EFFECTS OF TEE HEIGHT ON DRIVE DISTANCE

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Player testing setup at Cal Poly's Mustang Golf Academy.

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1 EXECUTIVE SUMMARY

Player (13 men and 7 women) and robot testing were conducted to evaluate driving distance as teeing height was reduced. Player data from 892 metal woods shots, primarily drivers, were collected and analyzed: 602 from men and 290 from women. Robot data collected and analyzed numbered 492 shots using drivers. Intial launch conditions were measured using Bridgestone Science Eye (robot) and GCQuad (player) launch monitors. Ball trajectories and bounce/roll were simulated using a United States Golf Association code [2].

Two Phases of player testing were completed. In Phase I, nine men players hit their own drivers at their normal and various reduced tee heights including drivers off the turf. An Alternate Driving Club (ADC) of 11-deg loft and 44-in length was selected as a claw-back club to mimic what manufacturers might produce as a driving club should allowable tee heights be drastically reduced or eliminated. In Phase II, seven men and seven women golfers hit drivers at their self-teed normal height and one inch height as well as the Alternate Driving Club (ADC) self-teed and off the turf. Three men hit in both Phase I and II testing protocols.

Summary of Results:

1. Robot driving distance was reduced from 2- to 13-yards, depending on club-ball combinations, when lowering the impact location 0.6-in and keeping all other swing characteristics the same.
2. In general, decreasing the tee height for players
   a) lowered the angle of attack, (Figs. 10a on page 13, 15a on page 20 and 19a on page 24)
   b) decreased club head speeds (Figs. 10b on page 13, 15b on page 20 and 19b on page 24)
   c) decreased ball speeds and launch angles and increased spin (Figs. 12 on page 15, 16 on page 22 and 21 on page 26)
   d) decreased driving distance carry and total distance (Figs. 13 on page 16, 18 on page 23 and 22 on page 27)
3. No relationship between men's or women's normal teeing height and driving distance was found. (Figs. 24a on page 29 and 24b on page 29)
4. It is inconclusive whether increasing angle of attack at normal teeing heights for men produces increasing total driving distance (Fig. 24c on page 29). Women's angle of attack is generally greater than men's and may be used to enhance distance (Fig. 25c on page 30).
5. An Alternate Driving Club (ADC) was chosen and fitted with different shaft options for low and no tee height testing (see Section 6 on page 18).
6. The Alternate Driving Club (ADC) was effective in producing more optimum launch conditions at lower tee heights for some players. (Figs. 26 on page 31)
7. The Alternate Driving Club (ADC) for low, or no, teeing for men and women will likely have to be substantially different designs.
8. Low, or no, tee heights would have much more negative effects on elite women than elite men.

Recommended Future Work:

1. Find tour level players (any tour) to test. This report had two players who were full time playing golf for a living trying for Korn Ferry status. Continued high level collegiate players testing would be good.
2. Experiment (take data) to find out the how tee height effects driving distance when elite players think, and swing, ”outside of the box” of their normal swings.

2 INITIAL ROBOT TESTING

Early robot testing on tee height was completed (see [1]; some of that report repeated herein) in an effort to eliminate as many driving distance variables as possible. In this case, the robot's angle of attack, the vertical angle the club head approaches the ball, was fixed to level as the tee-table was lowered to represent lower tee heights. No other robot variables were changed. In doing this, the same swing was accurately reproduced as the impact location on the face was lowered (see Fig. 2). Players make subconscious adjustments when tee height is lowered as will be reported with the player testing data.

For the robot testing, golf clubs were assembled using driver heads currently in the marketplace and used by the PGA TOUR and LPGA, representing major manufacturers, as well as a USGA 'Aeson' control club head and a small-sized driver, with steel shafts having the same properties as those of the control club. While steel shafts are not used in drivers by PGA TOUR and LPGA players, this was done to remove shaft variability in this preliminary testing phase.

Clubs were fixed in the USGA's mechanical golfer and set to a club head speed of 120-mph using the USGA's four-laser club head speed detector. A setup position was determined by measuring the launch conditions, using Bridgestone Science Eye launch monitors, with target 'nominal' conditions for a control ball at 10° launch angle and about 2,500-rpm. These swing parameters are effective for emulating elite men.

This setup impact location was the first impact location. Modern drivers have about a 2-in vertical height at the face center. Since the robot was programmed for a level angle of attack, the tee height would have to be a minimum of 1-in. To have a swing that wouldn't brush the ground, assume the setup position is a tee height of 1.2-in. Image analysis of Fig. 2a showed theis assumption to be reasonable.

From the setup impact location, the tee height was then lowered in 0.2-in increments for subsequent impact locations with nothing else changed until a last location which was 0.6-in below the setup location. Two sets of premium golf balls were used at each location: high and low spin. Examples of the 'setup' height and the lowest tee position can be seen in Fig. 2 . The goal was to have the presentation of the club head to the golf ball the same with the exception of lowing the impact location.

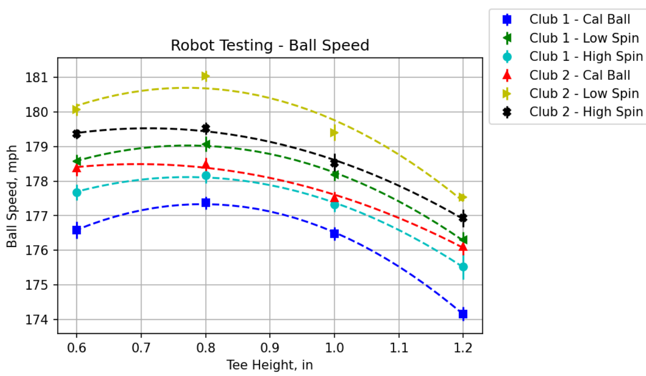
Ball speed increased as the impact postion (tee height) was lowered (see Fig. 3 on the next page). However, the ball speed increments decreased for each lower location until ball speed leveled off or decreased slightly. For the three plots of Fig. 3 on the following page, the symbol represents the mean of the 12 shots and the error bars are a 95% mean confidence interval. This shows, how precise the robot testing was– 95% confidence interval bars are slightly larger than the plot symbols. The dashed lines are a quadratic fit to the four tee heights for each club-ball combination. Curvature of the fit data likely means there are competing factors in ball speed as impact location is lowered. For instance, eccentric impact factors, face flexure, local stiffness, vertical gear effect and possibly others may independently add or subtract ball speed as impact is lowered.

(a) Highest Location **(b)** Lowest Location

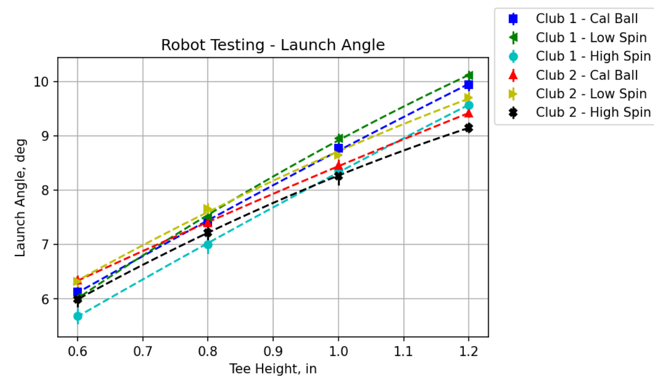
Figure 2: Imprints of extreme ball impact locations for robot testing.

Changing the impact location from an optimal, near face center, position by 0.6-in can be put into perspective by considering approximate face size of current (2021) drivers. The vertical height dimension of a driver face at the center is about 2-in from sole to crown. A driver hit off the turf with a horizontal angle of attack would impact the 0.84-in radius ball at a point 0.16-in below the face center. Locations and velocities of the ball's and club head's center of gravity play a critical role in the efficacy of the impacts. Club head center of gravities are generally located somewhere proximal to a line perpendicular to the face and passing through the face's geometric center, that is, lower than the face center by the depth of the center of gravity times sine of the dynamic loft angle. [1] So it is not surprising that the ball speed increases as the impact position was lowered.

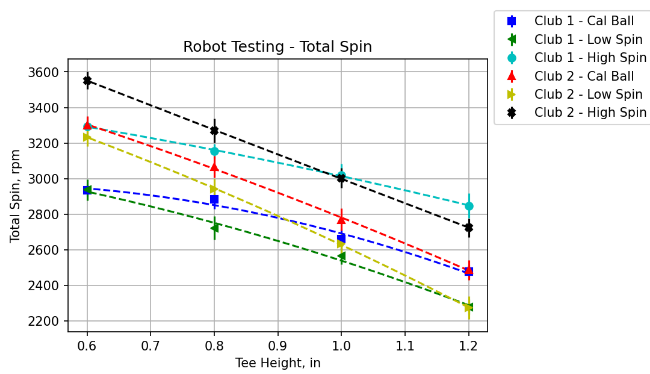
Great driving distance is not achieved by increased ball speed alone. In robot testing, the benefits of ball speed increase in terms of driving distance were offset by adverse trends of decreased launch angle due to face roll and increased spin due to vertical gear effect at low tee heights. However, launch and spin plots, Figs. 3b and 3c, show a much more linear variation than ball speed as tee height is lowered. The driving distance "stool" stands on three initial condition legs: ball speed, launch angle and spin. [2] With only one leg, ball speed, the stool is not effective.



(a) Ball Speed



(b) Launch Angle



(c) Spin

Figure 3: Effects of tee height on robot ball initial conditions.

Since inital ball speed, launch angle and spin are the essence of driving distance, plots showing these quantities will, in general, be grouped together throughout the report.

Driving distances were simulated using the initial conditions associated with each different ball/club/tee height combinations. These simulations used a robust set of aerodynamic data [2] (one associated with a higher-spin ball

1 It was assumed that the reader is quite familiar with golf club heads and their design. Simply put, the club head's center of gravity for the robot's swing here is vertically below the face center, and aligning the club center of gravity's velocity vector to pass through the ball's center of gravity makes for an efficient impact with respect to ball speed.

2 Throughout this report, spin is measured and used. 'Back' spin is a component of three dimensional vector spin. In studying driving distance, high quality shots were considered that have little side and rifle spin. Thus, spin is total spin having a perfect spin axis.

and one with a lower-spin ball) that captured the full range of aerodynamic performance associated with these experiments. Given the range of terminal (carry) conditions, a simplified bounce model applicable to a wide range of such conditions was utilized (see [4]) to compute total distance.

Distance results for robot shots with different clubs studied with each ball type are shown in Figure 4. In this plot, error bars are not shown since mean ball launch conditions at each tee height were used in the trajectory model. Large distance changes as impact position was lowered for the Control Club is not surprising since the club head volume was on the order of 100 cc less than the others. This would make this driver play much differently for off-center impacts. In some of the club-ball combinations, lowering the tee height results in a slight increase in total driving distance for a small tee height range. Further tee height reduction results in reduced total distance in all cases. For all club types, the lowest tee position was usually associated with the shortest drive distance.

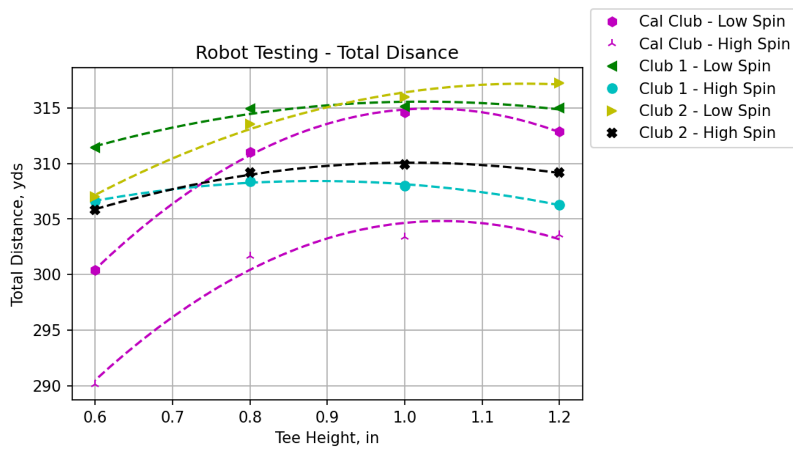


Figure 4: Effects of tee height on total distance for robot testing.

Figure 5 shows the relative performance between the maximum-distance tee height and the lowest-position tee height for the club-ball combinations tested. It can be seen that the lower-spinning ball was, in general, most affected by lowering tee height. Notably, it can also be seen that the club used had a significant effect on the outcome: the 360 cc Control Club saw reductions of 13-14 yards, while Club "1" saw a much lower reduction, 2-4 yards (with Club "2" in between).

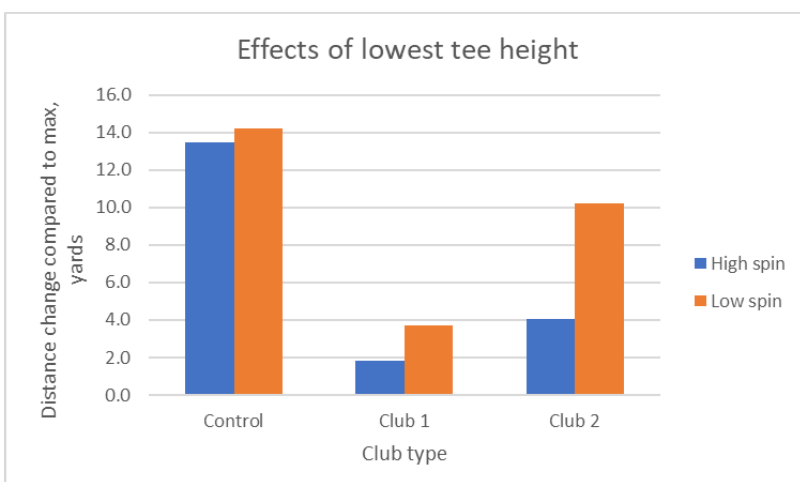


Figure 5: Robot driving distance losses at extreme tee heights tested.

Robot testing with everything held constant except tee height showed that driving distance is reduced as impact position was lowered. Players are able to adapt swings for different situations. Most of the time, this adaptation is subconscious and happens automatically. Golfers swing differently and tee the ball differently. After a quick look at high level players tee height estimates, player testing for decreasing tee heights will be examined.

3 ESTIMATED TEE HEIGHTS AT 2021 US OPEN

The height a player tees the ball up is a personal preference, and there is a wide variety of heights. Players hitting shots in different conditions can have them intentionally teeing the ball at different heights. This holds true for all skill levels. To get an idea of the variation of tee heights at the highest level of competition, tee heights for a small sampling of competitors in the United States Open at Torrey Pines (2021) were estimated.

Driving tee heights were obtained Friday, 18 June 2021, on several holes on the front nine. Images of players were taken on the 2nd, 5th and 7th tees. All of these holes were oriented in a general north-to-south direction with a light sea breeze blowing from the player's right to the left. Images were captured using an iPhone 12 Pro Max camera using the 2.5x lens with some digital zoom. On the whole, a zoom of 4x to 5x was used. Sample images are shown in Fig. 6 on the next page.

The images were analyzed using Image J (v. 1.53j) on a MacBook Air. The photos were taken from a distance and so the zooming in on the ball and tee was a bit grainy (see Fig. 7 on the following page), however, images were quite sufficient to obtain estimates of teeing height. Tee heights reported in this section are measured from the top of the grass to the bottom of the ball.

Scaling the number of pixels per inch to a known distance was done by using the 1.68-in ball's diameter. First, a circle was drawn around the ball as is shown in white in Fig. 7 on the next page. Then a line was drawn across the diameter of the ball using the drawn circle for a guide. The pixel length of that line was set to be 1.68-in within the Image J software. Drawing several diameter lines in different orientations (vertical, horizontal and off-angle) verified the image was calibrated. The line tool from Image J was used to measure from the bottom of the ball to the point where the tee met the grass. Five of these measurements were taken and averaged to get the resulting measured tee height. One of the tee measurement lines is show in yellow in Fig. 7 on the following page.

Table 1: 2021 US Open Estimated Tee Heights

Player	Hole	Estimated Tee Height, in
B. DeChambeau	2nd tee	1.669
S. Garcia	2nd tee	1.605
B. Watson	2nd tee	1.563
A. Scott	2nd tee	0.881
J. Rose	2nd tee	1.230
H. Matsuyama	5th tee	0.990
B. DeChambeau	5th tee	1.613
T. Strafaci	5th tee	1.254
W. Nienaber	7th tee	0.891

(a) Adam Scott **(b)** Sergio Garcia

Figure 6: Images of golfers from Torrey Pines GC 2nd tee 18 June 2021.

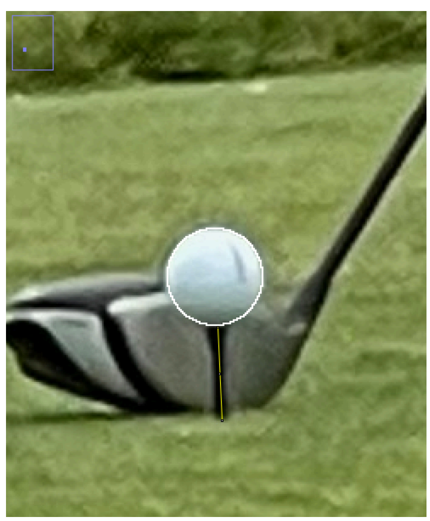


Figure 7: Zoomed in image view of ball-tee used for estimating height.

4 DATA ACQUISITION AND PROCESSING

Tee height was measured two different ways for Phase I and Phase II data. For both phases, tee heights for all shots were not measured. Nominally, about 3-5 tee heights were measured for the configurations needing measuring.

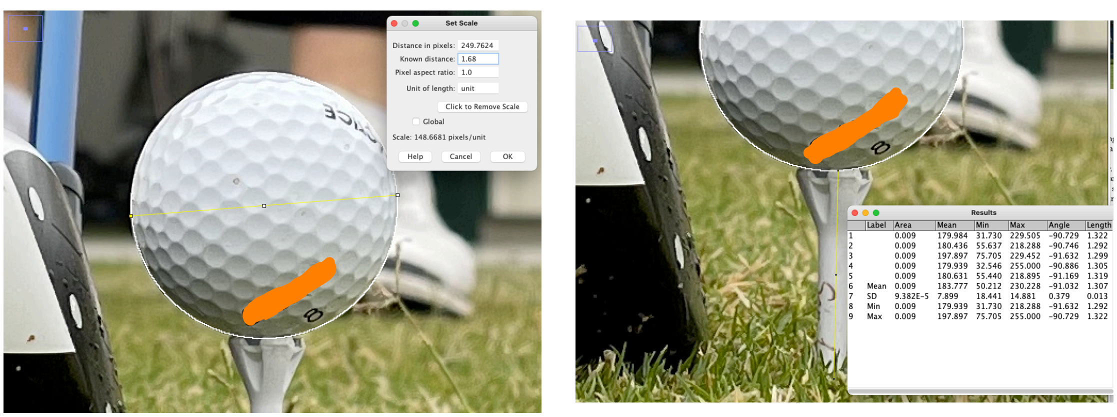
In Phase I, tee heights were measured with either a metal scale or calipers. Only the first golfer's tee heights used the metal scale. The distance from the ground to the center of the ball were recorded for both the metal scale and calipers. Tee height was calculated by subtracting the radius of the golf ball from this length. More details on Phase I tee height measurement are given in the Initial Player Testing Section 5 on page 12.

In Phase II, the normal and Alternate Driving Club (ADC) tee heights were measured by digital image analysis. For the low driver tee height, a wood step tee having nominal height of 1-inch when fully inserted into the ground was used insuring a 1-in tee height. Some digital images of the short teed ball were taken. Players teed the ball up themselves. For Alternate Driver Club, turf shots the players were allowed to hand place or use the club to produce their lie.

An iPhone 12 Pro Max was used to capture an image of the teed ball for normal, short and ADC tee heights. The phone was placed next to the GCQuad just outside the hitting area (please see the title page Fig. 1 for the setup). A preferred hitting area in the vicinity of the ”Y” in GCQuad's "READY" was found to be most effective for consistency and capture of club head data. Pictures were remotely taken with a link to an iWatch. Images were cropped on the phone and then transferred to a MacBook Air for further analysis.

ImageJ (v. 1.53j) was used to estimate the tee height with the procedure described above in Sec. 3 on page 8. Since the camera was much closer to the ball and club, the images were high quality. See Fig. 8 for screen captures from this process.

Since multiple testing locations were used, the mowed height of the grass was estimated using the short 1-in step tee images. Similar digital analysis was used to capture the tee height to the top of the grass as described above. Then this value was subtracted from the 1-in step tee height giving an additional length to be added to the intermediate tee height. This summed value was taken as the tee height from the ground-line to the top of the tee (which was the bottom of the ball).



(a) Calibration diameter line (thin yellow line) used.

(b) Estimate tee height values and the mean calculation.

Figure 8: Calibration and tee height estimation images.

Player's club head and ball data were measured with a Foresight CGQuad and stored on an iPad. Three GCQuad units were used in the testing. Table 2 on the next page lists the specifications of launch monitors used. GCQuad data was saved in an Excel® file for each player.

Each player's spreadsheet was read into a Python program for data reduction producing an Excel® file for all the data. Tee heights that were measured were input by hand in the Python code. The Python code identified and removed outliers, computed the means, standard deviations, shot counts (e.g., driver normal, driver short tee, driver turf) and confidence intervals. This second Excel® file contained all the player's data: raw data, means, standard deviations, outliers removed, shot counts and 95% confidence intervals.

Table 2: GCQuad Specifications For Units Used in Testing

Setting	Unit 1	Unit 2	Unit 3
Model	GCQ100	GCQ100	GCQ100
Serial	08119	07169	00117
Build	3.0.6.1	3.0.5.1	3.0.2.2
DOM	10 May 2021	23 Jan 2021	14 Jan 2017
HW Ver.	A6	A1	A1
Radio Ver.	1.6.8	1.6.8	1.6.8
BOOTLDR	1.0.1	1.0.1	1.0.1

Outliers were identified using Grubbs Test for the data in each club's sample. That is, for driver normal, driver short tee, driver turf, Alternate Driving Club teed and Alternate Driving Club turf. A two-sided test was used to check for values that were too high and too low. The Grubb's statistic, G, was calculated as

$$G = \frac{|Y_i - \bar{Y}|}{s} \quad , \tag{1}$$

where Y_i are the samples, $\bar{Y}$ is the mean of the samples, and s is the sample standard deviation. The hypothesis of no outliers is rejected if the Grubbs' statistic is greater than a specific value given by (see Reference [3])

$$G > \frac{N-1}{N}\sqrt{\frac{(t_{\frac{\alpha}{2N},N-2})^2}{N-2+(t_{\frac{\alpha}{2N},N-2})^2}} \quad . \tag{2}$$

where N is the number of samples, $t_{\frac{\alpha}{2N},N-2}$ is the critical value of the t distribution with $N-2$ degrees of freedom and a significance level of $\alpha/2N$. When the no outlier hypothesis was rejected, the sample having the largest difference from the sample mean was removed and the Grubbs test applied again until the null hypothesis was confirmed.

Data for club and ball measurements are the sample means of 8 to 12 shots for that tee height condition. Sample standard deviations and 95% confidence intervals were computed for each tee height condition as well. In most all of the plots shown in this report, error bars are the 95% confidence intervals and the dashed lines are linear regressions for each players data as a function of tee height. The 95% confidence interval is the interval where the difference between the sample mean and the population mean is not statistically significant at the 5% level. The two sided confidence intervals were calculated by

$$95\% \text{ Confidence Interval} = t_\alpha(n-1)\frac{s}{\sqrt{n}} \tag{3}$$

where n is the sample size, α is the statistical significance and t is the t-distribution.

For all player testing, the means of the initial lauch conditions (ball speed, launch angle and spin) for each tee height were input into a USGA trajectory model, assuming 75°F, 30-inHg, and 50% relative humidity, to compute carry and total distance. It was the same trajectory model used for robot testing [2].

5 INITIAL PLAYER TESTING – PHASE I

Phase I was an initial pass as the testing protocol being developed. Because of this, Phase I's early testing protocol slightly morphed for different players. While Phase I was a learning phase, there was useful data collected and deserves to be reported on. Nine men were tested in the first phase. Testing in Phase I was before the Alternate Driving Club was chosen and built, so players only hit their own drivers with varying tee heights.

The tee manufacturer's length used in this protocol were:

1. Player's normal tee (generally a tee around 2-3/4-inches in length),
2. Red tee 2-1/4-inch in length,
3. Orange tee 1-1/2-in in length,
4. Turf.

Tee heights, different from manufactured tee lengths, for all of this study are the distances from the ground plane to the bottom of the ball and were measured or controlled to be a fixed length. For all phases, the player's normal teeing height varied from player to player.

The tee height order players hit was the same as the manufacturers length enumerated above. Players cycled through the heights two or three times nominally hitting three shots at each height. That is, players hit 3 shots as they normally tee their driver, 3 shots with the ball teed lower, 3 shots teed quite low and three balls off the turf with no tee. The first three players tested only cycled through the tee order once hitting 8-12 shots at each height.

Players in Phase I hit mostly premium balls, however, three players hit a premium three piece range ball. Equipment used by all players is given in Table 7 on page 37.

Calipers were used to measure the distance from the ground plane to the center of the ball. The tee height was then calculated by subtracting the radius of the ball from that measurement. Measuring tee height this way was a little cumbersome and slowed the player's hitting flow. The final three Phase I players had their normal tee height measured with calipers and the test administer teed red and orange tees to a specific height of the red or orange stripe. Figure 9 shows the ground line and the heights of the bottom of the ball: red was 1.38-in and orange was 0.75-in. Red and orange heights were used in Phase I; yellow and blue heights were not used in this study.

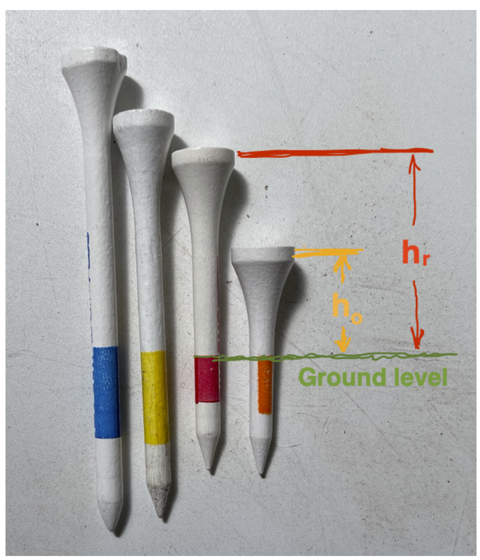
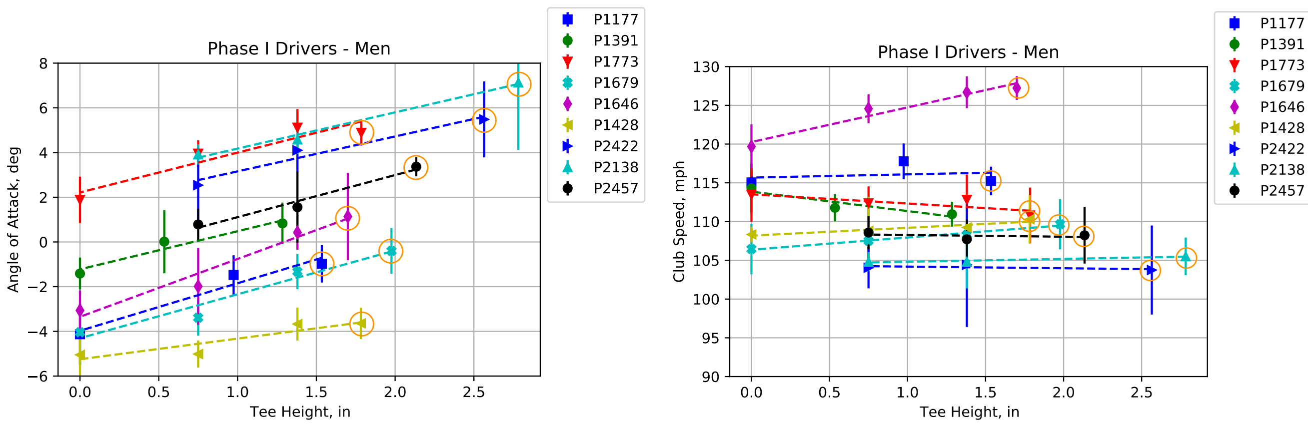


Figure 9: Tee heights h_r for red and h_o for orange measured from ground level.

Subconsciously, players adjust how the club head is presented to the ball when the tee height is lowered. Players understand the importance of hitting the ball near the center of the face. Adjustments in the swing avoid impacting the ball 0.6-in (15-mm) below the face center as the robot dutifully did. As players alter their swings the angle of attack, club head speed and vertical impact location on the face change. These are the first three parameters to look at for players hitting from decreasing tee heights.

All of the Phase I players angle of attack values decreased as the tee heights lowered (see 10a). None of the players contemplated how they were going to hit the shot; they simply let their instincts adjust their swings. Figure 10a shows the angle of attack means of 8 to 12 shots at each tee height as the symbol. Different colors are shown for different players. The error bars shown are the 95% confidence intervals for the data taken. A linear regression of the angle of attack as a function of tee height is shown as a dashed line in the color corresponding to the player. Linear regression values are given in Table 3 on page 17, and these sensitivities (or slopes) to tee heights are useful to evaluate player adaptation since players have a variety of normal shot baselines. Finally, player's normal tee height data symbol is circled. Player data throughout this report are presented in this pattern.



(a) Angle of Attack, deg

(b) Club Head Speed, mph

Figure 10: Phase I men's angle of attack and club head speed as a function of tee height. Circled symbols are the player's normal tee height.

Players hitting in Phase I had a wide variety of angle of attacks for their normally teed ball. The furthest tee height to the right for each player is their normally teed ball. There were three players having 5-deg or higher upward and one player having just under 4-deg downward angle of attack for normally teed balls. The remaining 5 players had angle of attacks ranging from just below level to just over 2-deg upward.

All of the players angle of attacks trended 2-3-deg downward as the tee height was lowered from their normal height to the turf. The linear regression seemed to represent the data well.

Club head speed (Fig. 10b) didn't change appreciably for the majority of players as tee height deceased. The exception to this statement was player P1646 whose club head speed dropped 4.47-mph/in of tee height. Four players had increases in club head speed as tee heights decreased. The mean loss in club head speed of all nine men tested was around 0.4-mph/in decrease in tee height. (In all parameter discussions of graphical data, please cross reference plots with Table 3 on page 17 for tabulated sensitivities.)

The final club head presentation parameter considered is the vertical position on the face that impact occured. The GCQuad measured this in millimeters and labels it vertical face deviation. Figure 11 on the next page shows the player's vertical face deviation as a function of tee height. As the tee height was lowered, all the players made contact with the ball lower on the face by, on average, 0.16-in (4.2-mm) per inch of tee height loss. Some players were better than others at maintaining impact location in a range of face center to 0.2-in (5-mm) below the face center where their normally teed ball made contact.

In the context of the robot testing, consider the setup impact vertical face deviation for the robot as 0-mm and the lowest robot impact at -15-mm vertical face deviation. The players do a better job keeping impact locations near, or just below, the face center position.

Players naturally altered the club head presentation to the ball to optimize the ball's initial launch conditions: ball speed, launch angle and spin. As tee height was reduced the ball speed dropped, the launch angle was lower and the back spin increased. This was what one would expect to happen.

PGA Tour players average launch conditions are [5]:

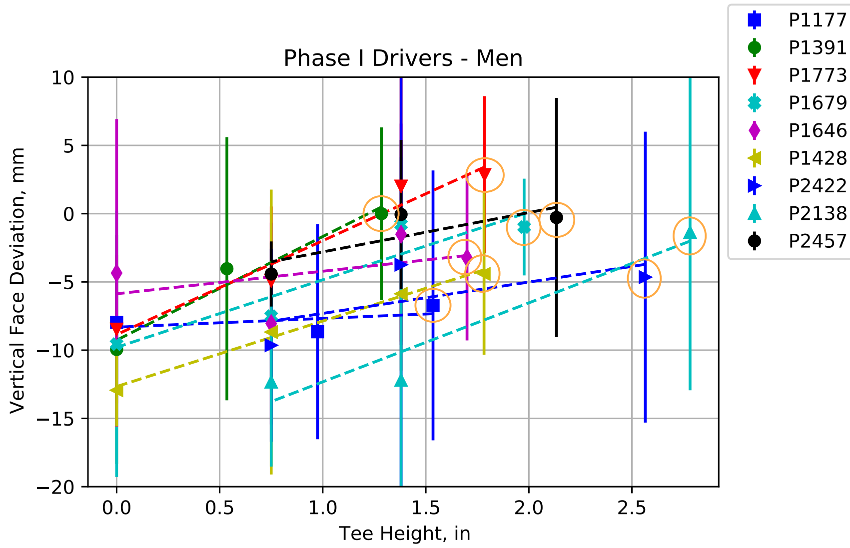


Figure 11: Phase I men's vertical face impact relative to face center as a function of tee height. Circled symbols are the player's normal tee height.

- Ball Speed = 167-mph,
- Launch Angle = 10.9-deg,
- Spin = 2686-rpm.

The players tested in Phase I initial launch condtions can be seen in Fig. 12 on the following page and were comparable, albeit the lower half distribution range, to the probable PGA Tour range. This was the case for Phase II testing presented in Section 7 on page 19 Fig. 16 on page 22.

Figure 12a shows the drop in ball speed for Phase I players as the tee height was reduced. Decreasing tee height reduced the ball speed by an average of 2.34-mph/in when including drivers off the turf. For the three players whose data didn't include drivers off the turf, ball speed increased by 0.728-mph/in as tee height decreased. This increase was less pronounced than the robot's ball speed increase as the tee table was lowered.

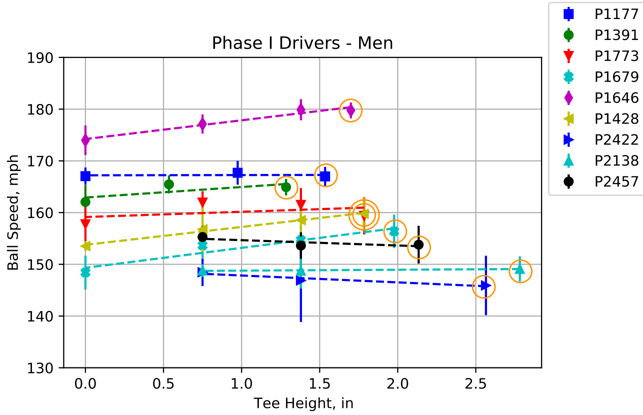
A steeper angle of attack along with lower vertical face deviation would cause a decrease in launch angle as can be seen in Fig. 12b on the next page. As would be expected, players with upward angle of attacks have the highest launch angles (P2422 and P 2138), and players with downward angle of attacks have lowest launch angles (P1428). All of the players had their launch angle reducing in a linear fashion as the tee height was reduced. Reduction in launch angle was proportionally more than the corresponding attack angles.

Back spin is the third initial condition of the ball that governs flight. As tee height went down the total spin increased partly resulting from the fact that angle of attack was decreasing with decreasing tee height (Fig. 12c). Additionally, as the tee height is reduced the players made contact lower on the face (Fig. 11). Impact low on the face results in more spin due to vertical gear effect. Only player P2422 was able to maintain similar spin as the tee height was lowered.

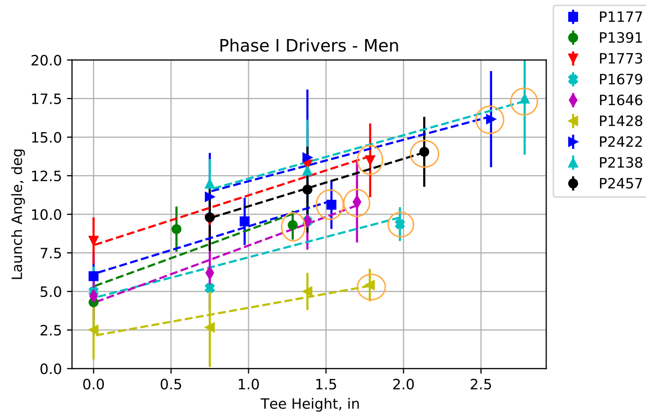
Up until this point, we have discussed club head presentation to the ball and the resulting ball's initial conditions as a function of tee height. The ball's launch conditions are what determines driving distance.

Figure 13a shows the carry distance in yards for varying tee height. As the tee height was reduced the carry distance dropped considerably. This should not be surprising since the ball's initial conditions changed for the worse as tee heights dropped. Furthermore, players whose carry data includes drivers hit off the turf have much more sensitivity to tee height than those not including drivers off turf. This would be expected.

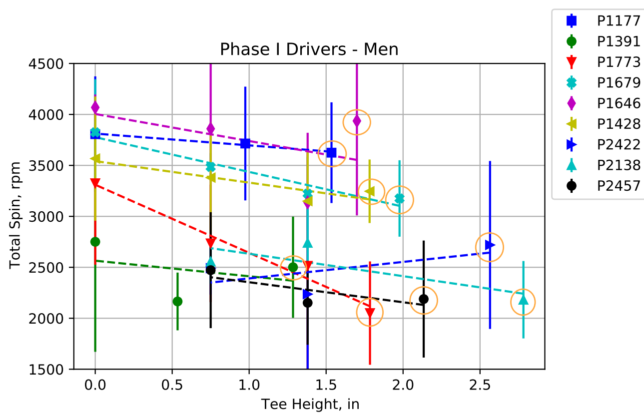
Angle of attack, impact position on face, launch angle, spin and ball speed all made for the loss in carry distance. However, lower tee height conditions can make up for some of the lost carry yards with more bounce and roll. Computed descent angles are shown in Fig. 13b and demonstrate that lower tee heights resulted in lower descent angles leading to more roll.



(a) Ball Speed, mph



(b) Launch Angle, deg



(c) Spin, rpm

Figure 12: Phase I men's launch conditions as a function of tee height. Circled symbols are the player's normal tee height.

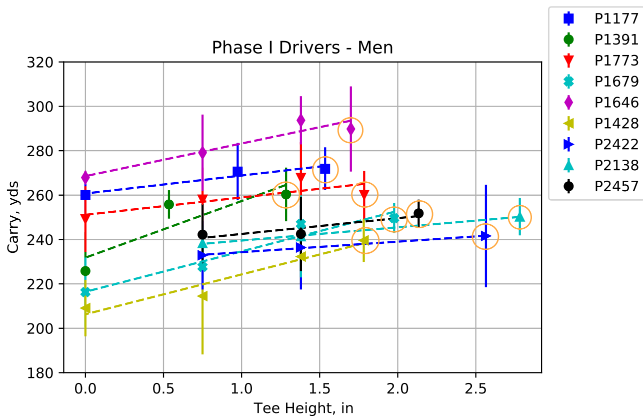
Since golfers at the highest level are being considered, the amount of bounce and roll was taken from a USGA model that modeled tour quality fairways. The bounce and roll is dependent on the descent angle (see [4])

$$d_{bounce} = 79.1 - 1.6\alpha_f \quad , \tag{4}$$

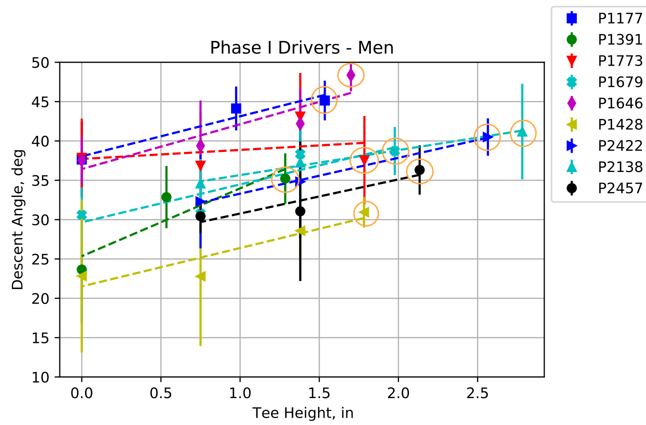
where the bounce and roll is in yards and α_f is the ball's descent angle.

Fig. 13c shows the total distances as a function of tee height. Descent angles for the lower teed balls allowed for some of the lost carry distance to be made up. Three of nine of the players were able to have slightly increasing distance as tee height was lowered. One of them, P1177, was among the players whose data included drivers off the turf. Referring to Table 7 on page 37 shows that his driver loft was 10.5-deg when tested. With a driver head speed of just over 115-mph and ball speed of 166-mph, it is likely that his driver was not a good fit for normal teeing heights. His spin rates indicate this as well. In fact, at the time of writing this document, we know that he went to a manufacturers to be fit and is now playing a 9-deg lofted driver.

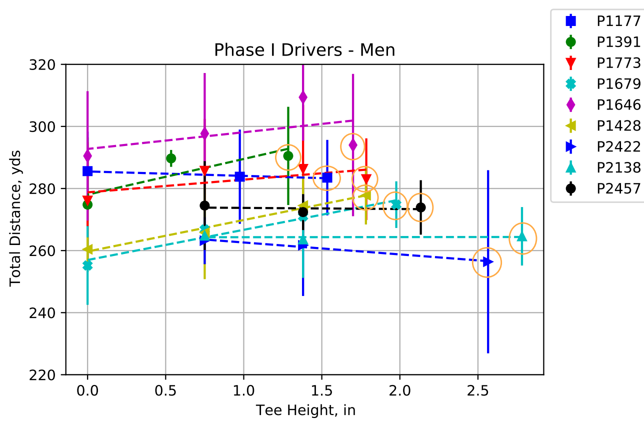
Because the players all had different statistics for their normal teeing heights, a good way to evaluate performance as a function of tee height is to consider rates of change. Consider the sensitivities, that is slopes, of quantities shown with respect to tee height. The linear regressions provide the sensitivities of a quantity (ball speed, launch angle or spin) to tee height. Table 3 shows the sensitivities for parameters associated with the initial launch conditions for the golf ball. For ball speed, club speed and total spin, a positive sensitivity (slope) indicated diminishing values as tee height is reduced. Positive sensitivity (slope) for angle of attach means that players are



(a) Carry Distance, yards



(b) Descent Angle, deg



(c) Total Distance, yards

Figure 13: Phase I men's carry/total distances and descent angle as a function of tee height. Circled symbols are the player's normal tee height.

hitting down on the ball as the tee height is reduced. Finally, positive sensitivity (slope) for launch angle means the ball is launching lower for lower tee heights.

Sensitivity to tee height is reported in a group of six and a group of three. The group of six hit their drivers off the turf as well as at varying tee heights. In the group of three, a slightly different protocol was used and drivers were not hit off the turf. Sensitivities (slopes) for players hitting the driver off the turf were not compared to sensitivities that didn't include drivers off the turf.

For the group of six, ball and club speed diminished as tee height was reduced. Players hit down (lesser angle of attack) on balls teed lower resulting in lower launch and more spin. In contrast, the group of three (players whose data didn't include drivers off the turf) had a slight increase in ball speed and negligible club head speed change. Angle of attack and launch changed similarly to those of the group of six. Spin increased, but to a lesser amount.

Table 3 also shows quantities associated with distance. Carry distance sensitivities being positive reflect a reduction in carry as the tee height is lowered. A positive sensitivity for descent angle is a reduction in descent angle as tee height is lowered. However, this enhanced bounce and roll and increases distance. Recall Eq. 4 on the preceding page which was used for calculating the bounce and roll. Vertical impact location sensitivity being positive means that the player is hitting the ball lower on the face reducing launch angle and increasing spin from gear-effect. Positive sensitivity for total distance is similar to carry distance in that it shows a decrease in total

Table 3: Phase I Men's Driver Sensitivities to Tee Height Reduction

Player	Ball Speed Loss[a], mph/in	Club Speed Loss[a], mph/in	Angle of Attach Loss[a], deg/in	Launch Angle Loss[a], deg/in	Total Spin Loss[a], rpm/in
Turf					
P1177	0.05	0.42	2.13	3.09	-116
P1391	2.04	-2.51	1.70	3.66	-153
P1773	1.02	-1.19	1.78	3.23	-668
P1679	3.86	1.58	1.96	2.64	-341
P1646	3.63	4.47	2.59	3.71	-265
P1428	3.46	1.01	0.92	1.81	-211
Average	2.34	0.630	1.847	3.02	-292
Std. Dev.	1.570	2.41	0.550	0.714	200.9
No Turf					
P2422	-1.33	-0.21	1.56	2.69	162
P2138	0.17	0.37	1.62	2.82	-220
P2457	-1.03	-0.22	1.88	3.08	-196
Average	-0.728	-0.021	1.69	2.86	-84.8
Std. Dev.	0.795	0.339	0.171	0.199	214

[a] Positive sensitivity/slope results in loss as tee height is reduced.

Player	Carry Distance Loss[a], yds/in	Descent Angle Loss[a], deg/in	Vertical Impact Location Loss[a], mm/in	Total Distance Loss[a], yds/in	Spin to Launch Ratio Loss[a], rpm/deg/in
Turf					
P1177	8.10	5.08	0.64	-1.42	-198
P1391	25.5	8.62	7.59	11.5	-267
P1773	7.82	1.15	6.88	4.10	-142
P1679	18.2	4.82	4.95	9.73	-245
P1646	14.7	5.69	1.65	5.38	-325
P1428	18.0	4.88	4.80	10.1	-517
Average	15.4	5.04	4.42	6.57	-282
Std. Dev.	6.75	2.39	2.77	4.87	131
No Turf					
P2422	4.74	4.55	2.30	-3.84	-26
P2138	5.98	3.18	5.79	0.04	-47
P2457	7.11	4.34	2.88	-0.35	-69
Average	5.94	4.02	3.65	-1.39	-47.3
Std. Dev.	1.19	0.741	1.87	2.13	21.3

[a] Positive sensitivity/slope results in loss as tee height is reduced.

distance for lowered tee heights. Finally, spin-to-launch ratio sensitivities which are negative show a decreasing efficiency as the tee height is lowered.

For the group of six, the sensitivity of carry distance was twice that of total distance reflecting the bounce and roll contribution as the tee height was lowered. This was the case for the group of three as well. In fact, the group of three total distance sensitively shows a slightly improved total distance.

6 claw-back/alternative driving club (adc) selection

Golf clubs hit from the turf require different swings and different designs. Fairway metals (woods), specifically 3–metal (or 3–wood), are made to maximize the ball speed, launch angle, and spin rate for optimum distance and accuracy. At the highest levels of the game, PGA Tour, 3–metals are to be a gap filing club between the driver and the high lofted fairway metal, hybrid, or utility iron. It should be noted than many of the 3-metals in the marketplace with strong loft adjustability simply would go too far for the typical high level player, such as a PGA Tour player. That said, the 3–metal is designed to have comparable carry distance of the driver to reach the longest par 5 in two, as well as used to precisely place the ball on tight Par 4's in the players optimal location. Not to get into the psychology of PGA Tour players on-course strategy, but many strong lofted 3–metals simply go too far.

The alternative driver design used in our testing for Phase II was a readily available fairway wood in the marketplace that can be adjusted to stronger head loft. It was known for having a low center of gravity and head compliance for higher launch and more ball speed, respectively. By setting for lower loft and modifying to a longer shaft the Alternate Driving Club (ADC) was meant to optimize distance. See Table 4 for Alternative Driving Club shaft options and club build specifications. The player was able to select the shaft flex that meet their needs, but only one brand model graphite shaft was supplied. Though this is not the optimum fitted club (shaft model, flex, and length) for each player, the graphite shaft model selection was based on generally well accepted specification across wide range of golf swings. It should also be noted, that the fairway metal model selected is still not the optimized specifications for center of gravity and moment of inertia properties. An expert in the art of club design, would consider alternative materials and design to create an optimized driving club from the tee or turf only for highest levels of competition. A potential follow up study, would be to make this optimum club and test it.

For our testing, we selected a 2021 titanium 3 fairway with a hosel setting producing 11-deg loft. This is a reasonable option for testing the turf and low tee driving conditions, but is not exclusively designed for this purpose for the highest levels of competition. Stock length was 43-1/4-in having a D-3 swing weight. A 44-in shaft was chosen since the club was intended to be as close to a replacement driver as possible. The 2-g weight was removed to bring the swing weight down to a reasonable value (see Table 4).

Table 4: Alternative Driving Club Shaft Options and Club Build Specs

2021 Titanium 3-W 13.5° (set at 11.5°; measured 11.0°) 206-g head					
Configuration	Flex & Length, in	Weight, g	FM	Launch	Swing Weight
1	R 44"	55	4.5	MID	D-3.9
2	S 44"	65	5.5	MID	D-4.2
3	X 44"	75	6.5	MID	D-4.2
4	XX 44"	75	6.5	MID/LOW	D-5.7
5	S 43.5"	65	6.5	MID	D-1.6

The shafts used were manufactured by a company that supplies stock shafts to several original equipment manufacturers. Measured lengths, frequencies and swing weights given in Table 4, and the shaft bending profiles are shown in Fig. 14 on the following page.

Also, unknown in our testing in all phases, is the learning curve of good players. In other words, high caliber players tend to find ways to accomplish the flight and performance characteristics desired. This comes from practice time they dedicate to accomplish specific goals. Therefore, given more time with an alternative driver club design for driving from turf or low tee only conditions, it is unknown, but possible they could accomplish similar results to their current driver with tee.

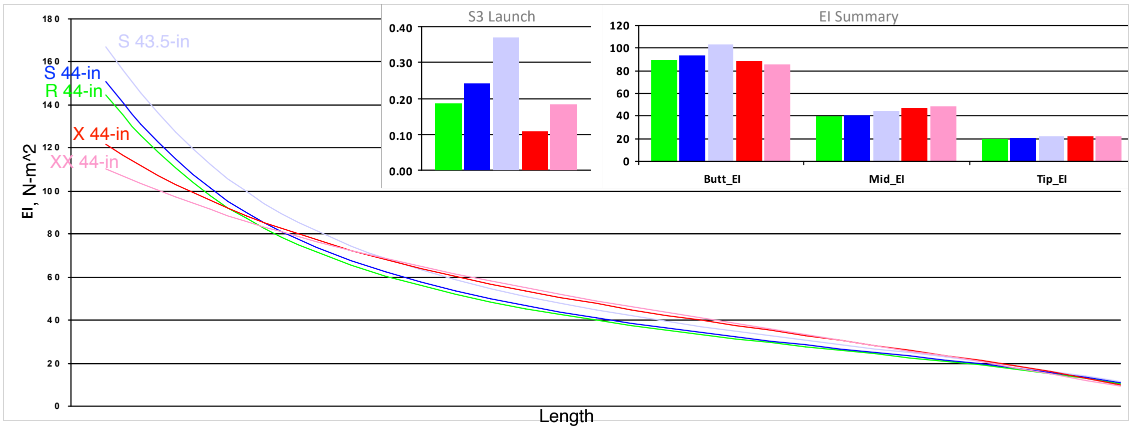


Figure 14: Bending stiffness profiles for shafts used in Alternate Driving Club (plots courtesy of Cool Clubs, Scottsdale, AZ).

7 FINAL PLAYER TESTING WITH ALTERNATE DRIVING CLUB (ADC) – PHASE II

In Initial Player Testing - Phase I (Sec. 5), the data shows the effect of tee height on driving distance for shots hit with player's "gamer" driver. A modern driver having a center face depth on the order of 2-in is not optimal for hitting tee shots off the turf or teed 0.5-in high. In this section, data are given for players hitting their "gamer" driver from their preferred height and from 1-in height. To mimic what driving clubs may be should the teeing height be greatly reduced, or eliminated, players hit the Alternate Driving Club (ADC) described in Sec. 6 teed up to a height of their choice and off the turf. Shot data was taken using a GCQuad and tee heights for player's normal tee height and the teed Alternate Driving Club were measured using image analysis (see Sec. 4).

7.1 Phase II Testing Protocol

With an Alternate Driving Club (ADC) selected and built, a Phase II testing protocol was carried out. This protocol was similar to that used in Phase I but with differences. Phase II used the players "gamer" drivers for two tee heights: their normal and 1-in heights. The Alternate Driving Club (ADC) was used teed and off the turf (no tee). Players teed the ball for ADC shots to whatever height they wanted. When hitting off the turf, players could place the ball using their hand or the club head. Before ADC data was taken, players chose the shaft flex they liked and hit several balls to validate their decision. All players chose 44-in length shafts.

The order of tee height shots was as follows:

1. Driver, Players Normal Height (variable),
2. Driver, 1-in Height,
3. ADC Teed Height (variable),
4. ADC Off Turf.

Players hit through the cycle enumerated above three times hitting 3 to 4 shots for each item.

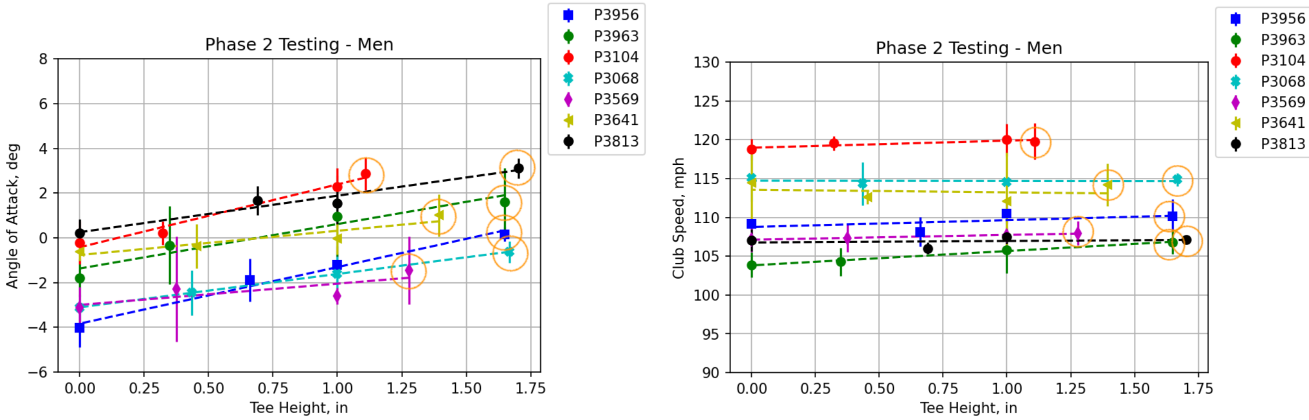
Tee heights were measured using digital image analysis as described in Sec. 4 on page 10 for Normal Driver and ADC Teed shots. Not all shots had the tee height measured. Normally, 3 to 4 shots captured images to measure the tee height. The mean of these heights is what is reported.

Club and ball data was taken with a GCQuad and processed as described in Sec. 4 on page 10.

7.2 Phase II Testing Results - Men

Just like Phase I testing, the player's angle of attack progressed more downward as the tee height was reduced (see Fig. 15a on the next page). No matter what their angle of attack was using their normally teed driver, the angle of attack decreased as the tee height decreased.

Data plots in this section are similar to those in Sec. 5 on page 12. The solid symbols represent the mean of 10-12 shots hit at the tee heights enumerated above: normal, 1-in step, ADC short and turf. Error bars represent 95% mean confidence interval for the 10-12 shots. Dashed lines represent a linear fit through the four tee heights for each player.



(a) Angle of Attack, deg **(b)** Club Head Speed, mph

Figure 15: Phase II men's angle of attack and club head speed as a function of tee height. Circled symbols are the player's normal tee height.

For the most part, players were able to maintain their club head speed with the ADC (see Fig. 15b). The slopes of the linear fits are given in Table 5 on the following page, but it is clear that there was only a slight reduction in club head speeds as tee height diminished. On average, players only lost 0.58 mph/in club head speed as the tee was lowered using the ADC for turf and low teed shots. Two of the seven player had a small negative slope for club head speed meaning there was no appreciable loss of club head speed as the tee height was decreased.

Figure 16a on page 22 shows the Phase II men's ball speed as a function of tee height. All but one of the players lost a little ball speed as tee height was lowered. On average, the ball speed dropped 1.78-mph/in as a function of tee height. The player having the negative sensitivity, P3963, was small and simply maintained ball velocity rather than increasing ball speed.

Comparing rates of ball speed loss for Phase I (players using only their drivers with turf shots) and with Phase II (players using the ADC for turf and low tee height) shows a reduction in average loss rates of 2.34-mph/in versus 1.78-mph/in, respectively. The Alternate Driving Club was effective in reducing ball speed loss as tee height was lowered.

Ball speed, launch angle and back spin optimization are the critical factors for driving distance. It was observed that angle of attack was lowered as teeing height decreased and that resulted in a lower launch angle for the players (see Fig. 16b). Back spin increased as the tee height decreased (Fig. 16c on page 22) as would be expected as well. However, comparing spins in Fig. 16c on page 22 to those in Fig. 12c on page 15 shows that the ADC was mitigating increased spin with lower tee heights. Of the three Phase II golfers having flat or increasing spin as tee height diminished, only one had a mean spin slightly over 3,000 rpm. That is, their spin rates weren't excessive.

Launch angle loss was mitigated by the ADC as can be seen by comparing Fig. 16b on page 22 to Fig. 12b on page 15. Comparing average results from Table 5 on the next page to Table 3 on page 17 launch angle decreased 1.04-deg/in with ADC versus 3.02-deg/in with their own drivers who hit off the turf. This was very likely because the ADC's loft was measured at 11-deg rather than the nominal loft slightly lower than 9-deg for these players (see Appendix Table 7 on page 37).

Since the ADC was more shallow (less crown-to-sole height at face center) than a traditional driver, one expects the impact location to be nearer the face center. Figure 17 on page 22 shows the impact location for players becoming lower as tee height is reduced. This is similar to the data for men players hitting their own drivers for decreasing tee height (11 on page 14). But comparing Table 5 on the following page to Table 3 on page 17 shows

Table 5: Phase II Men's Driver Sensitivities to Tee Height Reduction

Player	Ball Speed Loss[a], mph/in	Club Speed Loss[a], mph/in	Angle of Attach Loss[a], deg/in	Launch Angle Loss[a], deg/in	Total Spin Loss[a], rpm/in
P3956	1.82	0.88	2.5	1.9	375
P3963	-0.26	1.84	2.0	1.1	273
P3104	3.88	0.91	2.8	-0.4	-385
P3068	0.51	-0.03	1.5	1.9	-11
P3569	3.32	0.62	0.9	2.1	415
P3641	0.44	-0.34	1.1	0.2	386
P3813	2.77	0.19	1.6	0.5	-258
Average	1.78	0.58	1.78	1.04	114
Std. Dev.	1.60	0.73	0.70	0.97	332

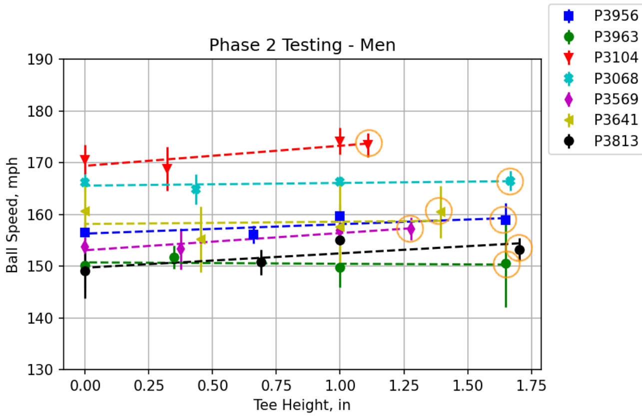
[a] Positive sensitivity/slope results in loss as tee height is reduced.

Player	Carry Distance Loss[a], yds/in	Descent Angle Loss[a], deg/in	Vertical Impact Location Loss[a], mm/in	Total Distance Loss[a], yds/in	Spin to Launch Ratio Loss[a], rpm/deg/in
P3956	17.0	7.6	1.7	4.6	-43
P3963	15.8	5.9	1.6	6.6	-26
P3104	4.9	-2.4	3.2	8.8	-26
P3068	11.6	4.3	3.0	4.1	-93
P3569	32.4	10.5	3.4	17.0	-117
P3641	2.0	3.5	-1.1	-3.0	33
P3813	5.9	-0.4	3.4	5.5	-26
Average	12.8	4.2	2.2	6.2	-43
Std. Dev.	10.3	4.5	1.6	6.0	49

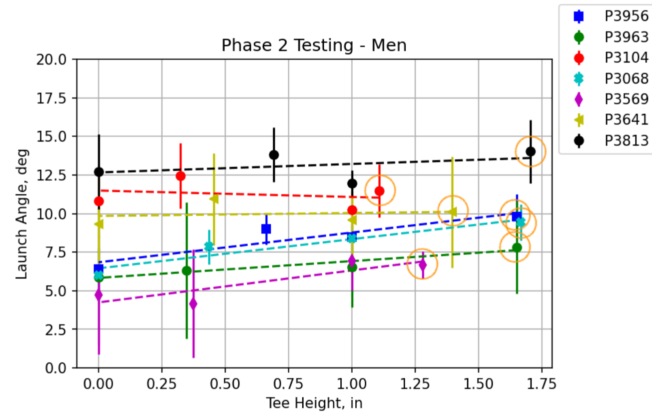
[a] Positive sensitivity/slope results in loss as tee height is reduced.

that the ADC reduces the rate at which the impact location falls below the face center as tee height diminishes. This helps to maintain ball speed and mitigate back spin increase as tee height is lowered.

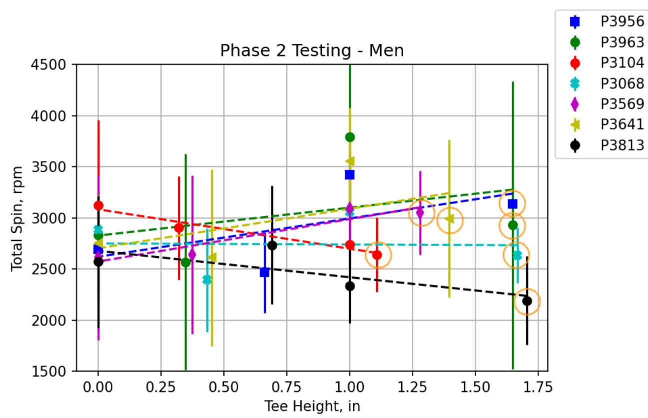
Driving carry and total distance for individual players was reduced as tee height was reduced (see Figs. 18a on page 23 and 18c on page 23). Average loss rates for carry and total distance from Table 5 in Phase II with the ADC were less than those of Phase I (with turf shots) given in Table 3. One has to examine individual player launch conditions to see where the ADC benefits some players. This is done in Sec. 9 on page 31.



(a) Ball Speed, mph



(b) Launch Angle, deg



(c) Spin, rpm

Figure 16: Phase II men's launch conditions as a function of tee height. Circled symbols are the player's normal tee height.

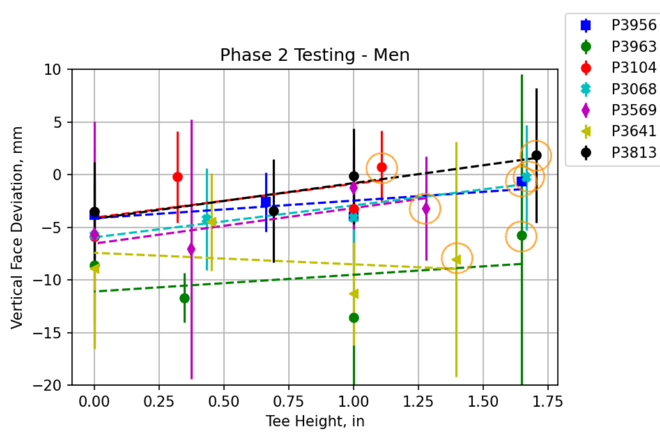
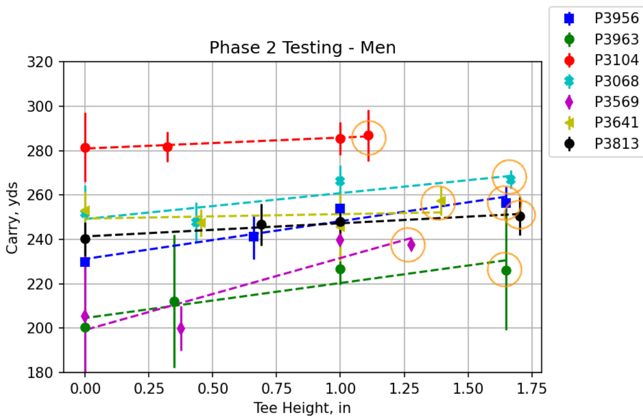
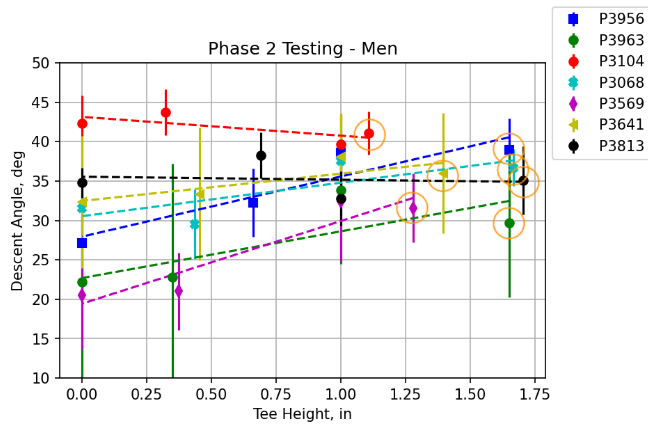


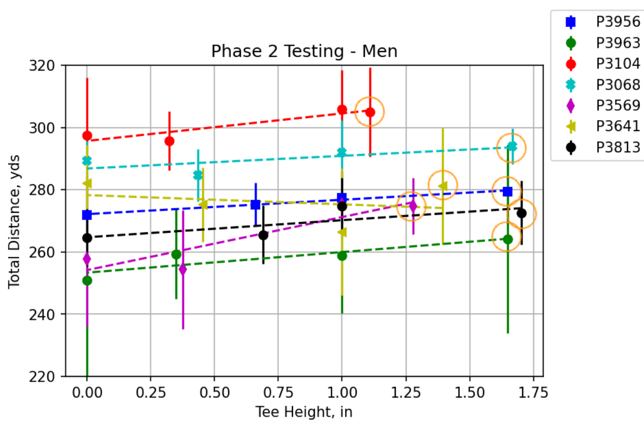
Figure 17: Phase II men's vertical face impact relative to face center as a function of tee height. Circled symbols are the player's normal tee height.



(a) Carry Distance, yards



(b) Descent Angle, deg

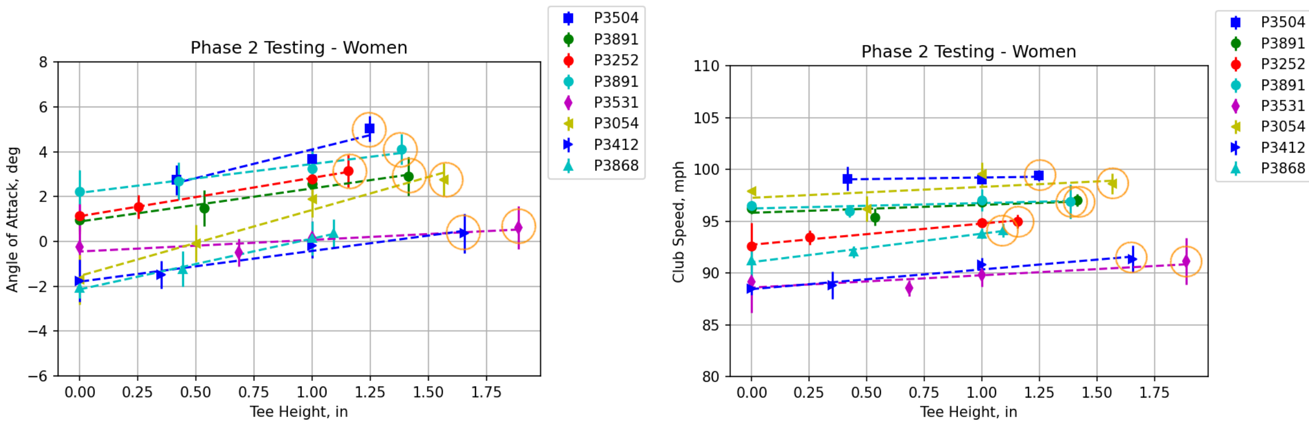


(c) Total Distance, yards

Figure 18: Phase II men's carry / total distances and descent angle as a function of tee height. Circled symbols are the player's normal tee height.

7.3 Phase II Testing Results - Women

First, look at the club head presentation to the golf ball for the women. Just like the men tested, the women automatically adjusted their angle of attack as the tee height was lowered (Fig. 19a). The woman's angle of attack deacreased in a nearly linear manner on average 1.8-deg/in (Table 6 on the following page). Club head speed dropped slightly as the tee height was lowered (Fig. 19b). The womens's average club head speed loss was 1.3-mph/in which was almost twice that of the men. One might expect this due to the average 1-in length difference in the ADC hit on the two lowest teed shots. (Player's driver lengths are given in Table 7 on page 37.)



(a) Angle of Attack, deg

(b) Club Head Speed, mph

Figure 19: Phase II women's angle of attack and club head speed as a function of tee height. Circled symbols are the player's normal tee height.

A last club head presentation variable considered was the vertical face deviation of impact (see Fig. 20 on the next page). The women's vertical face deviation taken as a whole looks more variable as a function of tee height than the men's. On average, the women's vertical impact location loss was 1.6-mm/in compared to the men's value of 2.2-mm/in, however, the standard deviation for the women was 6.8-mm/in compared to the men's 1.6-mm/in (from Table 5 on page 21 and Table 6 on the next page). This high deviation is likely an indication that the women were struggling with the ADC or lower tee height.

In the following Section 9 on page 31 the low spin characteristics of the ADC is discussed in context with men hitting in both Phase I and Phase II. One of the reasons the ADC was chosen is that a "hot" metal wood generally launchs high with low spin. Players are not trying to land on and "hold" a green when using "hot" clubs. In general, higher club head speeds create higher spin rates and apex heights. The ADC was likely below the threshold of acceptable club head speed to achieve quality launch conditions. In other words, the 11-deg loft in this head may have been too strong for players having club head speeds below, say, 100-mph. At sub-100-mph, the ADC was not able to produce enough spin for quality shots even though it had slightly more loft than those players were used to playing.

The challenge for under 105-mph club head speed players was evident in watching the women hitting the ADC. Below 100-mph club head speed, the ability to hit, and like, the ADC seemed to depend on a player's swing characteristics rather than universal acceptance. Multiple women players struggled with the ADC off the turf. One of the women could not get a quality golf shot off the turf with the ADC and only three tee heights were reported for her. Looking at her (P3504) launch initial conditions (Fig. 21 on page 26) for the ADC teed as the player chose (blue square marker at approximately 0.4-in height), shows her maintaining ball speed, slightly higher ball launch and an unacceptable spin below 2000-rpm. The increased launch was probably her swing's effort to get stable flight in spite of insufficient spin. Throughout the data reported player P3504 demonstrates that clubs benefiting players above a certain club head speed threshold may hurt players below that value.

Women golfers tested as tee height decreased were able to substantially maintain ball speed, lost some of their launch angle and subtantially lost total spin. In comparison to Phase II men, ball speed and launch angle losses

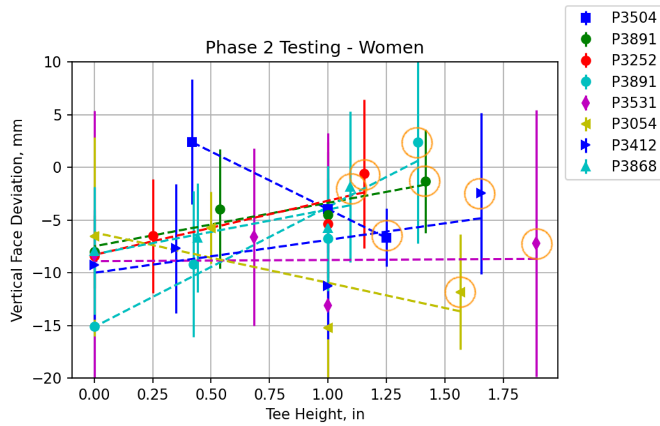


Figure 20: Phase II women's vertical face impact relative to face center as a function of tee height. Circled symbols are the player's normal tee height.

Table 6: Phase II Women's Driver Sensitivities to Tee Height Reduction

Player	Ball Speed Loss[a], mph/in	Club Speed Loss[a], mph/in	Angle of Attach Loss[a], deg/in	Launch Angle Loss[a], deg/in	Total Spin Loss[a], rpm/in
P3504	4.0	0.3	2.6	-0.9	1017
P3891	-0.6	0.8	1.5	2.3	839
P3252	6.6	2.0	1.7	0.4	71
P3891	-3.3	0.5	1.3	4.0	810
P3531	0.1	1.2	0.5	1.6	563
P3054	0.5	1.1	2.9	2.3	769
P3412	2.0	1.9	1.4	2.1	315
P3868	3.6	2.7	2.3	1.5	783
Average	1.6	1.3	1.8	1.7	646
Std. Dev.	3.1	0.8	0.8	1.4	312

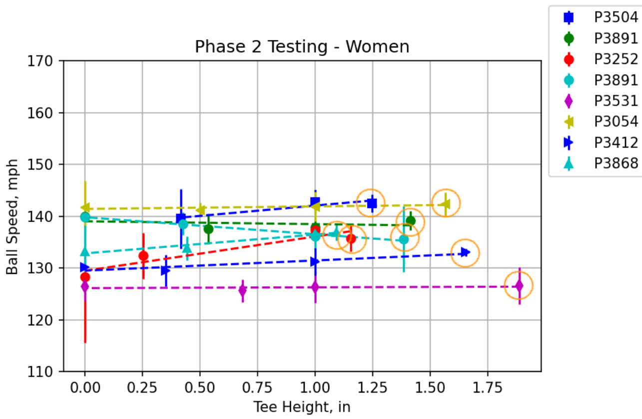
[a] Positive sensitivity/slope results in loss as tee height is reduced.

Player	Carry Distance Loss[a], yds/in	Descent Angle Loss[a], deg/in	Vertical Impact Location Loss[a], mm/in	Total Distance Loss[a], yds/in	Spin to Launch Ratio Loss[a], rpm/deg/in
P3504	71.1	15.2	-10.9	53	108
P3891	6.2	7.0	4.1	-11	16
P3252	21.8	3.3	5.1	17	3
P3891	9.3	9.2	11.4	-11	-29
P3531	20.1	7.2	0.1	10	15
P3054	32.5	11.0	-4.8	17	-14
P3412	26.7	7.7	3.1	15	-50
P3868	30.1	10.3	4.2	15	37
Average	27.2	8.9	1.6	13	11
Std. Dev.	20.0	3.5	6.8	20	48

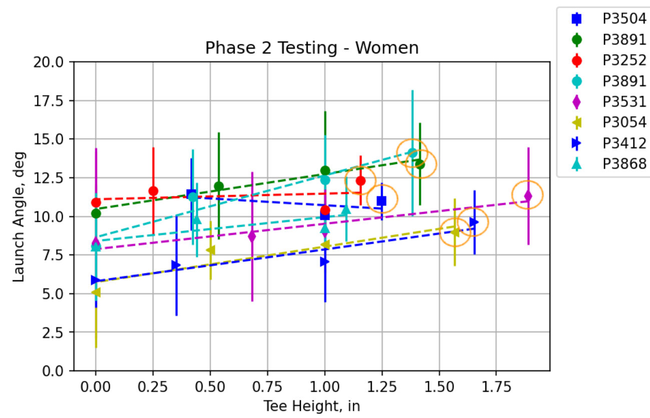
[a] Positive sensitivity/slope results in loss as tee height is reduced.

were comparable, but the spin lost using the ADC was 646- versus 114-rpm/in of tee height (see Tables 6 on the preceding page and 5 on page 21).

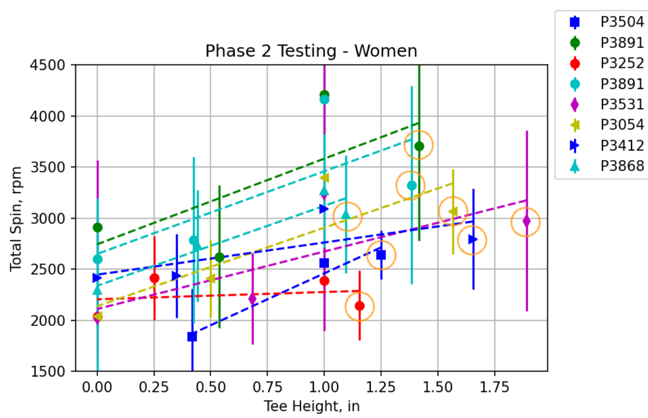
While men players gamer driver lofts are generally below the measured loft of the ADC, women's gamer driver lofts may be nearly equal to the ADC. Again, men and women players did not get loft/lie fitting for the ADC, only shaft flex fitting within one shaft model was conducted.



(a) Ball Speed, mph



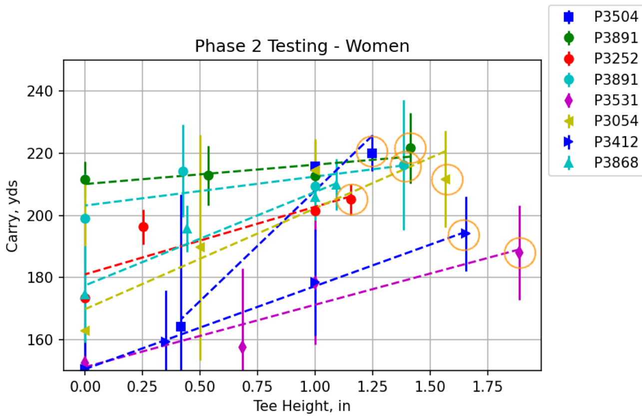
(b) Launch Angle, deg



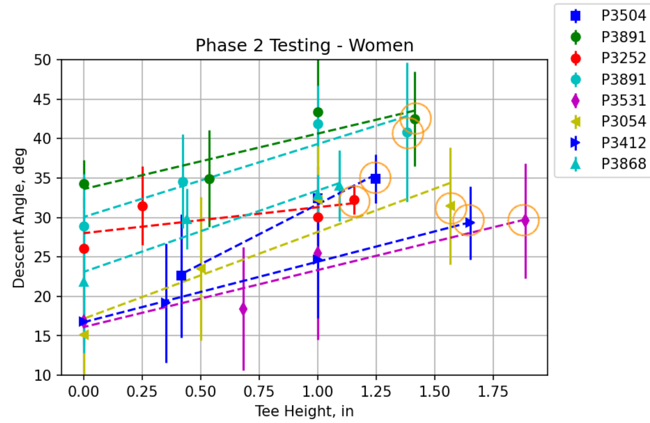
(c) Spin, rpm

Figure 21: Phase II women's launch condtions as a function of tee height. Circled symbols are the player's normal tee height.

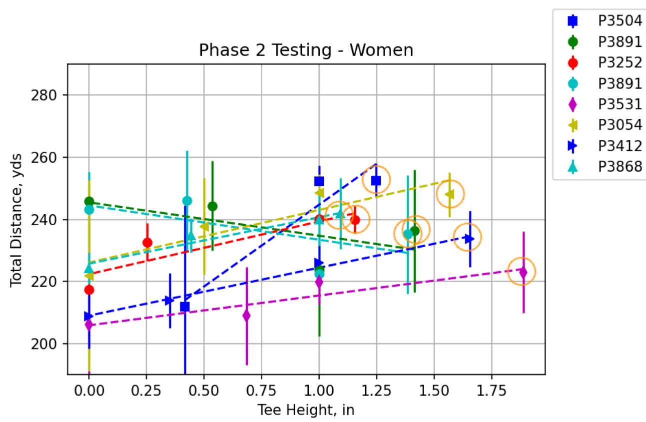
Carry distance for women decreased as tee height was reduced as is seen in Fig. 22a on the following page. This would be expected for a slight decrease in ball speed and lower launch angles. The mean carry distance loss per inch teeing height was 27.2-yds/in which was over double that value for men. The lower launch and spin values make for a flatter trajectory and the women made up lack in carry with added bounce and roll. Total distance loss per tee height for women was 13-yds/in. Again, this value was about twice that of Phase II men. Descent angles for women were quite a bit lower (more shallow giving more bounce and roll) than the men counterparts (see Fig. 22b on the next page and Fig. 18b on page 23). This was expected in light of the prior discussion on ADC spin values for women. The total distance loss for women would have been greater if it hadn't been for distance gains by player P3891 who was tested twice and whose total distance gained 11-yards/in tee height as the ball was teed lower. More analysis of this player follows. Not counting two test sessions with P3891, the women's total distance would have been reduced around 21-yds/in as tee height was decreased. Removing total distance values of players P3504, who struggled with the ADC and P3891 who hit the ADC exceptional compared to her driver, the women players lost 14.8-yds/in of tee height.



(a) Carry Distance, yards



(b) Descent Angle, deg



(c) Total Distance, yards

Figure 22: Phase II women's carry/total distances and descent angle as a function of tee height. Circled symbols are the player's normal tee height.

Only women player P3891 had an increase in ball speed as the tee height was reduced. Player P3891 also showed excellent efficiency in spin/launch ratio, nearly maintaining optimum conditions resulting in the least carry distance loss rate of 6.2 yards/in. This resulted in total distance loss rate -11 yards or an actual net gain in total distance in Fig. 22c.

Also note that player P3891 was tested twice nine days apart in Phase II testing. The reason for this was to verify the results from the first test with regard to increased ball speed as tee height was lowered. An additional curiousity was that she had the oldest driver head model (circa 2011, 440 cc) for all the men and women. Oldest by about 6-years as can be seen from Table 7 on page 37. The volume of the driver was slightly less than the second lowest volume of 445 cc. Total distance results for these two tests plus a circa 2020, 460 cc driver hit after Phase II protocol was finished shows the 2011 dated driver was likely why she had negative distance slopes (see Fig. 23 on the next page). The ADC was clearly a better driving club than her 10-year old model.

It was also interesting to observe the repeatability of a golfer for this testing. This can be observed thoughout the plots in this section. The only plot in which the two tests weren't quite similar was vertical face deviation, Fig. 20 on page 25.

One final observation on player P3891 is that her spin with her 2011 driver was high (see Fig. 21c on the previous page) which likely resulted in distance loss. So it is possible a poor shaft fit was one of the weaknesses in the 2011 driver.

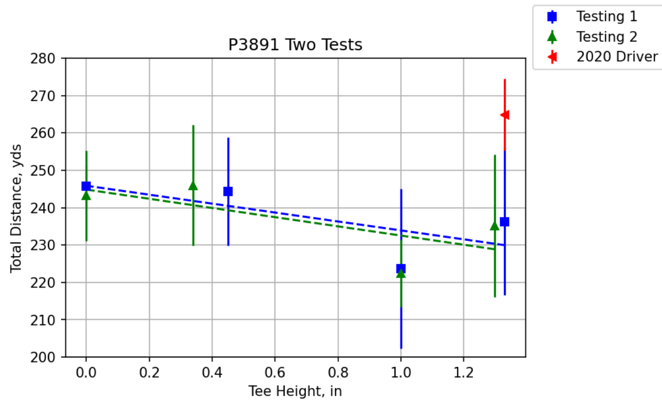


Figure 23: Total distance for two Phase II tests for player P3891 with 2020 driver added.

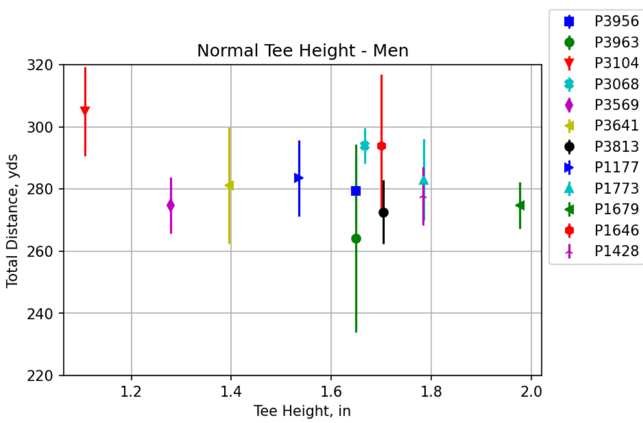
8 DRIVING DISTANCE AT PLAYER'S NORMAL TEE HEIGHT

The data from Phase I and Phase II were combined to examine if there was a correlation between tee height and driving distance for player's normal tee heights. Figure 24a on the following page shows total driving distance versus normal tee heights for men tested in both phases. Notice that the lowest normal tee height was used by the longest total driving distance player. Furthermore, there does not appear to be any correlation of total driving distance to normal tee height. Figure 24b on the next page shows a similar plot of carry distance for all men, and there is no apparent trend or relationship between carry distance and normal tee height.

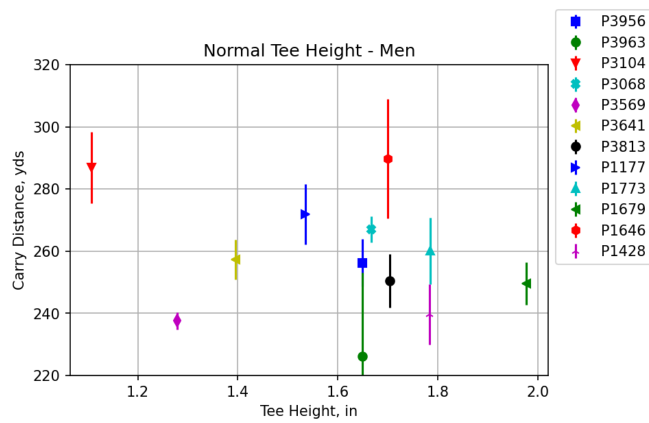
One of the reasons to tee the ball high is to make impact on the upswing. Figure 24c on the following page shows total distance versus angle of attach at player's normal teeing height for all men golfers tested. There may be a slight trend between higher angle of attack generating more total driving distance. However, it is not possible to see a definitive trend from data taken in this study.

Data from women players using their drivers and normal teeing height are shown in Fig. 25 on page 30. This data is Phase II data since women did not hit in Phase I. The top two subplots show total and carry distance as a function of tee height. As with the men's data in Fig. 24 on the following page, there is not correlation between tee height and driving distance. In fact, it might be possible to say that the women teeing the ball the highest had the shortest total and carry driving distance. A high tee height may have been used to achieve more distance that other swing characteristics did not provide.

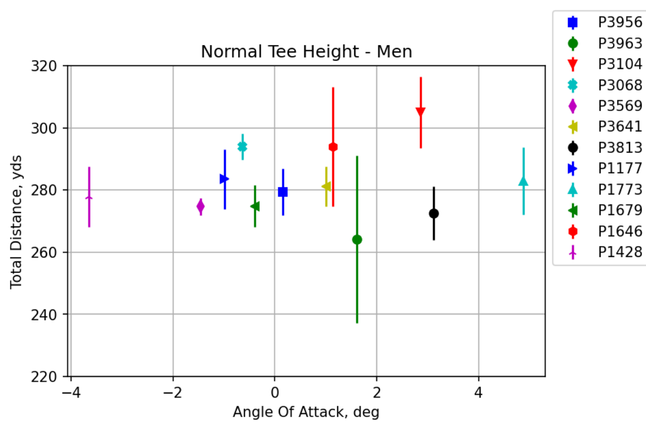
Total distance as a function of angle of attack (Fig. 25c on page 30) shows that women hit up on the ball more than men (Fig. 24c on the following page). None of the women had a negative angle of attack while about half of the men had a small negative angle of attack.



(a) Total Driving Distance, yards

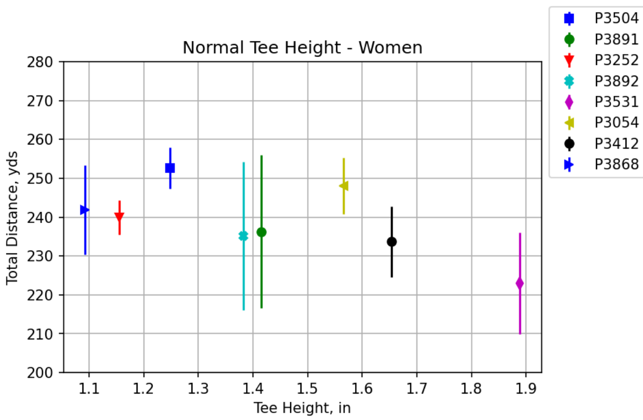


(b) Carry Distance, yards

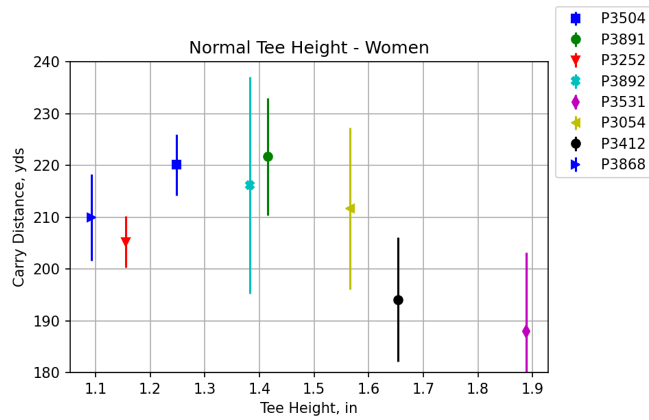


(c) Total Distance vs Angle of Attach

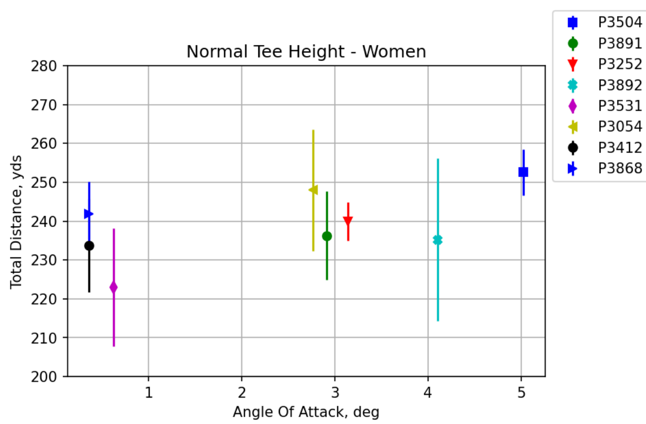
Figure 24: Men's normal tee height distance as a function of tee height and angle of attack.



(a) Total Driving Distance, yards



(b) Carry Distance, yards



(c) Total Distance vs Angle of Attach

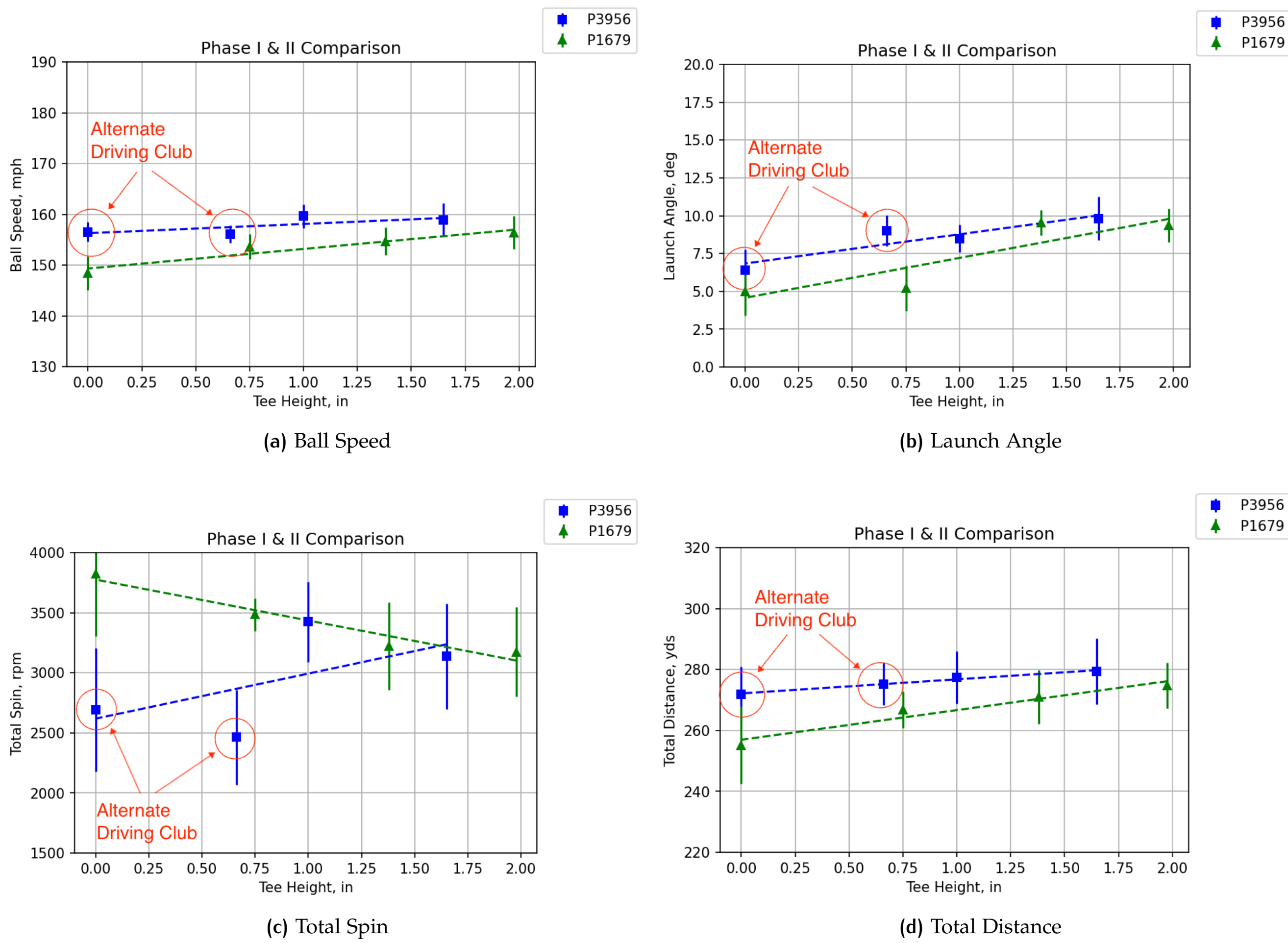
Figure 25: Women's normal tee height distance as a function of tee height and angle of attack.

9 EFFECTIVENESS OF THE ALTERNATIVE DRIVING CLUB (ADC)

In Sec. 7.2 on page 19 the effectiveness of the ADC was discussed a little bit. The off-the-shelf 3-wood chosen for the ADC was known to be a "hot" [3] 3-wood. A prototype ADC made for this study was deemed not appropriate and would have created delays in gathering data for this study. In this section, the effectiveness of the ADC chosen is examined.

Three players hit shots in both Phase I and Phase II. Players were men since only men's data was taken in Phase I. Dates that all three players hit were in May 2021 (Phase I) and in August 2021 (Phase II). Data for each player will show us how effective the ADC was in producing desired launch conditions.

The first player, labeled Player A, hit in May 2021 with legend data P1679 and in August 2021 with legend P3956. Ball speed, launch angle and back spin plots are shown for both test dates in Fig. 26. Ball speed and launch angle have similar data as a function of tee height. Data taken in August 2021 show a slight uniform increase in ball speed and launch angle. Shots hit with the ADC are circled in red. Back spin shows how the ADC performed better than his driver for balls teed low and off the turf. In fact, the ADC teed up 0.661-in produced his longest drive having an average total distance of 284.6-yards. The ADC off the turf ranked third in total distance at 278.5-yards. In between these two was his normally teed driver (from P3956) giving 279.8-yards total distance.



(a) Ball Speed

(b) Launch Angle

(c) Total Spin

(d) Total Distance

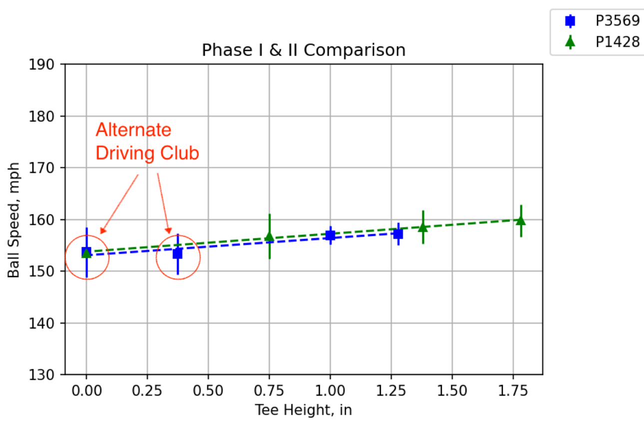
Figure 26: Phase I and II ball speed, launch, total spin and total distance data for Player A.

3 By "hot" we mean, for example, a titanium fairway wood that is conforming to the USGA/R&A Rules, Ltd. having excellent ball speed, a flat trajectory and plenty of bounce and roll.

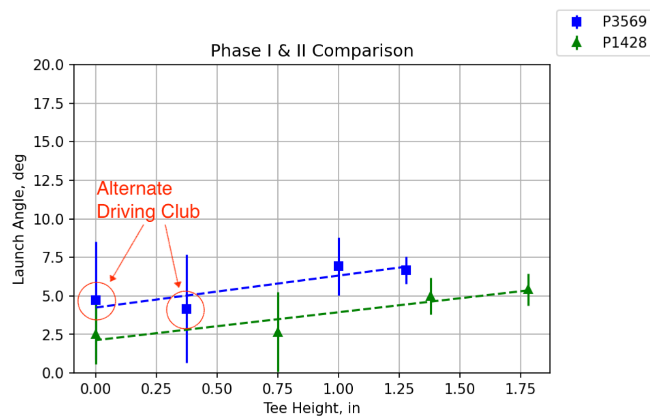
Results for Player A using a stock 3-wood metal that was hit only in the two tests indicate that it is likely that golfers would likely maintain all their total driving distance should tee heights be reduced. The current ADC would likely be optimized to perform even better in a total redesign. For instance, potential club length up to 45-in with adjustable weights for swingweight and center of gravity adjustment. Tungston heel-toe weights could increase forgiveness.

Player B Phase I and Phase II results are shown in Fig. 27. Phase I testing was done in May 2021 and Phase II testing was done in August 2021. Test P3569 used the Alternate Driving Club in August and test P1428 used only his driver in May. Ball speed is indistinguisable from the two testing dates. His launch angle was higher in the ADC test. His driver was set to 10.5-deg loft to help him launch the ball higher. However, Player B struggles with higher spin than is thought optimum. The ADC considerably reduced Player B's spin into a desirable range. This spin rate and a higher launch sould improve his driving performance. Even with less than optimal launch conditions, Player B lost considerable total distance with the ADC, 257.7-yards, which was under his normal tee height driving distance of 274.7-yards.

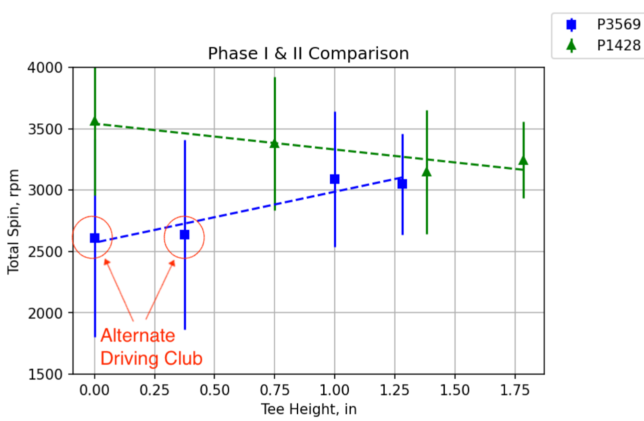
In Player's B hands, the ADC exhibited potential to regain total driving distance lost to tee height reduction seen in better spin values. However, with the current ADC he is losing valuable distance at lower tee heights.



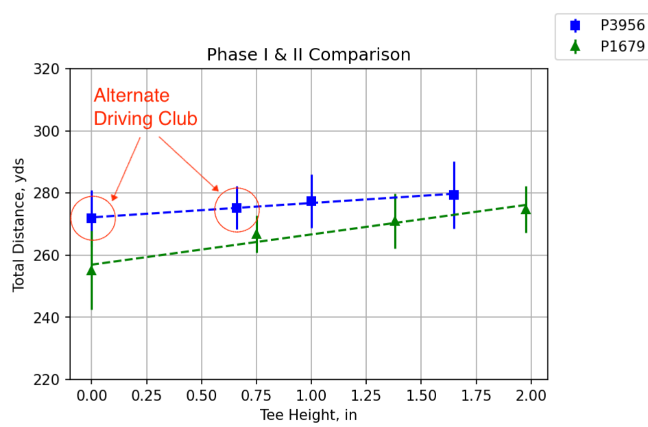
(a) Ball Speed



(b) Launch Angle



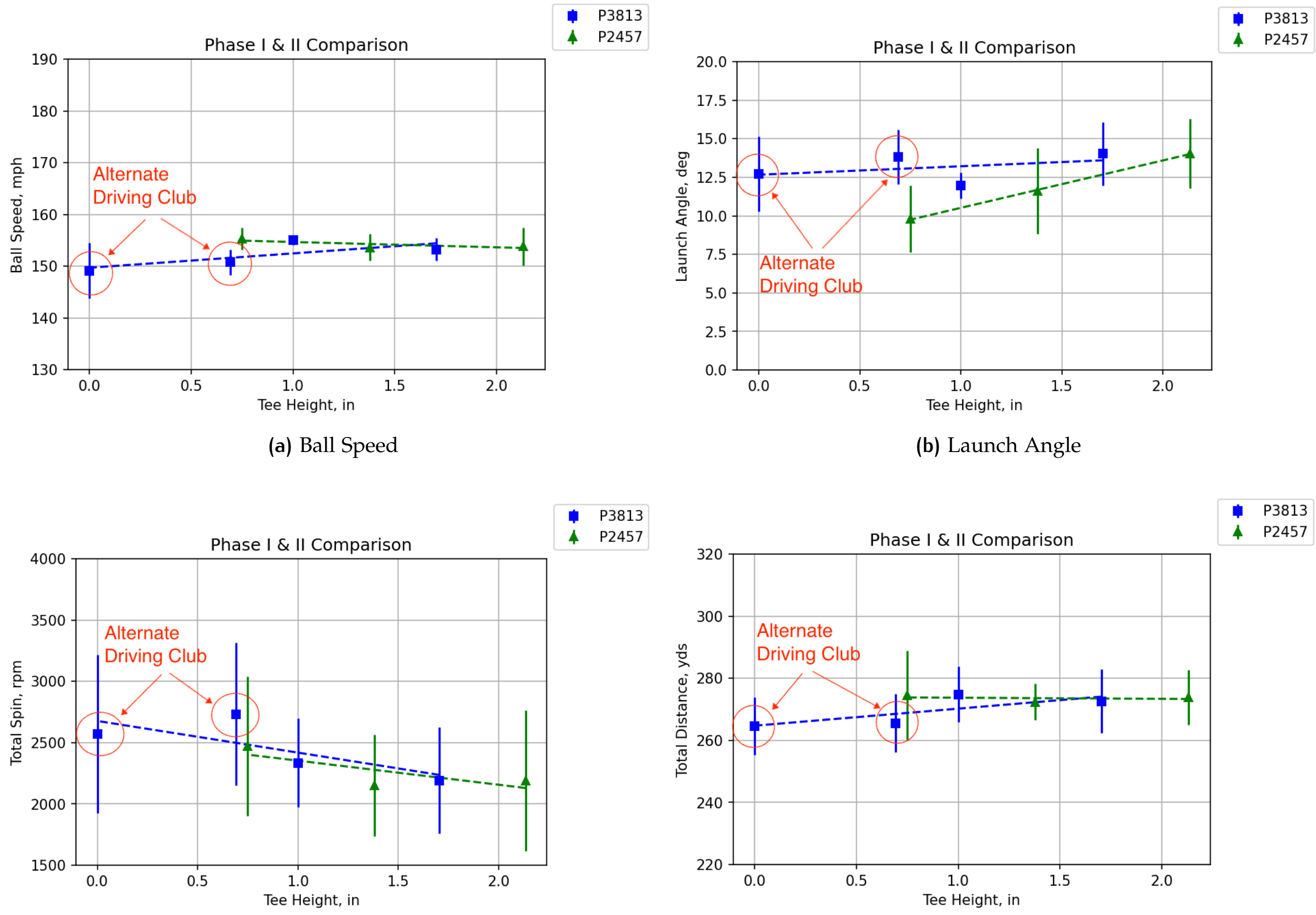
(c) Total Spin



(d) Total Distance

Figure 27: Phase I and II ball speed, launch, total spin and total distance data for Player B.

Player C was the third player to hit in Phase I (P1428 in May 2021) and Phase II (P3956 in August 2021), however, in his Phase I drivers weren't hit off the turf. (Phase I results in Figs. 10a on page 13 to 13 on page 16 with only three data points are the three players in this group.) Ball speed was comparable, albeit a bit lower, for the ADC (see Fig. 28 on the following page). Launch angle was higher for the ADC which was likely due to the ADC's loft of 11-deg versus Player C's loft of $8\frac{1}{2}$-deg. Player C's back spin using the ADC was comparable to that using his driver unlike Players A and B. However, the spin numbers of Player C look to be optimized very well indicating a very effective head-shaft combination.



(a) Ball Speed (b) Launch Angle

(c) Total Spin (d) Total Distance

Figure 28: Phase I and II ball speed, launch, total spin and total distance data for Player C.

There were enough differences between men's and women's results (compare Fig. 25c on page 30 to Fig. 24c on page 29 for example) that men's and women's Alternate Driving Clubs would likely have many different design features.

Data from players hitting in both Phase I and II indicate that the ADC helps players with low and no tee heights achieve better launch condtions than their "gamer" drivers.

10 PLAYER VERSUS ROBOT RESULTS

This project used robot and player testing to evaluate driving distance as teeing height was reduced. In the robot testing, tee height reduction corresponded to impact offset length below face center while players were able to make adjustments keeping impact closer to face center. Driving distance decreased for both robot and player testing. Comparing the robot test results to those of a couple of the players provides insight into both types of testing. Two of the players tested had speeds comparable to those used in robot testing.

Figure 29 shows total driving distance for all robot tests and two players who were tested. One of the players normally teed the ball higher than the the assumed robot height of 1.2-in and one player normally teed the ball lower. The 95% mean confidence inteval error bars were computed and are shown for the players since all the shots taken had total distance computed. Dashed lines are quadtratic fits to the four tee heights total distance.

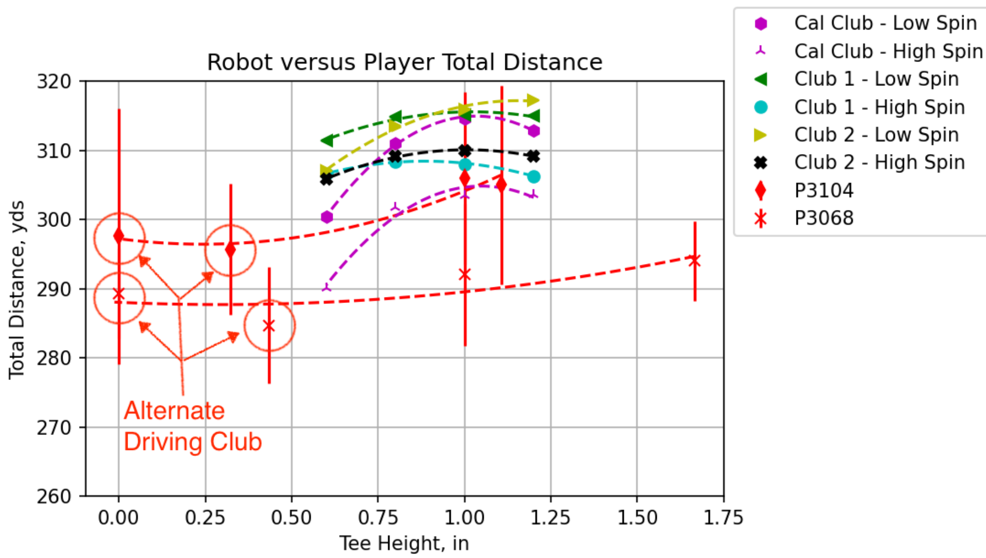


Figure 29: Total distance for robot testing and two players.

The range of tee height change is greater for the players than the robot. However, tee height for the robot and players are really two diffent quantities. For the robot, a change in tee height directly corresponds to the lower distance of impact down the face. A 0.6-in tee height for the robot is 0.6-inches below the face center. For the players, a tee height less than 0.5-in produced impact locations with the Alternate Driving Club of 0-in and about 0.12-in below the face center for P3104 and P3068, respectively. When a player hits driver off the turf (say, P1679) their average contact with the ball is about 0.24-in below face center. Clearly, the players adapt to produce better shots.

Finally, the quadratic fits for the players appear to be gaining back some distance the tee heights near the turf. This is likely the start of the "claw-back" distance, and it is evidence of effectiveness of the Alternate Driving Club in adding distance.

Another way to consider robot and player testing is to map the robot tee height data onto an interval similar to the player's tee heigth interval. Instead of the robot data ranging from 1.2-in to 0.6-in, the tee height axis is stretched from 0 (off turf) to 1.2-in. This plot is shown in Fig. 30 on the following page. The vertical face impact offset for robot data was actually more than that of the players. So this may be a better way to represent both data sets together. The quadratic fits for robot and players still have different curvatures: concave and convex.

At this time it is not clear on how to link the robot and player testing data.

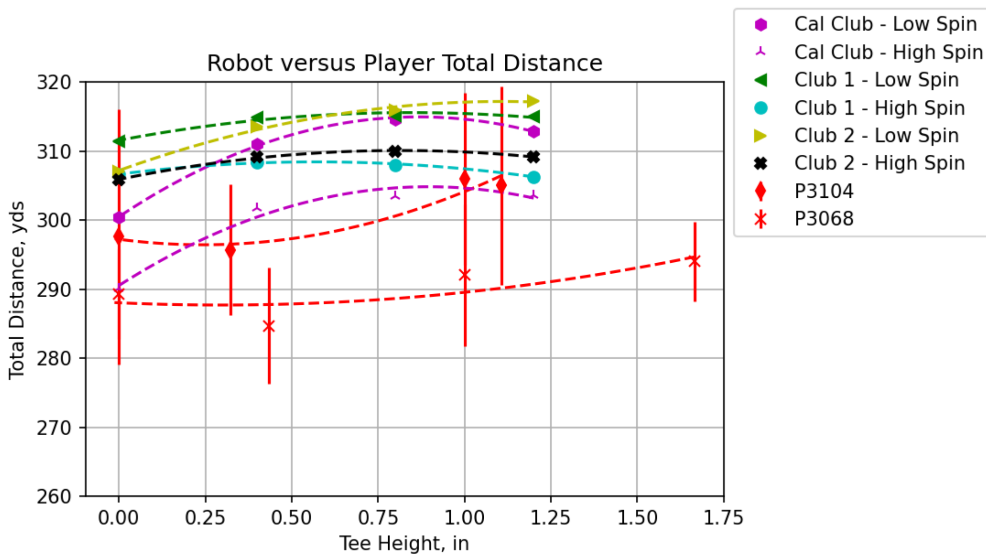


Figure 30: Total distance for robot testing and two players with robot tee height scaled..

11 ACKNOWLEDGEMENTS

The authors would like to thank:

1. Steve Quintavalla and John Spitzer and the United States Golf Associtation for their guidance, discussions and the loaner GCQuad launch monitor;
2. Cal Poly Men's and Women's coaches, Phil Rowe and Sofie Aagaard, players and the use of the beautiful Mustang Golf Academy;
3. Cool Clubs and Mark Timms for helping with choosing and building the Alternate Driving Club;
4. San Luis Obispo Country Club for access to the course in spite of a major course renovation;
5. All the players who took the time and effort to hit for us.

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[2] Internal code used at Untied States Golf Association at the time of writing this report

[3] National Institute of Standards and Technology (2021), "Engineering Statistics Handbook" , 1.3.5.17.1 Grubbs' Test for Outliers, URL: https://www.itl.nist.gov/div898/handbook/eda/section3/eda35h1.htm, Accessed 25 August 2021

[4] United States Golf Association, R&A Rules Limited, "Proposed Launch Condtion Limits Optimization of Overall Distance," 16 March 2021

[5] United States Golf Association, R&A Rules Limited, "Proposed Bounce Model for Use in Evaluating Optimum Overall Distance," 16 March 2021

APPENDIX

This appendix lists the players tested equipment specifications. Driver model year and volume was taken from the valueguide.pga.com web site and the manufacturer's site (accessed September 2021), respectively. Driver lofts were as player reported them of based on hosel connector settings and manufacturer's web site. Lengths were measured in the address position using an aluminum carpenters scale (i.e., a 48-in metal ruler).

Table 7: Player's Equipment Specifications

ID	Driver	Loft, deg	Flex	Len., in	Ball	ADC Configuration
P1177	2020 460 cc	$10\frac{1}{2}$	X	45	Premium	NA
P1391	2020 460 cc	9	X	45	Premium	NA
P1773	2019 460 cc	9	X	$45\frac{1}{2}$	Premium	NA
P1679	2019 460 cc	9	X	45	Premium	NA
P1646	2020 460 cc	9	X	45	Premium	NA
P1428	2021 445 cc	$10\frac{1}{2}$	X	$44\frac{3}{4}$	Premium	NA
P2138	2017 445 cc	9	S+	$45\frac{3}{4}$	Premium Range	NA
P2422	2020 460 cc	$7\frac{1}{2}$	X	$46\frac{1}{2}$	Premium Range	NA
P2457	2021 450 cc	$8\frac{1}{2}$	X	45	Premium Range	NA
P3963	2019 460 cc	9	X	45	Premium	S 44-in
P3956	2019 460 cc	9	X	45	Premium	X 44-in
P3504	2019 460 cc	$10\frac{1}{2}$	S		Premium	S 44-in
P3891	2011 440 cc	$10\frac{1}{2}$	S	$44\frac{1}{2}$	Premium	S 44-in
P3104	2021 445 cc	$7\frac{1}{2}$	X	44	Premium	X 44-in
P3252	2020 460 cc	$10\frac{1}{2}$	R	44	Premium	R 44-in
P3068	2021 460 cc	9	X	$44\frac{3}{4}$	Premium	X 44-in
P3569	2021 445 cc	$10\frac{1}{2}$	X	$44\frac{3}{4}$	Premium	X 44-in
P3641	2021 460 cc		TX	$44\frac{1}{2}$	Premium Range	X 44-in
P3531	2019 460 cc	$10\frac{1}{2}$	R	$45\frac{1}{4}$	Premium Range	R 44-in
P3813	2021 450 cc	$8\frac{1}{2}$	X	45	Premium Range	X 44-in
P3054	2020 460 cc	$10\frac{1}{2}$	S	$45\frac{3}{4}$	Premium	S 44-in
P3412	2017 445 cc	9	S	45	Premium	S 44-in
P3868	2019 435 cc	9	S	$45\frac{1}{8}$	Premium	S 44-in