Sports Engineering (2020) 23:8
https://doi.org/10.1007/s12283-020-0320-7

ORIGINAL ARTICLE

Reliability of repeat golf club testing sessions with modified club moment of inertia

Josh Turner[1] · **Stephanie E. Forrester**[1] · **Aimée C. Mears**[1] · **Jonathan R. Roberts**[1]

Abstract

The moment of inertia of a golf club, quantified about an axis at the butt of the handle, normal to the swing plane, has the potential to influence both clubhead and ball velocity. The purpose of this study was to assess the reliability of clubhead and ball velocity with changes to moment of inertia over repeat testing sessions and, if reliable, to quantify the effect of modifying moment of inertia. Eleven skilled male golfers hit 20 golf shots with three golf clubs, each with a different moment of inertia achieved through adding mass inside the club shaft and repeated this protocol over three sessions. A commercially available launch monitor was used to measure both velocity variables. Test–retest reliability was assessed via (1) limits of agreement, to determine reliability from a change in magnitude perspective and (2) linear-weighted kappa, to determine reliability from a directional perspective. The effect of moment of inertia on clubhead and ball velocity was determined using one-way, repeated measures analysis of variance tests, with partial eta squared being used to quantify the size of the effect. Increasing golf club moment of inertia reliably decreased clubhead and ball velocity, with fair to substantial kappa results revealed between sessions. The magnitude of decrease in these velocities, however, could not be reliably quantified. Statistically, the influence of moment of inertia was considered large ($\eta^2 \geq 0.662$ and 0.404) and significant ($p < 0.001$ and ≤ 0.006) for both clubhead and ball velocity, respectively.

Keywords Golf · Moment of inertia · Velocity · Test–retest reliability

1 Introduction

Golfers continually strive for improvements in performance. Two key performance variables in golf are the inbound velocity of the clubhead and outbound velocity of the ball, as these variables influence the distance that the ball travels. In an attempt to understand how the design of the golf club can enhance golfer performance, the effect of modifying various physical golf club properties on these velocities has been investigated [1–5]. As the golf swing is primarily a rotational motion, the moment of inertia (MOI) of the golf club, quantified about an axis at the butt end of the handle and normal to the swing plane, provides a key physical property of the golf club that could theoretically be modified to change these velocities [6].

Previous research has reported a decrease in the velocity of rackets [7], bats [8] and rods [9, 10] when increasing MOI. In golf, decreases in clubhead velocity have also been reported when increasing club MOI via clubhead mass [4, 5, 11, 12]. However, the total mass of the golf club was not controlled in these studies and increased with club MOI, which could have had a confounding effect on clubhead velocity. Furthermore, as increasing clubhead mass results in an increase in the effective mass at the impact location [13], similar decreases in ball velocity have not been observed [4, 5]. As the clubhead is considered to act as a free moving

---

This article is a part of Topical Collection in Sports Engineering on Measuring Behavior in Sport and Exercise, edited by Dr. Tom Allen, Dr. Robyn Grant, Dr. Stefan Mohr and Dr. Jonathan Shepherd.

✉ Josh Turner
J.Turner3@lboro.ac.uk

Stephanie E. Forrester
S.Forrester@lboro.ac.uk

Aimée C. Mears
A.C.Mears@lboro.ac.uk

Jonathan R. Roberts
J.R.Roberts@lboro.ac.uk

[1] Sports Technology Institute, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3QF, UK

projectile during impact with the ball [14], if the mass used to increase club MOI was located in the shaft, it is expected that a decrease in both clubhead and ball velocity would be observed. Mass has previously been added to the shaft as opposed to the clubhead [15, 16]; however, the small magnitude of mass used, and the location of this mass would have had only a small effect on MOI, hence sizeable differences in velocity were not observed. Whilst it is expected that increasing golf club MOI by adding mass to the shaft would result in decreases to clubhead and ball velocity, the golfer and the golf club are not a predictable mechanical system [15]; they form a complex, adaptable biomechanical system. It is therefore plausible that the effect of modifying MOI on the magnitude or direction of change in clubhead and ball velocity may not be consistent over time and repeat testing.

Various statistical analysis techniques can be used to assess the test–retest reliability of the change in clubhead and ball velocity when modifying MOI. From a magnitude perspective, the limits of agreement provides a method for assessing how the change in velocity between different club conditions systematically varies from session to session (bias) and randomly varies within the group (95% limits of agreement). Furthermore, the 95% limits of agreement can be interpreted as an interval within which the difference in velocity change between conditions would be expected to occur 95% of the time for a new individual from the population sampled [17]. The reliability of the MOI effect from a directional perspective can be quantified by assessing whether golfers achieve the same relative order of club conditions across different sessions, when ranked on velocity magnitude. Statistically, the reliability can be inferred using correlation coefficients, such as the Pearson product moment or intra-class correlation [17–19], although results from these measures are sensitive to the homogeneity of the sample group [19] and should not be compared to other studies or extrapolated to the wider population [17].The percentage agreement between session ranks can be used; however, this measure is limited as it does not take into account the extent of the disagreement between ranks [20]. An extension of the percentage agreement is the weighted kappa coefficient (κ), which accounts for the extent of the disagreement between ranked scores and the agreement due to chance. The weighted kappa method is typically used to determine inter-rater agreement [21], but could also be used to determine inter-session (test–retest) agreement as this does not violate any statistical assumptions.

Despite the abundance of literature dedicated to determining the influence of different golf club properties on performance, no study has ever quantified how reliably the club properties influence performance over time. This knowledge gap is a limitation for multiple aspects of the golf industry, such as golf club design and customisation, whereby durable changes to golfer performance are desired. Therefore, the purpose of this study was, firstly, to assess the reliability of clubhead and ball velocity with changes to golf club MOI over repeat testing sessions and, secondly, to report the overall effect of MOI on clubhead and ball velocity.

2 Methods

2.1 Data collection

Eleven skilled right-handed male golfers (mean ± SD: age 22.0 ± 6.9 years, handicap 6.3 ± 4.3 strokes) gave their informed consent prior to participating in the study, which was approved by Loughborough University Ethics Committee (reference number: R18-P196). The golfers all possessed handicaps equivalent to CONGU category 2 or less [22] and played golf at least once a month.

Three golf club conditions were used, each with a different MOI about the butt of the handle: low MOI: 2780.1 kg cm^2, mid MOI: 2985.5 kg cm^2 and high MOI: 3176.4 kg cm^2. MOI was measured using an Auditor MOI Speed Match System (Technorma Co., Ltd., Kaohsiung City, Taiwan) with an accuracy of ± 0.05 kg cm^2, derived from the calibration procedure. The changes in MOI were achieved by positioning approximately 50 g of mass at different locations inside identical Aldila NV 44 Magnum stiff-flex shafts (uncut specifications: mass, 45 g; torque, 4.6°; kick-point, mid [23]) (Fig. 1), therefore blinding golfers to the modifications. For the low MOI condition, the mass was located at the top of the golf shaft (Fig. 1a); for the mid MOI condition, the mass was located approximately 61% down the length of the shaft (Fig. 1b); and for the high MOI condition, the mass was located approximately 81% down the length of the shaft (Fig. 1c). The same Ping G30 clubhead (199.1 g, 10.5° nominal loft) was used across all conditions.

The additional mass used to modify golf club MOI resulted in the total mass of the club conditions being towards the upper extreme for a driver [5], whilst the variance in added mass location led to differences in swingweight and fundamental club frequency between the three club conditions (Table 1). Swingweight, an alternative measure of mass distribution, is the first mass moment about an axis 35.6 cm from the butt of the golf club [5], whilst fundamental club frequency was used as an indication of shaft stiffness [24]. The properties of mass, swingweight and club frequency were measured using an Ohaus EB EB6 bench scale (Mettler Toledo, Columbus, OH), Dynacraft golf swingweght scale and Golfsmith 8720 Shaft Frequency Analyzer (Dick's Sporting Goods, Inc., Coraopolis, PA), respectively.

Each golfer attended three separate sessions, each on a different day (mean ± SD: duration between sessions

Fig. 1 The locations of the additional mass used to vary the MOI of the three club conditions: **a** low MOI; **b** mid MOI; **c** high MOI

Table 1 Physical properties of the three MOI club conditions used in the investigation

Property	Low MOI	Mid MOI	High MOI
MOI butt (kg cm^2)	2780.1	2985.5	3176.4
Club mass (g)	351.6	352.5	354.4
Swingweight	B7.0	E1.0	F0.5
Club frequency (Hz)	4.2	4.1	4.0
Club length (cm)	114.3	114.3	114.3

8.5 days ± 7.0 days). Prior to data collection, each golfer performed an adapted active dynamic warm-up [25], consisting of ten practice swings with a short iron, followed by three shots with an 8-iron, 6-iron, 4-iron, fairway wood and driver. If, during the first session, golfers wanted to perform a further warm-up routine, this was noted and repeated in the remaining sessions, due to evidence suggesting that the type of warm-up can affect performance [25–28]. Thereafter, each golfer hit 20 shots with each club condition in each session, resulting in a total of 60 shots per session, where the order of club conditions was varied between sessions for each golfer and between golfers for each session. Golfers were given a short break (approximately, 3–5 min) between each block of 20 shots to minimise the risk of fatigue. A new golf ball of the same manufacturer and model (Titleist TruSoft) was used for every golfer and session.

The variables of clubhead velocity and ball velocity were measured indoors using a Trackman 4 launch monitor (TrackMan A/S, Denmark). Clubhead and ball velocity measurements from a former Trackman model (Trackman Pro 3e) have previously been compared to a gold standard optical tracking system to determine their accuracy (median and lower/upper quartile difference during driver shots: clubhead velocity − 0.18 m/s and − 0.54/0.13 m/s, ball velocity 0.09 m/s and 0.00/0.27 m/s) [29]. As a newer model, the accuracy of Trackman 4 in measuring these variables was expected to be comparable to, or better than, the Trackman Pro 3e. The launch monitor was set up according to the manufacturer's requirements, repositioned 2.8 m behind the impact area, with the screen being over 5 m in front of the impact area [30]. The device was aligned to the middle of the screen (located by a visual mark) using a laser (Leica Lino L360). A projection of the Trackman driving range (ball flight only, no quantitative variable information) was shown on screen to provide feedback to the golfers to make the testing more realistic and increase external validity.

2.2 Data analysis

2.2.1 Test–retest reliability

The limits of agreement method was used to assess how the change in magnitude of velocity between conditions varied from one session to another. The bias was calculated as the mean between-condition change in velocity difference between sessions, whilst the 95% limits of agreement were calculated as the standard deviation of the within-group change in velocity differences, multiplied by 1.96 [31]. Linear weighted kappa was used to assess whether golfers in the group maintained the same order of MOI conditions between sessions when ranked in velocity. Rankings were created for each golfer separately, where for each session the MOI condition which resulted in the highest velocity magnitude

Table 2 An example of a ranked score comparison between two test sessions

	Session 1			
Session 2	High (1)	Medium (2)	Low (3)	Total
High (1)	9	2	0	11
Medium (2)	1	8	2	11
Low (3)	1	1	9	11
Total	11	11	11	33

was given a rank score of 1, and the MOI condition which resulted in the lowest velocity magnitude was given a rank score of 3. The ranks from each golfer were then cumulated, resulting in 33 ranks per session (11 golfers × 3 conditions) and compared from one session to another (Table 2).

The observed scores in the 3 × 3 matrix (Table 2) were converted into proportions of the grand total (33, Table 2). A linear weighting was then applied to the scores, whereby ranks in perfect agreement between sessions (main diagonal of Table 2) were multiplied by 1, those in disagreement by one category (e.g. high rank in session 1 and medium rank in session 2) were multiplied by 0.5 and those in complete disagreement (e.g. high rank in session 1 and low rank in session 2) were multiplied by 0. The observed probability was then determined as the sum of the resulting scores in the 3 × 3 matrix. The expected probability score for each cell of the 3 × 3 matrix was calculated as 0.111 (row total × column total, divided by the square of the grand total). The same linear weighting was then applied to these scores, and the expected probability due to chance was determined as the sum of the resulting scores. The weighted kappa coefficient was calculated as

$$\kappa = \frac{P_o - P_e}{1 - P_e} \tag{1}$$

where P_o is the observed probability and P_e is the expected probability due to chance. The 95% confidence intervals for the kappa coefficient were calculated and the reliability was interpreted using the predetermined guidelines of a kappa coefficient of 0.00–0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80, 0.81–1.00 representing slight, fair, moderate, substantial and almost perfect agreement, respectively [32].

2.2.2 Effect of MOI on clubhead and ball velocity

The effect of club MOI on clubhead and ball velocity was quantified using a one-way, repeated measures analysis of variance (ANOVA) with a significance level of 0.05. Effect sizes were determined using partial eta squared (η^2) with values of 0.01, 0.06 and 0.14 representing small, medium and large effects, respectively [33]. Prior to conducting ANOVA tests, the data were assessed for normality (Shapiro–Wilk test) and sphericity (Mauchly's test) with a Greenhouse–Geisser correction being applied when the assumption of sphericity was violated. For statistically significant ANOVA results, post hoc pairwise t tests with a Bonferroni correction (p × number of multiple comparisons) were conducted to determine where the differences existed between conditions. At the individual golfer level, the median velocity of the 20 shots with each club condition was used as the measure of central tendency to minimise the effect of any extreme data points (outliers). All statistical analysis was conducted using SPSS v24.0 (SPSS, Inc., Chicago, USA).

3 Results

3.1 Test–retest reliability

The mean change in clubhead velocity between MOI conditions ranged from 0.5 to 1.3 m/s (mid–low MOI), 0.5 to 0.8 m/s (high–mid MOI) and 1.3 to 1.8 m/s (high–low MOI) (Fig. 2). The mean change in clubhead velocity magnitude was, therefore, fairly consistent, resulting in a small bias both between clubs and sessions (Table 3). The between-club bias was smaller across all three session pairings for the high–mid MOI comparison (Table 3), suggesting that the change in clubhead velocity was most reliable between these club conditions, whilst the between-club bias was greater across all session pairings for the mid–low MOI comparison (Table 3). Furthermore, the between-session bias was consistently greater for the session 2 and 3 pairing (Table 3), indicating weaker reliability between these sessions. Within the group, the individual golfers displayed noticeable variation in both the change in clubhead velocity as a result of modifying MOI (Fig. 2) and the consistency in this change in velocity, resulting in large limits of agreement (Table 3) which were greater in magnitude than the observed change in clubhead velocity for golfers (Fig. 2). Therefore, although the mean change in clubhead velocity magnitude was reliable, the change in clubhead velocity for individual golfers was not reliable.

The mean change in ball velocity between MOI conditions ranged from 0.7 to 2.4 m/s (mid–low MOI), 0.4 to 1.3 m/s (high–mid MOI) and 1.8 to 2.8 m/s (high–low MOI) (Fig. 3). The mean change in ball velocity magnitude was therefore less consistent across the different test sessions compared to clubhead velocity, resulting in larger systematic differences between sessions (Table 4). Similar to clubhead velocity, there was a tendency for a smaller between-club bias in ball velocity for the high–mid MOI comparison and a greater bias for the mid–low MOI comparison (Table 4). Furthermore, there was once again a tendency for a greater between-session bias for session 2 and 3 (Table 4). Within the group, the individual golfers were variable in the change in ball velocity achieved as a result of modifying MOI and the consistency in this change in velocity (Fig. 3), resulting in large limits of agreement (Table 4). As with the clubhead velocity results, the ball velocity limits of agreement were greater in magnitude than the observed change in ball velocity for golfers (Fig. 3) and, therefore, the magnitude change in ball velocity as a result of modifying golf club MOI cannot be considered reliable.

Acceptable reliability was observed in the change in velocity direction; particularly for clubhead velocity, where moderate to substantial agreement between session

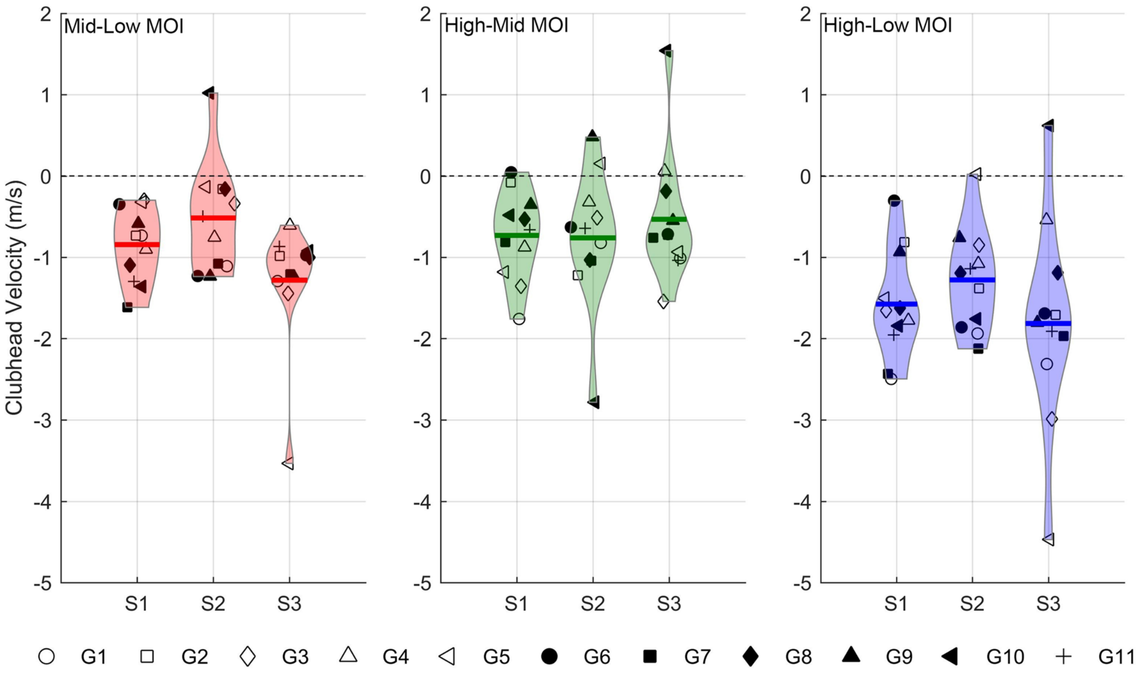


Fig. 2 Change in clubhead velocity between MOI conditions: **a** mid–low; **b** high–mid; **c** high–low. Scatter points represent individual golfers and the bold horizontal line indicates the group mean (bias). S1, S2, S3 = session 1, session 2, session 3

Table 3 The mean difference (bias) ± 95% limits of agreement for clubhead velocity between the three MOI conditions and across the three different sessions

Clubhead velocity (m/s)	S2–S1	S3–S1	S3–S2
Mid MOI–low MOI	0.33 ± 1.76	− 0.44 ± 2.09	− 0.77 ± 2.13
High MOI–mid MOI	− 0.03 ± 2.12	0.20 ± 1.58	0.23 ± 2.96
High MOI–low MOI	0.30 ± 1.59	− 0.24 ± 2.87	− 0.54 ± 3.37

S1, S2, S3 = session 1, session 2, session 3

ranks was observed (κ min, max = 0.591, 0.727), with fair to substantial agreement observed in ball velocity ranks (κ min, max = 0.386, 0.795) (Table 5). The choice of session pair was found to have a noticeable effect, with the strongest agreement in ranks occurring between sessions 1 and 3 and the weakest agreement occurring between sessions 2 and 3 for both clubhead and ball velocity (Table 5). Interestingly, when observing the golfer velocity rankings in each session, it was found that golfers adhered better to expectation in session 1, with all golfers achieving the highest clubhead velocity with the low MOI condition, and all but one golfer achieving the lowest clubhead velocity with the high MOI condition.

3.2 Effect of MOI on clubhead and ball velocity

Golf club MOI was found to have a large effect size and was statistically significant in all three test sessions, for both clubhead velocity (session 1: $F(2, 20) = 43.404$, $p < 0.001$, $\eta^2 = 0.813$, session 2: $F(2, 20) = 17.511$, $p < 0.001$, $\eta^2 = 0.637$, session 3: $F(1.337, 13.372) = 19.580$, $p < 0.001$, $\eta^2 = 0.662$) and ball velocity (session 1: $F(2, 20) = 35.710$, $p < 0.001$, $\eta^2 = 0.781$, session 2: $F(2, 20) = 6.776$, $p = 0.006$, $\eta^2 = 0.404$, session 3: $F(2, 20) = 13.395$, $p < 0.001$, $\eta^2 = 0.573$), respectively. The observed trend was that an increase in MOI resulted in a decrease in clubhead (Fig. 4) and ball velocity (Fig. 5). The post hoc pairwise comparisons for clubhead and ball velocity revealed significant differences ($p < 0.05$) between the low and high MOI conditions across all three sessions; however, the statistical significance of the other pairwise comparisons (low v mid and mid v high) varied depending on the choice of test session (Figs. 4, 5).

4 Discussion

The purpose of this study was, firstly, to assess the reliability of clubhead and ball velocity with changes to golf club MOI over repeat testing sessions and, secondly, to report the overall effect of MOI on clubhead and ball velocity. The results of this study suggest that increasing golf club MOI

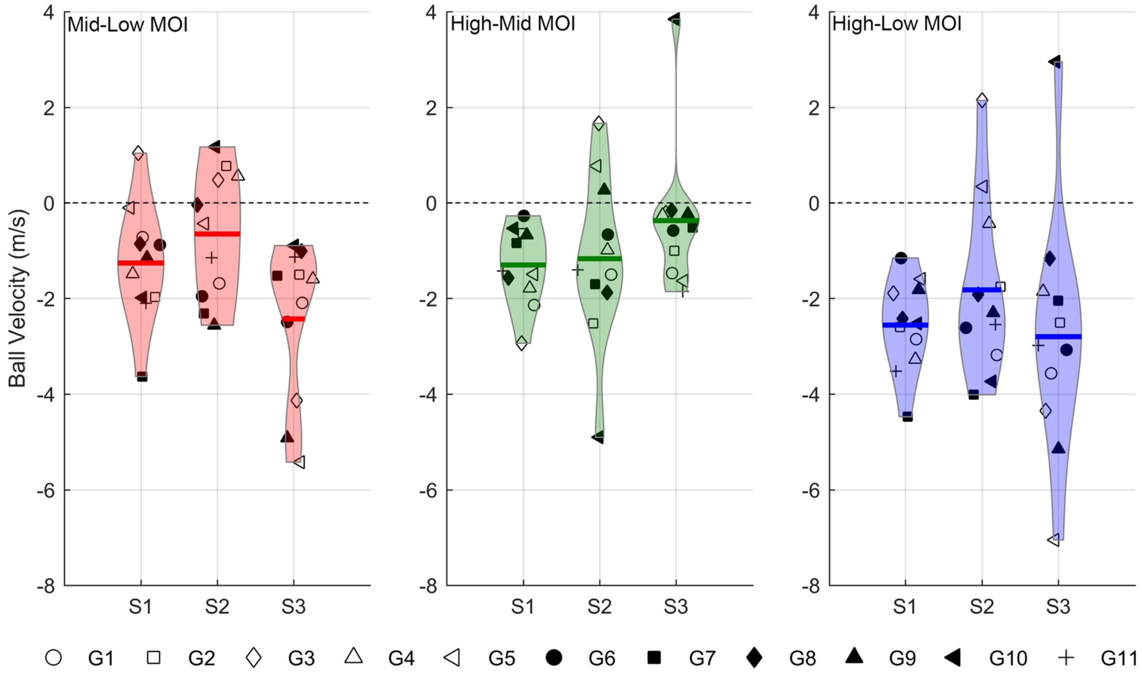


Fig. 3 Change in ball velocity between MOI conditions: **a** mid–low; **b** high–mid; **c** high–low. Scatter points represent individual golfers and the bold horizontal line indicates the group mean (bias). S1, S2, S3 = session 1, session 2, session 3

Table 4 The mean difference (bias) ± 95% limits of agreement for ball velocity between the three MOI conditions and across the three different sessions

Ball velocity (m/s)	S2–S1	S3–S1	S3–S2
Mid MOI–low MOI	0.61 ± 3.12	− 1.17 ± 5.02	− 1.78 ± 3.56
High MOI–mid MOI	0.13 ± 4.45	0.93 ± 2.95	0.80 ± 5.76
High MOI–low MOI	0.74 ± 3.29	− 0.24 ± 5.89	− 0.98 ± 7.51

S1, S2, S3 = session 1, session 2, session 3

reliably decreases both clubhead and ball velocity; however, the magnitude of decrease in these velocities could not be reliably stated.

The group mean clubhead velocity differences between the three MOI conditions used in this study were comparable to those reported when changing MOI via clubhead mass [4]. This study extended on previous literature by showing that increasing MOI decreases ball velocity when the mass is altered via the shaft rather than the clubhead (Fig. 5). Therefore, as the effect of MOI on ball velocity appears to be dependent on the location of the mass used to modify MOI, future work should state where mass has been added to the golf club. The magnitude differences between the MOI conditions were less reliable for the ball velocity data in comparison to clubhead velocity; however, this is to be expected, as ball velocity will be influenced by variability in other measures such as impact location and clubhead orientation. Practically, these findings combined with those from previous research provide two different scenarios when altering MOI for club designers and fitters. Firstly, if a skilled golfer wants to increase ball velocity, it appears that a reduction in golf club MOI would likely achieve this, provided that the decreases in MOI are achieved by reducing shaft mass rather than clubhead mass. Secondly, if a skilled golfer prefers the feel of a heavier golf clubhead, adding mass to the clubhead would achieve this preferred feel without compromising ball velocity [4, 5]. The potential increase in clubhead and ball velocity that a skilled golfer could expect to achieve when reducing golf club MOI, however, remains uncertain. The golfers in this study were variable in terms of their change in velocity when modifying golf club MOI (Figs. 2, 3). It

Table 5 The linear weighted kappa coefficient (κ) with 95% confidence intervals for both clubhead and ball velocity

Variable	S2–S1	S3–S1	S3–S2
Clubhead velocity	0.659 (0.453, 0.866)	0.727 (0.534, 0.921)	0.591 (0.345, 0.837)
Ball velocity	0.455 (0.211, 0.698)	0.795 (0.618, 0.973)	0.386 (0.107, 0.665)

S1, S2, S3 = session 1, session 2, session 3

Fig. 4 Mean (± 1 SD) clubhead velocity for each MOI condition across the three sessions. Significant post hoc pairwise comparisons highlighted: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$

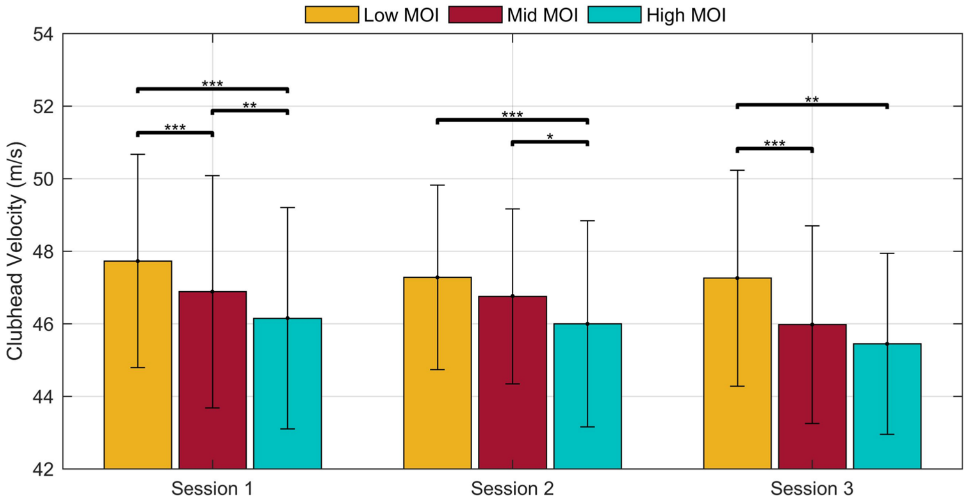
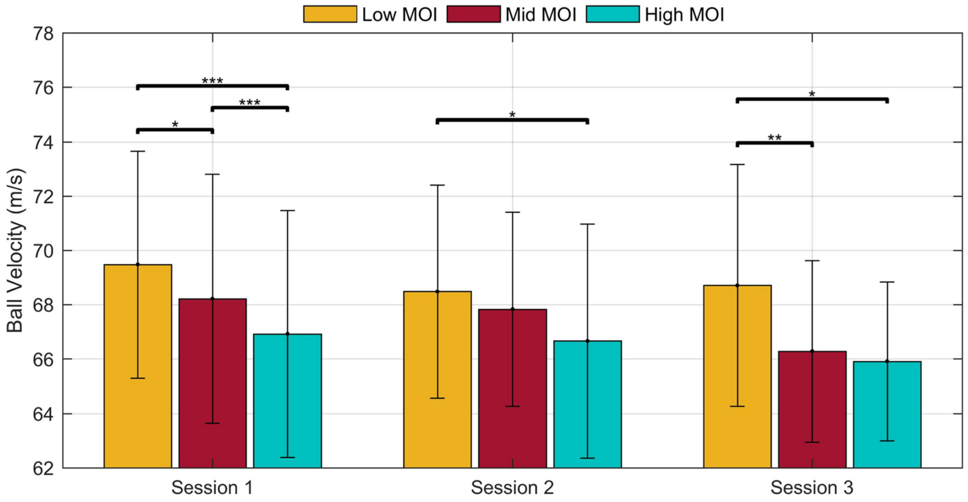


Fig. 5 Mean (± 1 SD) ball velocity for each MOI condition across the three sessions. Significant post hoc pairwise comparisons highlighted: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$



therefore appears that changes in velocity are golfer specific as opposed to consistent for all golfers. This finding agrees with previous research that has identified individual relationships between MOI and the velocity of golf clubs and rods [9, 12]. Furthermore, although it appears that reducing MOI will increase the clubhead and ball velocity of skilled golfers, there is likely to be a golfer-specific optimum MOI, which could be influenced by a golfer's technique and physical characteristics such as strength.

Previous biomechanics studies using human participants have recommended the use of a familiarisation session to obtain more reliable measurements [34–36] due to participants experiencing a learning effect during the first test session [35, 36]. There is no clear evidence from the results of this study that a familiarisation session would improve reliability, with the results from session 2 and session 3 demonstrating the weakest reliability across the different measures (Tables 3, 4, 5). The lack of need for a familiarisation session in this study type is plausible, as research into golfer adaptation to equipment has suggested it is a more immediate response [37] resulting in only a couple of trials being used for familiarisation purposes [2]. It is therefore suspected that the effect of any adaptation was negated in this study as a consequence of collecting a large sample of trials per condition ($n = 20$). Although the results from the first session should be sufficient when reporting the influence of MOI on velocity using a protocol similar to that used in this study, if a longitudinal study is of interest, then the test protocol will need to be carefully considered to ensure the most reliable outputs.

A common limitation when altering the physical properties of sports equipment is the difficulty in altering one property in isolation [4]. In this study, the modifications in MOI led to differences in swingweight and club frequency between conditions. The differences in swingweight were inevitable, given that like MOI, swingweight is also a measure of golf club mass distribution. The difference between MOI and swingweight in golf is the axis about which the mass distribution is measured, with MOI being measured about the butt of the golf club, compared to swingweight, which is measured 35.6 cm down from the butt [5]. Therefore, adding mass to the butt of the golf club would reduce swingweight whilst having a minimal effect on MOI, whereas adding mass at the swingweight axis would increase MOI whilst having a minimal effect on swingweight. Adding mass further down than the swingweight axis would increase both swingweight and MOI. The MOI intervals used in this study were chosen to provide a range representative of what is commercially available; however, the resultant swingweights of the three club conditions were different to what is considered standard for a driver (~ D0 [1, 2]). Therefore, the three MOI conditions would have felt different to what the golfers were used to, which could have influenced the way in which golfers performed. The small differences in club frequency (0.1 Hz per MOI condition) were considered unlikely to have had an influence on the results, given that larger differences (0.9 Hz) resulted in no meaningful differences to club delivery and ball launch parameters [2]. Furthermore, whilst the total mass of the golf clubs was kept relatively consistent between conditions (< 1% difference, Table 1), the greater than standard mass of the golf clubs could have also influenced golfer adaptation, impacting both the reliability and overall influence of MOI on clubhead and ball velocity.

This study primarily aimed to assess the test–retest reliability of a golf club property effect. The reliability of this effect will, in part, be dictated by the reliability of the entire protocol. Both skilled golfers and a large number of trials per condition were used in this study in an attempt to maximise the reliability of the protocol, with evidence suggesting that lower handicap golfers are more consistent in delivering the clubhead to the ball [38] and a large number of trials resulting in a more representative central tendency measure of the golfer's performance. A potential risk of using a large number of trials was introducing systematic effects such as fatigue into the results. Whilst the likelihood of golfers inducing fatigue in this study was minimised through rest periods during each session, it was noted that the mean clubhead velocity for each condition progressively dropped from one session to the next (Fig. 4). This could have been a conscious response by golfers after the first test session to preserve energy and ensure they can successfully complete the following test sessions. The changes in velocity observed in this study could have also been influenced by measurement error, due to the uncertainty of the launch monitor in measuring both velocity variables, and other factors such as day-to-day variation in the setup of the launch monitor. Future work should address the golfer-specific responses to changes in MOI from a biomechanical perspective, to improve the current understanding of the interaction between the golfer and club. Improving knowledge in this area will help progress the design and customisation of golf clubs.

5 Conclusion

Increasing golf club MOI reliably decreased clubhead and ball velocity; however, the magnitude of change in velocity as a consequence of altering MOI could not be reliably quantified. The protocol and findings of this study have important implications for both the research and commercial sectors. From a research perspective, when investigating the influence of an equipment effect on performance, the test–retest reliability of the effect should be reported so that both the consistency of the effect over time can be interpreted and confidence can be obtained in the results. The protocol used, in particular the reliability analysis, provides a methodology to be used for future investigations. From a club manufacturer and fitters' perspective, it appears that in general, a decrease in MOI about the butt of the handle, achieved through the repositioning of mass in the golf shaft, has the potential to improve the clubhead velocity, ball velocity and ultimately driving distance of skilled golfers, although it is expected that the size of the improvements will be golfer specific.

Acknowledgements We would like to thank Jack Beaumont from Loughborough University for his help with data collection and Culford school for their kind hospitality and use of their facilities and equipment.

Compliance with ethical standards

Conflict of interest Dr Aimée Mears is an Assistant Editor for Sports Engineering and Dr Stephanie Forrester is an Editorial Board Member for Sports Engineering. Neither author was involved with the Sports Engineering review process of this manuscript.

References

1. Joyce C, Burnett A, Cochrane J, Reyes A (2016) A preliminary investigation of trunk and wrist kinematics when using drivers with different shaft properties. Sport Biomech 15(1):61–75. https://doi.org/10.1080/14763141.2015.1123764
2. Betzler N, Monk S, Wallace E, Otto S (2012) Effects of golf shaft stiffness on strain, clubhead presentation and wrist kinematics.

Sport Biomech 11(2):223–238. https://doi.org/10.1080/14763141.2012.681796

3. Wallace E, Otto S, Nevill A (2007) Ball launch conditions for skilled golfers using drivers of different lengths in an indoor testing facility. J Sport Sci 25(7):731–737. https://doi.org/10.1080/02640410601113221
4. MacKenzie S, Ryan B, Rice A (2015) The influence of clubhead mass on clubhead and golf ball kinematics. Int J Golf Sci 4(2):136–146. https://doi.org/10.1123/ijgs.2015-0011
5. Harper T, Roberts J, Jones R (2005) Driver swingweighting: a worthwhile process? Proc Inst Mech Eng Part B J Eng Manuf 219(5):385–393. https://doi.org/10.1243/095440505X32247
6. Cross R, Nathan A (2009) Performance versus moment of inertia of sporting implements. Sports Technol 2(1–2):7–15. https://doi.org/10.1002/jst.88
7. Whiteside D, Elliott B, Lay B, Reid M (2014) The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. J Sci Med Sport 17(1):124–128. https://doi.org/10.1016/j.jsams.2013.03.001
8. Smith L, Broker J, Nathan A (2003) A study of softball player swing speed. In: Subic A, Trivailo P, Alam F (eds) Sports dynamics, discovery and application. RMIT University Press, Melbourne, pp 12–17
9. Schorah D, Choppin S, James D (2015) Effects of moment of inertia on restricted motion swing speed. Sport Biomech 14(2):157–167. https://doi.org/10.1080/14763141.2015.1027949
10. Cross R, Bower R (2006) Effects of swing-weight on swing speed and racket power. J Sport Sci 24(1):23–30. https://doi.org/10.1080/02640410500127876
11. Daish C (1965) The influence of clubhead mass on the effectiveness of a golf club. Phys Bull 16(9):347–349
12. Mather J (2002) The effect of mass distribution on the performance of golf clubs. In: Ujihashi S, Haake S (eds) The engineering of sport, 4th edn. Wiley, Hoboken, pp 360–367
13. Cross R (2014) Impact of sports balls with striking implements. Sport Eng 17(1):3–22. https://doi.org/10.1007/s12283-013-0132-0
14. Peterson W, McPhee J (2009) Shape optimization of golf clubface using finite element impact models. Sport Eng 12:77–85. https://doi.org/10.1007/s12283-009-0030-7
15. Haeufle D, Worobets J, Wright I, Haeufle J, Stefanyshyn D (2012) Golfers do not respond to changes in shaft mass properties in a mechanically predictable way. Sport Eng 15(4):215–220. https://doi.org/10.1007/s12283-012-0104-9
16. Joyce C, Burnett A, Herbert S (2012) The effects of the deflection point and shaft mass on swing and launch parameters in the golf swing. In: 30th International Conference on Biomechanics in Sports, pp 88–91.
17. Atkinson G, Nevill A (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 26(4):217–238. https://doi.org/10.2165/00007256-199826040-00002
18. Bruton A, Conway J, Holgate S (2000) Reliability: what is it, and how is it measured? Physiotherapy 86(2):94–99. https://doi.org/10.1016/S0031-9406(05)61211-4
19. Hopkins W (2000) Measures of reliability in sports medicine and science. Sport Med 30(1):1–15. https://doi.org/10.2165/00007256-200030010-00001
20. Hartmann D (1977) Considerations in the choice of interobserver reliability estimates. J Appl Behav Anal 10(1):103–116. https://doi.org/10.1901/jaba.1977.10-103
21. Mandrekar J (2011) Measures of interrater agreement. J Thorac Oncol 6(1):6–7. https://doi.org/10.1097/JTO.0b013e318200f983
22. CONGU (2019) CONGU unified handicapping system. https://www.congu.co.uk/wp-content/uploads/2019/06/2019-CONGU-Manual.pdf Accessed 27 May 2019
23. Aldila (2018) NV MAGNUM. https://www.aldila.com/sites/aldila/files/ALD-TECH%20SPEC-NV%20Magnum_r2v20181202_0.pdf Accessed 29 Sep 2019
24. Betzler N (2010) The effect of differing shaft dynamics on the biomechanics of the golf swing. Dissertation, Edinburgh Napier University
25. Gergley J (2009) Acute effects of passive static stretching during warm-up on driver clubhead speed, distance, accuracy, and consistent ball contact in young male competitive golfers. J Strength Cond Res 23(3):863–867. https://doi.org/10.1519/JSC.0b013e3181a00c67
26. Moran K, McGrath T, Marshall B, Wallace E (2009) Dynamic stretching and golf swing performance. Int J Sports Med 30(2):113–118. https://doi.org/10.1055/s-0028-1103303
27. Fradkin A, Sherman C, Finch C (2004) Improving golf performance with a warm up conditioning programme. Brit J Sport Med 38(6):762–765. https://doi.org/10.1136/bjsm.2003.009399
28. Tilley N, Macfarlane A (2012) Effects of different warm-up programs on golf performance in elite male golfers. Int J Sports Phys Thera 7(4):388–395
29. Leach R, Forrester S, Mears A, Roberts J (2017) How valid and accurate are measurements of golf impact parameters obtained using commercially available radar and stereoscopic optical launch monitors? Measurement 112:125–136. https://doi.org/10.1016/j.measurement.2017.08.009
30. Trackman (2015) Trackman Quick Start Guide. https://trackman.zendesk.com/hc/en-us/article_attachments/115010639168/2015-11-05_Quick_Start_Guide_PDF.pdf. Accessed 27 May 2019
31. Bland J, Altman D (1999) Measuring agreement in method comparison studies. Stat Methods Med Res 8(2):135–160. https://doi.org/10.1177/096228029900800204
32. Landis J, Koch G (1977) The measurement of observer agreement for categorical data. Biometrics 33(1):159–174. https://doi.org/10.2307/2529310
33. Cohen J (1988) Statistical power analysis for the behavioural sciences (2nd edn). Lawrence Erlbaum Associates
34. Hamill J, McNiven S (1990) Reliability of selected ground reaction force parameters during walking. Hum Mov Sci 9(2):117–131. https://doi.org/10.1016/0167-9457(90)90023-7
35. Nugent E, Snodgrass S, Callister R (2015) The effect of velocity and familiarisation on the reproducibility of isokinetic dynamometry. Isokinet Exerc Sci 23(3):205–214. https://doi.org/10.3233/IES-150582
36. Levinger I, Goodman C, Hare D, Jerums G, Toia D, Selig S (2009) The reliability of the 1RM strength test for untrained middle-aged individuals. J Sci Med Sport 12(2):310–316. https://doi.org/10.1016/j.jsams.2007.10.007
37. Osis S, Stefanyshyn D (2012) Golf players exhibit changes to grip speed parameters during club release in response to changes in club stiffness. Hum Mov Sci 31(1):91–100. https://doi.org/10.1016/j.humov.2011.02.006
38. Betzler N, Monk S, Wallace E, Otto S (2012) Variability in clubhead presentation characteristics and ball impact location for golfers' drives. J Sport Sci 30(5):439–448. https://doi.org/10.1080/02640414.2011.653981