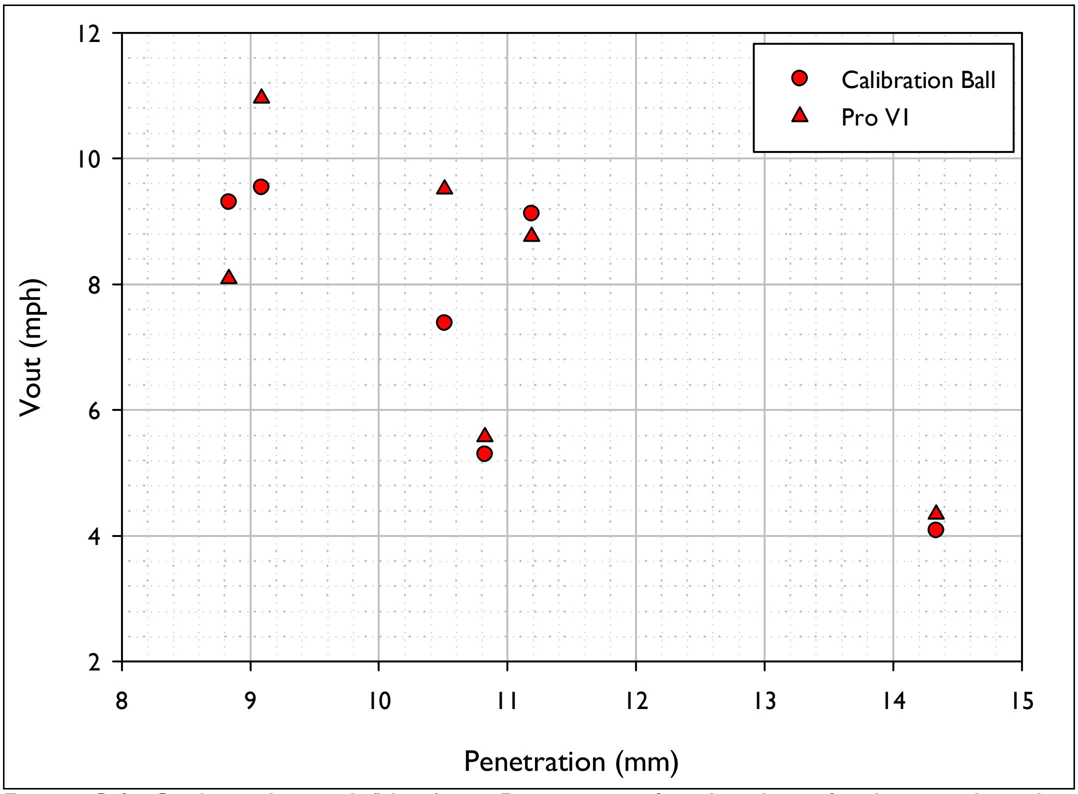

Figure G.1. Outbound speed (Vout) vs. Penetration for the shots fired using the inbound conditions akin to those for a Sand Wedge.

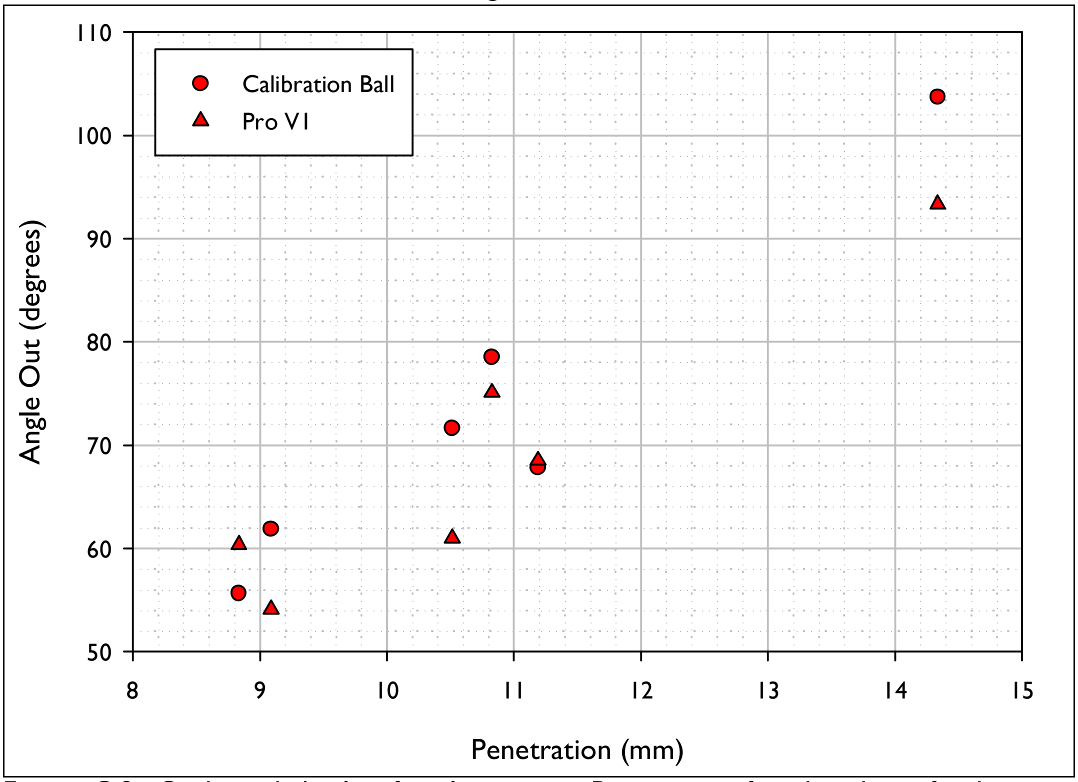

Figure G.2. Outbound Angle after Impact vs. Penetration for the shots fired using the inbound conditions akin to those for a Sand Wedge.

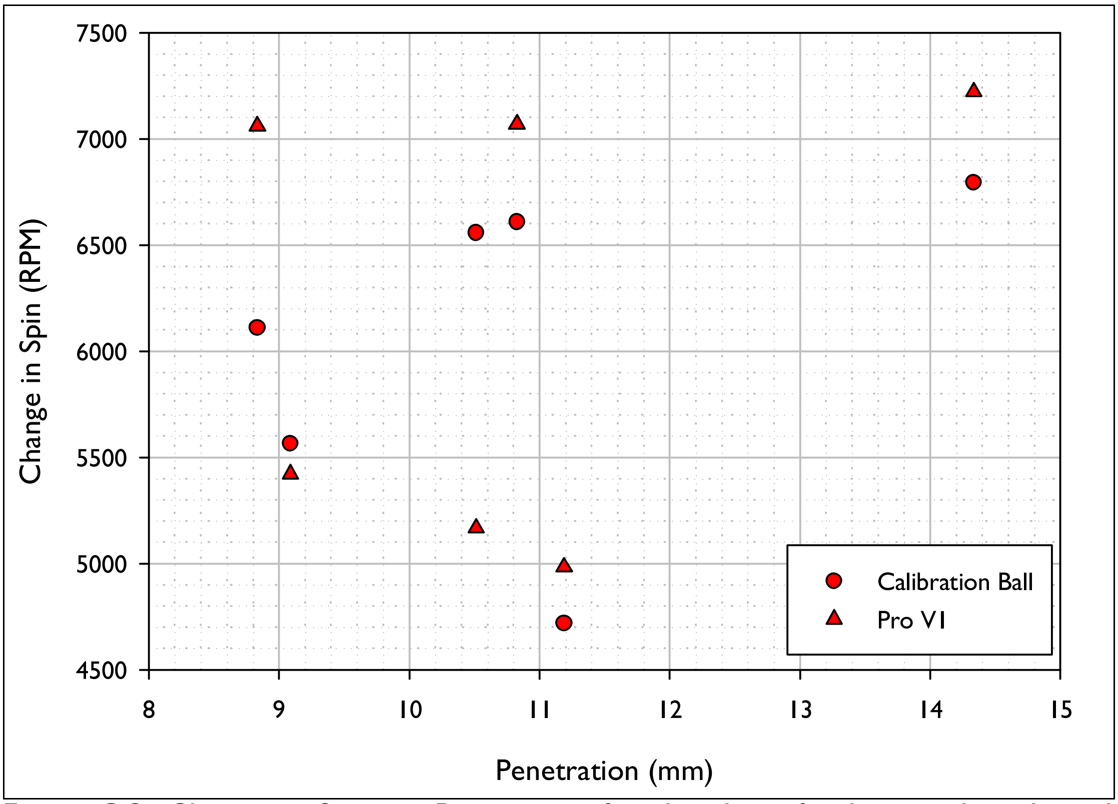

Figure G.3. Change in Spin vs. Penetration for the shots fired using the inbound conditions akin to those for a Sand Wedge.

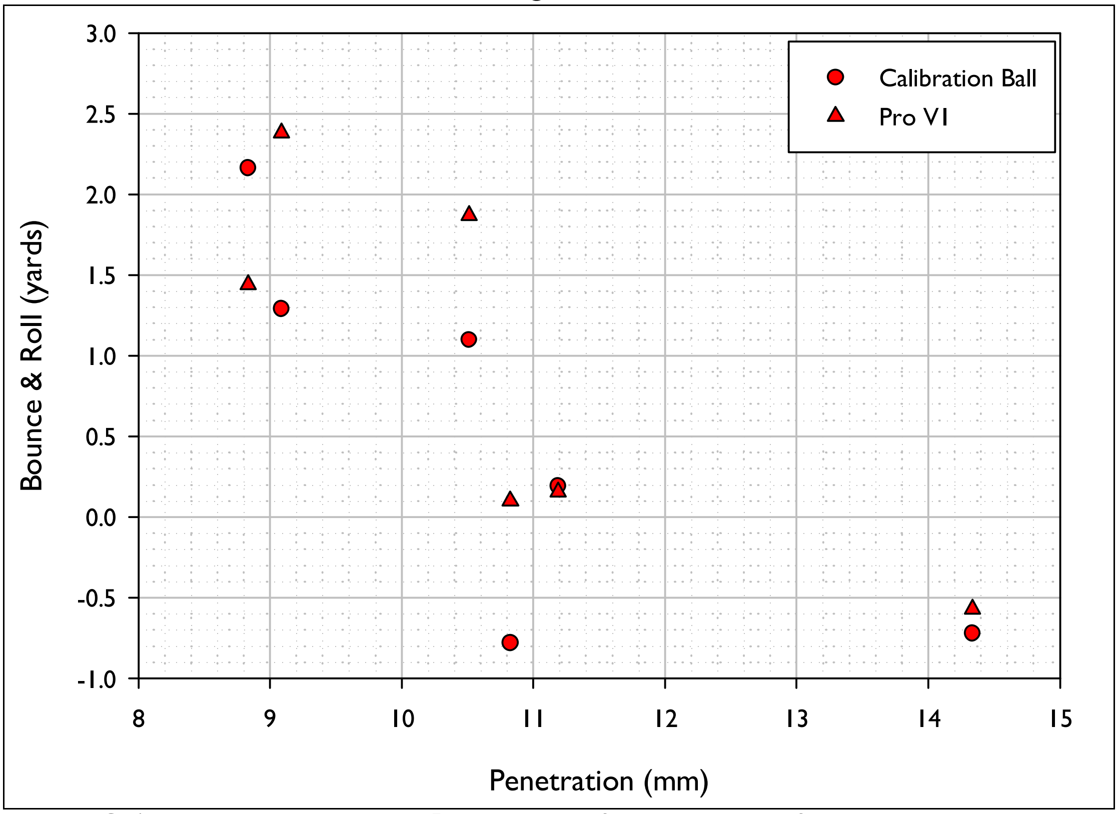

Figure G.4. Bounce & Roll vs. Penetration for the shots fired using the inbound conditions akin to those for a Sand Wedge.

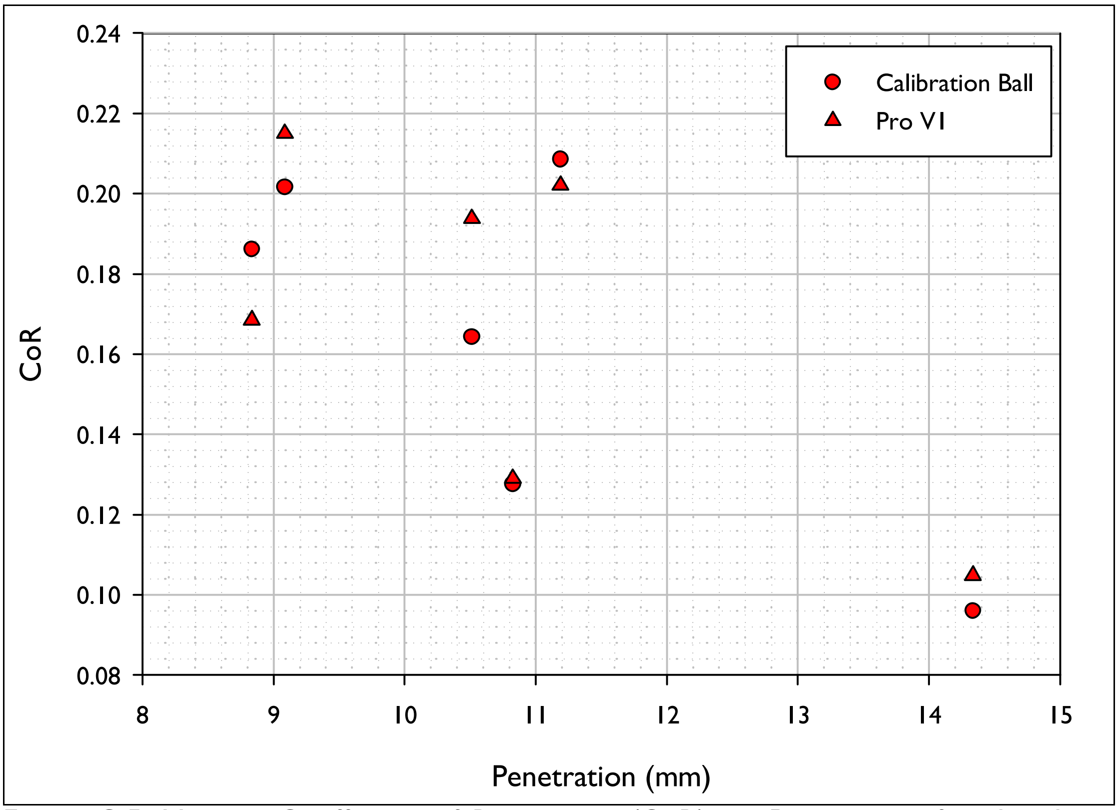

Figure G.5. Vertical Coefficient of Restitution (CoR) vs. Penetration for the shots fired using the inbound conditions akin to those for a Sand Wedge.

H. Recovery

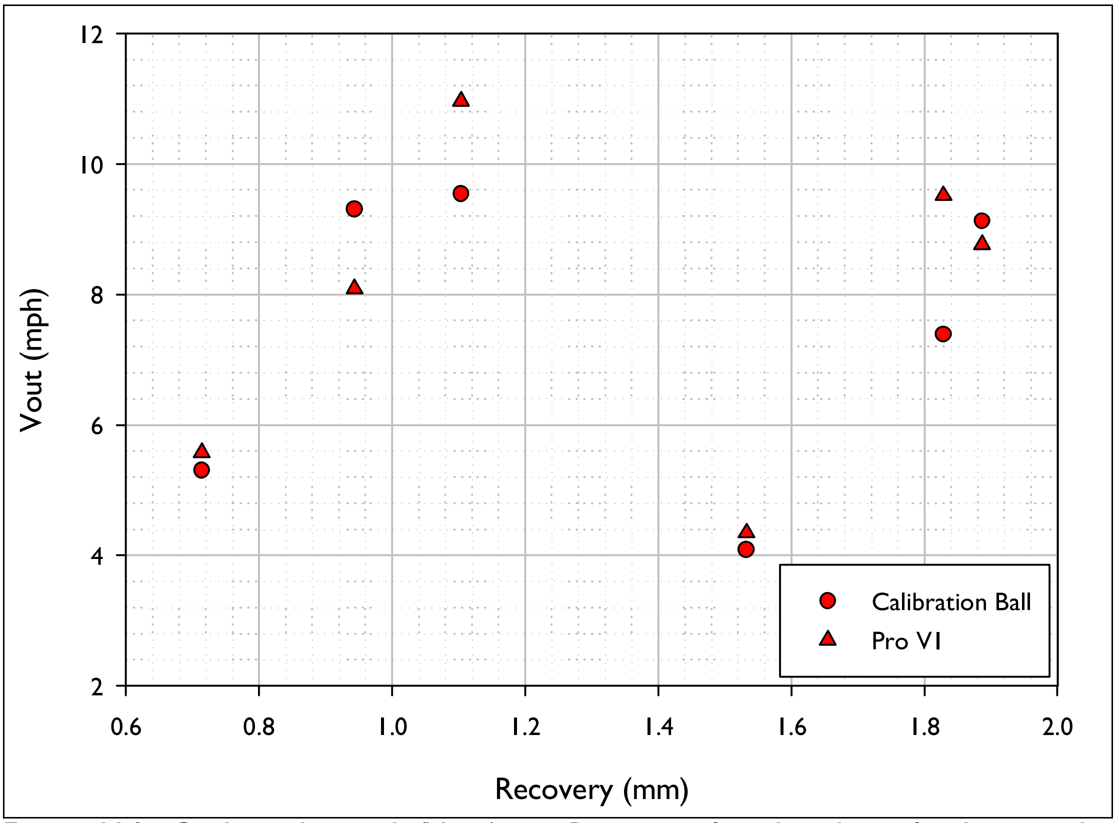

Figure H.1. Outbound speed (Vout) vs. Recovery for the shots fired using the inbound conditions akin to those for a Sand Wedge.

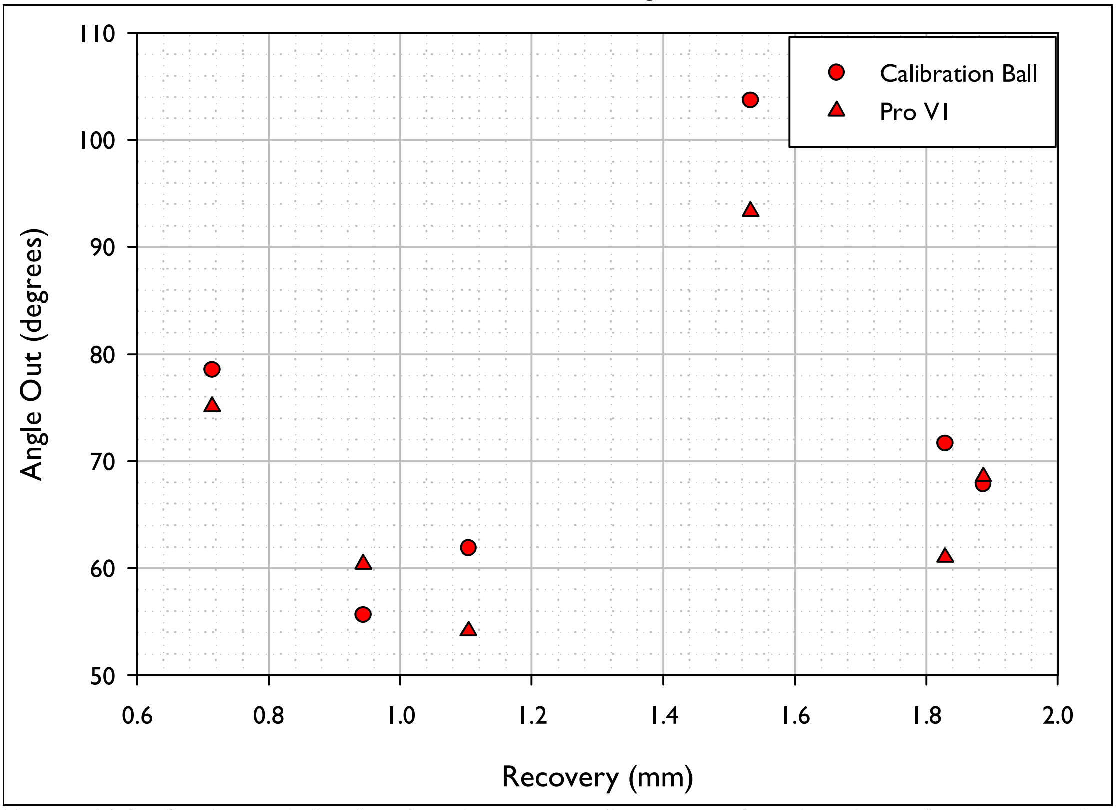

Figure H.2. Outbound Angle after Impact vs. Recovery for the shots fired using the inbound conditions akin to those for a Sand Wedge.

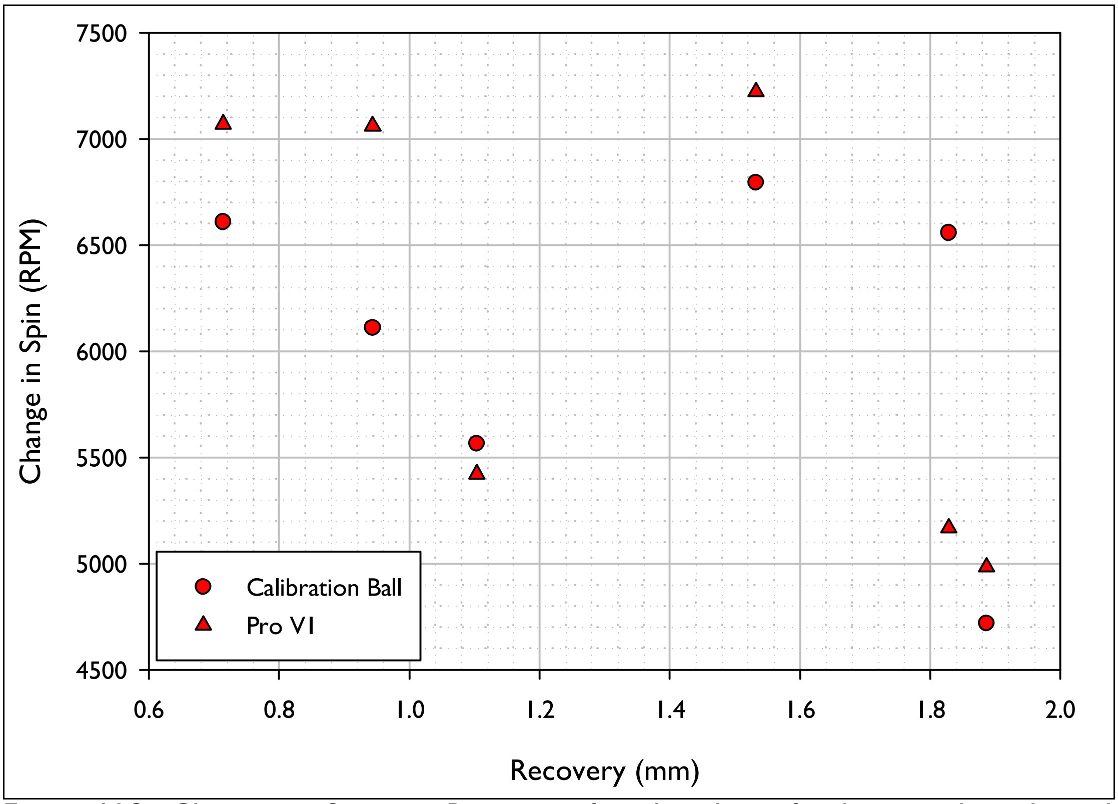

Figure H.3. Change in Spin vs. Recovery for the shots fired using the inbound conditions akin to those for a Sand Wedge.

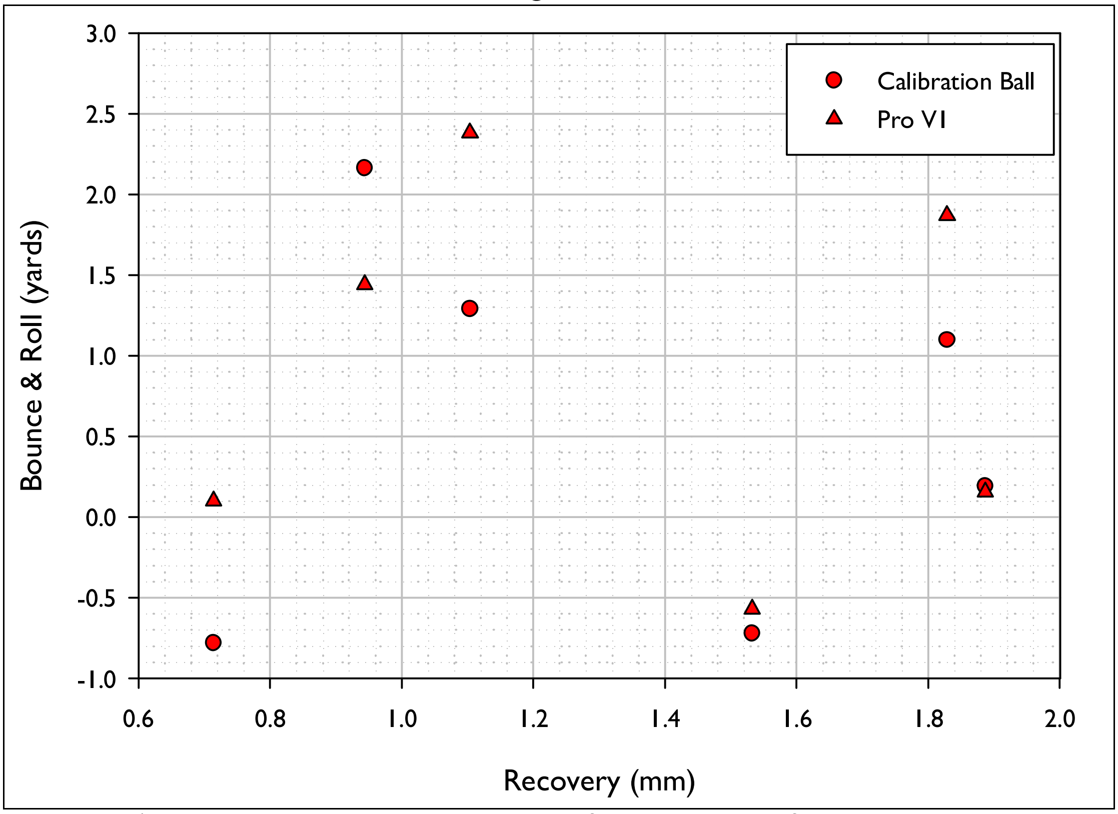

Figure H.4. Bounce & Roll vs. Recovery for the shots fired using the inbound conditions akin to those for a Sand Wedge.

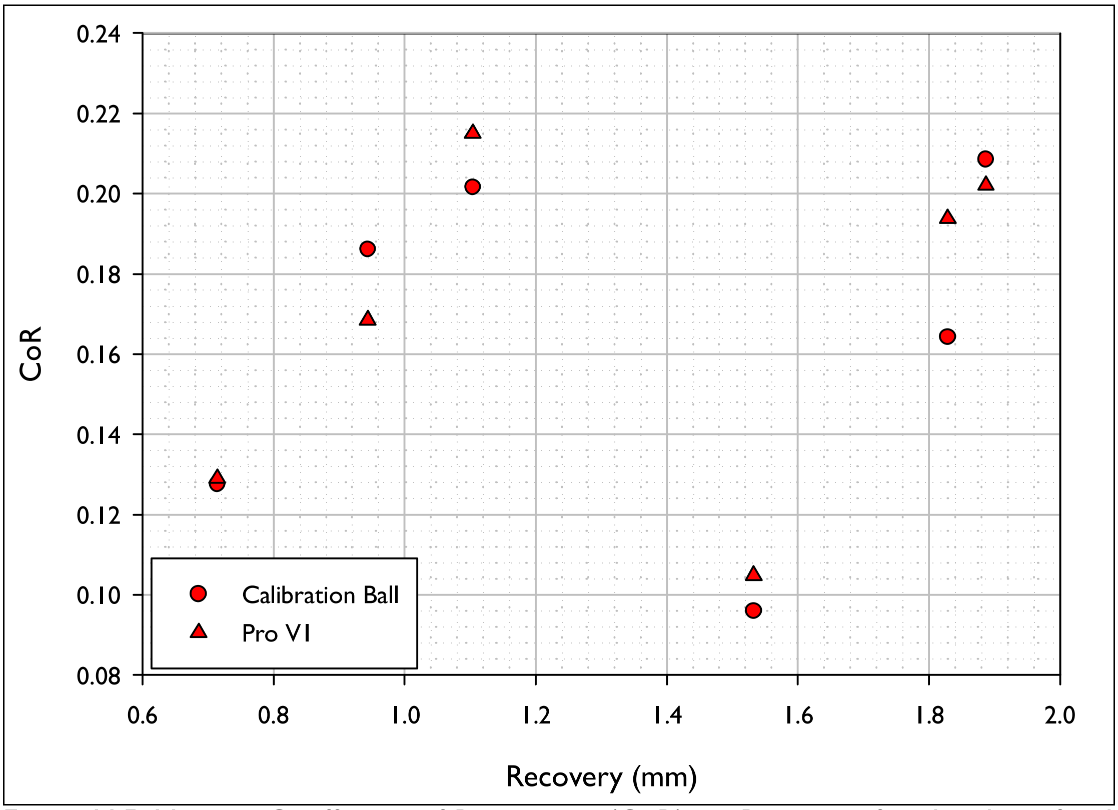

Figure H.5. Vertical Coefficient of Restitution (CoR) vs. Recovery for the shots fired using the inbound conditions akin to those for a Sand Wedge.

I. Moisture

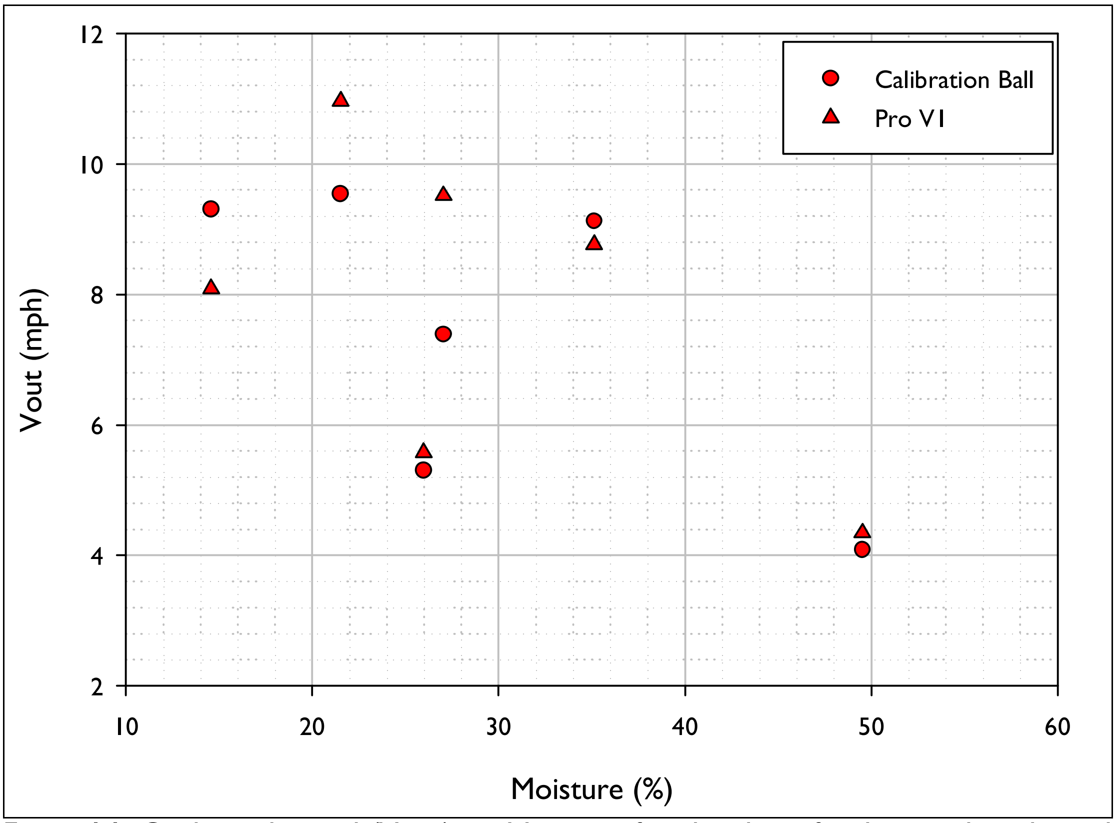

Figure I.1. Outbound speed (Vout) vs. Moisture for the shots fired using the inbound conditions akin to those for a Sand Wedge.

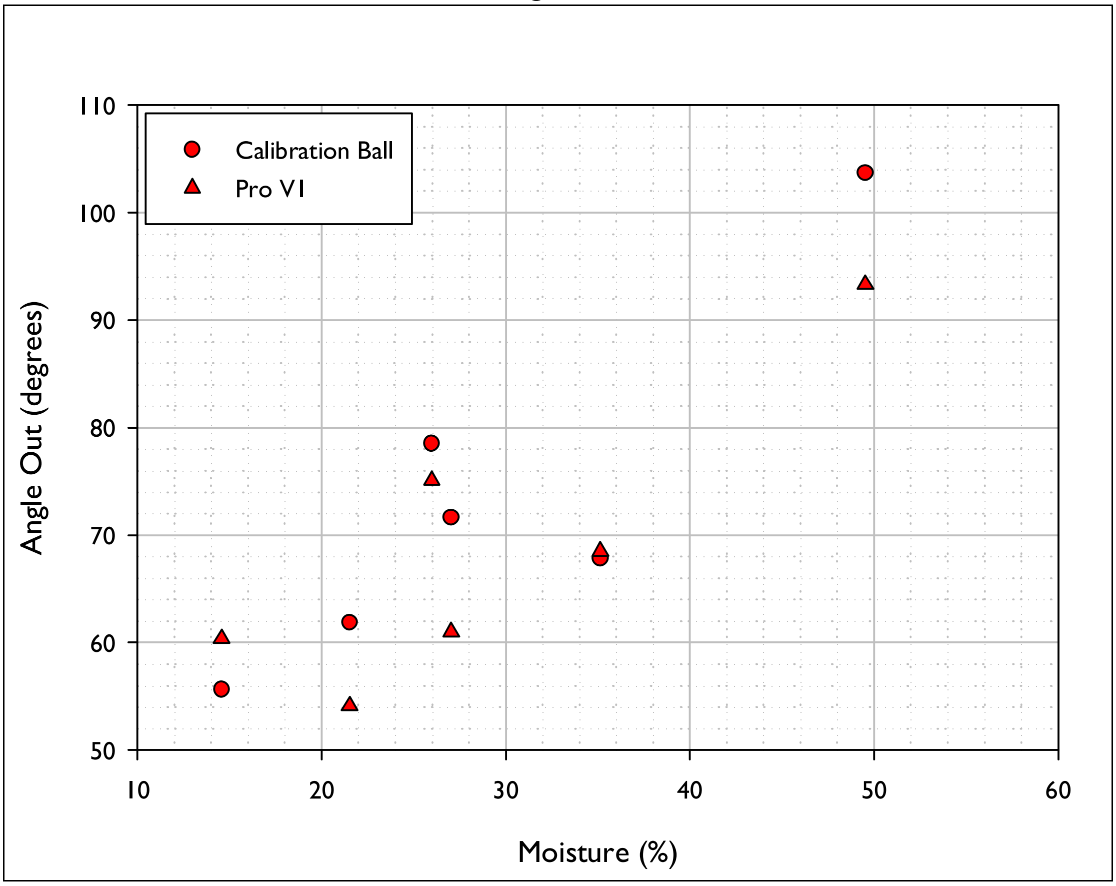

Figure I.2. Outbound Angle after Impact vs. Moisture for the shots fired using the inbound conditions akin to those for a Sand Wedge.

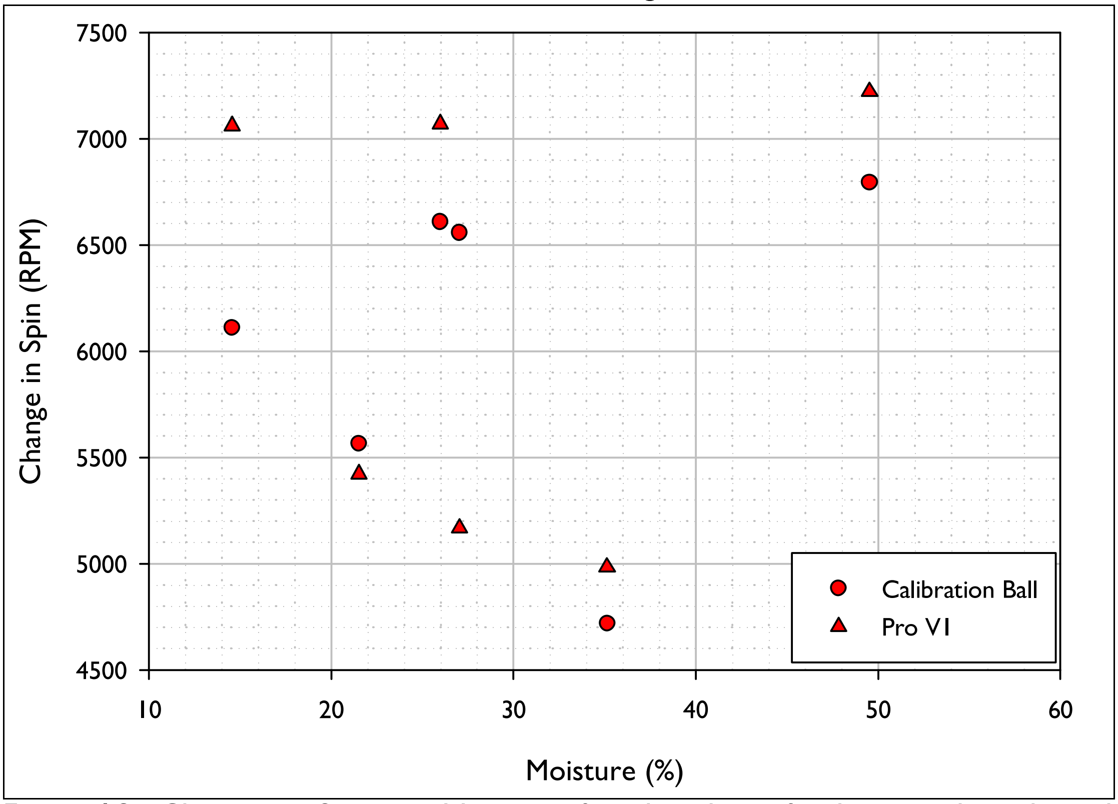

Figure I.3. Change in Spin vs. Moisture for the shots fired using the inbound conditions akin to those for a Sand Wedge.

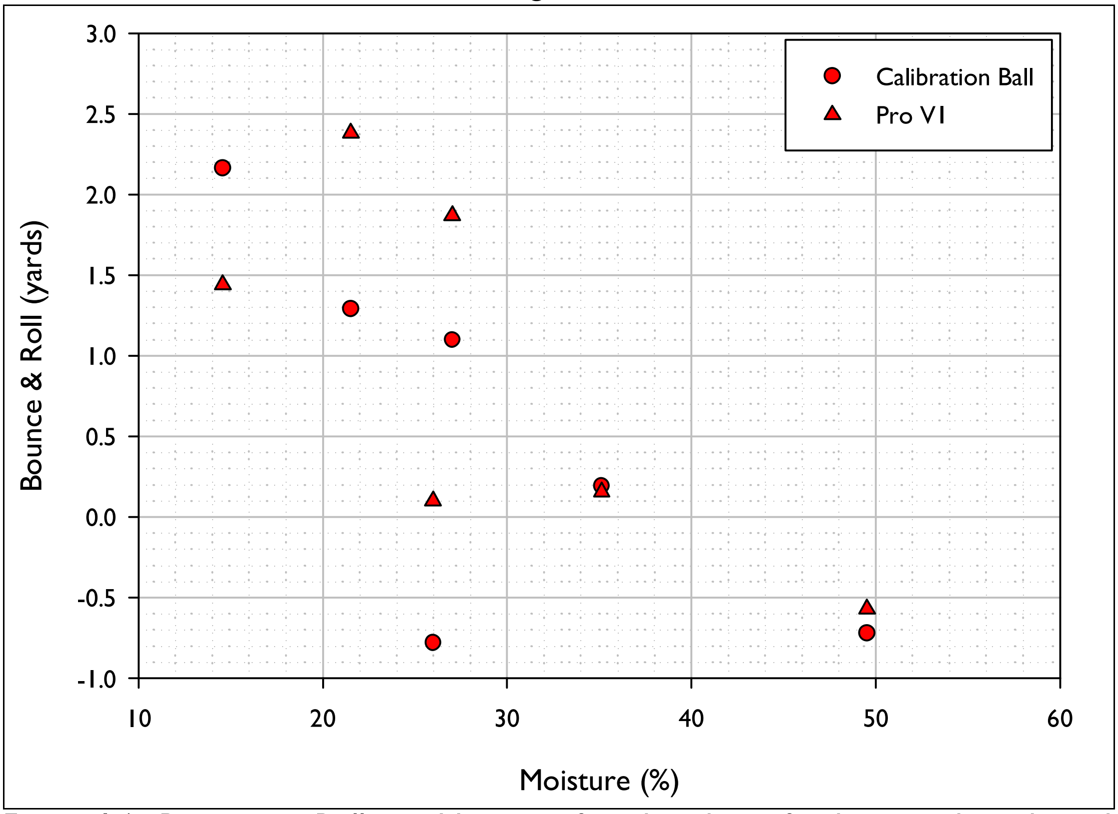

Figure I.4. Bounce & Roll vs. Moisture for the shots fired using the inbound conditions akin to those for a Sand Wedge.

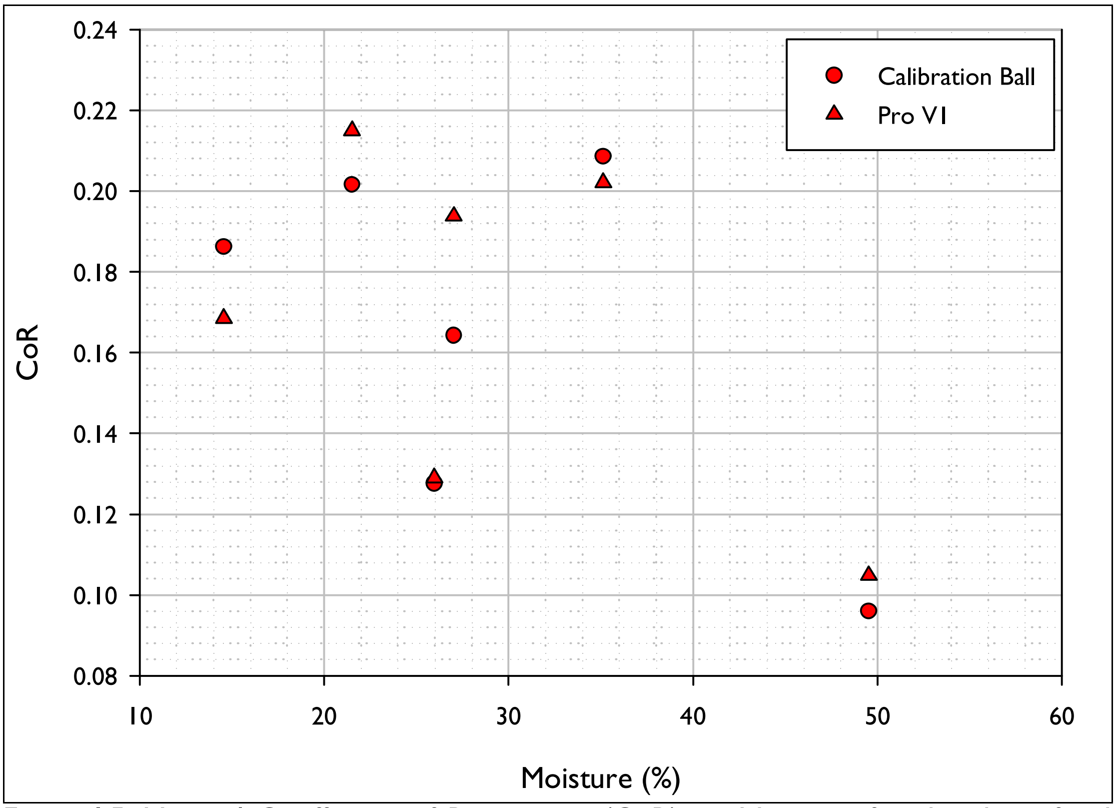

Figure I.5. Vertical Coefficient of Restitution (CoR) vs. Moisture for the shots fired using the inbound conditions akin to those for a Sand Wedge.