# Biomechanical Analysis: Different Phases Of Motion Of A Golf Ball During A Golf Putt Across A Range Of Speeds

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*Abstract*— **Putting is without a doubt the most crucial part of a golfer's game, if only for the fact that it is on the putting green where the margin between success and failure is at its finest. Pace control is an issue for many golfers and this study aims to take an in depth look at what factors can possibly affect the rate at which a golf ball will decelerate on a flat surface. Two methods of data collection were utilized during the course of this study; the Quintic ball roll system was used to analyse the sliding phase of a putt, whereas basic video analysis techniques were used to analyse the rolling phase. Initial velocities used in this research ranged from (3.91±0 – 7.14±0.053) mph. Using a regression equation to calculate the frictional force as well as the coefficient of friction, returned a linear deceleration for the sliding phase (-4.8750m.s² max) with the rolling phase returning (-0.2099m.s² max), with impact velocity during both phases of motion showing a positive correlation with time and displacement respectively. The frictional force produced, as well as the coefficient of friction were also directly correlated to the initial velocity ($R^2$>0.87). This research has found that a golf ball will decelerate at the quickest rate during the sliding phase, however this is dependent on initial velocity. An increase in frictional force and coefficient of friction, caused by a change in velocity will directly cause an increase in the rate of deceleration. This is relevant to golfers everywhere as the velocity at which a putt is struck will significantly alter the ideal line upon which it should be played. Understanding the fundamentals of this ball/surface relationship will allow a golfer to visualize their lines with more precision than ever before.**

**Keywords— friction; coefficient of friction; velocity; deceleration; regression; biomechanics; golf; putting;**

## I. Introduction

Dave Pelz, commonly known as 'the putting guru' stated that 80% of putts are missed due to poor speed control and this statement underpins the importance of understanding the ball/surface relationship. Although limited, the popular topic for discussion within literature is the rate at which the golf ball decelerates during the rolling phase and looking at ways in which to alter the coefficient of rolling friction (altering the golf ball used, or the surface properties), therefore looking at the effect that these manipulations have on the deceleration rate. This study looks at the rate of deceleration for both the sliding and rolling phases of motion, as well as the relative length of these phases (compared to the total putt length). This comparison will be measured across a range of speeds collected on a random sample basis, all putts were recorded and analysed in order to get a broad range of data within each selected speed grouping. Therefore, providing a true representation of the relationship. This research will directly affect the way in which a player may read putts from different lengths, as the speed at which a putt travels towards the hole will alter the optimal line. As testing during this study will be conducted on a level surface, the motivation behind it is purely to understand the foundations of the ball/surface relationship, after which further research may be conducted in order to implement these findings on real greens with slopes, moisture and grain.

There is a surprising lack of research based around the effect of speed on rolling and sliding friction, however, there are implications of properties surrounding the mechanics of the ball/surface relationship within various sports. There are 4 phases directly relating to variations in putting results: green reading, aim, stroke and ball roll (Karlsen, 2008). A golf ball should enter it's 'pure roll' stage at the point when 20% of the total putt length has been surpassed (Kollkowitz, 2007) or when the balls velocity reaches 5/7 of its original starting velocity (Rojas, 2004) where it then decelerates linearly until a threshold is reached, and the ball stops dead. Drane et al., (2014) suggested that the ball decelerates at $\sim 1.75 m.s^2$ when skidding/sliding and only at $\sim 0.4 m.s^2$ when rolling (putt distances of 0.25, 2.0, 5.0 & 6.0m) which supports Rojas & Simon, (2014), who states that once kinetic friction disappears (when the ball begins rolling) there is a linear deceleration until the ball reaches a threshold, where it ceases to travel. Pelz, (2000) suggested that 80% of putts were missed due to poor speed control, highlighting the importance of understanding this relationship for any golfer.

There are two sections of the 'Initial Phase' of motion. One 'Sliding Phase' immediately after the putter face makes contact with the golf ball; otherwise known as 'Impact'. This is then followed by an 'Initial-Rolling Phase'. In this phase, the ball is partially sliding and partially rolling, and the frictional force between the surface and the ball will determine the deceleration and the increase in rotational speed of the ball. The second phase of motion begins once the ball has reached 'True-Roll'; meaning that the golf ball is continually rolling end over end. For the purpose of this study the entirety of the motion from 'Impact' all the way up until the ball reaches 'True-Roll' will be considered as the 'Sliding Phase' and from 'True-Roll' until the ball comes to rest will be considered as the 'Rolling Phase'.

If certain conditions are met and controlled, in this case; a flat and level surface with a continuous 'nap' or 'grain effect' in the same direction relative to contact and a standardized length of surface fibers, which all contribute to a constant coefficient of friction; then according to previous research, the speed of the ball will linearly decelerate from the point of 'true-roll' until the point at which it comes to rest, (Rojas & Simon, 2014) which is around 20% of the total putt length (Kollkowitz, 2007). Therefore, you would assume that for a player to roll a successful putt and 'hole out', the ball would need to have reached its optimal line at the correct speed by this point, further highlighting the importance for players to understand how the ball may react in the period between impact and true roll and how much of this depends on the length of putt faced. Drane et al., (2014) surrounds the idea of the total distance that a putt rolled out after contact were categorized, however a key weakness in this method is that only 0.25m and 2.0m were experimentally tested, for distances larger than these figures an infinite model was used to calculate the way the ball would react. This study aims to support/disprove the current literary findings surrounding the ball/surface relationship, as well as exploring the trends of the various phases of motion and how these trends correlate with a change in initial velocity of the putt, in respect to both time and distance.

Previous research conducted suggests that once in true roll the ball speed decreases linearly in respect to both time and distance, this theory holds much credibility with similar results found too frequently for this to be relative to coincidence or chance, but more from the correct adaptation of scientific principles, with results found through in depth analysis and statistical appraisal. For that reason, I would expect this study to show similar results. However, supported by Drane et al., (2014) I would expect a similar linear relationship during the sliding phase, with a constant rate of deceleration ($\sim 1.75 m.s^2$ in this case). Furthermore, I would also expect the ball to decelerate at an increased rate when sliding, again based on the findings of Drane et al., (2014), certainly in the early stages, as the coefficient of rolling friction has not been reached at this point, therefore the surface will place maximal frictional force upon the ball, gripping at it until this threshold has been reached; roughly 5/7 of its original 'Impact Velocity' (Rojas & Simon, 2004). I would also expect the length of both, the sliding phase and the rolling phase to have a linear relationship with impact ball speed, with reference to findings from (Drane et al., 2014) as this study suggests that the deceleration rate was at a fixed rate (in respect to time) across a range of speeds. I realize that the sliding phase of a putt is a relatively unexplored territory, with little research surrounding the topic, in this light, my findings will be directly relative to other research surrounding these relationships and will open doors for future research.

## II. Methods

All testing was conducted at Machynys Peninsula Golf and Country Club Golf Academy. To analyse the two different phases of motion, multiple biomechanical analysis techniques were implemented, the first of which was the use of the Quintic Solutions "Ball Roll" system. In this instance the camera (with a frame rate of 350Hz) recorded the first 16 inches of a putt's path, providing both club and ball feedback (in this case, only the ball data will be used). In order for this feedback to be precise and accurate, the system needed to be calibrated (Appendix 2 & 3); using a T-Bar, two golf balls were placed 1.22m from the camera lens, the adjustable feet on the camera stand were then used to level the camera with respect to the surface used, with the aid of the computer screen. Putts were struck one by one, before each, the ball was calibrated with the system in its starting position (marked during setup, invisible to the camera), the assistant ensured that all 3 markers on the golf ball were visible (shown by three digitized marker points) on the computer screen. Once all three markers were automatically colour coded, the putt was struck. Data was instantaneously processed by the system and this file was then saved to the computer itself or an external hard drive (chosen method). Various file types were automatically saved from the BR system, however for this analysis the focus was placed on the Excel (.xls) files as this allowed me to transfer the necessary data directly into a spreadsheet.

The following key variables were extracted and consequently analysed; 'Impact Ball Speed', 'Zero Skid After' and the 'Time to Zero Skid'. The system provided information on the speed of the putt, which was the key variable, and the resultant variations in different aspects of the data, including; the time the ball took to enter 'true roll' which the system described as 'zero skid', data was also extracted in respect to distance to 'true roll'. Ball roll data was only used to process the sliding phase and the initial rolling phase durations, in respect to time as well as distance travelled. Using these figures, the deceleration rate was calculated using basic velocity/time principles by taking an in depth look at each of the points received by the system and smoothing data to remove any extremities, caused by either putter interference or a potential 'lag' caused by movement of the markings on the ball, leaving the field of view of the camera. Deceleration was taken into account for each individual phase of the putt as well as for the entirety of the putt taken. The data was labelled each time a piece of data was saved, in the event that the ball roll data could be paired with the video footage if needed at a later date. Each putt was labelled in numerical order for convenience. The ball roll Excel output file for the collected data was saved and these were then collected and analysed individually. The key points (previously mentioned) were inserted into a single Excel spreadsheet, where the data comparison techniques took place. All data was extracted from the system (in the case of the Ball Roll data) and extracted from the video footage (in the case of the Video-Analysis data), then transferred into a master spreadsheet.

The Quintic Ball Roll System returned ball speed feedback in Mph format, due to the precision of this experiment (relative to seconds), this was converted into Mps by multiplying the Mph figure by 0.44704. Ball speed was then tracked in relation to time, including the impact speed and this was then transferred into Excel. Once all data had been extracted, putts were placed in order of impact speed and these were then grouped into their relative speeds (3,4,5,6,7 Mph).

Video footage recorded was analysed using Quintic Biomechanics Software, with the aid of the marker and stopwatch utilities to determine relative time. The set frame rate for each video was 240fps, this was included in the calibration process with the distance between two marker points set at 0.5m. Using the marker function, time markers were then taken for each time the ball crossed the point between two markers; to aid this determination a thin line was projected between the centres of each marker and a time point was recorded when this line rested on the equator of the golf ball. Using the stopwatch function, the time from 'relative zero' (the first marker passed in the correct calibration) to each individual time point was recorded, which was in turn transferred to an Excel spreadsheet. Every putt was recorded along with their impact ball speed from the ball roll feedback and their putt number.

Once the data had been transferred into a spreadsheet, both the Velocity and Acceleration values were calculated for every putt at each marker point using the average gradient values, produced by the use of differentiation. This method calculated the velocity at the mid-point in question by using marker points either side of the subject value and dividing by the total time interval using the following formulae;

$$velocity = \frac{d}{t} \therefore @t^2 \; v = \frac{d^3 - d^1}{2\Delta t}$$

$$acceleration = \frac{\Delta v}{\Delta t} \therefore @t^2 \; a = \frac{v^3 - v^1}{2\Delta t}$$

Data retrieved from both techniques was then cropped to discard of as much noise as possible and to remove any extremities or inaccuracy from the data. Very few points returned by the ball roll system were extracted due to the high level of precision of the equipment. However, sections of the video footage were removed due to an error in the calibration of the recording, whereby the representation of relative time was flawed. Occurrences such as these arose in the initial and concluding frames of the footage; therefore, these points were removed and the first marker point reached with the recording in the correct calibration, was determined as the first data point for the putt. Similarly, in the instance that the error in calibration was at the conclusion of the recorded footage, these frames were again discarded and the data was collected up until the correct calibration was lost. For the purpose of this study, only completed distance intervals were accounted for in the data, this is to increase the precision of the results collected and to enable the representation of the 'ball/surface relationship' accurately. Ultimately eliminating the possibility of miscalculation due to camera movement (hand-held) and also ensuring that all putts were analysed with the same precision, irrelevant of the perception of the putt due to distance. Putt number 19 was also completely excluded from the video footage section as there was an error with the recording. Once all data had been cropped each putt was arranged into their respective 'impact ball speed' order, for both; ball roll data and video analysis feedback using the groupings previously mentioned. The ball roll data was presented in the form of a velocity-time graph, whereas the video analysis was presented in the form of a velocity-displacement graph due to the dissimilar analysis techniques.

At this point, the raw data was plotted in velocity/acceleration-time graphs for each individual grouping, as well as the whole data set, groupings were also colour coded to make sure the graphical representation was intelligible.

Once graphs and plots had been created, these were then used to analyse the deceleration rate of the ball, providing the frictional force and therefore the coefficient of friction for all of the groupings and putts recorded. By showing the equation of each trend line on the excel plots, the following information can be extracted from the following sample equation;

$$y = Bx - a$$

Ball Speed Deceleration (Slope) Initial Ball Speed (t=0)

From this equation the coefficient of friction was calculated with a two stage method. As the mass of the golf ball was already known (0.046kg) using the deceleration rate and the mass of the golf ball the frictional force value was calculated (below). In order to complete the second part of this calculation the first stage is to convert the mass of the golf ball into the weight of the golf ball by multiplying by acceleration due to gravity ($9.8m.s^{-2}$). Using the frictional force produced and the weight (N) of the golf ball the calculation of the coefficient of friction as shown below may be carried out:

$$F\ friction = Mass\ x\ Deceleration$$

$$\mu = \frac{F\ friction}{Weight}$$

From these findings the direct comparison of the coefficient of friction between different initial speed groupings, as well as the different phases of motion took place.

Secondly, video analysis techniques were used to analyse the golf balls rolling deceleration rate. To achieve this data, biomechanical reflective markers were placed at 50cm intervals in pairs, creating time gates for the ball to reach along its path (shown in Appendix 3) these markers were then secured with double sided tape. Although the reflective markers were set at 50cm intervals, the first pair of markers were set at 55cm away from the ball at rest, as this would ensure that there would be no sign of the reflective markers in the BR camera's field of view, thus it would not have an effect on the visual feedback received by the camera lens. A stoppage board was placed at 5m from the ball at rest, to help with calibration of the alignment of the markers (perpendicular to the direction of the putt), but also to stop the ball from continuing on its path when struck more firmly as the 5m distance provided 10 time points to be tracked which allowed analysis to be as in depth as necessary. As testing was conducted in a public space, this also prevented the ball disturbing others. A camera was placed directly behind the assistant, in a position where all of the reflective markers were visible, a lamp was also placed directly under the camera lens to assist the feedback received from the reflective markers. However, on the day of data collection the lamp's filament blew and the camera's battery would not start (even after replacing the batteries), therefore, an iPhone 6 with flash assist was used to record the video footage. This camera was set to slow-motion capture, which resulted in a 240fps 720p image.

Equipment was set up as shown (Appendix 3) and the markers (Appendix 2) are placed on the golf ball as shown, with the pattern shown facing the high speed camera. As this was a random sample study, there were no parameters for a putt to meet in order to be accepted; as the study was focused on the linear relationship as a pose to individual attributes. Therefore, putts were then hit at various speeds (shown by Ball Roll feedback and the distance to finish) due to the design of this study, both methods of data collection could be completed at the same time. However, although there was no way that an unfair test could be conducted (as both sets of data were collected simultaneously) it is still important to realise that standardizations still have a place in all scientific experiments to ensure a reliable and valid investigation. In this investigation the same golf ball (Titleist ProV1 with adhesive markings), the same putter (Titleist Scotty Cameron Newport 2-34") and the same direction of putt (relative to the potential grain of the surface) were all used throughout. Furthermore, if a reflective marker was moved during a putt, this putt was erased from the data base and the 50cm increments surrounding this point were measured again.

Quintic Biomechanics Software is a market leading video analysis tool used to aid development and rehabilitation across both, the sporting and clinical sectors, using industry leading 2D Biomechanical and Performance Analysis Software. Although there are various different levels of software provided by Quintic, the chosen platform for this study was the 'Quintic Biomechanics' package as this offers excellent digitization and tracking capabilities as well as a stop watch function.

## III. RESULTS

*Table 1.0 The average values of the ball speed groupings ±SD.*

| Speed | Average Speed (Mph) ±SD | n |
|---|---|---|
| ***(1) 3 Mph*** | 3.91 ± 0.0 | 1 |
| ***(2) 4 Mph*** | 4.74 ± 0.123 | 8 |
| ***(3) 5 Mph*** | 5.61 ± 0.264 | 26 |
| ***(4) 6 Mph*** | 6.37 ± 0.027 | 37 |
| ***(5) 7 Mph*** | 7.14 ± 0.053 | 3 |

### A. *Ball Roll Data*

The sliding phase shows linear deceleration in respect to time. The 6Mph grouping holds the quickest deceleration rate (-4.8750m.s²) and the highest coefficient of friction (0.4969N). The 3Mph group holds the slowest deceleration rate (-2.2506m.s²) and the lowest coefficient of friction (0.2294N).

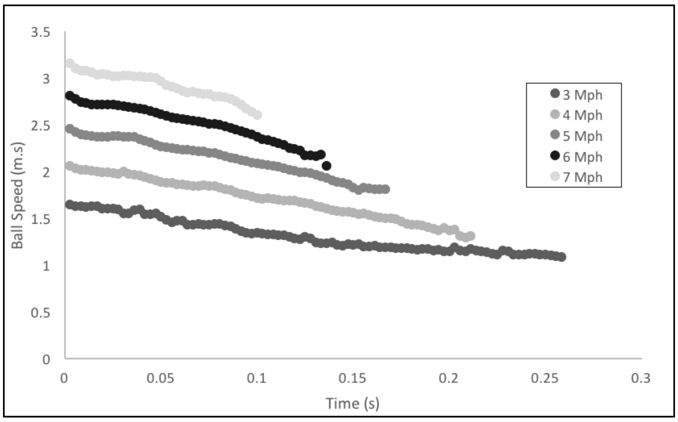


*Figure 1.0 A velocity-time graph illustrating the cropped data average values from the ball roll system.*

*Table 2.0 The coefficient of sliding friction calculated for the average values of each of the five speed groupings.*

| Speed | $R^2$ | sig./p-value | Regression Equation | Deceleration (m.s²) | F friction (N) | μ (N) |
|---|---|---|---|---|---|---|
| ***(1) 3 Mph*** | 0.9407 | 1.2004 | y = -2.2506x + 1.6406 | -2.2506 | -0.1035 | 0.2294 |
| ***(2) 4 Mph*** | 0.9930 | 1.6735 | y = -3.5264x + 2.0808 | -3.5264 | -0.1622 | 0.3595 |
| ***(3) 5 Mph*** | 0.9839 | 1.3687 | y = -3.9841x + 2.4772 | -3.9841 | -0.1833 | 0.4061 |
| ***(4) 6 Mph*** | 0.9673 | 1.4743 | y = -4.875x + 2.843 | -4.8750 | -0.2243 | 0.4969 |
| ***(5) 7 Mph*** | 0.9455 | 4.6146 | y = -4.6909x + 3.16 | -4.6909 | -0.2158 | 0.4782 |

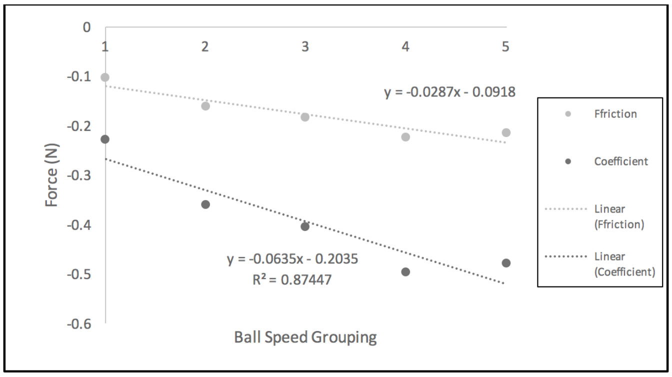


*Figure 2.0 A representation of the predicted linear relationship of the frictional force and the coefficient of sliding friction values.*

## B. Video Analysis Data

The rolling phase also shows linear deceleration (once the data had been cropped), this time in respect to distance travelled. Speed groupings 1 and 5 were eliminated from this data analysis, therefore the 6Mph grouping showed the quickest deceleration rate (-0.2099m.s²) along with the largest coefficient of friction (0.0214N). The 4Mph grouping returned the slowest deceleration rate (-0.1202m.s²) as well as the smallest coefficient of friction value (0.0123N).

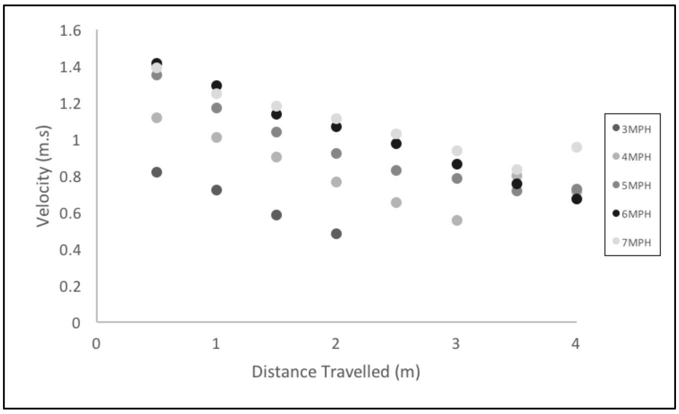


*Figure 3.0 A velocity-displacement graph illustrating the cropped data average values from the video footage analysis.*

*Table 3.0 The coefficient of rolling friction calculated for the average values of each of the five speed groupings.*

| Speed | $R^2$ | sig./p-value | Regression Equation | Deceleration (m.s²) | F friction (N) | μ (N) |
|---|---|---|---|---|---|---|
| (1) 3 Mph | 0.9958 | 0.0021 | y = -0.2291x + 0.9381 | -0.2291 | -0.0105 | 0.0234 |
| (2) 4 Mph | 0.6189 | 0.0205 | y = -0.1202x + 1.0839 | -0.1202 | -0.0055 | 0.0123 |
| (3) 5 Mph | 0.9192 | 0.0002 | y = -0.1787x + 1.3441 | -0.1787 | -0.0082 | 0.0182 |
| (4) 6 Mph | 0.9933 | 9.6211 | y = -0.2099x + 1.4946 | -0.2099 | -0.0097 | 0.0214 |
| (5) 7 Mph | 0.8910 | 0.0004 | y = -0.1414x + 1.4025 | -0.1414 | -0.0065 | 0.0144 |

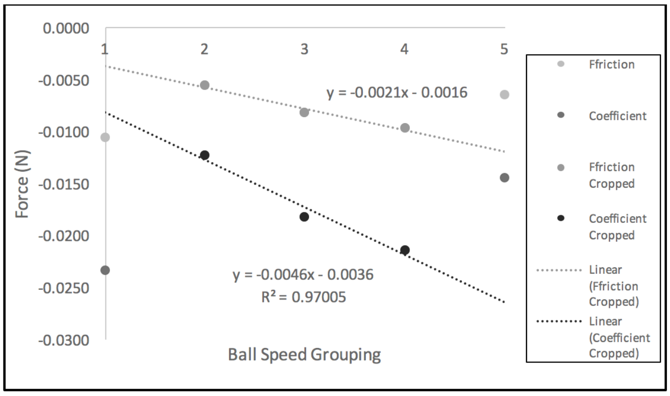


*Figure 4.0 A representation of the predicted linear relationship of the frictional force and the coefficient of rolling friction values.*

## IV. Discussion

The two key phases of motion have been analysed in this study, under monitored, controlled conditions, with the aim of establishing a detailed insight into the ball-surface relationship. An area of substantial interest was between the deceleration rate of a golf putt and to what extent this deceleration is dictated by the initial impact speed, throughout both phases of motion whilst being independently analysed.

Table 1.0 illustrates the number of putts taken in each speed grouping, as well as showing the standard deviation for each group. 3Mph and 7Mph groupings had substantially less content than the other three groups, however all groups apart from the 5Mph group had a SD of <12.5%. Figure 1.0 shows the average values of the velocity-time data retrieved from the ball roll system, this data shows that all groupings appear to have a negative (linear) correlation, indicating that velocity decreases linearly in respect to time during the sliding phase of motion. Table 2.0 supports the information provided by Figure 1.0, by confirming that there is a strong negative correlation for each of the five groupings ($R^2$ >0.89). This table also illustrates the gradual increase in deceleration rates, directly correlated with an increase in ball speed, with the exception of the 7Mph grouping. This shows that although in Figure 1.0 each series may appear parallel to one another, the slope of each is actually increasing relative to an increase in ball speed.

This relationship translates across to the frictional force values as well as the coefficient of friction, which both increase linearly relative to both time and distance travelled, indicating that the frictional properties of the ball-surface relationship are directly relative to ball speed. Again, in this instance the 7Mph grouping is an exception to this relationship.

Figure 3.0 shows the average values of the velocity-displacement data retrieved from the video analysis process, this data shows that again, all groupings appear to have a negative (linear correlation, indicating that in this instance velocity decreases linearly in respect to the distance travelled during the rolling phase of motion. As velocity is equal to the distance travelled divided by the time taken to travel the distance, this relationship also has a negative (linear) correlation in respect to time. Table 3.0 supports the information provided by Figure 3.0, by showing a strong linear correlation for each of the five velocity groupings, again illustrated by the x-value in the regression equation and the $R^2$ value. Again, a gradual increase in deceleration rates is demonstrated by confirming that there is a strong negative correlation for each of the five groupings ($R^2 > 0.89$) with the exception of the 6Mph grouping. Furthermore, these values proved to be statistically significant ($p<0.05$), meaning there is less than a 5% probability that these trends may have been caused by chance. This table also illustrates the gradual increase in deceleration rates, directly correlated with an increase in ball speed, with the exception of the 7Mph grouping. Both the 3Mph and the 7Mph groupings were removed from the stage of analysis due to the lack of quantity of data within the combined groups (n=4), therefore the average value was lower than would have otherwise been projected with more content.

Figures 2.0 and 4.0 both support the linear increase of frictional force (against the direction of travel of the golf ball) with 87.4% and 97% certainty, that the frictional force in Newton's is affected by the velocity at which the ball travels. These figures also illustrate that the coefficient of friction increases at a greater rate than the frictional force. Also supporting the theory that the value for both aspects for ball speed group 5 (7Mph) would have been expected to increase in line with other groupings, indicating a limitation due to the smaller sample range from this group: if more putts were taken at this speed with a greater range of velocities, or potentially an average velocity closer to the mid-point of the grouping, then you would expect to see the frictional force values increase. With the values before mentioned removed from Figure 4.0, further analysis showed a near 'perfect' linear relationship between velocity and frictional force ($R^2 = 0.97$). Therefore, it must be highlighted that the majority of the data collected (n=71/75) suggests that 97% of the frictional forced produced by the ball-surface relationship once in true roll, is directly affected by the velocity at which the ball travels at. Consequently, a linear relationship is assumed.

Based on the findings previously mentioned, utilising the principles of linear motion allows further assumptions to be made according to significant ($p<0.05$) results. Due to the linear deceleration value found in this study, the assumption can be made that an increase in velocity would also directly affect the total putt length, as well as the individual lengths of the sliding and rolling phases of motion. This assumption can be made due to the linear relationship between the ball speed grouping and the distance travelled in Figure 3.0. This finding is based purely on assumption and interpretation of the findings within this study, as the time to true roll is provided by the ball roll system, however, the total putt length was not able to be measured with a consistent level of accuracy across various lengths of putt, due to the camera angle and the perceptive effect of this position. Therefore, the results acquired for the total putt length were neither valid, nor reliable and therefore discarded from the study. Another contributing factor is the stoppage board placed at the 5m mark, this prevented any putts from travelling past this point.

With respect to the current literature surrounding the topic, my study supports work produced by Rojas (2004) and again Rojas (2014), whereby the idea of a continuous linear deceleration rate is proposed, at a time when a ball is rolling all the way until a ball stops dead. These findings are resoundingly supported by this study. Weizman et al., (2013) suggested that a ball in motion decelerates substantially more at a higher speed, but also that rolling friction increases with velocity. This study has found that the deceleration rate has a positive correlation with velocity, which again supports these statements.

This study however, does not support findings produced by Drane et al., (2014) who proposed a set deceleration rate across a range of speeds. The proposed deceleration rates of $1.75m.s^2$ for the sliding phase and $0.4m.s^2$ for the rolling phase, were not supported by this study. In addition, based on the findings of this study a linear positive correlation between the deceleration rate and the velocity at which a ball travels, would rule out the idea of a 'set deceleration rate' across a range of various speeds, as if the velocity of the ball was to increase or decrease, the deceleration rate would also in turn increase or decrease accordingly.

The findings of this study are directly relative to the putting success of individuals on a golf course. As before mentioned a putt is dictated by "green reading, aim, stroke and ball roll" (Karlsen, 2008), this research was focused upon the ball roll analysis, however, the results of this study have a direct relationship to both green reading and aim. If a putt's line of travel towards the hole is dictated by its velocity, then in order for the ball to travel along the correct line the individual applying force to the ball must understand the velocity-time or velocity-displacement relationship in order to understand the appropriate aiming point to focus upon (green reading and aim). In order for a player to roll a successful putt they must understand the factors which alter the deceleration rate of the ball including; velocity, terrain, moisture, grain, surface. To which these findings provide a platform to build upon. Based on the understanding that the ball-surface relationship is what provides the frictional properties to this equation, it is also key for a player to understand the various types of playing surface and the affect that this may have on the ball's ideal path. For example; a grainy green may have a higher coefficient of friction than a non-grainy green, or indeed certain types of grass may have various frictional properties such as coarser fibres leading to an alteration in ball behaviour (Steffen et al., 2007), also extended to the length at which a particular type of grass is cut.

From an alternative perspective, the findings presented here raise doubt regarding the validity of the time old method of measuring green speed which is the stimpmeter. Commonly a ball is released from a height of 76cm at an angle of 20º to the surface being measured according to USGA regulations (Gaussoin et al., 1995). The ball is released from the raised end of the stimpmeter whereby it eventually leaves the end of the tool and the distance of 'roll out' endured by the ball in both directions is converted into a universal green speed reading, known as a 'stimp reading'. Once the ball is released, it travels down the entirety of the stimpmeter, at which point a frictional force will begin to act on the ball, causing the ball to roll down the apparatus and onto the green, eliminating the sliding phase of motion. Therefore, due to the representation of two different frictional forces and deceleration rates (on the same putt) for the different phases of motion, as calculated during this study, is this a true representation of the way that the same golf ball would react off of a putter face? In this instance disregarding the 'initial bouncing' which is almost certain to take place, after a ball has been released from above a surface.

## V. Limitations

The accuracy of the video analysis process could have been improved by adding an additional camera to the set up. Also, the use of a tripod would have allowed the same calibration settings to be used for each video as the camera would have remained in the same position. As previously mentioned, due to the inaccuracies caused by the camera position, it was not appropriate to calculate the total putt length for this study. This research was also conducted inside on an artificial surface, in a controlled environment due to ease of access. This may represent dissimilar results to the same experiment conducted outside on a real grass putting surface. Furthermore, the lack of content in two of the various speed groupings has severely inhibited the spread of the results from this data set, increasing the number of marker points would make it easier to collect a wider range of data with higher accuracy during the video analysis process.

## VI. Recommendations

I would recommend that future experiments increase the number of putts recorded in order to get a wider spread and a more representative data set. Similarly, ensure that all data groups are focused upon, aiming to achieve similar quantity in each. If deemed necessary parameters could be introduced to ensure similarity between the contact and launch angle of putts recorded. It would also be wise to include the total putt length in the data for any future investigations, aiming to support/disprove current literature surrounding the topic. Finally, I would suggest conducting the same experiment on a non-artificial surface to understand the impact which exterior factors can place on the golf ball.

## VII. Conclusion

It can be concluded that the initial velocity of a golf putt directly affects the deceleration rate, the frictional force applied and ultimately the coefficient of friction of the surface-ball relationship in both phases of motion. It may also be stated that a golf ball decelerates significantly quicker whilst in the sliding phase of motion. Also, that frictional force produced as well as the coefficient of friction are both positively correlated with initial velocity, although the coefficient of friction increases at a greater rate.

## VIII. Acknowledgements

The authors would like to give special thanks to Dr Paul Hurrion of Quintic Consultancy, for allowing the use of the ball roll system throughout this study. With special thanks extended to Machynys Golf and Country Club for allowing the use of their Golf Academy facilities to collect the data for this study.

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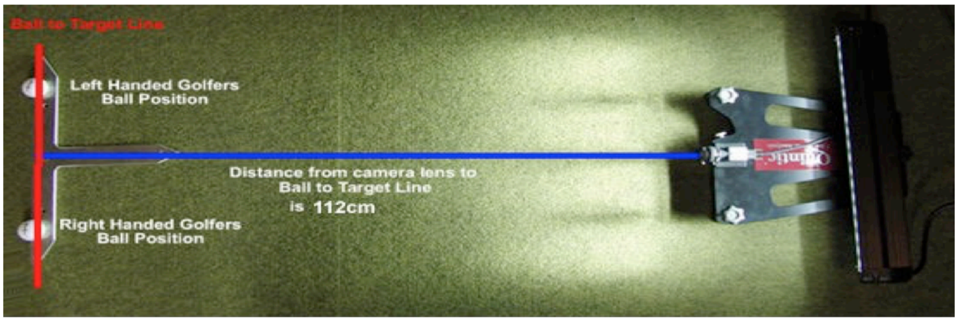
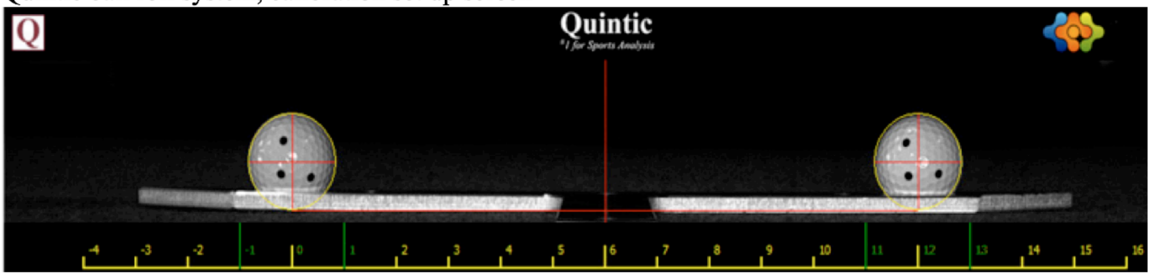
# X. Appendices

Appendix 1
Quintic ball roll system set up




Appendix 2
Quintic ball roll system, calibration set up screen




Appendix 3
Set up of equipment for this study