ARTICLE IN PRESS

Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Coordination of lower extremity multi-joint control strategies during the golf swing

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ARTICLE INFO

Article history:
Accepted 9 June 2018
Available online xxxx

Keywords:
Moment
Torque
Joint kinetics
Net joint moment
3D support moment
Leg plane
Multi-joint control

ABSTRACT

This study aimed to understand how players coordinate the multi-joint control strategies of the rear and target legs to satisfy the lower extremity and whole-body mechanical objectives during the golf swing when hitting shots with different clubs. Highly skilled golf players (n = 10) performed golf swings with a 6-iron and a driver. Joint kinetics were calculated using ground reaction forces and segment kinematics to determine net joint moments (NJMs) during the interval of interest within the downswing. Between club difference in NJMs and 3D support moments were compared across the group and within a player. Although player-specific multi-joint control strategies arose, players generally increased target leg ankle, knee, and hip NJMs when hitting with the driver while maintaining the relative contribution to the 3D support moment. Multi-joint control strategies used to control the target and rear legs were found to be different, yet the majority of the 3D support moment was produced by NJMs about an axis perpendicular to the leg planes. These results emphasize the importance of recognizing how an individual player coordinates multi-joint control from each leg, and highlights the need to design interventions that are player and leg specific to aid in improving player performance.

1. Introduction

During the golf swing, players need to coordinate multi-joint control of the lower extremities to satisfy the mechanical objectives of the task. At the whole-body level, players must regulate reaction forces (RFs) of the rear and target legs in relation to the center of mass (CM). This allows players to create rotation and limit translation to satisfy the net linear and angular impulse requirements of the task. At the limb level, the RFs generated in relation to lower extremity segments must also be effectively coordinated to facilitate multi-joint control of both legs. Determining how individuals satisfy the mechanical objectives of similar tasks within a class of actions has been effective in understanding subject-specific coordination strategies in other well-practiced, goal directed tasks such as dance turns and diving (Mathiyakom et al., 2006a, 2006b; Zaferiou et al., 2017). Understanding how an individual coordinates RF generation between legs as well as multi-joint control of each leg provides players and coaches a mechanistic foundation to design interventions that may facilitate improvements in player performance (McNitt-Gray et al., 2015).

When skilled players increase golf shot distance, the net angular impulse generated during the swing has been found to increase with the driver compared to the 6-iron by coordinating contributions from the rear and target legs (Peterson et al., 2016). Although individuals used player-specific strategies, the observed increases in net angular impulse with the driver were associated with increases in target leg resultant horizontal RF. When regulating shot distance within a 6-iron, players were also found to increase the RFs from the target and/or rear legs (McNitt-Gray et al., 2013). These reported increases in RFs and net angular impulse generation suggest that the mechanical demand imposed on the ankle, knee, and hip of the target and rear legs will also likely increase with increases in shot distance (McNitt-Gray et al., 2013; Peterson et al., 2016). We expect that between club differences in mechanical demand imposed on the target and rear legs can be captured by a three-dimensional (3D) support moment, as previously used in gait analysis (Winter, 1980). In this study, the 3D support moment is defined as the sum of squares of the resultant ankle, knee and hip NJMs as a metric of control that needs to be regulated by each leg (Fig. 1).

The regulation of RFs in relation to lower extremity segments is known to affect individual NJMs and multi-joint control of the leg (McNitt-Gray et al., 2001). The ankle, knee, and hip NJMs

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https://doi.org/10.1016/j.jbiomech.2018.06.004
0021-9290/

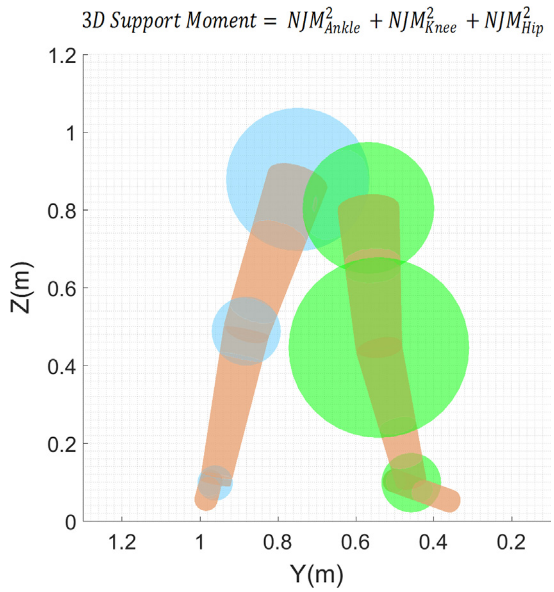

Fig. 1. Resultant net joint moments (NJMs) at the ankle, knee, and hip for the rear (left) and target (right) legs represented as circles at each joint (circles get larger with increasing magnitude) during the interval of interest. The 3D support moment is a measure of control for the leg, and is defined as the sum of squares of the ankle, knee, and hip NJMs of each leg.

controlling the limb are known to be sensitive to both the magnitude and orientation of the RF relative to the lower extremity segments and the NJMs at the adjacent joints (Goh et al., 2012; Macpherson, 1988; Mathiyakom et al., 2005; McNitt-Gray et al., 2001; Ting and Macpherson, 2004; Zaferiou et al., 2017). Modifying the limb configurations in relation to the RF has also been associated with the redistribution of the NJMs across the lower extremity joints (Mathiyakom et al., 2005). For example, some players increased RFs while maintaining a similar RF angle relative to the leg when increasing golf shot distance within or between clubs (McNitt-Gray et al., 2013; Peterson et al., 2016). We expect that differences in RF when swinging with a driver as compared to a 6-iron will contribute to differences in multi-joint control of the target and rear legs (Peterson et al., 2016).

Determining how players coordinate the 3D multi-joint control of the rear and target leg NJMs is important to understanding how individuals satisfy the lower extremity and whole-body mechanical objectives when regulating golf shot distance between clubs. Previously, studies on NJMs during the golf swing have focused on control of the wrists, back, and lower extremities (Donatelli et al., 2012; Foxworth et al., 2013; Gatt et al., 1998; Lynn and Noffal, 2010; Neal and Wilson, 1982; Vaughan, 1981; Ward, 2015). Greater external rotator moments were reported in the rear leg versus the target leg in middle handicap players swinging a driver (Foxworth et al., 2013). Changing the orientation of the target leg was discovered to contribute to reported differences in target leg, frontal plane knee moments for highly skilled players swinging a 5-iron (Lynn and Noffal, 2010). These studies highlight how reorientation of the leg relative to the RF could also affect multi-joint control of the limb (McNitt-Gray et al., 2001).

Understanding how individual players orient their legs when regulating golf shot distance within and between clubs can provide insight as to player-specific multi-joint control preferences (Lynn and Noffal, 2010; McNitt-Gray et al., 2013). Alignment of the RF with the leg plane acts to distribute the ankle, knee, and hip NJMs controlling the limb about an axis perpendicular to the leg plane. Aligning RFs in this manner may also simplify the multi-joint control of each leg by primarily taxing larger muscle groups (Zaferiou et al., 2017). This also may allow players to reposition the legs (e.g. changes in address position due to stance width, hip rotation, terrain, etc.) in global space while maintaining a similar multi-joint control strategy across clubs. Similar analyses of forces and moments in relation to a plane have previously been performed in upper extremity wheelchair propulsion and lower extremity dance turns to determine multi-joint control of the entire limb (Russell et al., 2015; Zaferiou et al., 2017).

This study investigated how skilled golf players coordinate multi-joint control of the rear and target legs to satisfy the mechanical objectives during the golf swing when using a 6-iron and driver. We hypothesized that (1) rear and target leg 3D support moments would increase with the driver as compared to the 6-iron during the interval of interest at a time in the downswing when two-dimensional (2D) moments about the CM in the transverse plane were being created. To achieve increases in leg 3D support moment, we hypothesized that (2) ankle, knee, and hip NJMs would increase while maintaining relative contributions to the 3D support moment. We expected that players would attempt to simplify their control strategies to take advantage of the larger muscle groups during swings with greater 3D support moments. Therefore, we hypothesized that (3) increases in 3D support moment would involve increases in ankle, knee, and hip NJM primarily about an axis perpendicular to the leg plane. We tested these hypotheses comparing the lower extremity NJMs in the rear and target legs for individual players during swings with a 6-iron and a driver.

2. Methods

Highly-skilled golf players (n = 10, 5 female, 5 male, handicap <5 (Worsfold et al., 2008)) volunteered to participate in accordance with the local institutional review board. Players performed 10 full swings each with a 6-iron and a driver (TaylorMade Golf, Carlsbad, CA, USA) as they normally would toward a target flag set behind a net that was positioned approximately 5 m downrange. Each player was given adequate time to complete their normal warm-up routine and acclimate to the laboratory setup prior to data collection. The golf swings were performed in blocks of 10 swings, starting with the 6-iron. Players completed golf swings in their own spikeless athletic shoes.

Reaction forces at the foot-surface interface were measured as players initiated golf swings from their preferred address positions with each foot supported by a force plate (1200 Hz, Kistler, Amherst, NY). A thin layer of artificial flooring (Atmosphere Runway 4 mm, To Market, Oklahoma City, OK) was secured on top of each force plate to provide frictional characteristics (McNitt-Gray et al., 2013; Williams and Cavanagh, 1983). The point of wrench application (PWA) was computed for each leg in lieu of the center of pressure to account for the horizontal forces of the task (Peterson et al., 2016; Shimba, 1996; Zatsiorsky, 2002). Segment kinematics were collected with a 16-camera motion capture system (100 Hz, Natural Point OptiTrack, Corvallis, OR) using Acquire3D software (C-Motion, Germantown, MD) and a custom, 97 retroreflective marker set. Kinematic data were filtered and any gaps in the data were filled using a cubic spline smoothing function where the degree of smoothing was determined by Jackson's method (Jackson, 1979). The kinematic data were simultaneously interpolated to synchronize with kinetic data during the filtering process.

Inverse dynamics were calculated to determine net joint forces and NJMs using custom Matlab software (The Mathworks, Natick, MA). Functional joint centers of the ankle, knee and hips were defined using functional movements based on work done by Schwartz and Rozumalski (Schwartz and Rozumalski, 2005). These functional joint centers represented the segment endpoints, and were utilized in defining the anatomical segment reference systems