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The Effect of Golf Club Moment of Inertia on Clubhead Delivery and Golfer Kinematics †

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Abstract: The purpose of this study was to determine the effect of modifying whole club moment of inertia (MOI) on clubhead delivery, thorax and wrist kinematics. Seven skilled golfers hit ~10 shots with two driver conditions (MOI difference ~400 kg·cm^2). A GOM system tracked the clubhead at impact and a 12-camera Vicon system was used to determine golfer biomechanics. Paired sample *t*-tests were conducted to quantify the effect of MOI on clubhead delivery, whilst biomechanical differences during the downswing were determined using statistical parametric mapping. Increasing MOI significantly reduced clubhead velocity (p = 0.001) but had a small and non-significant effect ($p \geq 0.294$) on clubhead direction and orientation. The increase in MOI significantly decreased lead wrist flexion, thorax lateral bend and thorax axial rotation velocities during the downswing. The timing and magnitude of the decreases in both thorax velocities, suggests that these were contributing factors of the observed decrease in clubhead velocity.

Keywords: golf; inertia; biomechanics; velocity

1. Introduction

Two possible questions that can be asked when determining the effect of golf club design on performance are what, and how? What happens to performance when the design of a golf club is modified? This first question has received noticeable attention in the field of golf research [1–3]. How does modifying the design of the golf club result in the observed performance changes? This second question is rarely addressed in research, yet knowledge of the golfer–club interaction and how golfers respond to club design modifications is crucial to golf club manufacturers, fitters and coaches.

A key design property of the golf club is the moment of inertia (MOI) of the whole club, quantified about an axis at the butt end of the handle and normal to the swing plane. It has been shown that increasing this MOI results in decreased clubhead velocity at impact [1–4] whilst having a mixed effect on clubhead direction and orientation [1]. However, modifications to whole club MOI have previously been a result of changes in clubhead mass, which could have had a confounding effect on results.

Additionally, the mechanism of how clubhead delivery is modified when increasing whole club MOI is unclear, although it is expected that biomechanical differences would occur primarily for the kinematics associated with the generation of clubhead velocity, namely the thorax [5,6] and wrist [5–7]. Therefore, the purpose of this study was to determine the effect of modifying whole club MOI on clubhead delivery, thorax and wrist kinematics.

2. Materials and Methods

2.1. Test Protocol

Seven skilled right-handed male golfers (age: 32.3 ± 10.9 years, handicap: 2.6 ± 2.6 strokes) took part in the study, which was approved by Loughborough University Ethics Committee. Following a self-guided warm-up, each golfer hit ~10 shots in an indoor laboratory with two different club conditions: reference and MOI (Table 1).

Table 1. Physical properties of the two club conditions used in the study. Values stated include the contribution of the passive markers used for tracking the club during the swing.

Property	Reference	MOI
MOI butt (kg·cm^2)	2877.5	3267.2
Mass (g)	389.9	392.7
Swingweight	C0	F3
Club frequency (Hz)	3.7	3.6
Club length (cm)	114.3	114.3

Both conditions used identical shafts (Aldila NV 44 Magnum, stiff flex) and grips (Golf Pride Tour Velvet), with the same head (Ping G30, 199.1 g, 10.5° nominal loft) being used throughout. The modification to MOI was achieved by positioning additional mass at different locations within the shaft. The reference condition had ~50 g located at the butt end of the shaft, whilst the MOI condition had ~50 g located approximately 80% distally, down the length of the shaft. The additional mass resulted in total golf club masses that were towards the industry upper limit [2], whilst the different locations of additional mass led to differences in swingweight and club frequency between conditions (Table 1). The order in which golfers received the club conditions was randomised to minimise the influence of order effects.

2.2. Data Collection

Two passive motion capture systems were used to determine golfer and club kinematics (Figure 1). A 12-camera Vicon Nexus system (Oxford Metrics Ltd., Oxford, UK) sampling at 500 Hz was used to capture the trajectories of 36 retroreflective markers located on the golfer's trunk, upper arms, forearms, hands, golf club and ball. A separate GOM system (GOM mbH, Braunschweig, Germany) with two Photron Fastcam SA1.1 (Photron, San Diego, CA, USA) high-speed video cameras (5400 Hz, 1/50,000 s) was used to determine clubhead delivery at impact. The system tracked 5 mm diameter markers located on the clubhead and 3 mm diameter markers on the golf ball. The set-up of the high-speed video cameras followed the procedure described by Leach et al. [8].

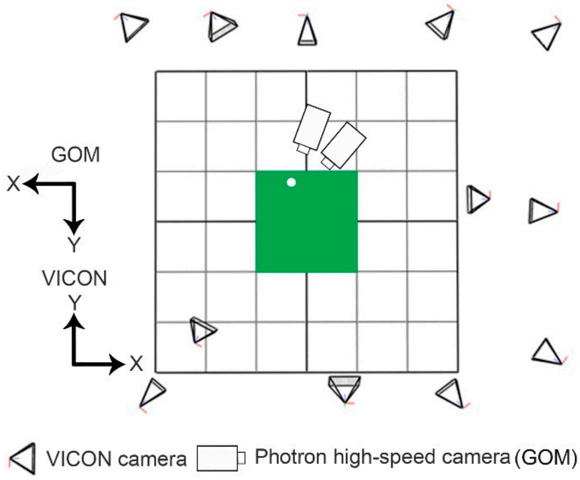

Figure 1. A schematic of the laboratory set-up used in the study.

2.3. Data Processing

The raw Vicon marker trajectories were filtered using a 4th order, zero-lag, low-pass Butterworth filter. Markers located on the trunk were filtered using a cut-off frequency of 15 Hz and those located on the upper-arms with a cut-off frequency of 20 Hz. Adaptive cut-off frequencies were applied to the markers on the forearms, hands and golf club, incrementing from 20 Hz at the start of the swing to 40 Hz at impact, due to evidence of higher frequency oscillations immediately post-impact as a result of the impact between the club and ball. The filtered marker trajectories were used to define and track the thorax, lead/trail forearm and lead/trail hand segments in Visual3D (C-Motion, Germantown, MD, USA). The thorax was defined by markers on the left and right acromion process (distal) and virtual markers on the left and right iliac crest (proximal). During the swing, the position and orientation of the thorax was determined from markers on the clavicle, sternum, right scapula, C7, T2, T8 and T10 vertebrae. The forearms were defined by markers on the radial and ulnar styloid processes (distal) and a virtual marker located mid-way between the medial and lateral humeral epicondyle (proximal). The virtual marker was reconstructed dynamically during the golf swing using three markers located on the upper arm as a technical reference frame and was used along with the radial and ulnar styloid markers to track the forearm during the swing. The hands were defined by markers on the head of the 3rd metacarpal (distal) and radial and ulnar styloid processes (proximal), with the same three markers being used to track the segment during the swing. Thorax kinematics were defined as the rotation of the thorax relative to the laboratory coordinate system (Figure 1) using the YXZ (lateral bend, flexion/extension, axial rotation) rotation order [9], whilst wrist kinematics were defined as the rotation of the hand relative to the forearm using the XZY (flexion/extension, axial rotation, radial/ulnar deviation) rotation order. All kinematics were time-normalised from the top of the backswing (0%) to impact (100%).

The high-speed video images of the golf club and ball were imported into GOM (Correlate Professional 2016). A coordinate system transformation was first applied to align the GOM global coordinate system with the golfer's target line (Figure 1). The calculation of the clubhead delivery variables followed the procedures of Leach et al. [8]. Clubhead velocity was defined as the velocity of the center of gravity (CG) averaged over 20 frames prior to impact. The CG of the clubhead was determined through independent testing at the R&A, and a virtual marker was created at this position in the software from a 3D clubhead scan (GOM ATOS). The direction of the clubhead was determined as the angles formed between the XZ coordinates of the CG trajectory and the ground level (attack angle) and the XY coordinates of the CG trajectory and the target line (club path) at the frame immediately prior to impact. The orientation of the clubhead was defined as the 2D angles formed between the clubface normal at the impact location and the ground level (dynamic loft) and the clubface normal at the impact location and the target line (face angle) at the frame of impact. Impact location was determined by fitting a sphere to the identified markers on the golf ball and projecting a vector from the clubface to the golf ball using the shortest distance.

The first trial for each club condition was considered to be an immediate familiarisation trial and, therefore, was not considered for analysis. From the remaining trials, the six trials that produced the smallest resultant impact location relative to the face center and were of acceptable quality were selected for statistical analysis.

2.4. Statistical Analysis

The effect of modifying whole club MOI on clubhead velocity, direction and orientation was quantified using paired sample *t*-tests ($\alpha = 0.05$). Effect sizes were determined using Cohen's *d* and interpreted as $d = 0.2$, 0.5 and 0.8 representing small, medium and large effects, respectively [10]. Parametric paired sample *t*-tests ($\alpha = 0.05$) were conducted on the downswing phase of the golf swing using statistical parametric mapping (SPM) to identify biomechanical differences as a result of modifying MOI. All statistical analyses were performed in Matlab R2016b (MathWorks, Natick, MA, USA) with the open source spm1d Matlab code (v0.4) being used to conduct all SPM analyses.

3. Results

As expected, modifying MOI had a large ($d = 2.262$) and significant effect ($p = 0.001$) on clubhead velocity. The increase in MOI in this study of ~400 kg·cm^2 resulted in a decrease of approximately 1.5 m/s (Table 2). The increase in MOI, however, only had a small (or negligible) and non-significant effect on the clubhead direction and orientation variables measured, with these values being similar in magnitude between conditions (Table 2).

Table 2. Mean (SD) values of the clubhead delivery variables for both the reference and moment of inertia (MOI) conditions, along with outcomes (*p*-value and effect size *d*) from the paired *t*-tests.

Club Variable	Reference	MOI	*p*	*d*
Clubhead velocity (m/s)	47.0 (3.6)	45.5 (3.2)	0.001	2.262
Attack angle (°)	0.6 (3.3)	0.6 (3.4)	0.688	0.159
Club path (°)	0.4 (4.7)	0.7 (4.6)	0.294	0.434
Dynamic loft (°)	15.8 (2.2)	15.6 (2.5)	0.683	0.162
Face angle (°)	0.4 (1.9)	0.3 (2.0)	0.869	0.065

From a biomechanical perspective, SPM analysis revealed regions in the lead wrist flexion/extension velocity (Figure 2a), thorax lateral bend velocity (Figure 2b) and thorax axial rotation velocity (Figure 2c) curves that differed significantly between the two club conditions. On average, increasing MOI significantly reduced lead wrist flexion velocity during the early part of the downswing (8%–10%), and significantly reduced thorax lateral bend and axial rotation velocities during the latter stages of the downswing (77%–100% and 90%–97%, respectively).

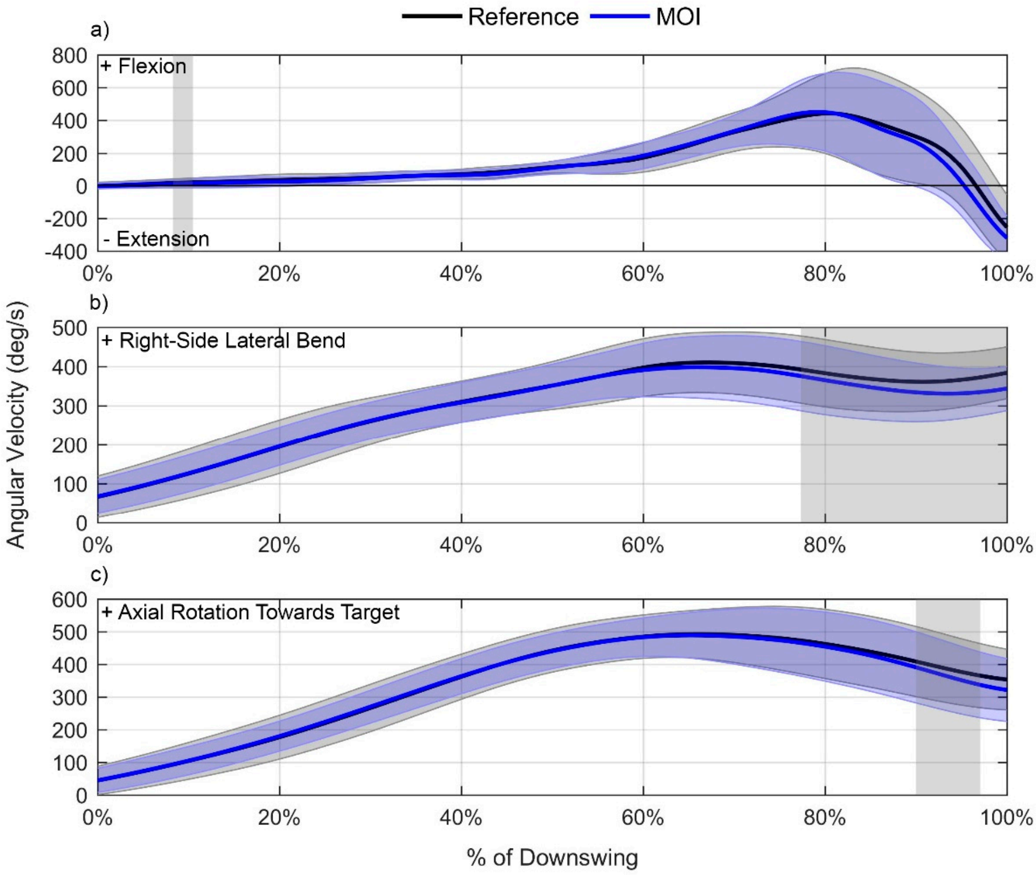

Figure 2. Mean biomechanical curves and statistical parametric mapping (SPM) results for three biomechanical variables: (**a**) lead wrist flexion/extension velocity; (**b**) thorax lateral bend velocity; (**c**) thorax axial rotation velocity. Shaded regions represent a significant difference ($p < 0.05$) between club conditions.

4. Discussion

The purpose of this study was to determine the effect of modifying whole club MOI on clubhead delivery, thorax and wrist kinematics. As expected, clubhead velocity at impact was significantly reduced when MOI was increased; however, no significant differences in clubhead direction and orientation were observed, with the effect of MOI being considered small (or negligible) for these variables. Biomechanically, the increase in MOI was found to significantly reduce wrist and thorax angular velocities during the downswing. The timing and magnitude of the decreases in thorax lateral bend and axial rotation velocities suggests that these were a contributing factor of the reduced clubhead velocity at impact.

The large reduction in clubhead velocity of 1.5 m/s (~3.3 mph) observed in this study (Table 2) was comparable to that previously reported when increasing MOI by a similar magnitude [1]. This study expanded upon the previous literature by incorporating biomechanical data into the analysis and addressing the "how?" question. The significant decrease in thorax lateral bend and axial rotation velocities (Figure 2b,c, respectively) during the latter stages of the downswing (77%–100% and 90%–97%, respectively) suggests that these were a contributing factor of the decrease in clubhead velocity at impact. This logically makes sense, given that both these velocities have been identified as significant predictors of ball velocity [6], a by-product of clubhead velocity. Reductions in angular velocity have previously been reported when indirectly increasing whole club MOI, via increases in shaft mass as a result of modifying the shaft kick-point [5] and via increases in club length [11]. Furthermore, reductions in peak shoulder, elbow and wrist angular velocities have also been reported in tennis when increasing racket MOI [12]. Interestingly, when observing the reductions in thorax angular velocities in this study, the significant decreases occurred after peak angular velocity was reached. These reductions could, therefore, have been a conscious adaption mechanism employed by golfers, for example, to maintain consistency in clubhead direction and orientation, rather than the result of physical characteristics such as insufficient golfer strength. This, however, cannot be concluded from the results of this study. Notably, manipulation of the proximal segments to achieve desired impact conditions has previously been reported when analysing biomechanical differences between different shot trajectories [13].

The MOI range used in this study of ~400 kg·cm^2 was guided by the practical limits achievable when altering commercially customisable driver clubhead mass [1]. The modifications to MOI achieved through additional mass, however, resulted in changes to other physical club properties (Table 1). The club conditions had a total mass which was greater than standard [1,2,14]. Whilst this was kept consistent between conditions (<1% difference), the greater mass could have influenced golfer and club kinematics. The large difference in swingweight between conditions was inevitable, given that swingweight is an alternative measure of golf club mass distribution. This property, however, is used as a measure of golf club feel [2], therefore, the large differences in feel between the two club conditions could have influenced how golfers responded and adapted to the different clubs. A small difference in club frequency (0.1 Hz) was also present between club conditions, however, this was not expected to have a large confounding effect on the results, given that much larger differences (0.9 Hz) were previously found to have no meaningful effect on clubhead delivery or biomechanical variables [14].

Future work should expand on this study by quantifying the individual golfer responses to modifying MOI as opposed to generalising as a group, whilst incorporating additional biomechanical variables into the analysis may yield further knowledge on how golfers respond to MOI modifications. In general, research into understanding why biomechanical differences are observed when the design of the golf club is modified is also recommended.

5. Conclusions

Increasing whole golf club MOI resulted in a large and significant decrease in clubhead velocity at impact; however, only small and non-significant changes in clubhead direction and orientation. Biomechanically, the increase in MOI significantly reduced lead wrist flexion velocity, thorax lateral bend velocity and thorax axial rotation velocity. The timing and magnitude of the decreases in thorax velocities during the downswing suggests that these were a contributing factor of the decrease in clubhead velocity at impact. It is unclear whether the reductions in thorax velocities were a consequence of physical golfer limitations or a conscious adaptation mechanism employed by golfers. Future work should investigate why biomechanical differences are observed when modifying golf club design, whilst investigating the effect of modifying whole club MOI on an individual golfer level and including more biomechanical variables may yield further knowledge.

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Conflicts of Interest: The authors declare no conflict of interest.

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