Chapter 3 - Impacts of golf balls on turf

3.1 Introduction

This chapter describes primarily the results and analysis of the photographs of ball/turf impacts produced with the apparatus described in the previous chapter . Photographs of golf ball impacts were taken on greens around the country. Sixteen sets of data resulted which contained 721 useful photographs of impacts. Statisical analysis was carried out on the impact data and explanations are offered for the results that were found. The tests were carried out for two reasons, (1) to evaluate the apparatus and test methods and (2) to find the important factors in ball turf/impacts. The evaluation of the apparatus is discussed later in Chapter 6 while the ball turf impacts are considered in the later sections of this chapter. Prior to the analysis of the ball/turf impacts, the effect of the construction of the ball on the impacts with the green is considered. Preliminary golf ball impacts studied using a high speed cine-camera are also described.

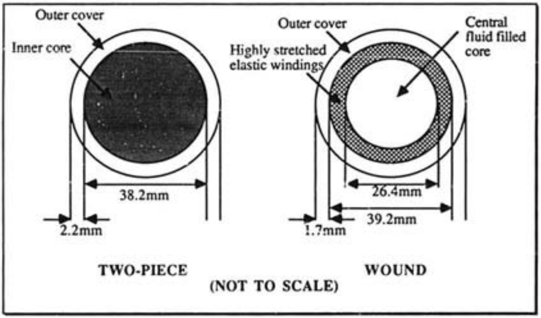

FIGURE 3.1. A diagram showing the construction of a wound and a two-piece golf ball. Both types of ball are covered in a hard plastic cover made from surlyn. The two-piece ball contains solid rubber while the wound ball contains a central fluid filled sac surrounded by tightly stretched elastic windings.

3.2 Tests to compare two constructions of golf ball

(i) The tests

Using the methods described in Chapter 2, two different types of golf ball were projected at a single golf green to determine the influence, if any, of the construction

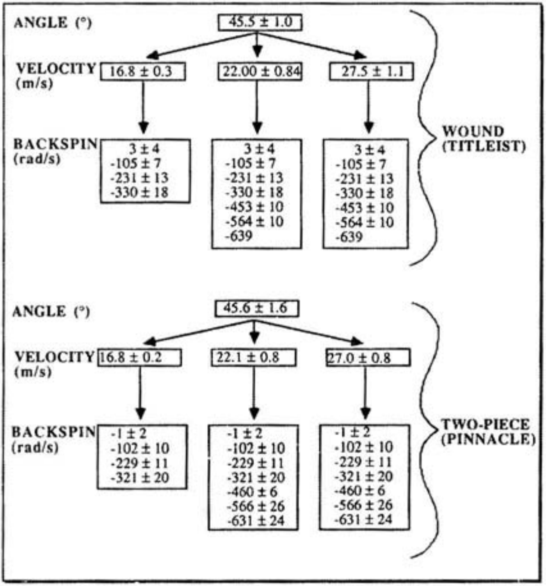

FIGURE 3.2. The means and standard deviations of the velocities, angles and spins used in projecting the Pinnacle and Titleist golf balls in tests to find the influence of ball construction on the impact with the turf.

of the ball on the impact. It might be expected that the construction of the ball would play a large part in this impact. On hard surfaces such as a golf club face, different constructions of ball bounce differently. It is not known, however, if the construction of the ball has the same effect on ball/turf impacts. If the construction has an important role in the impact then it must be incorporated into the model discussed in Chapter 5. If it is less important then it will simplify the modelling process dramatically.

Two types of golf ball were used in the tests described here; the Titleist 384 90 Tour wound ball and the Pinnacle 384 two-piece ball. These are shown schematically in Figure 3.1. Both types of ball conform to the standards laid down by the Royal and Ancient Golf Club of Saint Andrews, weighing a minimum of 45.93g and having a maximum diameter of 42.67mm. The two-piece golf ball has a solid rubber core covered by a shell of surlyn plastic. The wound ball also has this hard outer cover but has an inner core containing a fluid-filled sac surrounded by highly stretched elastic windings. The inner core contains fluid to ensure that the ball is above the minimum weight required.

Thirty one impacts were recorded with the wound ball while thirty two impacts were recorded using the two-piece ball. Information on the impacts was extracted from the photographs using the methods described in section 2.5 and are given in Appendix D. Figure 3.2 shows a comparison of the average initial velocities, angles and spins for the two types of ball. The golf balls were projected at the green at approximately 45° to the horizontal with speeds of about 16.8, 22.0 and 27.5ms^{-1}. The values shown are the averages for the set of data. For instance, the velocity of 22.0±0.8ms^{-1} for the wound ball is the average of 11 impacts at this velocity (Appendix E).

The spin was varied at each in discrete steps at each velocity - it should be noted here that backspin is chosen to be negative and topspin positive. It was possible to attain higher spins at higher velocities since the range of possible wheel speeds on the ball firing device was greater. A comparison of the initial velocities and spins shows that the spins speeds and velocities are essentially the same for each ball. It was concluded therefore that the results of the tests could be used to determine the effect of the construction of the ball on the ball/turf impact.

(ii) Results of the tests

The main body of results of the impacts are shown in Appendix D. Table 3.1, however, shows the results from four typical impacts at the highest velocity studied, two using the wound ball and two using the two-piece ball.

The first two impacts in the table have zero spin while the second two impacts have a backspin of about 640rads^{-1} (backspin is negative). In both cases the wound ball rebounded at a higher angle than the two-piece ball. The spin and the velocity of the ball after impact showed no particular relationship, however. With both types of ball, an increase in the backspin caused an increase in the rebound angle and a decrease in the velocity of rebound. The topspin of the ball also decreased after impact. At this stage, it is the effect of the construction of the ball on the impact that is being considered. Analysis of the effects of a change in velocity, angle and spin shall be considered in the next section.

It is difficult to determine whether the variations in the impacts above are due to the construction of the ball, inconsistencies in the green or variations in the incident velocity, angle and spin. Regressions were therefore carried out on the results for the two different balls to determine the relationships between the rebound velocity, angle and spin and the incident velocity and spin.

	VELOCITY (ms^{-1})		ANGLE (°)		SPIN ($rads^{-1}$)		DEPTH
	initial	final	initial	final	initial	final	(mm)
2P	27.7	9.1	44	44	0	380.5	3.6
W	27.2	8.3	47	53	0	299.4	4.3
2P	28.1	4.8	48	74	-641.2	178.7	5.3
W	30.5	5.3	48	76	-638.9	175.7	6.6

TABLE 3.1. A table to show the results of typical impacts using two types of golf ball. The letters at the beginning of each row refer to two-piece (2P) or wound (W) golf balls.

Stepwise regressions were used to calculate the relationships between the incident velocity and spin and the velocity, angle and spin after impact. This method calculates the best-fit relationship between the data for one dependent variable with two or more independent variables. Each independent variable is tested individually and then introduced into the equation in order of significance. Once the variable is entered into the equation, it is tested again and removed if it is not significant (see Snedecor and Cochran, 1974 for a fuller description of this method). The regressions are written in the form,

$$y = a + (b_1 \pm \sigma_1)\, x_1 + (b_2 \pm \sigma_2)x_2 + (b_3 \pm \sigma_3)x_3 + \ldots\ldots..(b_n \pm \sigma_n)x_n$$

where the b's are the coefficients for each independent variable, the σ's are the corresponding standard errors and n is the number of variables. A correlation coefficient (r) and a level of significance (p) are also given with the regression equation. These show how well the relationship describes the data and the probability that this relationship occurred by chance.

The regression equations found for the impacts with the two balls are shown in equations 3.1 (a), (b), and (c). In these equations V is the initial velocity, ω is the initial spin, Θ is the angle of incidence to the horizontal and the subscripts "i" and "f" denote the initial and final values of the variables respectively. The regressions found were,

(a) For the final velocity,

Two-piece ball: $V_f = 2.79 + (0.20 \pm 0.03)V_i + (0.0045 \pm 0.0006)\omega_i$; $r = 0.86$

Wound ball: $V_f = 2.12 + (0.23 \pm 0.03)V_i + (0.0041 \pm 0.0006)\omega_i$; $r = 0.87$

(b) For the final angle,

Two-piece ball: $\theta_f = 28.42 + (0.9 \pm 0.3)V_i - (0.035 \pm 0.004)\omega_i$ $r = 0.82$

Wound ball: $\theta_f = 30.60 + (0.8 \pm 0.2)V_i - (0.035 \pm 0.006)\omega_i$ $r = 0.90$

(c) For the final spin,

Two-piece ball: $\omega_f = 100.1 + (9.3 \pm 1.8)V_i + (0.26 \pm 0.03)\omega_i$ $r = 0.83$

Wound ball: $\omega_f = 162.7 + (5.7 \pm 1.2)V_i + (0.19 \pm 0.03)\omega_i$ $r = 0.81$

eqn. 3.1

The equations were all significant at the 0.01% confidence level. This means that, using this data, there is a probability of 1 in 10,000 that the relationship occurred by chance.

Consider, for instance, a wound and a two-piece ball impacting at $22ms^{-1}$ and with zero spin. The equations above predict within one standard error that the two-piece ball would rebound between 6.5 and $7.9ms^{-1}$, at an angle between 41.6 and 54.8° and with a spin between 265 and $344rads^{-1}$. The wound ball is predicted to rebound between 6.5 and $7.8ms^{-1}$, at an angle between 43.8 and 52.6° and with a spin between 262 and $315rads^{-1}$. The ranges for the two balls are very similar and it is difficult to say whether the construction of the ball effects the impacts or not. It is therefore necessary to test the coefficients of velocity and spin to find if they are significantly different within their standard errors. If the coefficients are different this would indicate that the construction of the ball has an effect on the impact. The coefficients were tested as follows. If the standard errors of two coefficients b_1 and b_2 were σ_1 and σ_2 respectively, then the variable d can be calculated using the formula,

$$d = \frac{b_1 - b_2}{\sqrt{(\sigma_1^2 + \sigma_2^2)}} \qquad \text{eqn. 3.2}$$

The magnitude of d determines the level of significance of the difference between the two coefficients b_1 and b_2. This can be found using Table 3.2. The coefficients in equations 3.1 (a) and (b) were not found to be significantly different. Since there appeared to be more variation in the coefficients in equation 3.1 (c), the tests to determine the significance of their differences are shown below. For the coefficient of the initial velocity,

$$d = \frac{9.3 - 5.7}{\sqrt{(1.8^2 + 1.2^2)}} = \frac{3.6}{\sqrt{4.68}} = 1.664$$

and, for the coefficient of the initial spin,

$$d = \frac{0.26 - 0.19}{\sqrt{(0.03^2 + 0.03^2)}} = \frac{0.07}{\sqrt{0.018}} = 1.650$$

Comparing these values to those in Table 3.2 it can be seen that the coefficients are different at the 10% level of confidence. The accepted level of confidence used is 5% and therefore these coefficients are not considered to be significantly different.

p	0.10	0.05	0.02	0.01	0.002	0.001
d	1.645	1.690	2.326	2.576	3.090	3.291

TABLE 3.2. A table containing the values of *d* (the unit standard deviation) required for a level of significance p (Bailey, 1959).

There were therefore no significant differences between the coefficients of the regressions for the wound and two-piece balls at the velocities and spins studied. Thus, at the velocities, angles and spins tested, the ball's construction did not affect the impact of the ball with the green. This suggests that the ball can be considered as a rigid solid during impact and will simplify greatly the models of impact formulated in Chapter 5.

3.3 Studies of golf ball impacts using high speed film

(i) Introduction

The use of a high speed camera was tested during the evaluation of methods for recording the ball/turf impact. Test films were subsequently developed and these were found to be quite useful in revealing the dynamic processes involved in an impact. The high speed films could give estimates of the contact time, the depth of penetration of the ball into the ground, and the deformation of the ball. These factors are potentially useful in the development of a model of impact.

The Fastax WF17 high speed camera used in these tests employed a rotating prism mechanism and was able to take pictures at rates up to 8000fps. At this speed, 30m of 16mm film was exposed in 0.7 seconds. The camera was activated by a remote switch and the speed of the film through the camera was altered by varying the voltage applied to the camera motor. Two 1kW video lamps were used to provide additional illumination during the impact. Pegs were placed in the ground in the field of view of the camera to provide a distance scale with which to make measurements. The camera was placed about 5m from the point of impact and a long focal length lens used to minimise the effects of parallax. A disc marked out in segments attached to a motor rotating at 25 revolutions per second was placed behind the impact zone. This provided a time base for the camera and was required to facilitate calculations of velocity and spin.

The ball projection device described in Chapter 2 was used to project golf balls at turf near to a convenient power supply as it was not possible to produce the power required with a portable generator. An analysing projector was used to view the resultant films frame by frame. The rotation of the disc between frames indicated the time lapsed per frame and, by marking the positions and orientations of the ball on successive frames, the velocities, angles and spins were calculated.

(ii) Results

Four impacts with the turf were studied using the high speed camera running at between 1201 and 3260fps (Table 3.3). The impacts studied were carried out on different areas of turf and on different days and were carried out to evaluate the method of high speed photography. The analysis shown here, therefore, is quite general since it is difficult to draw specific conclusions from four different impacts.

Columns 1 to 6 in Table 3.3 show the velocities, angles and spins before and after impact. The next column shows the depth of the pitchmark measured just after the impact. In column 8 it can be seen that the balls were in contact with the ground between 6.1 and 9.2msecs. This is 12 to 18 times longer than the impact of a golf ball with a golf club. Using the change in momentum in the horizontal and vertical directions and the time of contact, the approximate force and its direction were calculated.

Velocity ms^{-1}		Angle °		Spin $rads^{-1}$		D mm	T msecs	Film speed	Average F	Average τ	Force angle	Rad (eff)
i	f	i	f	i	f			fps	N	Nm	°	mm
24.5	6.1	51	67	-562	274	12	9.2	1201	144	.757	63	5.3
15.0	3.7	52	62	-341	152	8	6.2	1617	125	.633	64	5.1
22.0	7.7	39	70	0	322	7	6.1	3260	192	.440	56	2.3
21.2	7.4	38	42	0	300	7	6.5	3087	150	.385	58	2.6

TABLE 3.3. A table showing the information on four impacts studied using high speed film. Negative spin indicates backspin.

The total average force, the average torque and the angle to the horizontal at which the force acts are shown in columns 10, 11 and 12 in Table 3.3. Since the average force and the average torque are linked (by $\tau = Fr$) it is possible to calculate the effective radius at which the torque is applied (column 13). Figure 3.3 shows the application of the average force during a typical impact. It can be seen that the average force acts off-centre. The resultant torque modifies the initial spin of the ball. Table 3.3 shows that the effective radius varies from 2.3 to 5.3mm (about one tenth to one fifth of the ball's radius) and is larger in the case when the initial backspin is high. As expected, the forces experienced by the ball are a combination of that due to the spin of the ball and the interaction of the ball's translational motion with the surface.

The magnitude of the vertical force experienced by the golf ball was about 130N, equivalent to a maximum deceleration of about 2800ms^{-2}. The nature of the impact can be considered further if the impact is compared to the motion of a mass on a spring. The maximum deceleration would vary with mass$^{-1/2}$ (analysis based on simple harmonic motion). As will be seen in Chapter 4, the maximum deceleration found using the 0.5kg Clegg indenter averaged over all the greens visited was about 57*g* or 563ms^{-2}. The ratio of the mass of the golf ball to the Clegg indenter is 1 to 10.9; the maximum decelerations would therefore be expected to vary in the ratio 3.3 to 1. It can be seen that the decelerations are in fact in the ratio of about 5 to 1. This difference is not surprising since the analogy of the single spring was not expected to be correct; the ball would not lose energy during the impact. The motion must have a viscous component since the coefficient of restitution is not unity. The use of springs and damper components to model the ball turf impact is discussed later in Chapter 5.

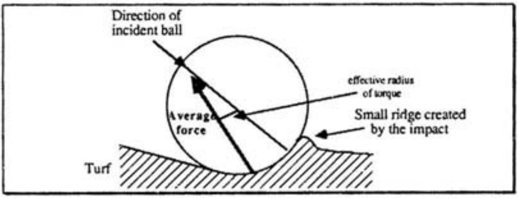

FIGURE 3.3. A diagram to show the direction of the average force in the impact of a golf ball on a golf green as deduced from high speed films of impacts.

An interesting feature seen on the high speed films was that the initial backspin of the ball was modified almost instantaneously to topspin at the beginning of the impact. Furthermore, it appeared that the ball rolled off the surface. It is possible to calculate the spin required for the ball to roll off the surface using,

$$\omega = \frac{V}{r} \qquad \text{eqn. 3.3}$$

where V is the translational velocity and r is the radius of the ball. The first impact shown in Table 3.3 had a rebound velocity of 6.1ms^{-1} and with a radius of 0.0213m, the equivalent spin required for rolling was about 286rads^{-1}. This is not too far from the actual spin of the ball as it left the surface. If the same calculation is performed on the other three impacts it is found that the rolling spins are almost the same as the

VELOCITY(ms^{-1})		ANGLE (degrees)		SPIN ($rads^{-1}$)		Depth
i	f	i	f	i	f	(mm)
17.5	6.4	44	40	0	277.0	3.8
17.8	5.8	45	41	0	245.7	3.1
17.7	6.9	45	38	0	339.5	2.5
17.5	6.3	45	40	-98.3		2.5
17.1	6.0	45	36	-102.7	259.1	2.3
17.4	6.3	46	39	-89.3	268.0	2.0
17.7	6.5	45	40	-218.9	245.7	2.5
17.7	6.4	45	37	-205.5	259.1	1.8
17.7	5.0	45	50	-326.1	234.5	2.3
17.6	5.2	45	47	-328.4	234.5	2.0
22.0	8.1	44	39	0		3.1
22.3	6.8	45	46	-107.2	290.4	3.1
21.8	7.2	45	44	-116.1	254.6	3.3
21.7	6.6	43	47	-107.2	292.6	4.3
22.5	6.5	43	49	-216.7	308.2	
22.1	7.3	44	40	-232.3	277.0	4.3
22.2	6.8	44	46	-214.4	296.3	1.8
22.6	5.9	43	52	-328.4	247.5	4.1
22.0	5.9	44	48	-326.1	249.4	4.3
22.6	7.5	44	43	-457.9	107.2	3.1
21.7	7.6	43	40	-428.9	134.0	2.5
22.7	7.6	43	43	-437.8	147.4	2.5
22.8	7.5	43	44	-536.1	-37.4	2.3
22.5	8.0	44	38	-567.4	-69.2	3.3
27.0	9.1	43	39	0	402.3	3.3
27.5	8.8	45	39	0	402.3	1.2
26.7	7.9	43	45	-99.4	325.4	3.1
28.5	8.3	44	44	-106.2	329.9	4.1
27.1	7.4	45	50	-221.5	305.1	3.8
27.5	5.7	44	63	-212.4	230.5	7.4
26.4	7.1	45	48	-203.7	311.9	5.1
27.5	7.3	44	48	-198.8	316.4	4.1
26.7	6.6	45	51	-348.0	262.1	4.8
28.4	7.1	45	52	-339.0	297.7	4.6
27.7	7.3	44	54	-452.0	230.5	5.1
27.8	7.8	44	44	-565.0	103.9	6.4
28.0	5.7	44	61	-551.4	212.4	6.4
28.2	5.5	44	63	-560.5	212.4	
27.0	8.5	45	48	-90.4	346.9	3.1
28.4	8.0	44	43	-488.2	219.2	4.1
26.9	6.6	45	51			
26.9	6.2	45	54	-664.5	-78.5	
27.5	8.2	44	42	-678.0	-88.1	4.1
25.9	5.9	44	50	-650.9	-59.3	4.6
25.5	6.0	44	54	-650.9	-35.2	

TABLE 3.4. A table containing the results of the impact tests at Ganton golf club. The subscripts "i" and "f" are assigned to the variables before and after impact respectively, the depth is the depth of the pitchmark created by the impact and blank spaces indicate that the variable was not measured.

actual spins of the ball after impact. This suggests that, in these impacts, there was no slip between the surface of the ball and the turf at the end of impact.

In most of the impacts the ball appeared to penetrate up to almost half its diameter into the turf but subsequent measurements found the pitchmarks to be at the most 12mm in depth. This indicated that, if the ball did not compress significantly during impact, then the ground must have partially recovered after the impact had taken place. This may be an important consideration in the modelling of the impacts in Chapter 5.

3.4 Results from the stroboscope photographs of golf ball impacts

(i) The velocities, angles and spins used in the impacts

This section shows the results and analysis of the results from the photographs of ball/turf impacts. The methods described in Chapter 2 were used to project Titleist 384 golf balls at a single green on 16 golf courses. This resulted in 721 photographs of impacts; 450 from 11 greens on which the angle of incidence was fixed at 45° to the horizontal and 271 on 5 greens where the angle of incidence was varied. The photographs of impacts were analysed using the methods described in section 2.5.

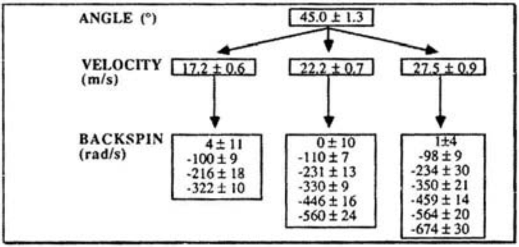

FIGURE 3.4. The velocities and spins and their respective standard deviations used in the golf ball impacts projected at 45° to the horizontal. Negative spin indicates backspin.

The initial and final velocities, angles and spins of all the impacts are shown in Appendix E since there are too many to show here. As an example, the data on the impacts from the green studied at Ganton golf club are shown in Table 3.4. The letters "i" and "f" indicate the initial and final values of the velocity, angle and spin. The depth refers to the depth of the pitchmark created by the impact and blank spaces in the table indicate that the measurement of the variable was not possible.

COURSE	ANGLE	VELOCITY	SPIN
	(°)	(ms⁻¹)	(rads⁻¹)
Belfry	35.1 ± 1.2	16.8 ± 0.4	2 ± 2, -117, -218 ± 3, -378 ± 5
		22.1 ± 0.5	0, -119 ± 5, -246 ± 6, -318 ± 12, 443 ± 7, 590 ± 26
		27.6 ± 0.9	2 ± 3, 119 ± 4, 232 ± 8, 376 ± 13, 478 ± 17, 543 ± 22, 676 ± 22
	44.4 ± 0.9	17.3 ± 0.5	0, -328 ± 6
		22.81 ± 0.4	-2 ± 2, -585
		27.4 ± 0.5	-5, -639
Crewe	36.9 ± 1.3	16.9 ± 1.1	0, -303 ± 18
		22.3 ± 0.2	0, -334 ± 3, -567 ± 33
		27.9 ± 0.7	-7 ± 2
	45.8 ± 1.1	18.0 ± 0.8	0 ± 0, -343 ± 7
		23.1 ± 0.4	6 ± 4, -363 ± 9, -568 ± 1
		27.9 ± 0.3	4 ± 4, -356 ± 4, -648 ± 16
	54.8 ± 1.3	17.4 ± 0.8	0 ± 0, -323 ± 5
		22.7 ± 0.3	6 ± 2, -345, -574 ± 7
		27.4 ± 0.3	-3 ± 3, -384 ± 3, -641 ± 19
Hill Valley	35.0 ± 0.5	17.3 ± 0.3	0 ± 0, 321 ± 7
		22.0 ± 0.3	4 ± 3, -327 ± 3, -545 ± 3
		26.3 ±0.6	35.3 ± 20, -335, -631
	45.9 ± 1.6	17.5 ± 0.2	-1 ± 1, -344
		22.7 ± 0.4	0, -344, -548
		27.1 ± 0.1	-344
Newcastle	45.8 ± 1.3	18.1 ± 0.8	0 ± 0, -341 ± 15
		23.6 ± 0.5	0 ± 0, -530
		29.1 ± 0.8	0 ± 0, -347
	54.2 ± 0.6	18.0 ± 0.7	5 ± 3, -108 ± 7, -227 ± 4, -320 ± 6
		22.5 ± 0.5	5 ± 3, -111 ± 7, -222 ± 14, 330 ± 2, -459 ± 5, -572 ± 4
		27.5 ± 0.4	0 ± 7, -95 ± 4, -238 ± 2, -352
Sutton Park	39.2 ± 0.7	17.2 ± 0.2	5 ± 0, -153 ± 3, -218 ± 6, -317 ± 11
		21.6 ± 0.4	5, -110 ± 4, -230 ± 7, -337, -444 ± 22, -551 ± 3
		27.1 ± 0.3	0 ± 6, -85 ± 2, -239 ± 3, -368 ± 2, -476 ± 8, -573 ± 15, -660 ± 10
	50.2 ± 0.5	16.4 ± 0.5	14 ± 12, -306 ± 21
		22.0 ± 0.2	-2 ± 7, -550± 4
		26.8 ± 0.6	0 ± 5, -543 ± 7

TABLE 3.5. A table containing the velocities, angles and spins of balls projected at the turf on five greens. The errors assigned to the values are the standard deviations.

The velocities and spins for the impacts at 45° are shown in Figure 3.4. Three velocities were studied, approximately 17, 22 and 27ms^{-1}. At zero spin, both wheels on the projection device were set at the same velocity. As stated in section 2.4, the speed of the bottom wheel was then decreased by 2.2ms^{-1} and the top wheel increased by the same amount. In this manner the spin of the ball was gradually increased while keeping the velocity of projection fixed.

The errors shown in Figure 3.4 are the standard deviations of the means. The velocities, angles and spins used on the 5 greens where the angle was varied are shown in Table 3.5. Angles of incidence of 35 and 45° were used at two greens, 45 and 55° were used at one green, 40 and 50° were used at one green and 35, 45 and 55° were used at one green. The angles of impact used on the green at Sutton Park were meant to be 45 and 55° but were 5° lower due to an error in the positioning of the apparatus. Velocities of approximately 17, 22 and 27ms^{-1} were studied at all these angles and the spin was varied in the same way as before. On some greens, however, spins in the mid-range were omitted so that a greater variety of angles could be studied in the time available.

It can be seen in Figure 3.4 and Table 3.5 that the spins attained by the golf balls reached limits at each velocity studied. This was because the lower wheel reached its minimum velocity. Increasing the velocity of the top wheel to increase the spin would also have increased the velocity of the ball.

The spins and angles used encompass those of balls arriving at greens hit with a driver and a 5-iron. These shots therefore, may be considered when analysing the results of the impacts.

(ii) Results: the influence of the initial velocity, angle and spin on the velocity, angle and spin of the ball after impact

If the results in Table 3.4 are considered, relationships between the variables can be observed. For instance, if the velocity of impact is increased then, in general, the velocity of rebound is also increased. However, superimposed on top of this relationship is the effect of the backspin on the impact (in Table 3.4 the angle of impact is kept fixed). However, due to irregularities in the green (and perhaps in the ball) some impacts do not fit exactly a given relationship. Therefore, the most suitable method of expressing the effects of velocity, angle and spin on the impact is in multiple regression form. These are used to determine the "best-fit" relationship. Regressions were used in section 3.2 to determine the effect of the construction of the ball on the impact.

Velocity after impact									
Course	Int	C_V	dC_V	C_Θ	dC_Θ	C_ω	dC_ω	r	p
Austerfield	2.30	0.18	0.03	FIXED ANGLE		.0028	.0005	.73	0.0001
Belfry	11.64	0.21	0.07	-0.23	0.08			.55	0.0001
Bingley	2.47	0.24	0.03	FIXED ANGLE		.003	.001	.86	0.0001
Crewe	11.98	0.10	0.02	-0.16	0.01	.0034	.0003	.94	0.0001
Formby	3.21	0.18	0.01	FIXED ANGLE		.0036	.0006	.91	0.0001
Ganton	4.00	0.14	0.04	FIXED ANGLE		.0017	.0007	.55	0.0001
Hallowes	2.45	0.25	0.04	FIXED ANGLE		.004	.001	.88	0.0001
Hill Valley	18.74			-0.27	0.03	.0016	.0004	.87	0.0001
Keighley	6.52			FIXED ANGLE		.0048	.0008	.71	0.0001
Lindrick	4.51	0.10	0.05	FIXED ANGLE		.0029	.0006	.66	0.0001
M. Allerton	5.29			FIXED ANGLE		.0040	.0008	.64	0.0001
Moor Hall	5.35	0.06	0.02	FIXED ANGLE		.0052	.0005	.84	0.0001
Moortown									
Newcastle	13.48	0.04	0.01	-0.16	0.01	.0043	.0003	.95	0.0001
Sandmoor	3.72	0.16	0.02	FIXED ANGLE		.0038	.0005	.83	0.0001
Sutton Park	12.77	0.10	0.03	-0.19	0.02	.0027	.0006	.79	0.0001

TABLE 3.6. The regression coefficients for the equations relating the velocity of the rebounding ball with the initial velocity and spin. Blank spaces indicate that the variable was not significant in the regression.

The regressions in this section relate one dependent variable with three independent variables (the incident velocity, angle and spin). The coefficients of the regressions for the velocity, angle and spin after impact for each green are shown in Tables 3.6, 3.7 and 3.8. The names of the columns indicate the following:-

- **Int** - the intercept of the equation,
- C_V, dC_V - the coefficient and respective standard error of the velocity component,
- C_Θ, dC_Θ - the coefficient and respective standard error of the angle component,
- C_ω, dC_ω - the coefficient and respective standard error of the spin component,
- **r** - the correlation coefficient,
- **p** - the significance level of the regression.

A blank space in the table indicates that the variable was not significant in the regression for that green.

For example, the regressions found for Crewe were,

$$V_f = 11.98 + 0.10V_i - 0.16\Theta_i + 0.0034\omega_i \qquad \text{eqn. 3.4}$$

$$\Theta_f = -30.3 + 0.98V_i + 1.21\Theta i - 0.027\omega_i \qquad \text{eqn. 3.5}$$

and

$$\omega_f = 584.8 + 2.9V_i - 7.7\Theta i + 0.2\omega_i \qquad \text{eqn. 3.6}$$

The standard errors for each coefficient, correlation coefficients and levels of significance can be also be found in Tables 3.6, 3.7 and 3.8. The meaning of the regressions above become clearer if a specific example is considered. A ball impacting on the green at Crewe at a velocity of $22ms^{-1}$ at an angle of 45° to the

Angle after impact									
Course	Int	C_V	dC_V	C_θ	dC_θ	C_ω	dC_ω	r	p
Austerfield	25.6	1.1	0.2	FIXED ANGLE		-0.023	0.004	.79	0.0001
Belfry	-24.3			1.71	0.24	-0.008	0.004	.73	0.0001
Bingley	29.0	0.6	0.2	FIXED ANGLE		-0.032	0.006	.75	0.0001
Crewe	-30.3	1.0	0.2	1.21	0.10	-0.027	0.003	.93	0.0001
Formby	36.3	0.3	0.1	FIXED ANGLE		-0.028	0.004	.81	0.0001
Ganton	27.2	0.8	0.3	FIXED ANGLE				.33	0.0001
Hallowes									
Hill Valley	-60.1	1.7	0.3	1.74	0.22			.86	0.0001
Keighley	11.5	1.7	0.3	FIXED ANGLE		-0.053	0.008	.86	0.0001
Lindrick	22.6	1.1	0.6	FIXED ANGLE		-0.019	0.007	.66	0.0001
M. Allerton	-14.6	3.1	0.6	FIXED ANGLE		-0.047	0.014	.85	0.0001
Moor Hall	14.1	1.5	0.3	FIXED ANGLE		-0.043	0.005	.86	0.0001
Moortown	17.4	1.7	0.3	FIXED ANGLE		-0.016	0.006	.68	0.0001
Newcastle	-49.9	1.3	0.2	1.40	0.18	-0.036	0.004	.91	0.0001
Sandmoor	36.3	6.6	0.2	FIXED ANGLE		-0.026	0.004	.80	0.0001
Sutton Park	-53.0	1.4	0.2	1.64	0.19	-0.021	0.005	.84	0.0001

TABLE 3.7. The regression coefficients for the equations relating the angle of the rebound to the initial velocity and spin. Blank spaces indicate that the variable was not significant in the regression.

Spin after impact									
Course	Int	C_V	dC_V	C_θ	dC_θ	C_ω	dC_ω	r	p
Austerfield	159.3	5.3	1.4	FIXED ANGLE		0.15	0.03	.63	0.0001
Belfry	672.3	5.5	1.6	-12.0	1.8	0.31	0.06	.91	0.0001
Bingley	100.3	11	1.0	FIXED ANGLE		0.21	0.04	.89	0.0001
Crewe	584.8	2.9	0.9	-7.7	0.5	0.20	0.02	.96	0.0001
Formby	147.8	7.4	0.8	FIXED ANGLE		0.35	0.03	.90	0.0001
Ganton	185.6	8.7	2.7	FIXED ANGLE		0.59	0.05	.88	0.0001
Hallowes	90.3	9.7	1.6	FIXED ANGLE				.80	0.0001
Hill Valley	824.6			-12.0	2.2	0.25	0.07	.89	0.0001
Keighley	250.5			FIXED ANGLE		0.29	0.04	.76	0.0001
Lindrick	267.3			FIXED ANGLE		0.16	0.03	.68	0.0001
M. Allerton	217.5			FIXED ANGLE		0.18	0.03	.80	0.0001
Moor Hall	279.1			FIXED ANGLE		0.22	0.02	.85	0.0001
Moortown									
Newcastle	745.3			-9.5	1.1	0.20	0.02	.90	0.0001
Sandmoor	198.7	4.4	0.9	FIXED ANGLE		0.19	0.03	.79	0.0001
Sutton Park	658.7	5.6	0.9	-11.0	0.9	0.29	0.03	.94	0.0001

TABLE 3.8. The regression coefficients for the equations relating the spin after impact with the initial velocity and spin. Negative spin indicates backspin and blank spaces indicate that the variable was not significant in the regression.

horizontal and with zero spin is predicted to rebound with a velocity between 6.4 and 7.6ms^{-1}, at an angle between 39 and 52° and with a spin between 272 and 332rads^{-1}. It should be remembered that backspin is negative spin. These predictions are within one standard error.

In general, the form of the regressions in equations 3.4, 3.5 and 3.6 were found for all the greens studied. The general meaning of these regressions are outlined below. An increase in the incident velocity caused the ball to,

(1) rebound faster

(2) rebound at a steeper angle and

(3) rebound with more topspin.

An increase in the angle of incidence caused the ball to,

(1) rebound slower

(2) rebound at a steeper angle and

(3) rebound with less topspin.

An increase in the backspin of the incident ball caused the ball to,

(1) rebound slower

(2) rebound at a steeper angle and

(3) rebound with less topspin.

If the initial backspin is high enough then backspin would be expected to be retained after impact. It would be very useful to know if impacts in which the ball retains backspin behave in the same way as impacts in which the ball rebounds with topspin. The effect of backspin on the impact is discussed more fully in the following section.

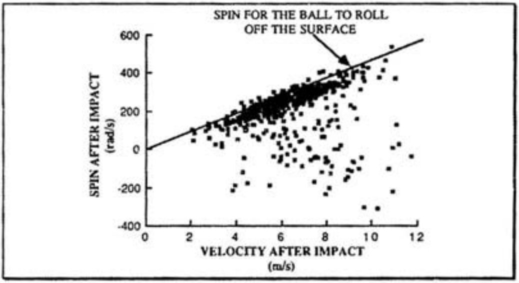

FIGURE 3.6. A graph showing the relationship between the spin after impact and the velocity after impact for all 721 impacts studied. The impacts nearest the line are more likely have rolled off the surface.

(iii) The effect of slip

The analysis of the high speed films in section 3.3 showed that the balls tended to roll off the surface after impact. The relationship between the spin and the velocity after impact for all the impacts recorded using stroboscope photography is shown in Figure 3.6. The line shows the theoretical spin required by a ball for it to roll off the surface, calculated using equation 3.3. For example, a golf ball of radius 21.3mm rolling along the surface at a speed of $5ms^{-1}$ would have a topspin of $234.7rads^{-1}$.

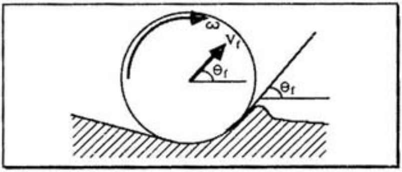

FIGURE 3.7. A schematic representation of a golf ball rolling up the front inclined face of the pitchmark with a topspin related to its absolute velocity.

It can be seen in Figure 3.6 that many of the impacts studied lie close to the line indicating rolling spin. It should be stressed that the velocities used to create this diagram are the absolute velocities and not simply their horizontal components. The closer the impacts lie to the line the more likely it is that the ball rolled off the surface at the end of the impact. The surface along which the ball rolled at the end of the impact must have been at an angle to the horizontal since the ball left the surface at an angle. It is likely, therefore, that the balls rolled up the forward inclined plane of the pitchmark shown schematically in Figure 3.7.

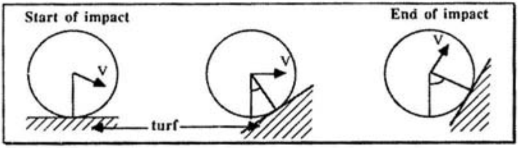

FIGURE 3.8. A diagram representing the modification of the pitchmark during impact. The final direction of the turf determines the direction of the ball after impact.

It can be seen in Figure 3.6 that the main band of points lies parallel to the line for rolling spin and about $50rads^{-1}$ away from it. Thus, many of the balls rebounded from the turf with a topspin just less than that required for rolling. One of the possible explanations is that most of these impacts *did* roll off the surface and that the topspins were slightly less than the rolling spins because of the modification of the shape of the pitchmark during impact. For instance, consider Figure 3.8. At the beginning of the impact, the plane in contact with the ball is horizontal. As the ball penetrates further the plane alters in angle until it reaches the final angle at which the ball leaves. From the ball's point of view it appears that the ground has rotated around its outer surface.

Thus, if the angle of the ground was altered by 45° and the time of contact was about 9msecs (as found in section 3.3) then the equivalent apparent topspin of the ball was about,

$$\omega = \frac{45^{\circ}}{9\times10^{-3}\text{s}} = 5000^{\circ}\text{s}^{-1} \approx 90\text{rads}^{-1}.$$

which is the same order of magnitude as the difference between the band of impacts and the line for impacts to have rolled off the surface in Figure 3.6.

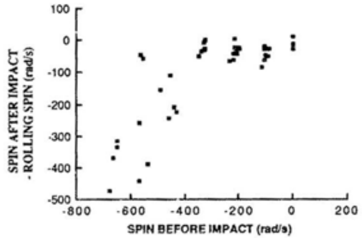

FIGURE 3.9. A graph showing the difference between the actual spin after impact and the spin required for rolling versus the spin before impact for Ganton golf club.

All impacts involve slip to some extent. Only in some of the impacts, however, does the ball slip throughout. It is possible for a ball to rebound with topspin and still to have slipped off the surface. In this case, the topspin of the ball will be lower than that required for the ball to roll across the surface. The larger the difference between the spin of the ball after impact and the spin required for rolling (i.e. the further the impact is away from the line in Figure 3.6) the more likely it is that the ball slipped throughout impact. Figure 3.9 shows a graph of this difference against the initial backspin for the impacts studied at Ganton golf club (Table 3.4). At low backspins the balls leave the surface with spins comparable to that required for rolling, i.e. the difference between the spin after impact and that for rolling is small. At higher backspins, the balls tended to rebound from the turf with spins much lower than that required for rolling. This indicates that slipping must have taken place. In Figure 3.9 this occurs at a value of about $-350 rads^{-1}$.

Graphs similar to Figure 3.9 were plotted for each green (Appendix F) and balls that slipped throughout impact were chosen arbitrarily as points below the line $y = -100 rads^{-1}$. The sets of results for each green (Appendix E) were then altered so that they contained only impacts where the ball was considered to have rolled off the surface. Stepwise regression were used to observe the effect of the removal of these slipping impacts from the data set. The coefficients of the regressions are shown in Appendix G. It was not possible to carry out statistical analysis on the slipping impacts alone as there were so few slipping occurrences on each green.

Removing the slipping occurrences caused some variables (e.g. spin, velocity) to be removed from the regressions described by equations 3.4, 3.5 and 3.6. In other cases, the form of the regression stayed the same but the value of the coefficients were changed. The individual effects of removing the "slipping " impacts from regressions are too numerous to discuss here. Therefore, the important effects will be described by considering the effect of slip on two different greens.

Figures 3.10 and 3.11 show the results of the impacts on the greens at Austerfield Park and Ganton respectively. The points represent the means of the impacts studied with a single setting of the ball firing device. For example, the average velocity of rebound for impacts at $17ms^{-1}$ at 45° to the horizontal and with zero spin for Ganton (the first three rows in Table 3.4) is $6.4ms^{-1}$. The standard error was $0.3ms^{-1}$. To increase the legibility of the graphs in Figures 3.10 and 3.11, the maximum standard error found at each velocity is shown instead of the standard error for each point.

Figure 3.10 shows, in graphical form, the results from the stepwise regressions for Austerfield Park (similar to those in equations 3.4, 3.5 and 3.6) but with the angle of incidence fixed at 45°. At a fixed velocity, an increase in the backspin causes the velocity of the rebounding ball to decrease, the angle of rebound to increase and the positive spin to decrease (i.e. tend more towards backspin). The graphs for Ganton in Figure 3.11 are similar to those for Austerfield but differ at higher backspins. There appears to be a discontinuity in the mid spin range. It is likely that on the green at Ganton the ball slipped off the surface at higher backspins.

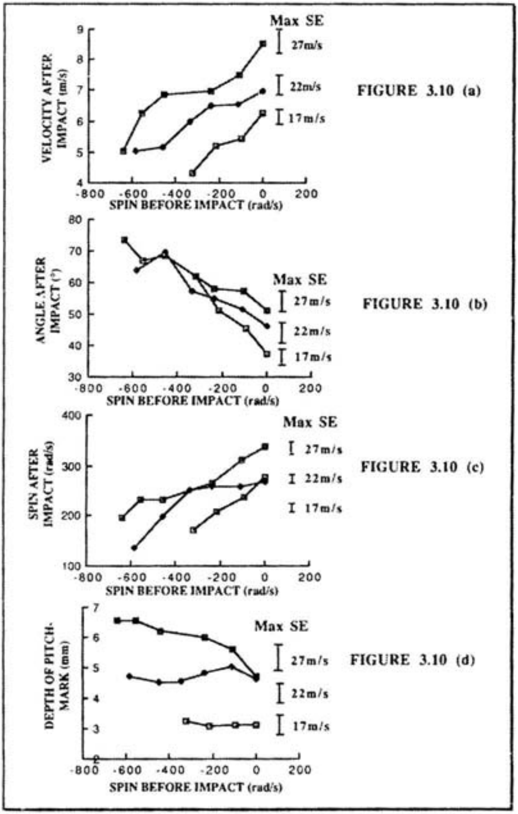

FIGURE 3.10. A series of graphs showing the effect of an increase in spin on the velocity, angle, spin after impact and the depth of the pitchmark for different initial velocities at Austerfield Park.

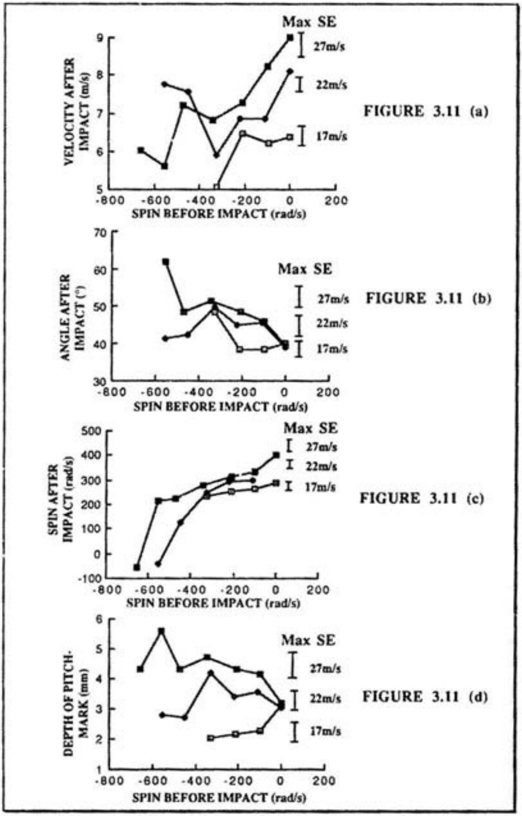

FIGURE 3.11. A series of graphs showing the effect of an increase in spin on the final velocity, angle and spin and the depth of the pitchmark for different initial velocities at Ganton.

This agrees with Figure 3.9 in which it was seen that gross slip started to occur at backspins greater than about -350rads^{-1}. Thus at Ganton, the relationships similar to those in equations 3.4, 3.5 and 3.6 are not strictly valid since they are no longer linear.

Apart from the stroboscope photographs, the only other information of the impact is the pitchmark that was created. This was measured using the green hardness tester described Chapter 2. The effects of the velocity, angle and spin of the incoming ball on the depth of the pitchmark were investigated using multiple regressions. The coefficients are shown in Table 3.9.

Depth of the pitchmark									
Course	Int	C_V^2	dC_V^2	C_θ	dC_θ	C_ω^2	dC_ω^2	r	p
Austerfield	1.60	.0059	.0008	FIXED ANGLE				.71	0.0001
Belfry	-1.84	.0024	.0003	.07	.02			.75	0.0001
Crewe	-0.97	.0030	.0003	.033	.008			.84	0.0001
Ganton	1.17	.0043	.0008	FIXED ANGLE				.65	0.0001
Hill Valley	0.03	.0029	.0005					.70	0.0001
Lindrick	0.70	.0066	.0013	FIXED ANGLE		4.1×10^{-6}	1.4×10^{-6}	.82	0.0001
Moor Hall	-0.23	.0094	.0008	FIXED ANGLE		3.4×10^{-6}	1.3×10^{-6}	.90	0.0001
Newcastle	0.25	.0029	.0002			1.5×10^{-6}	0.5×10^{-6}	.88	0.0001
Sandmoor	1.68	.0046	.0010	FIXED ANGLE				.60	0.0001
Sutton Park	-2.05	.0033	.0003	.05	.01	1.3×10^{-6}	0.4×10^{-6}	.89	0.0001

TABLE 3.9. The coefficients of the stepwise regressions for the depth of the pitchmark created during impact. The depth was measured in mm.

These regressions suggested that the pitchmark depth was directly related to the square of the velocity before impact and in some cases to the initial spin squared. The square of the velocity is a measure of the translational energy of the ball while the spin squared is a measure of the rotational energy of the ball. The regressions coefficients shown in Table 3.9 agree with observations in the field; increasing the incoming energy of the ball increased the depth of the pitchmark.

It was observed that the shape of the pitchmark changed between impacts. Figure 3.12 shows the shape of a pitchmark created by a golf ball with a large amount of spin. At high backspins the grass and roots were sheared through so that the bottom of the pitchmark was bare. The loose material was pushed towards the front of the pitchmark forming part of the ridge seen in Figure 3.12. This material was very loose and on some occasions was projected away from the pitchmark by the impacting ball. These facts suggest that the turf acts as two separate layers, the top layer consisting of grass roots and the lower layer consisting of soil and thatch (dead plant material). This idea is pursued further in Chapter 5.

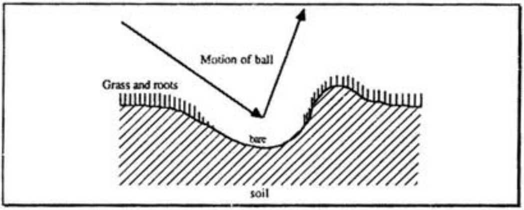

FIGURE 3.12. A schematic diagram of the pitchmark created by a golf ball with a large amount of backspin.

Differences in the pitchmark depth were also observed between greens. Figures 3.10 (d) and 3.11 (d) suggest that the pitchmarks were shallower at Ganton than at Austerfield Park. At Austerfield the depth of the pitchmark was approximately constant at each velocity while on the green at Ganton the depth of the pitchmark appeared to decrease at high backspins. It was observed that this decrease in depth was accompanied by an increase in length and was probably caused by the ball slipping across the surface. This tends to agree with earlier findings which showed that gross slip started to occur on the green at Ganton at these high backspins.

In can be seen in Figure 3.11(a) that the velocity tends to increase when the ball slips throughout impact and that the angle of rebound decreases at high incident backspins. This may be explained by considering the variation in the shape of the pitchmark. As just described, the pitchmark tends to become long and shallow at these high backspins. The front inclined face of the pitchmark is therefore less steep and the ball would tend to rebound at a lower angle. Since the horizontal motion of the ball is opposed less, the ball rebounds at a higher velocity.

It was found that the results from the greens could be split into two categories; (1) those that were like Austerfied Park and mostly had impacts in which the ball rolled off the surface, and (2) those like Ganton in which the ball slipped throughout impact if the backspin exceeded a certain threshold. The numbers of slipping and rolling impacts on each green were determined using the graphs similar to that in Figure 3.9 (Appendix F). Table 3.10 shows numbers of impacts on each green that rolled and those that slipped. The letters "R" and "S" indicate greens on which impacts were likely to roll off the surface at the end of impact and on which the ball could slip off the surface at the end of impact if the backspin was high enough. On eleven of the greens most of the impacts studied rolled at the end of impact, while on five greens there was gross slip occurred in a large number of impacts. It should be stressed that the ball must slip initially in all the impacts since the peripheral velocity of the ball is not the same as that required for rolling.

Course	Rolling	Slipping	
Austerfield	61	2	R
Belfry	25	33	S
Bingley	36	1	R
Crewe	37	25	S
Formby	37	3	R
Ganton	33	12	S
Hallowes	23	0	R
Hill Valley	23	14	S
Keighley	33	4	R
Lindrick	28	5	R
Moor Allerton	36	0	R
Moor Hall	49	1	R
Moortown	41	2	R
Newcastle	48	3	R
Sandmoor	36	7	R
Sutton Park	39	24	S

TABLE 3.10. The relative numbers of rolling and slipping impacts that occurred on each green. The letter "R" indicates that an impact is likely to roll throughout impact while the letter "S" shows that there was a possibility of slip if the backspin was high enough.

(iv) The effect of slip on subsequent bounces

Table 3.10 shows how greens can be categorised into "rolling" and "slipping" greens. The former is characterised by impacts which rebound at low velocities and at high angles and predominantly with topspin. On the latter type of green the balls rebound at higher velocities and at lower angles. For spins exceeding the "slip threshold" an increase in backspin causes a direct decrease in positive spin after impact. For spins beneath this threshold, the spin after impact does not vary much and depends upon the velocity of the rebounding ball (since $v=\omega r$).

These results become more significant if we consider what is likely to happen to the ball on the second bounce for a ball arriving on a rolling green and on a slipping green with a backspin in excess of -350rads^{-1}. A ball rebounding from the rolling green would tend to have topspin. On the second bounce, the ball would bounce onwards since it already has a spin equivalent to its rolling spin. On the slipping green, the ball would tend to bounce forwards with backspin. This would tend to check or even stop the ball on the second bounce due to the frictional forces at the point of impact opposing the forward motion of the ball and trying to reduce its backspin. If the backspin is high enough, the retarding frictional forces may overcome the forward motion of the ball and cause it to "screw back" along the ground.

These effects are frequently seen by golfers and the ability of the ball to stop on the green is perceived as its "holding power". What may surprise golfers is that this perception may have different meanings on different greens. For instance, on the rolling green, the ball comes to almost a dead stop on the first bounce and can even rebound in the direction from which it came. Since the ball has topspin after impact, it rolls forwards. On the slipping green, if the backspin on the ball is high enough, the ball can rebound forwards, while retaining some backspin, and "check" on the second bounce. In both cases the ball may end up in the same position relative to the initial impact, but will have arrived there by different means. The golfer may consider, therefore, that both types of green "held" the ball equally as well.

The results in Figure 3.11 also explains the frustration felt by some golfers who find that their shots tend to bounce forwards on the green ending up far from the flag, while professional golfers can play the same green and cause their shot to "screw back" every time. In Figure 3.11 (c) it was seen that, for low amounts of backspin, the ball rebounds with positive rolling spin, i.e. a spin proportional to the velocity of the ball. Thus, a golfer applying spins in this range, will find that the ball bounces forwards after rebounding. Once the golfer applies backspins to the ball exceeding -350rads^{-1}, however, it becomes much easier to cause the ball to screw back. Any increase in the backspin given to the ball produces a corresponding increase in the backspin retained by the ball after impact. It becomes much easier for the golfer to create impacts in which the ball can screw back if backspins are applied above this threshold.

3.5 Summary

One of the conclusions found in this chapter that may have surprised some golfers was that the construction of the ball had little effect on the ball/turf impact (at least for impacts at the velocities, angle and spins tested). Many golfers find that the impact of the ball with the green *is* affected when different golf balls are used and it is concluded that this is due to the differences in the initial spin acquired by the ball on impact with the club face. This causes the trajectories of the balls to be different with the result that the ball arrives at the green with different velocities, angles and spins resulting in dissimilar rebounds. As already stated, the result of this is that the ball can be considered as a rigid solid and will simplify the models of impact which shall be considered later in Chapter 5.

High speed films of the impacts showed that the time of contact of the ball with the turf was approximately 6 to 9msecs and that the forces experienced by the ball were consistent with the ball rebounding from the front forward inclined face of the pitchmark. It was also seen that the impacts tended to roll off the surface at the end of the impact. This fact was also evident in many of the 721 stroboscope photographs of impacts that were studied.

The results of the regressions carried out on the velocity, angle and spin of the ball after impact could be explained by the variation in the depth of the pitchmark created. A deepening of the pitchmark involved a steepening the front plane and this caused the ball to rebound at a high angle. It was found that some of the regressions for certain greens were dissimilar from the rest and that these differences were due to the golf balls slipping throughout impact. Two different types of green emerged. On the first type of green, the ball rolled off the turf and left the surface with a topspin equivalent to the ball rolling up the inside of the pitchmark. In these impacts, the ball invariably rebounded with a low velocity and at a large angle to the horizontal and may even have rebounded in the direction from which it came. On the second type of green, the golf balls always rebounded at a lower angle, at higher velocities and in some cases retained backspin after impact. It was found that there was a threshold for the backspin below which the ball rolled off the surface and above which the ball slipped off the surface. Once the spin of the ball was above this threshold, each additional amount of spin was retained after impact.

The results of this chapter give a clear indication of the effect of a change in velocity, angle or spin on the rebounding ball. These effects are used in the Chapter 5 in the formulation of a model of impact. One of the most important effects that has to be modelled is the discontinuity between impacts which roll or slip off the surface at the slip threshold of -350rads^{-1}.

It is useful to identify the playing characteristics of the two types of green found in this section. A greenkeeper could then do a series of tests on the green to determine how it would play and the maintenance required to cause it to play in the manner requested by the members of the club. The next Chapter assesses the relationship between the impacts and the playing quality and distinguishes between the two types of green.