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ARTICLE

The Influence of Clubhead Mass on Clubhead and Golf Ball Kinematics

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The purpose of the study was to determine the influence of head mass on driver clubhead kinematics at impact as well as the resulting kinematics of the golf ball. Three clubhead mass conditions (174, 190, and 200 g) were tested by 18 low-handicap (1.7 ± 2.2) golfers representing a range of clubhead speeds (40–58 m/s). Each participant executed 12 drives per condition using the same driver, which accommodated screws of varying mass in the clubhead. Increasing clubhead mass was found to decrease clubhead speed ($p < .001$), but have no meaningful influence on ball speed. Similarly, increasing clubhead mass was associated with greater dynamic loft ($p = .001$), a steeper angle of attack ($p < .001$), and more spin ($p < .001$). There was no net influence on carry distance and only a relatively small effect on the total predicted distance of carry + roll. Increasing clubhead mass tended to create more fade spin ($p < .001$) as well as start the ball further to the right ($p < .001$), which resulted in meaningful differences in the average lateral finish location among conditions ($p < .001$). This finding has important implications for club fitters and manufacturers.

***Keywords*:** golf, clubhead speed, ball flight, clubhead mass, distance, spin rate

The mass of a golf clubhead will influence both the kinematics with which it is delivered to the ball, by the golfer, as well as the initial ball flight parameters

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resulting from the collision of impact. Increasing the mass of the clubhead will increase the overall inertia of the club (i.e., both the mass and moment of inertia (MOI)). All else equal, from a mechanics standpoint, increasing the inertia of the club will theoretically result in a reduction in the clubhead speed with which a given golfer can deliver to the ball at impact. Yet, for a given clubhead speed at impact, an increase in clubhead mass will result in an increase in ball speed (Daish, 1972; Jorgensen, 1994).

The bulk of previous research suggests that increasing the inertia of a striking implement will reduce the maximum velocity that can be obtained when wielding the implement (Daish, 1965; Reyes & Mittendorf, 1998; Smith, Broker, & Nathan, 2003; Cross & Bower, 2006; White, 2006; Cross & Nathan, 2009). More specifically, it would appear that maximum striking velocity is influenced to a greater degree by an implement's MOI than it is by the implement's mass (Smith et al., 2003; Cross & Nathan, 2009). More recently, however, Haeufle et al. (2012) recruited 12 golfers to investigate the influence of increasing shaft mass (22 g increase) on clubhead speed. On average, they found no difference in clubhead speed. At the individual level, only a single participant generated a significantly slower clubhead speed with the heavier shaft. Interestingly, the only other significant difference was achieved by a participant that swung the heavier club faster. It is possible that the difference in MOI created by the addition of the 22 g at a distance of 355 mm from the butt was not large enough to create a meaningful effect.

A few studies have investigated the concept of maximizing ball speed via determining the optimal clubhead mass. Daish (1965) affixed brass discs to the end of a 3-iron shaft to simulate six clubhead masses ranging from 100 to 350 g. Four participants executed 10 swings each per condition and Daish used this information to establish a relationship between clubhead speed and clubhead mass. He coupled this data with an impact model and concluded that the optimal clubhead mass for maximizing ball speed was approximately 200 g. Employing computer simulation techniques, other researches arrived at similar values using simplified double-pendulum models (Reyes & Mittendorf, 1998; White, 2006).

There is no published research isolating the effect of clubhead mass on driving performance with live golfers hitting golf balls. This may be because there is sufficient evidence to suggest that a wide range of practical clubhead masses will produce very similar ball speeds. However, clubhead mass will also have an effect on clubhead orientation at impact due to shaft deflection (MacKenzie & Sprigings, 2010). Clubhead orientation will influence spin and launch angle, which can have important implications for carry distance (MacKenzie & Sprigings, 2009). Further, there is anecdotal commentary on the PGA Tour, which implies that heavier golf clubs can be swung more consistently (Johnson, 2014), resulting in less variable ball finishing positions. This notion is supported by recent research demonstrating that rods with higher moments of inertia were swung in a more consistent manner (Schorah, Choppin, & James, 2014). Therefore, the purpose of this study was to determine how clubhead mass influences both the kinematics of the clubhead at impact as well as the resulting kinematics of the ball through to the final resting location.

Methods

Participants

Eighteen right-handed, low-handicap golfers (handicap: 1.7 ± 2.2; height: 1.78 ± 0.1 m; mass: 75.6 ± 12.5 kg) volunteered to participate. The study was approved by the University's Research Ethics Board, and testing procedures, risks, and time required were fully explained to each participant before they provided an informed consent.

Procedures

Three clubhead mass conditions were tested in a repeated measurements design. The tested clubhead masses were 174 g, 190 g, and 200 g, which yielded club MOIs—about the butt of the grip—of 2539 kg·cm^2, 2741 kg·cm^2, and 2867 kg·cm^2 respectively. MOI was measured using an Auditor MOI Speed Match system (Technorama Co Ltd., Kaohsiung City, Taiwan). The loft of the driver was 9° and the length was 1.16 m. The combined shaft (82 g) + grip (50 g) mass was 132 g. The shaft was rated as "Stiff" by the manufacturer and the static kick point was 0.63 m from the tip of the shaft. The same driver was used for all swings to maximize internal validity, and head mass was manipulated by screwing plugs of varying mass in three available ports. These conditions represent the largest clubhead mass change for a driver, which was commercially available at the time of testing, thus maximizing effect size while maintaining practical applicability of the findings. Changing the clubhead mass did result in small changes to the location of the center of gravity of the clubhead and the moments of inertia (Figure 1, Table 1). Each participant

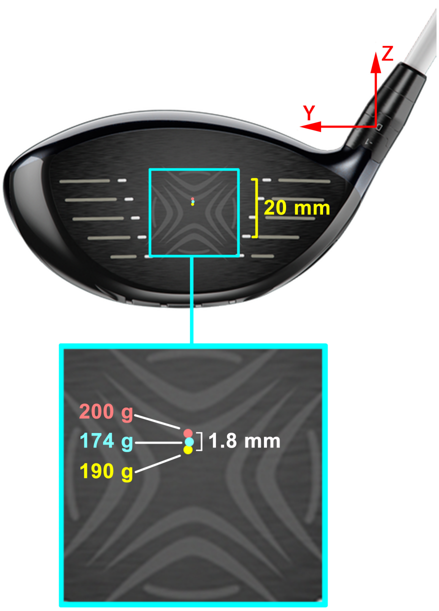

Figure 1 — Center of gravity of each clubhead mass condition projected onto the face.

Table 1 Golf Club Inertial Properties

Head Mass	CG_X	CG_Y	CG_Z	I_{XX}	I_{YY}	I_{ZZ}	Swing Weight	MOI Butt	Club Mass
g	cm	cm	cm	g·cm^2	g·cm^2	g·cm^2		kg·cm^2	g
174	2.42	6.01	-2.75	2432	1983	3319	C7.4	2539	306
190	2.43	6.08	-2.83	2526	2021	3398	D4.2	2741	322
200	2.48	6.04	-2.65	2673	2025	3576	D9.3	2867	332

CG_X, CG_Y, CG_Z: location of the head center of gravity. See Figure 1 for reference frame

I_{XX}, I_{YY}, I_{ZZ}: Head moments of inertia relative to the head center of gravity

Table 2 Order of Head Mass Condition Employed by Each Participant During Testing

Participant #	Shots 1–6	Shots 7–12	Shots 13–18	Shots 19–24	Shots 25–30	Shots 31–36
1, 7, and 13	174 g	190 g	200 g	174 g	190 g	200 g
2, 8, and 14	174 g	200 g	190 g	174 g	200 g	190 g
3, 9, and 15	190 g	200 g	174 g	190 g	200 g	174 g
4, 10, and 16	190 g	174 g	200 g	190 g	174 g	200 g
5, 11, and 17	200 g	190 g	174 g	200 g	190 g	174 g
6, 12, and 18	200 g	174 g	190 g	200 g	174 g	190 g

executed 12 drives with each clubhead mass condition. Head mass was changed every 6 shots and the order of conditions was set to minimize any ordering effect (Table 2). Shots were executed every 30 seconds within a block of 6 shots with approximately 180 seconds of rest between blocks. A Doppler radar launch monitor and associated software (TrackMan IIIe, TrackMan Golf, Vedbæk, Denmark) was used to capture information on clubhead and golf ball kinematics for each drive.

Before testing, participants performed a standardized golf warm-up consisting of dynamic stretches and swings of increasing intensity, which lasted approximately 5 minutes. Following this initial warm-up, participants hit six practice drives—using the 190 g clubhead—and were instructed to imagine that they were hitting predominately for distance, with their most typical shot shape (e.g., high draw), on a par-5 that was potentially reachable in two shots. The six practice drives were performed to help familiarize the participants with the testing conditions before data collection. All shots were executed at an outdoor driving range using premium golf balls. The landing area was well defined and there were clear indicators of the target line on which the golf ball was intended to finish.

Statistical Analysis

A bespoke software program was written in MatLab (version R2010a, MathWorks, Natick, MA, USA) to process the raw data exported from the launch monitor software into an organized form usable by the statistical package SPSS V22.0 for Windows (IBM Co., NY, USA). One-way repeated measures analyses of variance (ANOVA) were conducted on each dependent variable of interest (e.g., ball speed). The within-participants independent variable (clubhead mass) had three levels: 174 g, 190 g, and 200 g. If the assumption of sphericity was not met, as determined using Mauchly's Test, then Greenhouse-Giesser corrections were applied. When significant values were determined, Bonferroni post hoc tests, with adjustments to control for Type I error, were used to determine where significant differences existed between conditions. Effect sizes were estimated using partial eta squared (η_p^2). Statistical significance was set at $\alpha \leq .05$ for all tests.

Results

On average, the 174 g condition was associated with a significantly higher clubhead speed (48.2 m/s) than the 190 g (47.4 m/s), which was significantly higher than the 200 g (47.0 m/s), ($F(2, 34) = 278$, $p < .001$, $\eta_p^2 = .61$) (Figure 2a). Average clubhead speeds for individual golfers ranged from 40 to 58 m/s. The trend shown in Figure 2a was observed in the majority of participants (16/18). The reverse trend was observed for smash factor, with the 200 g condition (1.45) being significantly higher than the 174 g (1.42), ($F(2, 34) = 51.3$, $p < .001$, $\eta_p^2 = .22$) (Figure 2b). There was a marginally significant difference in ball speed, with the 174 g condition yielding approximately 0.3 m/s more ball speed in comparison with the 200 g, ($F(2, 34) = 3.73$, $p = .025$, $\eta_p^2 = .02$) (Figure 2c).

On average, the 200 g condition was associated with significantly higher dynamic loft in comparison with the lighter conditions (~0.7° more loft), ($F(2, 34) = 33.1$, $p = .001$, $\eta_p^2 = .04$) (Figure 2d). However, there was a systematic decrease in angle of attack as clubhead mass increased, with the 200 g condition being approximately 0.8° steeper in comparison with the 174 g, ($F(2, 34) = 21.1$, $p < .001$, $\eta_p^2 = .11$) (Figure 2e). The heaviest condition generated significantly more ball spin (3330 rpm) than both the 190 g (2997 rpm) and 174 g (2933 rpm) conditions, ($F(2, 34) = 10.5$, $p < .001$, $\eta_p^2 = .06$) (Figure 2f). There were no differences in terms of vertical launch angle or carry distance among mass conditions (Figures 2g and 2h). The heaviest condition was associated was significantly less total distance than the lighter conditions, with the differences being approximately 3–3.5 yards on average, ($F(2, 34) = 6.1$, $p = .002$, $\eta_p^2 = .03$) (Figure 2i).

On average, relative to the target line, the 200 g condition was associated with a significantly more open face angle at impact (1.5°) compared with the 190 g (0.7°), which was significantly more open than the 174 g (-0.1°), ($F(2, 34) = 33.1$, $p < .001$, $\eta_p^2 = .14$) (Figure 3a). Consequently, the same pattern was observed with horizontal launch angle, with the 200 g condition resulting in an average ball launch that was approximately 1.5° more to the right in comparison with the 174 g condition ($F(2, 34) = 36.8$, $p < .001$, $\eta_p^2 = .16$) (Figure 3b). On average, the 174 g condition was associated with significantly more negative spin axis tilt (-3.8°) than the 190 g (-1.8°), which was significantly more negative than the 200 g (0.4°), ($F(2, 34) = 18.0$, $p < .001$, $\eta_p^2 = .08$) (Figure 3c). The 174 g condition was associated with average ball final resting locations (lateral error) that were significantly

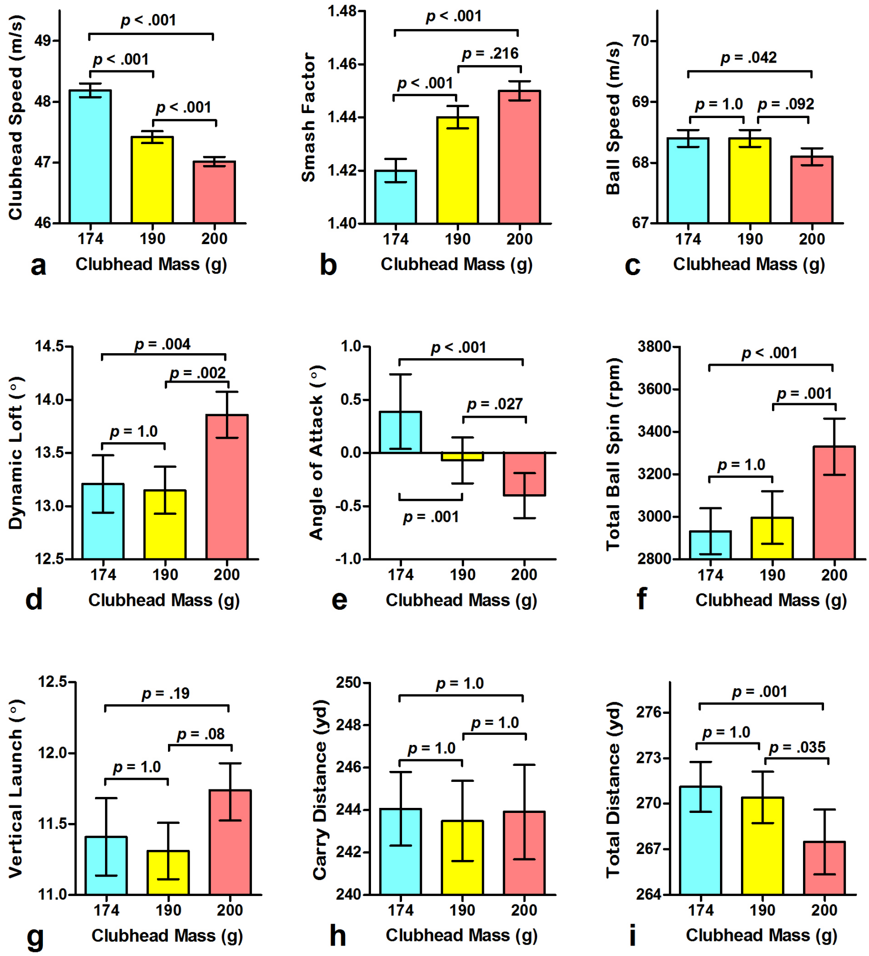

Figure 2 — The graphs above show the average values for each clubhead mass condition. (a) Clubhead speed. (b) Smash factor. (c) Ball speed. (d) Dynamic loft (the loft of clubface at the physical point of ball contact during impact). (e) Angle of attack (the vertical path of the clubhead during impact). (f) Total ball spin. (g) Ball vertical launch angle (h) Ball carry distance (i) Total predicted distance including roll-out. P-values correspond to Bonferroni adjusted comparisons at which $p < .05$ was considered statistically significant. Error bars represent 95% within-participant confidence intervals.

farther to the left (-9.1 yards) than the 190 g (1.5 yards), which was significantly left of the 200 g (10.4 yards), ($F(2, 34) = 38.0$, $p < .001$, $\eta_p^2 = .16$) (Figures 3d and 3e). While there appeared to be a trend of decreasing lateral variability with increasing head mass (Figure 3f, Figure 4), the means were not reliably different ($F(2, 34) = 2.2$, $p = .11$, $\eta_p^2 = .01$)

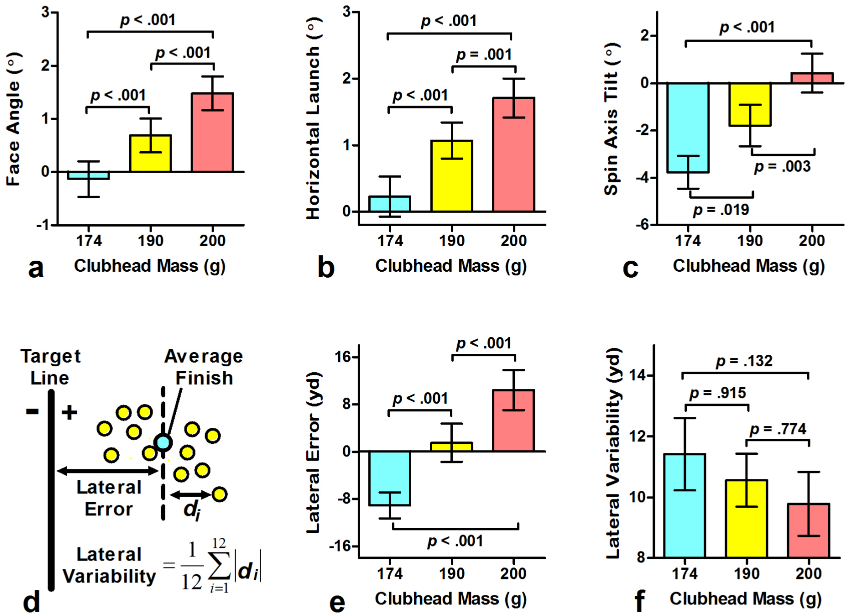

Figure 3 — (a) Face angle. Positive values indicate an open face pointing to the right. (b) Horizontal launch. Positive values indicate that the initial ball velocity was to the right of the target line. (c) Spin axis tilt. Negative values are associated with a right-to-left ball flight (i.e., a draw for a right-handed golfer). (d) Top view of ball finish locations for one participant for one condition showing definitions for lateral error and lateral variability. (e) Lateral error. A positive value indicates that the average final ball resting location was to the right of the target line. (f) Lateral variability. This represents the lateral dispersion of the drives. P-values correspond to Bonferroni adjusted comparisons at which $p < .05$ was considered statistically significant. Error bars represent 95% within-participant confidence intervals.

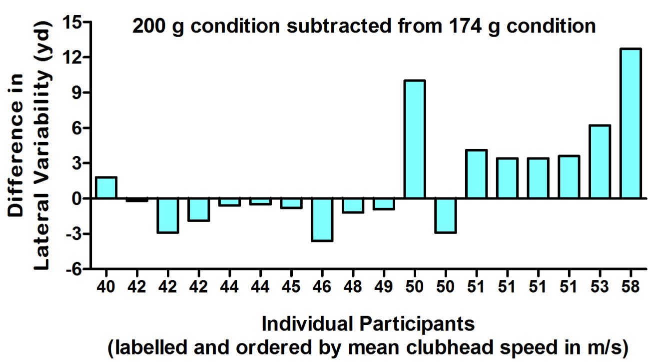

Figure 4 — This graph demonstrates the difference in lateral variability of the final ball position between the heaviest and lightest conditions. Positive values indicate a greater amount of variability with the light (174 g) condition.

Discussion

The purpose of this study was to determine how clubhead mass influences both the kinematics of the clubhead at impact as well as the resulting kinematics of the ball through to the final resting location. In addition to understanding the influence of clubhead mass on clubhead speed and ball speed, a goal of this paper was to understand the influence on practical outcomes such as ball flight tendencies and variability in final finish position.

As expected, there was a statistically significant trend demonstrating that clubhead speed increases as the inertia of the club decreases (Figure 2a). This trend did not hold through to ball speed (Figure 2c), since adding mass tended to result in higher transfers of energy to the ball (Figure 2b). It is possible that the higher energy transfers, as indicated by smash factor, were not solely the result of increased mass. The increased club inertia may have resulted in a more repeatable swing and thus a tighter distribution of impact location around the spot on the face that delivered the highest smash factor. Clubhead mass was increased partly through inserting additional mass into ports at the toe and heel of the clubhead, which would increase the MOI of the clubhead. Increasing the MOI of the clubhead would positively influence the smash factor on an off-center impact; this mechanism could also be partly responsible for the higher smash factors associated with increased clubhead mass.

While maximizing ball speed is clearly important for increasing the distance of a golf drive, the golf ball vertical launch angle and spin also have meaningful influences. Dynamic loft and angle of attack are two key impact parameters affecting launch and spin. Dynamic loft—defined by TrackMan as the vertical club face orientation at the center-point of contact between the club face and golf ball at the maximum compression of the golf ball (Tuxen, June 24, 2014)—was significantly higher for the heaviest clubhead mass condition (Figure 2d). Given the data collection methods, it is not possible to know how much of the difference in dynamic loft can be attributed to a change in shaft deflection, a change in grip orientation, or a change in impact location on the face. Based on the mechanisms of shaft deflection presented in the literature (MacKenzie & Sprigings, 2010), it is likely that the more massive head would result in greater lead deflection (and therefore greater dynamic loft) just before impact. The greater inertia of the club might also affect the swing in such a way that, just before impact, the golfer has the grip oriented such that loft is 'added' to the clubhead. Further, coupled with the small changes noted in the location of the clubhead's center of gravity between conditions, it is possible that the heavier clubhead resulted in a systematic change in the average impact location to a point higher on the face, thus resulting in the dynamic loft increasing during the first half of the impact interval with the golf ball. It should also be noted that a higher impact location in and of itself will increase dynamic loft due to the vertical roll of the clubface. The attack angle of the clubhead will also mediate the relationship between the impact location on the face, the location of the clubhead center of gravity, and the change in dynamic loft during impact.

Interestingly, angle of attack, which Trackman states is measured at the moment of maximum ball compression, significantly increased in steepness as the clubhead increased in mass (Figure 2e). It is not possible to discern how much this instantaneous angle of attack measure was influenced by how the clubhead was moving just before impact versus how much was the result of the interaction with the ball during the first half of the impact interval. Regardless, the significantly higher dynamic loft coupled with the significantly steeper angle of attack, for the heaviest clubhead condition, had two important consequences on initial ball kinematics. First, these clubhead kinematics would work in synergy to increase ball spin, which explains the significantly higher ball spin for the heaviest condition (Figure 2f). Second, these clubhead kinematics would work in opposition with respect to vertical launch angle, which explains the lack of significance for vertical launch (Figure 2g). The combined effect of ball speed, ball spin, and vertical launch angle resulted in no significant differences for carry distance across conditions (Figure 2h). Yet, based on the final measured ball kinematics, the Trackman software did predict that the two lightest conditions generated total distances that were both farther than the heaviest condition. However, on average, the heavier condition was only about 3–3.5 yards less than the other two. Further, one-third of the participants had an average total distance with the 200 g condition that was further than one of the other lighter conditions.

While understanding how clubhead mass can influence how far the golf ball travels in the air and on the ground is important, it is also relevant to understand how clubhead mass can influence tendencies and variability in ball finish locations. The term used in this study to characterize the position of the ball left and right of the target line is *lateral*. For a given golfer, the lateral finish position of a drive is primarily determined by the horizontal launch angle and spin axis tilt of the golf ball. In particular, horizontal launch is heavily influenced by face angle. Face angle is to horizontal ball motion as dynamic loft is to vertical ball motion. The results from this study demonstrate that as clubhead mass increased the clubface was pointed significantly more to the right during impact (Figure 3a). Lead deflection and toe-down deflection act in opposition to influence face angle, with toe-down deflection tending to open the face (MacKenzie & Sprigings, 2009). Notably, with current drivers, the amount of toe-down deflection at impact typically exceeds that of lead deflection; therefore, a heavier clubhead generating more deflection in general would tend to be associated with a more open face. Face angle, as measured by TrackMan, is also influenced by the same factors as dynamic loft noted in the previous paragraph. So, for example, a systematic change in impact location toward the toe could also be responsible for some, or all, of the more open face angle with the heavier clubhead. Regardless of the mechanism, the face angle results corresponded to equivalent differences in horizontal launch angle between conditions, with the ball launching more right as clubhead mass increased (Figure 3b). Acting in synergy with launch angle, to separate the finish positions between conditions, was the spin axis tilt of the ball (Figure 3c). For example, the heaviest condition tended to launch the ball the farthest right with a fade spin, while the lighter conditions were associated draw spin. The end result of these interactions is quite clear as the heaviest condition had an average finish location approximately 20 yards right of the lightest condition (Figure 3e). Interestingly, while manufactures have designed clubheads so that the center of gravity location can be moved to manipulate ball flight, it would seem that an overall change in clubhead mass has a meaningful influence.

A final objective was to determine the influence of club inertia on performance consistency. Since each participant was clearly instructed to attempt to hit the same golf drive for all trials, it was felt that the variance in lateral finish position of the ball was a good reflection of consistency. In driving, it is typically more important to have less lateral variability than it is to have less variability in distance. The lateral variability measure used in this study indicates how far, on average, the 12 shots per condition were away from the average location of those 12 shots. Collectively across all participants, there appeared to be a trend of improved consistency as clubhead mass increased; however, these results were not statistically significant (Figure 3f). Interestingly, when ordered by clubhead speed, a trend does seem evident, in that participants with higher clubhead speeds were relatively more consistent with the heavy condition (Figure 4).

It is challenging to isolate the effects of changing specific golf club parameters. While the stated aim of this study was to examine the influence of clubhead mass, other golf club parameters were inevitably changed. Specifically, adding mass to an existing clubhead will also increase the MOI of the clubhead, the MOI of the overall club, and swing weight. Although costly and challenging, it would have been possible to build three separate clubs such that the differences in these other club parameters were minimized. However, there would still be differences and, perhaps more importantly, this is not a practical solution for a club fitter. A heavier clubhead will also be associated with larger shaft deflections given the same shaft and swing. While using different shafts with each head mass condition was possible, it was decided that this would have a net negative influence on internal validity. Overall, it was decided that only changing clubhead mass (e.g., not adding mass to the grip to keep swing weight constant) was the best way to isolate the influence of changes in clubhead mass. That said, several of the findings can likely be attributed to the mediating influence of clubhead mass on other club parameters. For example, the increased whole club MOI—due to added head mass—was likely responsible for the differences in clubhead speed and lateral finish position. Since adding mass to an existing head will always increase whole club MOI, it is not essential to know, from a club fitter's perspective, which parameter is influencing performance.

Conclusions

This study has provided novel insights into the understanding of how the mass of a driver's clubhead influences driving performance. Increasing clubhead mass within a commercially available range was found to decrease clubhead speed, but have no meaningful influence on ball speed. Similarly, increasing clubhead mass had clear influences on dynamic loft, angle of attack, and spin, but there was no net influence on carry distance and only a relatively small effect on the total predicted distance. Collectively, this suggests that manipulating clubhead mass to increase driving distance is not likely a worthwhile exercise. Clubhead mass did a have a meaningful influence on where the ball finished laterally due to differences in both launch angle and spin. Increasing clubhead mass tended to create more fade spin as well as start the ball further to the right, which resulted in meaningful differences in the average lateral finish location among conditions. This finding has important implications for club fitters and manufacturers. When adjusting the clubhead center of gravity location to manipulate ball flight tendencies, it would seem important to only 'move' mass, while keeping the total clubhead mass constant, so as to avoid confounding mechanisms. Finally, there appears to be some evidence to suggest that golfers with higher clubhead speeds may perform more consistently with heavier clubheads.

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