Doctoral Thesis

Influences of trunk muscularity and motion strategy on club head speed during golf swing

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Doctoral Program in Sport and Health Science
Graduate School of Sport and Health Science
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Influences of trunk muscularity and motion strategy on club head speed during golf swing

（ゴルフスイングにおけるクラブヘッドスピードに及ぼす体幹部の筋形態および動作方略の影響）

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Chapter 1 Introduction

1-1. Preface

Golf players are required to hit a ball into a series of holes on a course with the fewest strokes possible. A golf club called the driver, which can make the longest distance shot of any golf club, is usually used for the first shot in each hole. Due to decreasing distance between the stroked ball and cup for the second and following shots, an increased shot distance with the driver helps players to achieve substantially lower scores (Broadie, 2008, 2012; Hellstrom et al., 2014; Wiseman & Chatterjee, 2006). One of the determinant factors for the distance of the driver shot is the club head speed (CHS) during the golf swing (Hellstrom, 2009; Hume et al., 2005).

Many biomechanical studies have examined influential factors for achieving a fast CHS (Chu et al., 2010; Neal et al., 2008; Pickering & Vickers, 1999; Sprigings & Mackenzie, 2002; Tinmark et al., 2010), and reported that the angular velocity of the trunk axial rotation and lateral flexion for the swing direction are associated with faster CHS (Chu et al., 2010; Joyce, 2017; Joyce et al., 2013; Kwon et al., 2013). This implies that the trunk motion strategy for effectively accelerating the club head during the driver shot plays an important role in achieving a fast CHS. In addition, it has been shown that resistance exercises for the trunk muscles, such as the crunch, trunk twist, and good morning (trunk flexion/extension), improved trunk muscle strength and golf driving performance (Kim, 2010; Sung et al., 2016). In general, the force generation capability of a muscle is closely related to its size (Fukunaga et al., 2001; Maughan et al., 1983). Considering these ideas and the importance of trunk motion during the golf swing, it could be said that the size of trunk muscles might also be an influential factor for golf performance.

The golf swing requires the trunk to rotate asymmetrically. In the downswing for a right-handed golf player, the trunk rotates to the left and flexes laterally to the right while remaining in forward flexion

(Horan & Kavanagh, 2012). The bilateral asymmetry (difference) in trunk muscle size (i.e., muscle thickness, cross-sectional area, and volume) is well documented as a profile of muscularity in athletes of sports that require asymmetric trunk motions, such as tennis (Sanchis-Moysi et al., 2010; Sanchis-Moysi et al., 2013), baseball (Tsuchikane et al., 2017), and the throwing events of track and field (Muramatsu et al., 2010). Moreover, it is known that, for baseball players, the trunk muscle thickness on the dominant side positively correlates with the bat swing speed, while that on the non-dominant side does not (Tsuchikane et al., 2017). Considering these findings, it is assumed that golf players have a bilateral asymmetry in the size of trunk muscles, and its magnitude would correlate with the CHS during a golf swing.

In most previous studies that examined the relationship between CHS and other kinematic variables during the golf swing, the analyzed parameters were represented by values at specific swing events, such as the point at which the maximum value is observed (Chu et al., 2010; Joyce, 2017; Joyce et al., 2013; Kwon et al., 2013). In the rotary motion of the body-tool (racket/club) system, increasing the system angular momentum by generating an external moment about the whole-body center of mass, and transferring the angular momentum between adjacent body segments through reciprocal action and reaction, is essential for accelerating the distal-end segment (i.e., club head). However, no study has examined how golf players rotate the trunk to effectively accelerate the golf club toward ball impact.

The general purpose of this thesis, therefore, was to elucidate the effects of trunk muscularity (i.e., muscle volume and asymmetry) and motion strategy on the club head speed during the driver shot in skilled male golf players. The trunk segment plays an important role for connecting between lower and upper extremities through rotary motion in most sports that include throwing and hitting motions. Examining the profiles of trunk muscularity and motion strategy during the golf swing, as well as their influence on the performance of skilled golf players, will deepen existing knowledge of the mechanisms of trunk motion and the characteristics of trunk muscularity, potentially providing useful information for all athletes who participate in sporting events that require them to swing a tool held with both hands.

1-2. Terminology

Bilateral asymmetry

"Bilateral asymmetry" refers to the difference between the larger and smaller sides within the body in muscle size (i.e., thickness, cross-sectional area, and volume) or muscular activities during a specific movement. In this thesis, the relative difference in the muscle volume for the muscles located in both sides of the trunk is referred to as the bilateral asymmetry in muscle size. As a parameter presenting the bilateral asymmetry, the ratio of the muscle volume on the larger side to the smaller side (asymmetric ratio) was calculated using the following equation (Rankin et al., 2006): asymmetric ratio (%) = [(larger side − smaller side) / larger side] × 100.

Club head speed

"Club head speed" refers to the magnitude of the velocity vector produced at the club head during the golf swing. In this thesis, the magnitude of vector of the velocity immediately before the ball impact in the driver shot is adopted as the club head speed.

Dominant/Non-dominant

"Dominant" and "Non-dominant" refer to the side of the dominant hand and the non-dominant hand, respectively, of all participants in the thesis. For right-handed golf players in this thesis, the dominant side is the right side and the non-dominant side is the left side. For non-golf players in this thesis, the dominant side is the side of the dominant hand and the non-dominant side is the opposite hand. The right side of right-handed non-golf players is the dominant side, and the left side of left-handed non-golf players is the dominant side.

Muscle size

"Muscle size" refers to a spatial dimension of the muscle. In this thesis, muscle size is described by thickness, cross-sectional area, and volume.

Rotary motion of body-tool system

"Rotary motion of system" refers to the relative motion of each body segment and tool, such as a golf club or tennis racket, and the ball, around the whole-body center of mass. In this thesis, the system consisted of a 15-segment model (14 body segments and the golf club) as the body-club system.

Swing plane

"Swing plane" refers to the virtual plane of the club head path during the golf swing. In this thesis, the swing plane was computed using least squares orthogonal distance fitting in accordance with the procedures used in previous studies (Kwon et al., 2012; Morrison et al., 2014). The club head trajectories during the downswing phase, especially the phase from a horizontal situation of the club shaft to the ball impact, was using for computing the swing plane.

Trunk

The term "trunk" is generally used to describe the central part of the human body. In this thesis, the trunk is defined as the body segment separated from the head and limbs by specific body landmarks: the C7 spinous process, the sternum, the acromion process of the shoulders, and the greater trochanter of the femur (Ae, Tang and Yokoi, 1992; Ishiguro et al., 2006).

Trunk muscle

“Trunk muscle” refers to the muscles locating in the trunk. In this thesis, the trunk muscle consists of six muscles: the rectus abdominis, the lateral abdominal wall (including the external abdominal oblique, internal abdominal oblique, and transverse abdominal), the psoas major, quadratus lumborum, erector spinae, and the multifidus.

Trunk muscularity

“Trunk muscularity” refers to a dimension of the muscle, such as muscle size (i.e., thickness, cross-sectional area, and volume) and bilateral asymmetry in muscle size. In this thesis, the muscle volume is used as the representative variable for muscle size and is determined using magnetic resonance imaging of the trunk.

Trunk motion strategy

“Trunk motion strategy” refers to the way in which the trunk is moved to obtain a specific result, i.e., swinging a golf club and hitting a golf ball. In this thesis, the kinematics and kinetic variables of the trunk during the golf swing are analyzed to determine the optimal trunk motion strategy for achieving fast CHS.

1-3. Abbreviations

CHS: Club head speed

CSA: Cross-sectional area

EO: External abdominal oblique

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ES: Erector spinae

$\boldsymbol{H}$: Angular momentum vector of the body-club system about the whole-body center of mass

$\boldsymbol{H_C}$: Angular momentum vector of the golf club

$\boldsymbol{H_{C.M.}}$: Angular momentum vector of the whole-body

$\boldsymbol{H_{LT}}$: Local angular momentum vector of each body segment about the transverse axis

$\boldsymbol{H_{LL}}$: Local angular momentum vector of each body segment about the longitudinal axis

$\boldsymbol{H_T}$: Transfer angular momentum vector of each body segment

$\boldsymbol{I}$: Moment of inertia (vector)

ICC: Interclass correlation coefficient

IO: Internal abdominal oblique

JTP: Joint torque power

LA: Lateral abdominal wall

MF: Multifidus

MRI: Magnetic resonance imaging

PM: Psoas major

%CV: Coefficient of variation

%D_{AM}: The relative difference from maximum angular momentum to angular momentum at the ball impact

QL: Quadratus lumborum

RA: Recuts abdominis

SD: Standard deviation

STP: Segment torque power

TA: Transverse abdominal

m: Mass

$\boldsymbol{r}$: Position vector

$\boldsymbol{v}$: Velocity vector

$\boldsymbol{\omega}$: Angular velocity vector

1-4. Literature Review

The general purpose of this thesis was to elucidate the effects of trunk muscularity and motion strategy on the CHS during the driver shot in skilled male golf players. Most previous studies on this subject focused on the kinematic parameters of the trunk during the golf swing, and on physical parameters such as the activities and strength-capability of the trunk muscles, to analyze an effective golf swing motion. In this section, previous publications are reviewed from the following viewpoints: 1) phases of the golf swing, 2) muscle activities during the golf swing, 3) the associations of muscle strength and muscularity with golf performance, 4) event-related profiles of trunk muscularity, 5) the relationships between the trunk angular velocity and golf performance, and 6) the strategy of body rotation for an effective golf swing. In addition, previous results obtained from research that examined athletes who do not play golf but whose competitive activities require the performance of asymmetric motion similar to a golf swing are also reviewed to describe 7) the strategy of body rotation for high throwing and hitting performance.

1-4-1. Phases of the golf swing

The golf swing is generally divided into the four phases: address, backswing, downswing, and follow-through (Figure 1) (Hume et al., 2005). In the address, golf players grip the golf club with both hands and position the body, including the knee flexion and trunk forward flexion, with respect to the ball. In the backswing, the golf players take the club head away from the ball while rotating their trunk to prepare for hitting the ball.

In the downswing, the golf players swing the club head downward by rotating and flexing the trunk laterally to hit the ball. The follow-through is the deceleration phase of the body and club head after hitting the ball (or "ball impact"). The goal of the driver shot is to hit the golf ball as far as possible. The downswing phase is especially important for an effective ball impact, because the roles of the downswing are to accelerate the club head and to strike the ball with maximum velocity (Hume et al., 2005).

In the downswing, golf players create the external moment about the whole-body center of mass in the swing direction by generating a ground reaction force (Han, Como, Kim, Lee, et al., 2019; McNitt-Gray et al., 2013; Peterson et al., 2016). Then, the upper body including the trunk and arms is rotated in the swing direction to generate torque from the left hip flexor and adductor, and from the right hip extensor and abductor (Foxworth et al., 2013; Takagi et al., 2019). In coaching literature (Hogan et al., 2014; Leadbetter & Kaspriske, 2015), a typical upper body rotation during the golf swing is explained as a swinging motion of the arm segment "synchronously" with trunk (shoulder) rotation. Anatomically, because the golf club is being held with both hands (Hume et al., 2005), trunk (shoulder) rotation should be required to swing the arms and club. These aspects suggest that elucidating the profile of trunk rotation during the golf swing would provide valuable information for discussing the influential factors of achieving a fast CHS.

1-4-2. Muscle activities during a golf swing

The golf swing consists of an asymmetric trunk motion. In the downswing for a right-handed golf player, the trunk rotates to the left and flexes laterally to the right while remaining in forward flexion (Horan et al., 2010; Joyce, 2017; Okuda et al., 2010). This motion is provided by the activities of the trunk muscles such as the recuts abdominis (RA) and lateral abdominal wall (LA). The RA is an agonist of trunk forward flexion and ipsilateral lateral flexion, and the major roles of the LA including the external abdominal oblique (EO) and internal abdominal oblique (IO) are an ipsilateral and contralateral trunk axial rotation (Schunke, 2014). Moreover, the erector spinae (ES) works to maintain posture and contributes to trunk extension with activities on both sides, as well as trunk lateral flexion and trunk axial rotation on the ipsilateral side with activity on one side (Schunke, 2014). The asymmetric activities of the trunk muscles during the golf swing have been well documented (Bulbulian et al., 2001; Cole & Grimshaw, 2008; Lim et al., 2012; Marta et al., 2013; Pink et al., 1993; Sorbie et al., 2018; Watkins et al., 1996). For example, the activity of the RA is larger on the right side than on the left side (Marta et al., 2013; Pink et al., 1993; Watkins et al., 1996). For the LA, while the activity of the IO is larger on the left side compared to the right side in the downswing, that of the EO is the opposite (Cole et al., 2008; Lim et al., 2012; Pink et al., 1993; Watkins et al., 1996). Furthermore, it is known that the ES during the downswing also has bilateral asymmetry, and its extent is phase dependent. In the early phase of the downswing, the activities of the ES for the right side are greater than that for the left side (Bulbulian et al., 2001; Cole et al., 2008; Pink et al., 1993; Sorbie et al., 2018; Watkins et al., 1996). However, in the late phase of the downswing, the activity of the ES is reported to be either higher in the left side than in the right side (Bulbulian et al., 2001; Marta et al., 2013; Sorbie et al., 2018), or similar on both sides (Cole et al., 2008; Pink et al., 1993; Watkins et al., 1996). During the downswing, the activity of the ES has been reported to be larger in low-handicap players than in high-handicap players (Cole et al., 2008). Moreover, these activities of the abdominal muscles during the golf swing are associated with the magnitude of the trunk rotation (Bulbulian et al., 2001).

1-4-3. Associations of muscle strength and muscularity with golf performance

For golf players, trunk muscle strength becomes a physical factor relating to golf performance. For example, trunk axial rotation strength is greater in low-handicap players than in high-handicap players (Keogh et al., 2009; Sell et al., 2007) and in the left side (target direction) as compared to the right side (counter-target direction) in skilled golf players (Bae et al., 2012; Ehara et al., 2017). The trunk muscle strength for each of trunk axial rotation, flexion/extension, and lateral flexion each significantly correlates to the CHS (Ehara et al., 2017; Hellström, 2008; Keogh et al., 2009; Lewis et al., 2016; Read et al., 2013). In addition, a resistance training program for the trunk muscle, consisting of exercises such as the crunch, trunk twist, lateral flexion, and good morning (trunk flexion/extension), improves trunk muscle strength and golf driving performance (Fletcher & Hartwell, 2004; Kim, 2010; Lephart et al., 2007; Sung et al., 2016).

It is well known that the force generation capability of a muscle is closely related to its size (Fukunaga et al., 2001; Maughan et al., 1983). Considering this with the aforementioned findings, it is hypothesized that trunk muscle size would be associated with golf performance. So far, only one study has determined the cross-sectional areas (CSAs) of the RA, LA, ES, and psoas major (PM) in golf players, and the authors observed a positive correlation between the CSA of the LA and CHS (Ehara et al., 2017). However, a previous study determined the CSA at the limited level of the trunk, i.e., the level of the fourth and fifth intervertebral lumbar spines. There is a greater variety in the insertion and origin positions of these trunk muscles compared to those of extremity muscles (Schunke, 2014). In addition, it is likely that the level at which the CSA reaches its maximum value may differ among different trunk muscles. Thus, it is difficult to evaluate the size of each trunk muscle using the CSA determined at the limited level. In addition, it is well documented that hypertrophic muscle change induced by resistance training is not uniform along its length of a muscle (Narici et al., 1989). For example, resistance training consisting of unilateral leg extensions at 80% of one's repetition maximum induced significantly different hypertrophic changes between and within the four constituents of the quadriceps (Narici et al., 1996). The non-uniform muscle hypertrophy is attributable to the differences between and within the exercising muscles in the extent of the activities performed during a prescribed training regime (Narici et al., 1996; Wakahara et al., 2012). Combining these aspects with the asymmetric profiles of trunk muscular activities during the golf swing, it is likely that muscle volume is a more valid variable when compared to muscle CSA for examining the relationship between the trunk muscularity of golf players and their golf performance.

1-4-4. Event-related profiles of trunk muscularity

Bilateral asymmetry in trunk muscle size has been well documented in muscularity profiles of skilled athletes, since asymmetric trunk motions are required in training and competitive activities. For example, volumes of the RA and LA are larger by 58% and 30%, respectively, in professional tennis players than in non-active people (Sanchis-Moysi et al., 2010; Sanchis-Moysi et al., 2013). In addition, volumes of the RA, LA, and iliacus muscle in tennis players are greater by 35%, 18%, and 13%, respectively, on the non-dominant side than on the dominant side (Sanchis-Moysi et al., 2010; Sanchis-Moysi et al., 2011, 2013). In throwing events of track and field, asymmetric hypertrophy has been observed in the PM (Muramatsu et al., 2010). The total volume of the trunk muscle (Tanaka et al., 2013) and CSAs of the PM and ES (Ohkawa et al., 2004) significantly correlate with throwing performance. Moreover, baseball players have greater thickness of the IO and LA on the non-dominant side than on the dominant side (Hasegawa & Ono, 2012; Tsuchikane et al., 2017). For baseball players, both sides of the IO thickness are positively correlated with the pitching ball speed (Hasegawa et al., 2012), and the LA thickness is correlated with the bat swing speed only on the dominant side (Tsuchikane et al., 2017).

1-4-5. Relationships between the trunk angular velocity during the golf swing and CHS

It is known that the kinematic variables of trunk motion during the golf swing correlates with the CHS (Chu et al., 2010; Joyce et al., 2013; Myers et al., 2008). The maximum angular velocity of pelvic axial rotation in the downswing and its angular velocity at the middle phase of the downswing, defined as the horizontal situation of the club shaft during the downswing, are positively correlated with the CHS (Chu et al., 2010; Myers et al., 2008). The maximum angular velocity of the thorax axial rotation, and the angular velocities of thorax axial rotation and lateral flexion at the middle downswing and 40 ms before the ball impact are also positively correlated with the CHS (Chu et al., 2010; Joyce et al., 2013; Myers et al., 2008). Moreover, there is a significant correlation between the maximum angular velocity of the thorax axial rotation relative to the pelvis and the CHS (Myers et al., 2008).

1-4-6. Strategy of body rotation for an effective golf swing

The speed of the distal-end segment (tool; golf club, racket, ball) is augmented through sequential angular motion, such as by the proximal to distal segment (Putnam, 1993). This sequential motion is an important concept for sports that include throwing and hitting, in which body rotation acts to accelerate the end segment (Fuchs et al., 2018; Marshall & Elliott, 2000; Wagner et al., 2014). In the golf swing, the time sequence of the peak angular velocity (Cheetham et al., 2008; Han, Como, Kim, Hung, et al., 2019; Horan et al., 2012; Neal et al., 2007, 2008) and the peak joint torque (Sprigings et al., 2002) for each of the upper body segments during the driver shot have been analyzed to determine a swing strategy for an effective golf swing. After the beginning of the downswing, the rotational direction of the upper body segments changes in the order of the pelvis, thorax, shoulder, and arm (Han, Como, Kim, Hung, et al., 2019). The proximal-to-distal sequences of the peak angular velocity (pelvis/thorax) is yielded during the downswing (Cheetham et al., 2008; Han, Como, Kim, Hung, et al., 2019; Horan et al., 2012; Joyce et al., 2013; Zheng et al., 2008), and the angular velocity of the wrist peaks at the end of the time sequence immediately before the ball impact (Chu et al., 2010). In contrast, the thorax/arm sequence during the downswing has only been partially described (Cheetham et al., 2008; Han, Como, Kim, Hung, et al., 2019; Neal et al., 2007, 2008).

1-4-7. Strategy of body rotation for high throwing and hitting performance

In the rotary motion of the body-tool system, the increased speed of the distal-end segment (tool) is considered to be due to angular momentum transfer between adjacent body segments through reciprocal action and reaction. Furthermore, external force effects on the body and the external moment about the whole-body center of mass are also associated with acceleration for rotary motion of the body-tool system (Han, Como, Kim, Lee, et al., 2019). During tennis serves and baseball pitches, in which the racket or ball is held with one hand, the increase of arm angular momentum exceeds that of the body-tool system from the start of the forward swing to the ball impact/release (Bahamonde, 2000; Lin et al., 2003; Martin et al., 2013). This implies that players accelerate the racket/hand not only by external moment generation through the throwing or hitting motion but also by angular momentum transfer from the proximal to distal segment. In the two-handed backhand tennis stroke, however, both the angular momentum of the trunk and racket increase toward the ball impact, while those of the arms reach a maximum immediately after the end of the backswing and decrease toward the point of ball impact (Wang et al., 2010). This suggests that, in the two-handed backhand tennis stroke, the players accelerate the racket and trunk by generating an external moment through the racket swing without sequential motion from the proximal (trunk) to distal (arm) segment.

1-5. Research questions and hypotheses

As described in the review of the electromyographic literature (Section 1-4-2), the activities of the trunk muscles during the golf swing are asymmetrical in a way that reflects the profiles of the golf swing motions. In addition, skilled athletes, who require asymmetric trunk motions during training and competitive activities, show bilateral asymmetry in trunk muscle size. Considering these aspects, it is hypothesized that long-term golf players would have a bilateral asymmetry in the volume of their trunk muscles. However, no study has addressed the profiles of trunk muscularity in this subject. In addition, it is known that trunk muscle strength significantly correlates to the CHS. Although it is well known that the force generation capability of a muscle is closely related to its size, the relationship between the trunk muscularity and a golf performance such as CHS is unclear. Previous findings on the relationship between trunk muscularity and physical performance in baseball players tempts the speculation that not only trunk muscle volume but also the magnitude of the bilateral asymmetry would be related to the CHS during the golf swing.

In the review of the literature in Section 1-4-5, trunk angular velocity influences the CHS. However, the identified variables in the previous studies were represented with the value at specific swing events, such as the point at which the maximum value is observed. It remains unclear how golf players effectively accelerate the club head and consequently achieve a fast CHS. Considering that the golf swing is the rotary motion of a body-tool system, it is likely that the transference of angular momentum between adjacent body segments and increasing angular momentum of the body-tool system by generating an external moment would be required for accelerating the tool. However, there is no information on the changes in angular momentum during the golf swing, being the product of the moment of inertia and angular velocity (thus, the angular analogue of linear momentum), in each body segment as well as the total (body-club) system and their associations with CHS.

In the two-handed backhand tennis stroke, while the angular momentum of the arms reaches a maximum immediately after the end of the backswing and decreases towards the point of ball impact, the angular momentum of both the trunk and racket increase towards the ball impact. Considering that the golf club is held with both hands, trunk motion and changes in angular momentum of the upper body during the golf swing would be comparable to that during a two-handed backhand tennis stroke. In fact, as described above, the thorax/arm sequence during the downswing is only partially elucidated. Therefore, it is assumed that the pattern of changes in the angular momentum of the trunk and arms during the golf swing would very similar to the two-handed backhand tennis stroke, and the club head would be accelerated without the trunk/arm sequence through the downswing.

1-6. Purpose

The general purpose of this thesis was to elucidate the effects of trunk muscularity and motion strategy on the CHS during the driver shot in skilled male golf players. To this end, this thesis examined 1) the volume of the trunk muscle and the degree of its bilateral asymmetry in skilled golf players (Section 1 of Chapter 2), 2) the association between trunk muscularity and CHS (Section 2 of Chapter 2), and determined 3) the changes in angular momentum for each body segment and the golf club during the golf swing (Chapter 3). Skilled male golf players who had at least 10 years of experience in golf practice voluntarily participated in this study.

In Chapter 2, the trunk muscularity (muscle volume and the degree of bilateral asymmetry) was determined in skilled golf players by comparison with a matched non-active participant group (Section 1). Then, how the volume of trunk muscles and their bilateral asymmetry are related to CHS was examined in skilled golf players (Section 2).

In Chapter 3, the changes in angular momentum during the golf swing were measured in skilled golf players by using a three-dimensional method, and its associations with CHS were determined.

In Chapter 4, the main results of the thesis were described, and the contribution of trunk muscularity to achieving a fast CHS was discussed in relation with the strategy of trunk motion during golf swing.

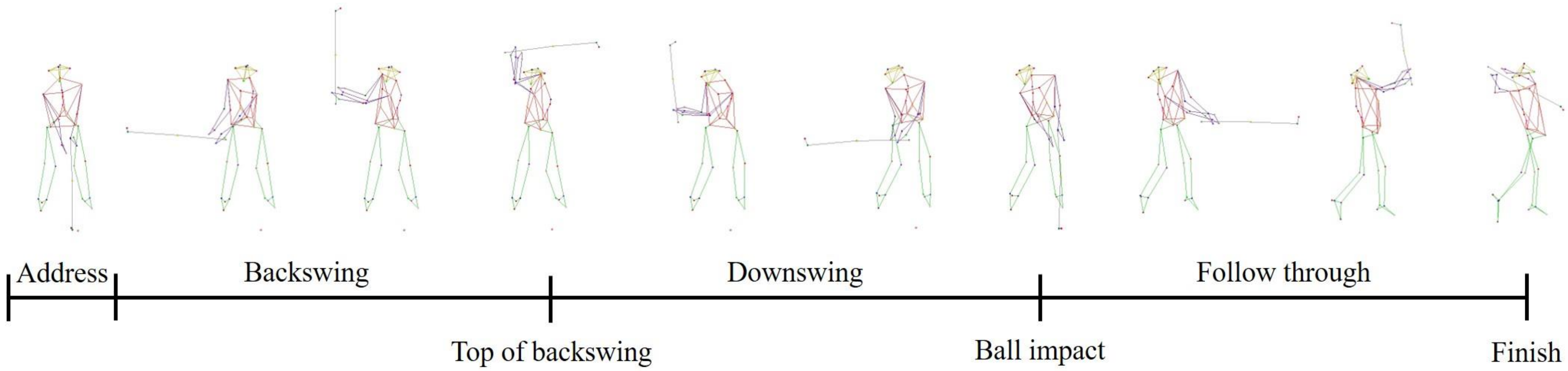

Figure 1. Definitions of events and phases of golf swing in this thesis.

Chapter 2 Trunk muscularity and its relationship with CHS of skilled golf players

Section 1 Bilateral asymmetry in the trunk muscle volume of skilled golf players

2-1-1. Introduction

Golf swing requires the players to perform asymmetric trunk motion. In right-handed golf players, the trunk rotates to the left and flexes laterally to the right side while remaining in forward flexion during the downswing (Horan et al., 2010; Horan et al., 2012). The trunk muscles are activated separately on both sides during golf swing (Marta et al., 2013; Watkins et al., 1996) and larger trunk rotation is associated with greater activation in the abdominal muscles (Bulbulian et al., 2001). Considering these, frequent golf swing practice may cause asymmetric hypertrophy of the trunk muscles, and skilled golf players who participated in golf practices and competitive activities in the long term would have greater degree of bilateral asymmetry in trunk muscles compared to non-active people who have never played the golf.

The purpose of this section was to investigate the degree of bilateral asymmetry in the trunk muscles of skilled golf players who participated in golf practices and competitive activities in the long term by comparing with a matched non-active participant group.

2-1-2. Methods

Participants

Seventeen male right-handed golf players and eleven male non-golf players (nine right-handed and two left-handed) agreed to participate in this section (Table 2-1-1) and were assigned to two groups, golf players and non-golf players, respectively. There were no significant differences in the physical characteristics between the two groups ($p > 0.05$). The golf players had at least 10 years of experience in golf practice (12.4 ± 2.8 years, mean±SD), and they performed the game at a relatively high level (best score, 65.5 ± 1.8 strokes/round; average score during the last month, 74.5 ± 2.2 strokes/round). All non-golf players had never played the golf and had not been involved in regular physical exercise for the last six months before the measurements. The study of Section 1 was approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2013-015), and written informed consent was obtained from each participant, confirming that they understood the purpose of the study and the possible risks of participating.

Data collection

Magnetic resonance (MR) images of the trunk were obtained with a 1.5 tesla magnetic resonance system (Signa HDxt 1.5T; GE Healthcare UK Ltd, Buckinghamshire, England) while the participants lay in the supine position. Serial transverse MR images (repetition time, 6700 ms; echo time, 7.2 ms; slice thickness, 10 mm; inter-spaced distance, 0 mm; field of view, 480 × 480 mm; matrix size, 512 × 512) were obtained perpendicular to the anterior abdominal wall from the first lumbar to the first sacral vertebra.

Data analysis

MR images were used to determine the volume of both the left and right trunk muscles (Figure 2-1-1). The CSAs of the trunk muscles, i.e., the LA, ES, PM, RA, quadratus lumborum (QL) and multifidus (MF), were manually determined using an image analysis software (SliceOmatic 5.0 Rev-4b2, Tomovision, Magog, Canada), and the areas of all slices were added to estimate the muscle volume of each trunk muscle. Manual segmentation of each trunk muscle was performed by a well-trained examiner. Intrarater repeatability of manual segmentation of each trunk muscle from MR image was assessed with the use of intraclass correlations (ICCs). The ICC (1, 2) for the volume of the trunk muscles among three participates was >

0.97. All trunk muscle volumes were normalized for the body mass of the participant. We defined the "dominant side" of trunk muscle volume as the side of the dominant hand in both golf players and non-golf players and the non-dominant side as the opposite side. The degree of bilateral asymmetry for each trunk muscle was calculated as the ratio of the muscle volume on the larger side to the smaller side.

Statistics

All results are presented as mean ± SD. All trunk muscle volumes of the dominant and non-dominant side were confirmed as being normally distributed in both groups. In the comparison of muscle volumes, a two-way ANOVA adjusted for multiple comparisons using the Bonferroni method was used to examine the effect of both the group (golf player vs. non-golf player) and body side (dominant vs. non-dominant) of each trunk muscle. For the comparison of the asymmetry ratio and the total volume of each trunk muscle, which was sum of the dominant and non-dominant side, between the two groups, an independent t-test was used. All statistical analysis was performed with the IBM Statistical Package for the Social Sciences Statistics for Windows, version 19 (IBM Corp., Armonk, N.Y., USA). The probability level for statistical significance was set at 0.05.

2-1-3. Results

The total volume of each trunk muscle in golf players was significantly larger than that of non-golf players (LA; 12.36 ± 1.12 vs. 9.96 ± 0.94 cm^3/kg, ES; 9.12 ± 1.16 vs. 7.88 ± 0.84 cm^3/kg, PM; 6.27 ± 0.88 vs. 5.51 ± 0.98 cm^3/kg, RA; 4.15 ± 0.54 vs. 3.50 ± 0.64 cm^3/kg, MF; 3.61 ± 0.41 vs. 3.05 ± 0.40 cm^3/kg, $p < 0.05$), except for QL muscle volume (1.81 ± 0.24 vs. 1.82 ± 0.25 cm^3/kg, $p > 0.05$) (Figure 2-1-2). Table 2-1-2 summarizes the muscle volume on the dominant and non-dominant side and the asymmetry ratio for each trunk muscle in golf players and non-golf players. In the golf players, the muscle volume was significantly larger on the non-dominant side than on the dominant side for the LA, ES, and PM, while the muscle volume on the dominant side was significantly larger than on the non-dominant side for the RA and MF. In non-golf players, there was a significant difference between muscle volumes on the dominant and non-dominant side for the LA and MF.

The asymmetry ratios of the LA and PM in the golf players were significantly larger than those in the non-golf players. There was no significant difference between the golf and non-golf players in the asymmetric ratio for each of the ES, RA, MF and QL.

2-1-4. Discussion

The golf players in this section, who performed the game at a relatively high level and had been playing for more than ten years, had a larger trunk muscle volume, except for the QL, than non-golf players, while basic physical characteristics did not differ between the two groups. The primary results of this section were that the golf players had bilateral asymmetry in their trunk muscle volumes (LA, ES, PM, RA, and MF) compared to non-golf players. In particular, the muscle volume of the LA, PM and RA, and the degree of the bilateral asymmetry in the volume of the LA and PM in the golf players was significantly larger than that of the non-golf players. The golf players had a greater LA and PM volume on the non-dominant compared to the dominant side (meaning the side of their dominant hand), and greater RA volume on the dominant compared to the non-dominant side. The findings of this section confirm our original hypothesis that participating in golf practices and competitive activities in the long term leads to golf-specific trunk muscle hypertrophy.

Our finding that the RA is bilaterally hypertrophied in golf players is interesting. Previous studies have shown that bilateral asymmetry of trunk muscles occurs in athletes who require trunk rotation in one direction (Sanchis-Moysi et al., 2010; Sanchis-Moysi et al., 2011, 2013). Tennis players had a 58 % larger RA volume compared to non-active people, and RA volume was 35 % larger on the non-dominant compared to the dominant side where they hold the racket (Sanchis-Moysi et al., 2010; Sanchis-Moysi et al., 2013). This is because trunk lateral flexion to the non-dominant side is affected by the RA of the non-dominant side, which also carries the mechanical load, in tennis players during their serve. From an anatomical standpoint, this appears illogical, since the major role of the RA is forward flexion of the trunk, but an additional role of the RA is lateral flexion of the trunk to the side where it contracts (Schunke, 2014). Right-handed golf players flex their trunk laterally to the dominant (right) side during the downswing (Horan et al., 2010; Horan et al., 2012; Okuda et al., 2010). Electromyographic studies support this explanation, since asymmetric activation of the RA muscles was observed during the downswing (Marta et al., 2013; Watkins et al., 1996), meaning that the RA muscle on the dominant side is activated to a greater extent than the RA on the non-dominant side. Therefore, frequent golf practice could lead to a hypertrophied RA muscle on the dominant, but not on the non-dominant side, in right-handed golf players.

In this section, the LA showed a large total muscle volume and bilateral asymmetry in golf players. Previous studies demonstrated that tennis players had 30 % larger LA volumes compared to non-active people, and the LA had an 18 % larger volume on the non-dominant compared to the dominant side (Sanchis-Moysi et al., 2013). A larger LA on the non-dominant side in golf players is most likely associated with trunk motion during a right-handed golf swing. Right-handed golf players rotate their trunk to the non-dominant side during the downswing (Horan et al., 2010; Horan et al., 2012; Okuda et al., 2010). The major role of the IO is to rotate the trunk to the ipsilateral side. The LA muscles on both sides are activated separately during the downswing (Marta et al., 2013; Watkins et al., 1996). Thus, the golf swing generates asymmetric activation and, in the long term, hypertrophy of the LA on the non-dominant side. Moreover, in this section, hypertrophy in the LA exceeded the hypertrophy of all other trunk muscles in golf players. The asymmetry ratio of the LA was the second largest of the six examined trunk muscles. In recent studies of baseball players, bilateral asymmetry was observed in the LA muscles, and muscle thickness was positively correlated with bat swing speed (Tsuchikane et al., 2017). Considering the points above, asymmetric LA hypertrophy might be essential for improving the speed of trunk rotation. However, in order to discuss a potential mechanism for improving the speed of the golf swing, further studies are required to elucidate the effect of asymmetric trunk muscle hypertrophy on club head speed.

In addition, the volume and asymmetry ratio of the PM of golf players were significantly different to that of non-golf players, and the PM on the non-dominant side was significantly larger than that of the dominant side. The major role of the PM is hip flexion, meaning that the PM is one of the major contributors to ipsilateral hip flexion (Schunke, 2014). The PM of elite Australian football players shows bilateral asymmetry of about 3.5 % larger CSA on the side of the dominant kicking leg, due to repetitive kicking throughout the season using mainly the same leg (Hides et al., 2010; Stewart et al., 2010). A previous study in right-handed golf players indicated that non-dominant hip joint torques were generated in the direction of flexion during the downswing (Foxworth et al., 2013). These results suggest that the PM on the non-dominant side may be used for rotating the trunk to the non-dominant side during the downswing. In tennis players, the iliacus and psoas muscles, which support similar motions as the PM, show bilateral asymmetry with a 13 % greater volume on the non-dominant side (Sanchis-Moysi et al., 2011). Therefore, recurrent right-handed golf swing practice causes asymmetrical hypertrophy of the non-dominant PM, because non-dominant hip flexion during the downswing causes a mechanical load on the non-dominant PM in right-handed golf players. However, to draw definite conclusions, electromyographic studies are required to investigate PM activation during the golf swing.

2-1-5. Summary

The study of Section 1 determined the total trunk muscle volume for both the dominant and non-dominant body side and the degree of the bilateral asymmetry in these volumes in skilled golf players and non-golf players. The results demonstrate that skilled golf players who participated in golf practices and competitive activities for the long term have large volumes and bilateral asymmetry of their trunk muscles. The bilateral asymmetry in muscle volumes of the LA, PM, and RA may be due to the side-related difference in the magnitude of the activities of these muscles during the golf swing.

Table 2-1-1. Baseline physical characteristics of golf players and non-golf players and experience and performance level of golf players

Variables	**Golf players**	**Non-golf players**	***p***
N	17	11	
Age (years)	20.3 ± 0.9	22.2 ± 0.9	< 0.05
Height (cm)	171.0 ± 5.5	171.6 ± 4.6	n.s.
Body mass (kg)	70.2 ± 8.9	66.5 ± 9.9	n.s.
Golf experience (years)	12.4 ± 2.8		
Best score (strokes / round)	65.5 ± 1.8		
Average score (strokes / round)	74.5 ± 2.2		

Notes: Mean ± SD. n.s., not significant.

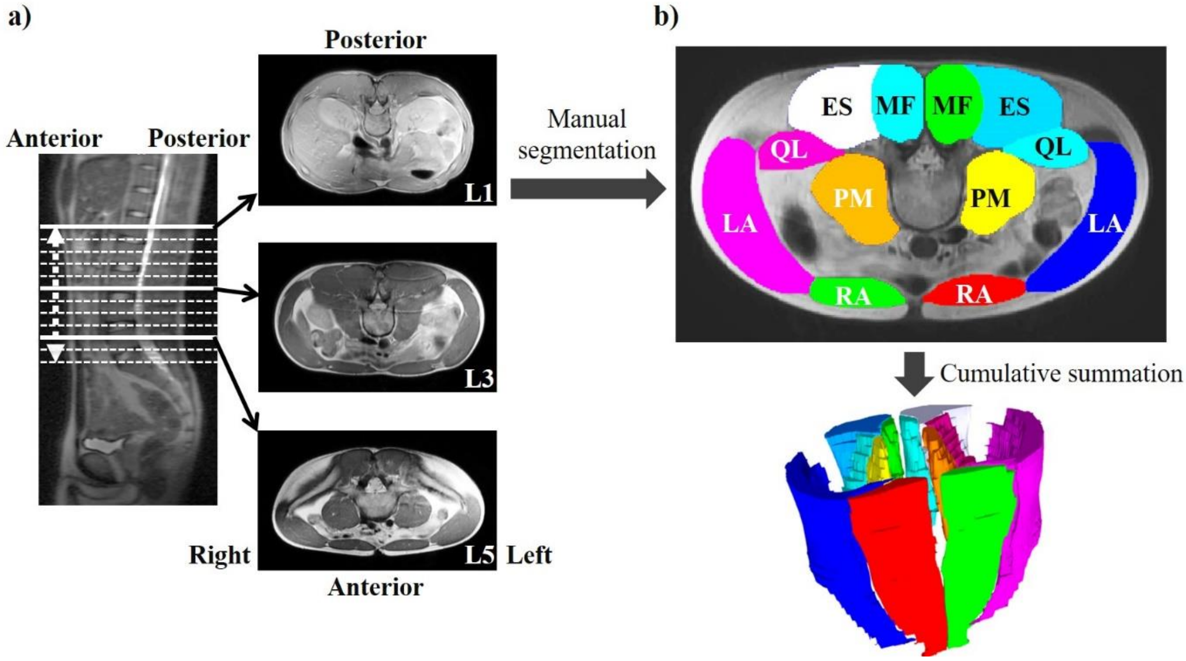

Figure 2-1-1. a) Transverse magnetic resonance images of the trunk; b) Manual segmentation of the trunk muscles and cumulative summation of the CSA: LA, lateral abdominal wall; ES, erector spinae; PM, psoas major; RA, rectus abdominis; MF, multifidus; QL, quadratus lumborum.

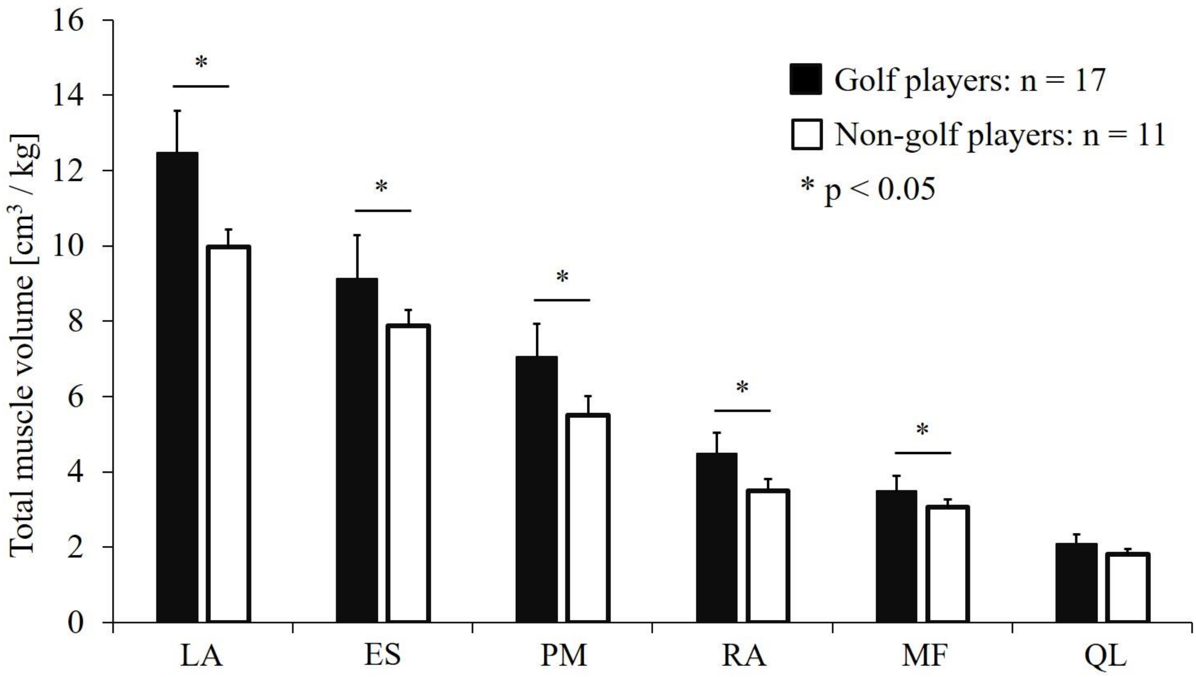

Figure 2-1-2. Total volume of each trunk muscle (sum of the dominant and non-dominant side) in golf players and non-golf players after normalizing for body mass: LA, lateral abdominal wall; ES, erector spinae; PM, psoas major; RA, rectus abdominis; MF, multifidus; QL, quadratus lumborum. *, statistically significant difference ($p < 0.05$).

Table 2-1-2. Volume of trunk muscles on the dominant and non-dominant side and asymmetry ratio in golf players and non-golf players

	Golf players: n=17			Non-golf players: n=11		
Muscles	**Dominant side (cm^3/kg)**	**Non-dominant side (cm^3/kg)**	**Asymmetry (%)**	**Dominant side (cm^3/kg)**	**Non-dominant side (cm^3/kg)**	**Asymmetry (%)**
LA	5.89 ± 0.55 †	6.48 ± 0.65 * †	7.71 ± 6.00 †	5.03 ± 0.47 *	4.93 ± 0.49	2.68 ± 1.95
ES	4.46 ± 0.56	4.65 ± 0.63 *	5.06 ± 4.38	3.91 ± 0.42	3.98 ± 0.44	4.37 ± 3.27
PM	3.00 ± 0.42	3.27 ± 0.47 * †	8.15 ± 4.34 †	2.74 ± 0.47	2.76 ± 0.52	5.51 ± 2.02
RA	2.15 ± 0.32 * †	2.00 ± 0.24 †	7.72 ± 4.66	1.74 ± 0.34	1.76 ± 0.31	4.55 ± 6.26
MF	1.84 ± 0.21 *	1.78 ± 0.21	5.27 ± 3.13	1.56 ± 0.19 *	1.50 ± 0.21	4.92 ± 3.69
QL	0.91 ± 0.11	0.90 ± 0.15	6.44 ± 4.85	0.89 ± 0.12	0.93 ± 0.14	8.22 ± 6.47

Notes: Mean ± SD. LA, lateral abdominal wall; ES, erector spinae; PM, psoas major; RA, rectus abdominis; MF, multifidus; QL, quadratus lumborum. *, Significantly larger than the other side ($p < 0.05$); †, significant larger in golf players than non-golf players ($p < 0.05$). Dominant side, right side; non-dominant side, left side.

Section 2 Relationship between trunk muscularity and club head speed in male golf players

2-2-1. Introduction

In Section 1 of Chapter 2, the absolute volume of the LA and PM muscles on the non-dominant side, and the RA muscle on the dominant side were larger in golf players comparing the same side of non-athletes. In addition, the degree of the bilateral asymmetry in the LA, PM and RA in golf players was greater than that of other trunk muscles (Izumoto et al., 2019). The major roles of the LA, PM and RA are trunk rotation, hip flexion, and trunk laterally flexion, respectively. Notably, the PM is one of the major contributors to ipsilateral hip flexion (Schunke, 2014). A previous study reported that in right-handed golf players, non-dominant (left) hip joint torque was generated in the direction of flexion during the downswing (Foxworth et al., 2013). CHS correlates positively with the rotational angular velocity of the trunk towards the downswing direction (Chu et al., 2010; Joyce et al., 2013). Taking together, it is assumed that not only the volume of the LA and PM but also the degree of their bilateral asymmetry may be an influential factor for CHS.

The purpose of this section, therefore, was to investigate how the degree of bilateral asymmetry in addition to the absolute volume of the trunk muscles are related to the CHS in golf players. It was hypothesized that the absolute volume of the LA and PM, among other trunk muscles, as well as the magnitude of their bilateral asymmetry would contribute to fast CHS.

2-2-2. Methods

Participants

Fourteen right-handed male golf players participated in this section (age: 20.1 ± 0.8 years; height: 1.71 ± 0.05 m; body mass: 69.9 ± 9.5 kg; mean ± standard deviation [SD]). They had at least 8 years of experience in golf practice (12.1 ± 2.9 years) and participated in competitions, with the best score of 65.4 ± 1.8 strokes/round and an average score of 74.6 ± 2.0 strokes/round in the month before the experiment. The study of Section 2 was approved by the Ethics Committee of Ritsumeikan University (BKC-IRB-2015-027), and was conducted in accordance with the ethical standards of the International Journal of Sports Medicine (Harriss et al., 2017). Written informed consent was obtained from each participant, confirming that they understood the purpose of the study and the possible risks involved.

Data collection

MR images of the trunk for determining volume of the trunk muscles were obtained based on the method used in Section 1 of Chapter 2.

The participants completed five full driver shots using their own driver at an indoor driving range in our motion analysis laboratory (Motion Capture MAC 3D System, Raptor-E digital, Motion Analysis Co., CA USA). CHS was calculated based on three-dimensional positions of a reflective marker placed on the club head during the golf swing (sampling at 250 Hz), and calculated CHS immediately before impact was used for analysis. The CHS from the five shots was averaged to produce the criterion value. Some participants performed the driver shots before the MR scans, and others took the MR scans first due to unavoidable scheduling conflicts. In both cases, an interval of at least 30 min was taken between the shots and scans.

Data processing and analysis

Volume for each trunk muscle and its degree of bilateral asymmetry were measured and calculated based on the method used in Section 1 of Chapter 2 (Figure 2-1-1). Intrarater repeatability of manual segmentation of each trunk muscle from MR images was also assessed in Section 1of Chapter 2 using intraclass correlation coefficient (ICC), and the mean of the coefficient of variation (%CV).

Statistical analysis

The descriptive data are presented as mean ± SD. A paired t-test was used to compare the muscle volume between the dominant and non-dominant side. Pearson's product-moment correlation coefficients were calculated to examine the relationship between the CHS and either the muscle volume or its asymmetric ratio of each muscle. Stepwise multiple linear regression analysis was performed with the CHS as a dependent variable and the volume and asymmetric ratio for trunk muscles that were significantly correlated with the CHS as independent variables. All statistical analyses were performed using SPSS software (version 25, IBM Co., Tokyo, Japan). The probability level for statistical significance was set at 0.05 for each analysis.

2-2-3. Results

The CHS was 44.58 ± 2.50 m/s. The muscle volume of the non-dominant side was significantly larger than that of the dominant side for the LA, ES and PM, and vice versa for the RA and MF ($p < 0.05$, Table 2-2-1).

The CHS was correlated positively with the volume of both sides of the ES and RA, and the non-dominant side of the QL as well as the asymmetric ratio of the PM, and negatively with the QL asymmetric ratio ($p < 0.05$, Table 2-2-2). Among these variables, the stepwise multiple regression analysis selected the muscle volume of the dominant ES ($ES_{dominant}$) and the asymmetric ratio of the PM (PM_{ratio}) as the significant contributors to predicting CHS [$R^2 = 0.797$, $\beta = 0.674$ ($p < 0.001$) for $ES_{dominant}$, and $\beta = 0.495$ ($p = 0.004$) for PM_{ratio}, Figure 2-2-2]. The stepwise multiple regression equation was obtained as follows:

$$\text{CHS (m/s)} = 0.043 \times [\text{ES}_{\text{dominant}}\ (\text{cm}^3)] + 0.334 \times [\text{PM}_{\text{ratio}}\ (\%)] + 28.658$$

2-2-4. Discussion

The main finding obtained here was that the stepwise multiple regression analysis selected the muscle volume of the dominant ES and the asymmetric ratio of the PM as the significant contributors to a CHS in the skilled golf players. The findings of Section 1 suggested that participating in the training and competitive activities of golf for long term leads to hypertrophy and bilateral asymmetry in the trunk muscles. The absolute volume of ES and PM were significantly larger in golf players than in non-golf players, with golf-specific asymmetry. The current result that the PM asymmetric ratio was selected as an influential factor for CHS partly supports our hypothesis. However, the LA and PM muscle volume and the LA asymmetric ratio were not selected as determinant factors for the CHS, which partly contradicts the hypothesis. Consequently, the current results indicate that a large part (79.7%) of the variation in the CHS can be explained by the volume of the dominant ES and the asymmetric ratio of the PM. In other words, it is said that while not only greater absolute volume but also bilateral asymmetry in trunk muscles become in influential factors for CHS, the corresponding muscles would be limited.

As a result of the simple correlation analysis, the volumes of both sides of the ES positively correlated with the CHS, and the stepwise multiple regression analysis selected the volume of the dominant ES. These results suggest that greater ES muscle volume, especially that of the dominant side, is advantageous for achieving faster CHS. The major roles of the ES are trunk lateral flexion for the ipsilateral side and trunk axial rotation for contralateral side with activity on one side (Schunke, 2014). In the downswing, right-handed golf players flex their trunk to the dominant (right) side and rotate their trunk to the non-dominant (left) side. During the early phase of the downswing, the activity of the dominant ES is higher than that of the non-dominant side (Pink et al., 1993; Sorbie et al., 2018; Watkins et al., 1996), whereas the activity of the non-dominant ES is higher than that of the dominant side in the late phase of the downswing (Marta et al., 2013; Sorbie et al., 2018; Watkins et al., 1996). On the basis of these findings, it appears that the dominant ES acts to flex the trunk to the dominant side in the early phase of the downswing, and the non-dominant ES contributes to the rotation of the trunk to the non-dominant side in the late phase of the downswing. This may be the reason for the current result showing that the muscle volume of both sides of the ES was significantly correlated to the CHS. In addition, it has been shown that low-handicap golf players have greater activation of the dominant ES at the start of the downswing than high-handicap golf players (Cole et al., 2008). Improving muscle strength of the back lumbar region leads to faster CHS (Kim, 2010; Sung et al., 2016). Taking these into account, it is assumed that greater ES size, especially on the dominant side, leads to greater mechanical work and power production during the downswing, and consequently this may be a reason for the selection of the ES as a significant influential factor for CHS.

For the PM, the asymmetric ratio was selected as a positive factor influencing the CHS, but the muscle volume was not. All participants in this section had a larger volume of the PM on the non-dominant than the dominant side. These results suggest that for right-handed golf players, the PM bilateral asymmetry, being greater muscle volume in the non-dominant side in greater muscle volume than the dominant side, is important for achieving a fast CHS. The PM is one of the major contributors to ipsilateral hip flexion (Schunke, 2014); thus, the non-dominant PM is used in the non-dominant hip flexion. In the downswing, right-handed golf players rotate their trunk to the non-dominant (Horan et al., 2012), and joint torques at the non-dominant and dominant hips are generated in the opposite directions; flexor torque in the non-dominant hip and extensor torque in the dominant hip (Foxworth et al., 2013). Namely, golf players are required to flex their non-dominant hip while rotating their trunk to the non-dominant side. To our knowledge, no studies have examined the activities of the PM during the downswing. However, an electromyographic analysis of lower limb muscles during the golf swing have shown that as compared with high-handicap golf players, low-handicap golf players had greater activation of the non-dominant rectus femoris (a hip flexor) to produce non-dominant hip flexion in the early phase of the downswing (Bechler et al., 1995; Marta et al., 2016a, 2016b). Taking these aspects into consideration, it is assumed that the non-dominant hip flexion rather than the dominant hip extension would be important for twisting the trunk to the non-dominant during the golf swing, and consequently, the degree of bilateral asymmetry of the PM might have been selected as a significant contributor to achieving a fast CHS.

At the start of this section, we hypothesized that the absolute volume and bilateral asymmetry of the LA as well as PM would contribute to a fast CHS. In the current results, however, the muscularity parameters for the LA did not significantly correlate with the CHS, although the volume of this muscle had bilateral asymmetry. The major role of the LA is trunk rotation (Schunke, 2014). In particular, the IO mainly acts to rotate the trunk to the ipsilateral side, and the EO to the contralateral side (Schunke, 2014). In the downswing, therefore, the right-handed golf players rotate their trunk to the non-dominant side using their dominant EO and non-dominant IO. From the electromyographic analysis of the LA during the downswing, the activation level of the dominant EO is greater than that of the non-dominant side (Cole et al., 2008; Lim et al., 2012; Pink et al., 1993; Watkins et al., 1996), whereas the activation level of the non-dominant IO is greater than that of the dominant side (Lim et al., 2012). In this section, the EO and IO were analyzed together as the LA, because of difficulty in separating these muscles' CSAs of on the MRIs (Figure 2-1-1b). Thus, we cannot rule out the possibility that if the EO and IO were separately analyzed, the relationship observed between the muscularity parameters of each muscle and CHS would differ from those obtained for the LA. Further study is needed to clarify this point.

The volumes of RA and ES in both sides significantly correlated with the CHS. However, the RA volume was not selected as influential factor for CHS. This implies that in terms of the magnitude of contribution to the CHS, the volume of the RA was less influence than that of the ES. In the downswing, right-handed golf players flex their trunk to the dominant side (Horan et al., 2012), and asymmetrically activate their RA (Marta et al., 2013; Watkins et al., 1996). Although the RA contributes to lateral flexion for the ipsilateral side with unilateral activity, the major role of the RA is to flex trunk forward with activities on both sides (Schunke, 2014). During the downswing, golf players also extend their trunk to posterior direction from a position of forward flexion (Horan et al., 2012) and use ES to extend trunk in addition to lateral flexion (Schunke, 2014). Thus, it is speculated that the contribution of both side of the RA to achieving a fast CHS would be smaller as compared to the ES of the dominant side, and consequently the volume of RA might have not been selected as a significant contributor to CHS.

2-2-5. Summary

The study of Section 2 examined how the volume of trunk muscles and its bilateral asymmetry are related to CHS in skilled golf players. The results indicate that for skilled golf players, the greater absolute volume of the ES on the dominant side and a larger degree of the bilateral asymmetry in the PM are significant influential factors for the CHS, the combination of which can explain ~80% of the interindividual variation of the CHS.

Table 2-2-1. The volume of trunk muscles on the dominant and non-dominant sides and the asymmetry ratio

Muscles	Dominant side (cm³)	Non-dominant side (cm³)	Asymmetry (%)
LA	414.9 ± 47.7	449.2 ± 44.6 *	7.7 ± 6.4
ES	305.6 ± 39.2	320.5 ± 37.3 *	5.9 ± 4.6
PM	205.5 ± 28.0	224.6 ± 31.5 *	8.4 ± 3.7
RA	149.2 ± 28.1 *	138.5 ± 22.8	8.2 ± 5.1
MF	127.1 ± 14.9 *	122.8 ± 12.3	5.3 ± 2.8
QL	61.7 ± 9.1	60.6 ± 8.9	5.6 ± 3.6

Notes: Mean ± SD. LA, lateral abdominal wall; ES, erector spinae; PM, psoas major; RA, rectus abdominis; MF, multifidus; QL, quadratus lumborum. *, Significantly larger than the other side ($p < 0.05$); n = 14.

Table 2-2-2. Correlation coefficients between the club head speed and the volume of trunk muscles on the non-dominant and right sides and the asymmetric ratio

Muscles	Dominant side		Non-dominant side		Asymmetry ratio	
	r	*p*	r	*p*	r	*p*
LA	0.189	0.517	0.040	0.892	-0.207	0.479
ES	0.747	0.002	0.674	0.008	0.070	0.812
PM	0.290	0.314	0.455	0.102	0.594	0.025
RA	0.642	0.013	0.644	0.013	0.310	0.281
MF	0.071	0.810	0.026	0.929	-0.112	0.704
QL	0.507	0.065	0.629	0.016	-0.641	0.014

Notes: LA, lateral abdominal wall; ES, erector spinae; PM, psoas major; RA, rectus abdominis; MF, multifidus; QL, quadratus lumborum. n = 14.

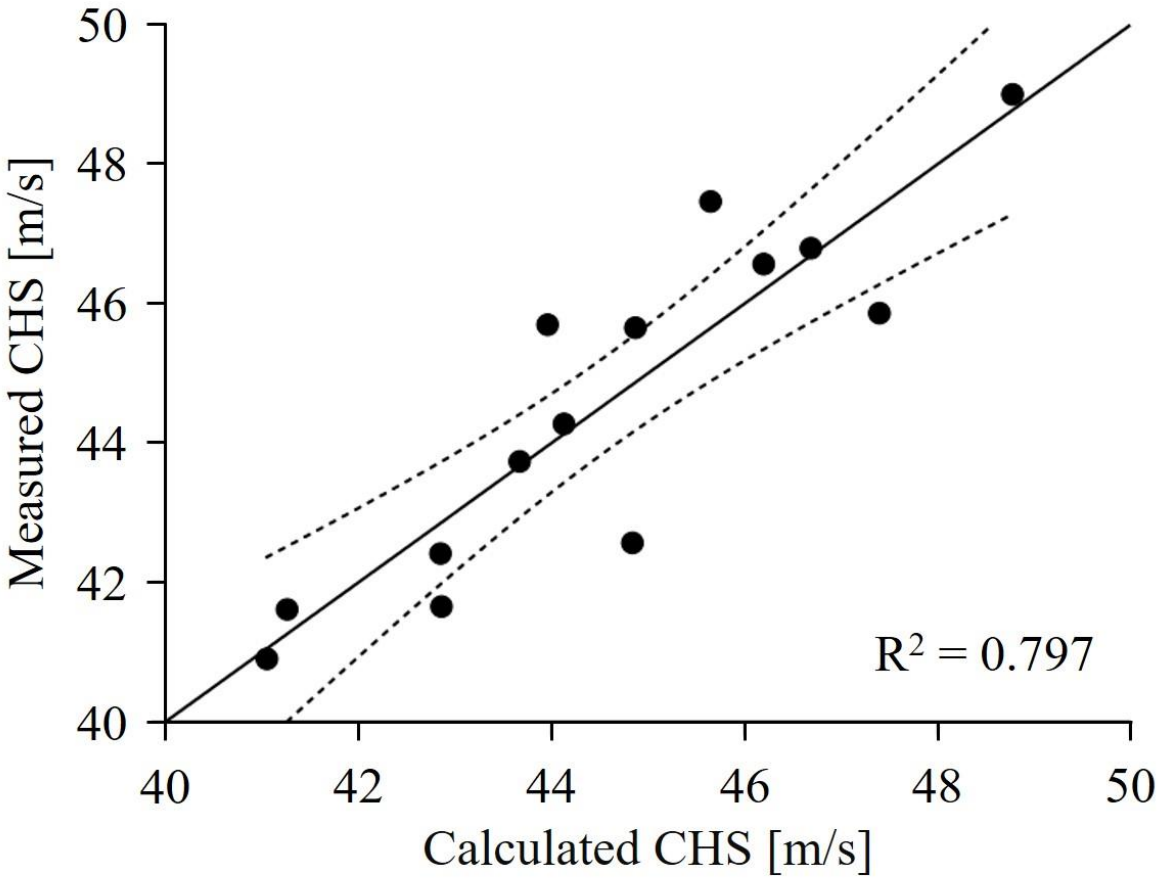

Figure 2-2-1. Relationship between the measured club head speed (CHS) and calculated CHS: black line, regression line; dots curve, the 95% confidence intervals.   n = 14.

Chapter 3 Changes in angular momentum during the golf swing and their association with club head speed

3-1. Introduction

In the rotary motion of the body-tool system, the distal-end segment is accelerated by increasing external moment about the whole-body center of mass and transferring angular momentum between adjacent body segments, usually from the trunk to the arm. On the other hand, the proximal-to-distal sequence of the peak angular velocity (thorax/arm) is observed partially during the downswing (Cheetham et al., 2008; Han, Como, Kim, Hung, et al., 2019; Neal et al., 2007, 2008). This is because, a typical body rotation during the golf swing is described as swinging the arm segment “synchronously” with trunk (shoulder) rotation (Hogan et al., 2014; Leadbetter et al., 2015). Additionally, the trunk generates approximately 70% of the total mechanical work done by the body during the golf swing (Nesbit & Serrano, 2005). Considering these aspects, it is speculated that the golf players would accelerate the club head by generating external moment through the golf swing without trunk/arm sequence and can achieve a fast CHS for having large trunk angular momentum during the golf swing. In other words, the magnitude of angular momentum transfer between adjacent body segments (i.e., trunk and arms segments) after its peak toward the impact would be small. If so, the key body segment contributing to achieving a fast CHS may be the trunk. Elucidating these should provide useful information regarding the strategies employed by golf players to effectively accelerate the golf club and consequently achieve a fast CHS.

The purpose of this chapter was to elucidate 1) the changes in angular momentum of each segment of the body and golf club during the golf swing, as well as 2) their association with CHS.

3-2. Methods

Participants

Seventeen right-handed male collegiate golf players were recruited for this chapter (age: 20.2 ± 0.8 years; height: 1.71 ± 0.05 m; body mass: 67.9 ± 9.9 kg; mean ± SD). They each had at least 4 years of golf experience (12.1 ± 3.6 years) and participated in competitions, with the best score of 65.6 ± 2.0 strokes/round and an average score of 75.1 ± 2.6 strokes/round in the month before the experiment. The study of Chapter 3 was approved by the Ethics Committee of Ritsumeikan University (BKC-2015-017), and written informed consent was obtained from each participant, confirming that they understood the purpose of the study and the possible risks involved.

Data collection

All data were collected at an indoor driving range in our motion analysis laboratory (Figure 3-1). The participants used their own driver and sports shoes. After sufficient warm-up and golf swing practice, participants completed five full driver shots in their preferred stance position. The tee was set on a golf mat at the participants' preferred heights. The participants were asked to swing as they usually perform driver shots and hit the ball straight toward a target on a net positioned approximately 4 m away from the initial ball placement. Sixteen infrared cameras (Motion Capture MAC 3D System: Raptor-E digital, Motion Analysis Co., CA USA) captured three-dimensional trajectories of reflective markers during the golf swing (sampling at 250 Hz). The x-axis of the laboratory reference frame was parallel to the direction of the target from the initial ball placement (Figure 3-2). The y-axis was aligned with the direction from the toe to the heel of the right-handed golf players at address, and the z-axis was vertical upward. Thirty-eight reflective markers were attached to the following body landmarks: the top and sides (front, back, right and left) of the head, spinous process of seventh cervical spine, spinous process of first lumbar spine, sternum, both sides of the acromion, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, internal and external condyles of the humerus, radial and ulnar styloid process, middle phalanx of the hand, internal and external condyle of the femur, internal and external malleolus, 2nd distal interphalangeal joint, and heel of the foot. Three markers were placed on the players' drivers (end of the grip, middle of the club, head of the club) and one on the golf ball.

Data processing and analysis

Raw coordinates of the marker trajectories were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 8 Hz (Horan et al., 2012). Data analysis was based on the downswing phase defined as the time point from the top of the backswing to the point of ball impact. In accordance with previous studies (Han, Como, Kim, Lee, et al., 2019; Kwon et al., 2012), the times of the top of the backswing, middle downswing, and ball impact were defined as the minimum point of CHS during the backswing, horizontal situation of the club shaft, and contacting the club head face to the ball, respectively. In order to find these time points, the trajectories of reflective markers for the club and ball were confirmed before filtering. A 15-segment model (14 body segments and the club) was created on the basis of the body and club landmarks (modified from Bahamonde (Bahamonde, 2000)). The center of mass parameter for each body segment was taken from the data presented in a prior study (Ae, Tang, and Yokoi, 1992) (Table 3-1). The position of the whole-body center of mass was calculated from the model as the weighted sum of the body segmental center of mass of 14 body segments.

The angular momentum of the body was calculated using a modified version of the method described elsewhere (Bahamonde, 2000; Dapena, 1978). The angular momentum of each segment consisted of a transfer term about the whole-body center of mass and a local term about the center of mass of each segment. The transfer angular momentum of the segments was calculated using the following equation:

$$\boldsymbol{H_{Ti}} = m_i \cdot (\boldsymbol{r_i} \times \boldsymbol{v_i}) \tag{1}$$

where $\boldsymbol{H_{Ti}}$ is the transfer angular momentum vector of segment i, m_i is the mass of segment i, $\boldsymbol{r_i}$ is the position vector from the center of mass of the whole-body to the center of mass of segment i, and $\boldsymbol{v_i}$ is the instantaneous velocity vector of the center of mass of segment i relative to the velocity of the whole-body center of mass. The local angular momentum of each segment about its transverse axis was computed using the following equation:

$$\boldsymbol{H_{LTi}} = \boldsymbol{I_{Ti}} \cdot \boldsymbol{\omega_{Ti}} \tag{2}$$

where $\boldsymbol{H_{LTi}}$ is the local angular momentum vector of segment i about its transverse axis, $\boldsymbol{I_{Ti}}$ is the moment of inertia of segment i about its transverse axis, and $\boldsymbol{\omega_{Ti}}$ is the angular velocity vector of segment i about its transverse axis. The local angular momentum of the trunk, upper arm, and forearm about their longitudinal axis was computed using the following equation:

$$\boldsymbol{H_{LLi}} = \boldsymbol{I_{Li}} \cdot \boldsymbol{\omega_{Li}} \tag{3}$$

where $\boldsymbol{H_{LLi}}$ is the local angular momentum vector of segment i about its longitudinal axis, $\boldsymbol{I_{Li}}$ is the moment of inertia of segment i about its longitudinal axis, and $\boldsymbol{\omega_{Li}}$ is the angular velocity vector of segment i about its longitudinal. The inertia parameter for each body segment was taken from the data presented in a prior study (Ae, Tang, and Yokoi, 1992) (Table 3-2). The total angular momentum of each segment about the whole-body center of mass ($\boldsymbol{H_{C.M.i}}$) was calculated as the sum of the transfer ($\boldsymbol{H_{Ti}}$) and local ($\boldsymbol{H_{LTi}}$, $\boldsymbol{H_{LLi}}$) angular momentum vectors as follows:

$$\boldsymbol{H}_{\boldsymbol{C.M.i}} = \boldsymbol{H}_{\boldsymbol{Ti}} + \boldsymbol{H}_{\boldsymbol{LTi}} + \boldsymbol{H}_{\boldsymbol{LLi}} \tag{4}$$

The angular momentum of the club ($\boldsymbol{H}_C$) was computed as the sum of the transfer angular momentum vector of the club about the whole-body center of mass and local angular momentum vector of the club about its transverse axis as follows:

$$\boldsymbol{H}_{\boldsymbol{C}} = m_C \cdot (\boldsymbol{r}_{\boldsymbol{C}} \times \boldsymbol{v}_{\boldsymbol{C}}) + \boldsymbol{I}_{\boldsymbol{TC}} \cdot \boldsymbol{\omega}_{\boldsymbol{TC}} \tag{5}$$

where m_c is the mass of the club, $\boldsymbol{r}_c$ is the position vector from the center of mass of the whole-body to the center of mass of the club, $\boldsymbol{v}_c$ is the instantaneous velocity vector of the club relative to the velocity of the whole-body center of mass, $\boldsymbol{I}_{TC}$ is the moment of inertia of the club about its transverse axis, and $\boldsymbol{\omega}_{TC}$ is the angular velocity vector of the club head about its transverse axis. The mass of 315g was used for the club in the analysis as all golf players used a club of 310-320g mass. The angular momentum of the body-club system ($\boldsymbol{H}$) was calculated as the sum of the angular momentum vectors of all body segments and the club using the following equation:

$$\boldsymbol{H} = \sum_{i=1}^{n} \boldsymbol{H}_{\boldsymbol{C.M.i}} + \boldsymbol{H}_{\boldsymbol{C}} \tag{6}$$

where n is the number of body segments. In this chapter, the segmental angular momenta were grouped into 6 segments of the trunk, dominant (right) arm, non-dominant (left) arm, dominant leg, non-dominant leg, and club, as well as the total body-club system (modified from Bahamonde (Bahamonde, 2000)).

In accordance with previous studies (Kwon et al., 2012; Morrison et al., 2014, 2018), the calculated angular momentum was projected to the swing plane. The swing plane was computed using least squares orthogonal distance fitting. The distances between the club head and the plane were determined by the club head trajectories during the phase from the middle downswing to the ball impact. The maximum orthogonal distance of a trajectory point from that plane and the root-mean-square error were calculated to assess the planarity of that phase. Only the Z component of the swing plane angular momentum was used for the analysis. The Z-axis of the swing plane was aligned with the normal vector of the swing plane extending upward and forward (Figure 3-2). Here, a positive value meant counter-clockwise rotation and a negative value meant clockwise rotation.

For each segment and the body-club system, the maximum value of angular momentum was defined as the maximum angular momentum. The difference between the maximum angular momentum and angular momentum at the ball impact for each body segment was calculated and expressed as the relative change from the maximum angular momentum (%D_{AM}). The %D_{AM} was used to examine the magnitude of angular momentum transfer between adjacent body segments after its peak toward the impact, and its association with CHS. CHS was calculated based on the club head marker position during the swing, and that immediately before the impact was used for analysis.

Statistical analysis

For each analyzed variable, data from the five shots were averaged to produce the criterion values. The descriptive data are presented as mean ± SD. Pearson's product-moment correlation coefficients were calculated to examine the relationship between the CHS and the maximum angular momentum of the body-club system, club, and each body segment, and between the CHS and the %D_{AM} of each body segment. Stepwise multiple linear regression analyses were performed with the CHS as a dependent variable and the maximum angular momentum and %D_{AM} of each body segment as independent variables. Variables were excluded if the variance inflation factor was > 10. All statistical analysis was performed using SPSS software (version 25, IBM Co., Tokyo, Japan). The probability level for statistical significance was set at 0.05 for each analysis.

3-3. Results

Figure 3-3 shows the changes in the angular momentum of the body-club system as well as those of each segment, including the trunk, dominant arm, non-dominant arm, dominant leg, non-dominant leg, and club about the Z-axis of the swing plane passing through the whole-body center of mass during the driver shots. The angular momentum of the body-club system and club continuously increased from the onset of the downswing toward the point of ball impact. While the angular momentum of the arms and non-dominant leg reached a maximum before the middle downswing, defined as the horizontal situation of the club shaft, the angular momentum of the trunk and dominant leg peaked at the late phase (after the middle) of downswing.

Table 3-3 shows descriptive data of the maximum angular momentum during the downswing, angular momentum at the ball impact, and the relative difference between the maximum angular momentum and angular momentum at the impact (%D_{AM}). The CHS was 44.21 ± 2.70 m/s and positively correlated with the maximum angular momentum of the body-club system (r = 0.703, p = 0.002), club (r = 0.804, p < 0.001), trunk (r = 0.703, p = 0.002), dominant arm (r = 0.667, p = 0.004), non-dominant arm (r = 0.670, p = 0.003), and non-dominant leg (r = 0.512, p = 0.036) but not with that of the dominant leg (r = 0.301, p = 0.241). Stepwise multiple regression analysis selected the maximum angular momentum of the trunk (β = 0.703, R^2 = 0.494, p = 0.002) as the sole contributor to the CHS among the body segments.

The %D_{AM} of the trunk negatively correlated with the CHS (r = - 0.492, p = 0.045) (Figure 3-4). For the other body segments, the corresponding associations between the %D_{AM} and CHS were not significant.

3-4. Discussion

The main findings obtained were that during the golf swing: 1) the angular momentum of the arms and non-dominant (left) leg reached a maximum before the middle downswing and that of the trunk and dominant (right) leg peaked after the middle downswing; and 2) the CHS positively correlated with the maximum angular momentum of the trunk, which was selected as the sole contributor to the CHS, and negatively correlated with the $\%D_{AM}$ of the trunk. These results support our hypothesis and indicate that during the golf swing: 1) the club head is accelerated by increasing angular momentum of the body-club system without sequential motion from the proximal (trunk) to distal (arm) segment; and 2) gaining large trunk angular momentum during and after the middle downswing is essential for achieving a fast CHS.

The observed changes in the angular momentum of the trunk and arms were similar to those reported for the two-handed backhand tennis stroke (Wang et al., 2010), suggesting that the trunk angular momentum continuously increased through the swing and reached a maximum near the point of ball impact. Angular momentum of the body-tool (racket/club) system is theoretically augmented by increasing external moment about the whole-body center of mass. In addition, angular momentum can be transferred between adjacent body segments, usually from a proximal to distal segment, through reciprocal action and reaction (Bahamonde, 2000; Lin et al., 2003; Martin et al., 2013). This effectively accelerates the distal-end segment in rotary motion of the system consisting of body parts and a tool held with a hand(s). In fact, it is known that during the tennis serve and baseball pitching, where the racket or ball is held with one hand, the generated trunk angular momentum is transferred to the arm to accelerate the distal end segment (i.e., racket or ball) (Bahamonde, 2000; Lin et al., 2003; Martin et al., 2013). Nevertheless, the current result of the pattern of the change in the angular momentum for the trunk and arms suggests that the golf swing does not involve sequential motion from the trunk to the arms. In other words, our results suggest that golf players accelerate the golf club by increasing the angular momentum of the body-club system without the angular momentum transfer between the proximal (trunk) and distal (arm) segments, as observed in the tennis serve and baseball pitching (Bahamonde, 2000; Lin et al., 2003; Martin et al., 2013).

The maximum angular momentum of all body segments except the dominant leg correlated with CHS. Among the body segments, however, regression analysis selected the maximum angular momentum of the trunk as the only contributor to a CHS. This result suggests that the key body segment for achieving a fast CHS is the trunk. Furthermore, the $\%D_{AM}$ of the trunk negatively correlated with CHS. This suggests that, for golf players, maintaining the trunk angular momentum after its peak toward the ball impact is a factor for achieving a fast CHS. The observed negative correlation between the $\%D_{AM}$ of the trunk and CHS supports the aforementioned assumption that the golf swing does not involve a sequential motion from the trunk to the arms in which angular momentum is transferred between the two segments. As described earlier, a typical body rotation during the golf swing is described as swinging the arm segment "synchronously" with trunk (shoulder) rotation (Hogan et al., 2014; Leadbetter et al., 2015). Chu et al. (2010) reported that maximum trunk rotation velocity that peaked in the late part of the downswing significantly correlated with CHS. In the present study of this chapter, the maximum value of the trunk angular momentum was observed after the middle downswing, and it was selected as the sole contributor to the CHS among the body segments. Considering these, it appears that for golf players, gaining large angular momentum in the trunk and maintaining it toward the point of ball impact is a strategy for achieving a fast CHS.

This chapter analyzed the trunk segment as only one segment without separating the upper (shoulder or thorax) and lower (pelvis) trunk segments, because there was a methodological limitation of the data collection such as a marker set. The degree of separation between the shoulder and pelvis line projected to the horizontal plane of the global reference frame, called "x-factor", is known to be associated with CHS (Cheetham et al., 2001; Myers et al., 2008). To determine the changes in the angular momentum during the golf swing, rotary motion of the body should be analyzed on the swing plane. In fact, it is reported that the angle and angular velocity of the x-factor, computed by the relative angular position of the shoulder and pelvis line projected on the swing plane, did not correlate with CHS (Kwon et al., 2013). In the same way as for the prior study (Kwon et al., 2013), this chapter determined the angular momentum during the golf swing. It is likely that even if the upper and lower trunk segments were separately analyzed, this would not provide more useful information beyond the current results regarding changes in trunk angular momentum during the golf swing and its relationship with CHS.

3-5. Summary

The study of Chapter 3 measured changes in angular momentum during a golf swing and determined its associations with CHS. During the golf swing, 1) the club head was accelerated by increasing angular momentum of the body-club system without sequential motion from the proximal (trunk) to distal (arm) segment, and 2) gaining large trunk angular momentum during and after the middle downswing were essential for achieving a fast CHS.

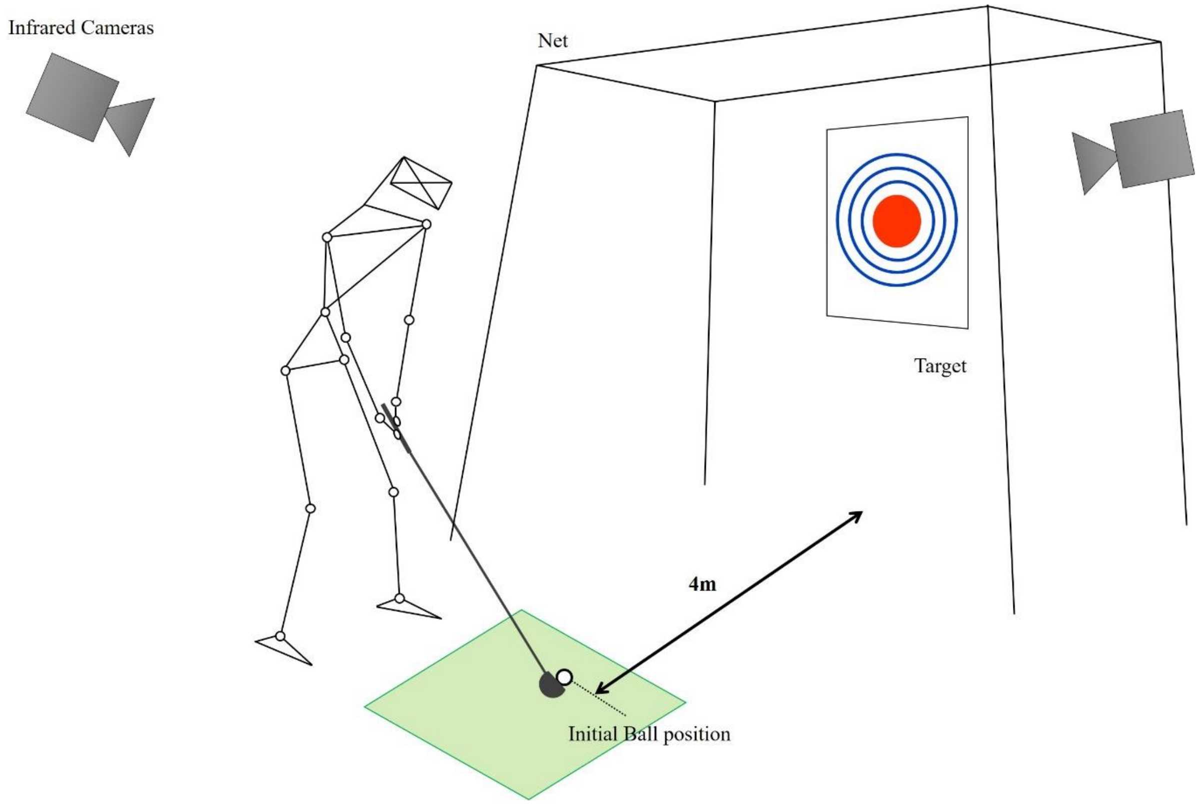

Figure 3-1. Experience setting for the indoor driving range in motion analysis laboratory

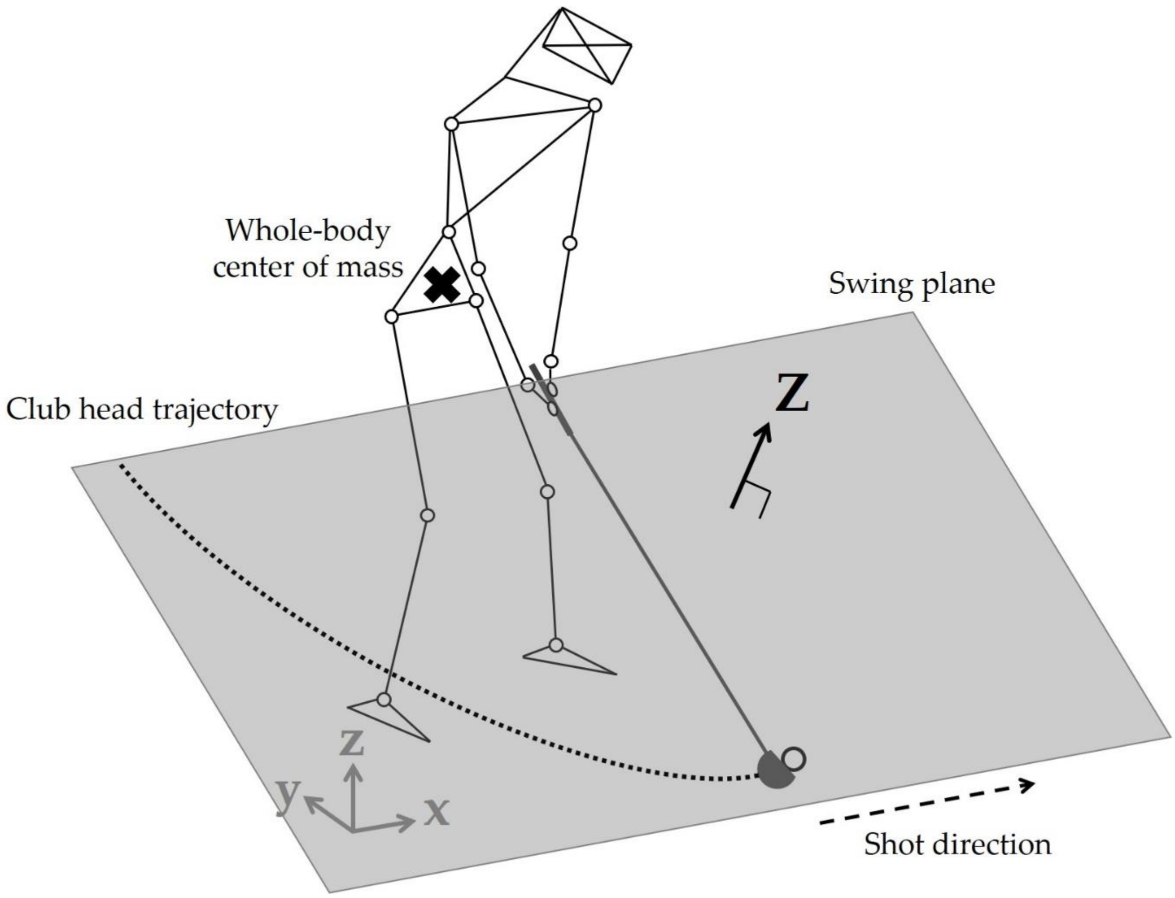

Figure 3-2. Schematic diagram of the laboratory and swing plane reference frames: Gray arrows, the laboratory reference flame; black arrows, the swing plane reference flame. The swing plane was obtained by the club head trajectory (black dot curve) during the phase from the middle downswing to the ball impact. Z-axis of the swing plane was aligned with the normal vector of the swing plane extending upward and forward.

Table 3-1. Definition of the segment lengths, the scaling factors for the position of center of mass, and the coefficients of regression estimation computation expression (= a0 + a1 * segment length + a2 * body mass) for the segment mass (Ae, 1992)

Segment	Segment length definition	Scaling factors for position of center of mass (% segment length)	Coefficients of regression estimation computation expression for segment mass		
			a0	a1	a2
Head	Head top to middle point of side	82.1	- 1.1968	25.6526	0.02604
Trunk	Sternum to middle point of greater trochanter	49.3	-10.1647	18.7503	0.48275
Upper arm	Acromion to elbow joint center	52.9	- 0.36785	1.15588	0.02712
Forearm	Elbow joint center to wrist joint center	41.5	- 0.43807	2.22923	0.01397
Hand	Wrist joint center to middle phalanx of the hand	89.1	- 0.01474	2.09424	0.00414
Thigh	Greater trochanter to knee joint center	47.5	- 4.53542	14.5253	0.09324
Shank	Knee joint center to ankle joint center	40.6	- 1.71524	6.04396	0.03885
Foot	2^{nd} distal interphalangeal joint to heel	59.5	- 0.26784	2.61804	0.00545

Notes: The segment mass [kg] calculated linear regression expression follow: a0 + a1 * segment length [m] + a2 * body mass [kg].

Table 3-2. Definition of the coefficients of regression estimation computation expression (= a0 + a1 * segment length + a2 * body mass) for the tensor of inertia (Ae, 1992)

Segment	X: transverse component			Y: sagittal component			Z: vertical component		
	a0	a1	a2	a0	a1	a2	a0	a1	a2
Head	- 367.903	2843.24	2.71413	-354.077	2680.71	2.4924	-138.956	1307.37	1.24856
Trunk	- 25180.2	43095.5	200.723	-25902.6	43759.1	217.775	-2482.2	-385.282	83.2293
Upper arm	- 317.679	1007.85	1.85249	-312.14	999.691	1.74277	-11.1029	-44.8794	0.71203
Forearm	- 145.867	562.219	0.85722	-146.449	576.661	0.79727	-13.4756	26.3785	0.24644
Hand	- 6.36541	80.3581	0.10995	-7.30695	82.0684	0.14433	-1.67255	9.0812	0.05381
Thigh	- 2127.91	5684.2	11.83	-2043.38	5547.75	10.6498	-350.308	418.338	6.6271
Shank	- 1190.24	3093.33	5.27481	-1175.66	3048.1	5.19169	-62.7928	104.746	1.10838
Foot	- 38.9258	214.578	0.01445	-6.29702	37.6738	0.01248	-40.9844	228.138	0.00753

Notes: The tensor of inertia [kg*cm^2] calculated linear regression expression follow: a0 + a1 * segment length [m] + a2 * body mass [kg].

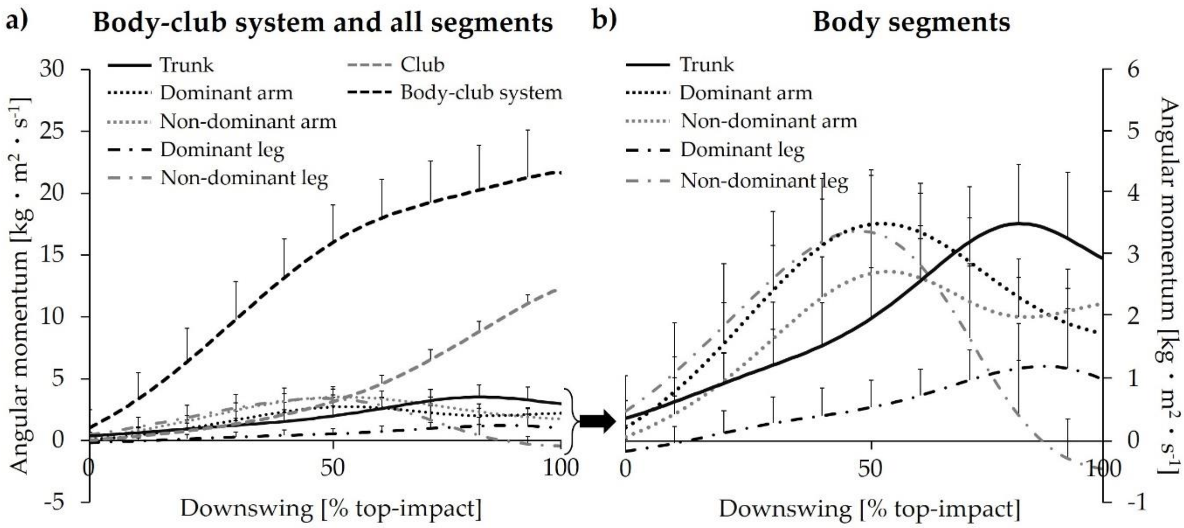

Figure 3-3. Changes in the angular momentum about the Z-axis of the swing plane from the top of the backswing (0%) to the point of ball impact (100%): a) angular momentum for each of the body-club system, club, trunk, dominant arm, non-dominant arm, dominant leg, and non-dominant leg; b) enlarged view of the trunk, dominant arm, non-dominant arm, dominant leg, and non-dominant leg. Black line, trunk; black dots line, dominant arm; gray dots line, non-dominant arm; black dashed line, dominant leg; gray dashed line, non-dominant leg; black broken line, body-club system; gray broken line, club. The lines and error bars drawn for each of the body-club system, the club, and body segments indicate the mean values for all participants (n = 17) and the standard deviations of each angular momentum at every 10% of the downswing, respectively.

Table 3-3. Angular momentum about the whole-body center of mass (maximum value and at the ball impact) and %D_{AM} of each segment

	Maximum ($kg·m^2·s^{-1}$)	Ball impact ($kg·m^2·s^{-1}$)	%D_{AM} (%)
Trunk	3.67 ± 0.95	2.88 ± 1.10	23.18 ± 15.02
Dominant arm	3.61 ± 0.77	1.73 ± 0.53	52.22 ± 11.53
Non-dominant arm	2.86 ± 0.65	2.24 ± 0.77	21.69 ± 16.8
Dominant leg	1.48 ± 0.82	0.93 ± 1.02	43.04 ± 39.61
Non-dominant leg	3.61 ± 0.97	- 0.48 ± 0.49	115.02 ± 15.02
Club	12.44 ± 0.62	12.44 ± 0.62	—
Body-club system	21.91 ± 4.08	21.91 ± 4.08	—

Notes: Mean ± SD. "Maximum" is the maximum value of angular momentum during downswing; "Ball impact" is angular momentum at ball impact; %D_{AM} is the relative change in the angular momentum of the maximum value and that at the ball impact. Because the maximum angular momenta of the body-club system and club were observed at the ball impact, their %D_{AM} values were not computed. n = 17.

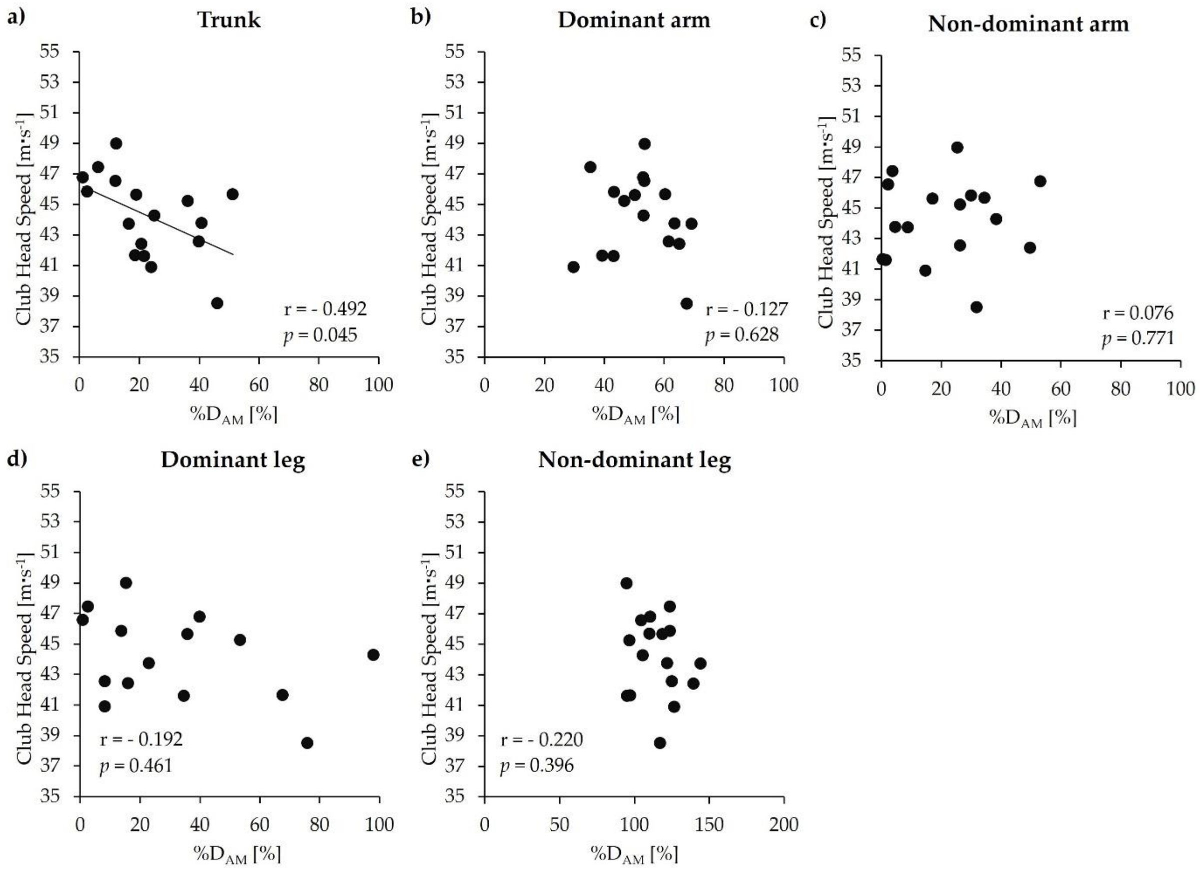

Figure 3-4. Relationship between the club head speed (CHS) and the relative difference in the angular momentum of maximum value and that of ball impact (%D_{AM}). (a) trunk; (b) dominant arm; (c) non-dominant arm; (d) dominant leg; (e) non-dominant leg. Each plot indicates a mean value across five shots for each participant (n = 17).

Chapter 4 General Discussion

In this chapter, firstly, the main findings obtained in this study are summarized. Secondly, the effect of trunk muscularity on the CHS is discussed in relation to the strategy of trunk motion during golf swing. Finally, the conclusion of this thesis is stated.

4-1. Summary of the main findings

In Chapter 2, trunk muscularity of skilled golf players (Section 1) and its association with CHS (Section 2) were examined. First, the results showed that skilled golf players who participated in golf practices and competitive activities for long term had large volumes and bilateral asymmetry of their trunk muscles (LA, ES, PM, RA, and MF) compared to non-golf players (Section 1 of Chapter 2). Secondly, the results of the regression analysis suggest that the greater absolute volume of the ES on the dominant side and a larger degree of bilateral asymmetry in the PM are significant contributors to achieving a faster CHS (Section 2 of Chapter 2).

In Chapter 3, changes in angular momenta of body segments during golf swing were determined, and their associations with the CHS were examined. The findings obtained were that during golf swing, 1) the club head was accelerated by increasing angular momentum of the body-club system without sequential motion from the proximal (trunk) to distal (arm) segment, and 2) gaining large trunk angular momentum during and after the middle downswing phase were essential for achieving a fast CHS.

4-2. Contribution of trunk muscularity to CHS

The results of the regression analysis suggest that the greater absolute volume of the ES on the dominant side and a larger degree of bilateral asymmetry in the PM are significant contributors to achieving a fast CHS (Chapter 2). The ES supports trunk rotation during golf swing because the major roles of this muscle are trunk extension with activities on both sides and trunk lateral flexion for the ipsilateral side with unilateral activity (Schunke, 2014). The PM connects the motion of the lower extremities and trunk since it runs from the transverse processes of the first through fifth lumbar spines, lateral surfaces of the twelfth thoracic to fourth lumbar spines, and neighboring intervertebral discs to the lesser trochanter of the femur (Schunke, 2014). Additionally, golf players with a fast CHS accelerated their club head by continually creating the amount of external moment so it was sufficient to increase the club and trunk angular momenta through the downswing (Chapter 3). This finding implies that in golf players with a fast CHS, the external moment about the whole-body center of mass generated by the ground reaction force is effectively transferred from the lower extremities to the trunk segment in order to gain large angular momentum of the trunk. Considering these aspects, it is assumed that the ES and PM contribute to gaining a large angular momentum of the trunk by supporting trunk rotation and by combining the activities of the lower extremities and trunk, respectively.

For the consideration based on the anatomical structure of the ES and PM, however, it is necessary to identify the motion of the hip joint and trunk during golf swing. In this section, therefore, the angle and angular velocity of the hip joint and trunk were re-examined using a modified version of a method described elsewhere (Horan et al., 2010; Mun et al., 2015). In addition, the joint torque of the hip and lumbar joints, which were estimated using a method described in previous studies (Dumas, Cheze, et al., 2007a; Dumas, Chèze, et al., 2007b; Reed et al., 1999), were also calculated using inverse dynamics (Robertson & Winter, 1980; Robertson et al., 2004; Winter, 2009). The kinematic profiles of the hip joint and trunk were examined as an angle and angular velocity of a thigh coordinate system relative to a pelvis coordinate system (Mun et al., 2015), as well as the angular change of the trunk segment relative to a trunk coordinate system based on the position of the address (Horan et al., 2010). The kinematic and kinetic parameters during the driver shot were calculated using the data obtained in Chapter 3.

4-2-1. Kinematic profiles of the hip joint and trunk during golf swing

Figure 4-1 shows the trunk angle (a) and angular velocity (b) during the downswing. The trunk rotated to the non-dominant side (swing direction) and flexed laterally to the dominant side (swing direction) during the downswing (Figure 4-1a), and the angular velocity peaked during the late phase of downswing (Figure 4-1b). The CHS did not correlate with the maximum angular velocity in all directions (Figure 4-2a-c). However, the relative difference between the maximum angular velocity and angular velocity at the impact of the trunk lateral flexion negatively correlated with the CHS ($r = -0.674$, $p = 0.003$; Figure 4-3a). For each of the other kinematic variables, a significant correlation was not found with the CHS (Figure 4-3b, c).

Figure 4-4 shows the kinematic profile of the hip joint during the downswing: the angle (Figure 4-4a-c) and angular velocity (Figure 4-4d-f). For adduction/abduction and internal/external rotation, changes in the angles of the dominant and non-dominant hips were in the opposite directions through the downswing (Figure 4-4a, b), and the angular velocity decreased in the late phase of the downswing (Figure 4-4d, e). While the dominant hip extended through the downswing, the non-dominant hip flexed in the early phase of downswing and extended in the late phase downswing (Figure 4-4c), and the angular velocity of extensor direction for both sides peaked in the late phase of the downswing (Figure 4-4f).

4-2-2. Kinetic profiles of the lumbar and hip joints during golf swing

The lumbar joint torques of extension and axial rotation toward the non-dominant side (swing direction) were exerted through the downswing (Figure 4-5). The lumbar joint torque of the lateral flexion toward the dominant side (swing direction) was exerted from the beginning to 80% of the downswing, and that of the lateral flexion toward the non-dominant side (counter-swing direction) was exerted in the late phase of the downswing.

Figure 4-6 shows the hip joint torques during the downswing. For the dominant hip, the abductor and internal rotator torque was exerted in the early phase of the downswing and the adductor and external rotator torque was exerted in the late phase of the downswing (Figure 4-6a, b). For the non-dominant hip, the adductor and external rotator torque was exerted through the downswing (Figure 4-6b). While the dominant hip generated the extensor torque through the downswing, the non-dominant hip generated the flexor torque in the early phase of the downswing and the extensor torque in the late phase of the downswing (Figure 4-6c).

4-2-3. Contribution of the ES muscularity to CHS from the view of kinematic and kinetic profiles of the trunk during golf swing

As shown in Figure 4-1, the trunk flexed laterally to the dominant side during the downswing, and the angular velocity of the trunk lateral flexion peaked in the late phase of the downswing. The lateral flexor torque towards the dominant side was exerted before the ball impact at the lumbar joint (Figure 4-5). The relative difference between the maximum angular velocity and angular velocity at the impact of trunk lateral flexion negatively correlated with the CHS, but its maximum angular velocity did not (Figure 4-2, 4-3). This result implies that preventing the decline in angular velocity of trunk lateral flexion during the late phase of downswing is essential to preserve the trunk angular momentum in the corresponding phase, and this is consequently linked with a fast CHS. One of the major roles of the ES is lateral flexion for the ipsilateral side with unilateral activity (Schunke, 2014). Taking this into account together with the aforementioned results, it is suggested that the dominant ES would contribute to trunk lateral flexion on the dominant side and play an important role in maintaining angular velocity of lateral flexion in the late phase of the downswing.

Golf players hold their club by both hands and hit the ball on the ground. Thus, to increase angular velocity of the club in the swing direction, arm angular velocity must also increase in the same direction on the frontal plane. Arm angular velocity is more effectively increased by translating both sides of the proximal end (trunk side) and distal end (club side) in the opposite direction compared to the case in which only the distal end is translated in the swing direction. Typical body rotation during golf swing is described as swinging the arm segment "synchronously" with trunk (shoulder) rotation (Hogan et al., 2014; Leadbetter et al., 2015). In the late phase of the downswing, therefore, large angular velocity of the club in the swing direction can be generated by translating the proximal end of the arm (i.e., trunk) to counter the swing direction. In this case, effectively preventing the deceleration of trunk lateral flexion on the dominant side would contribute to maintaining trunk angular momentum in the late phase of the downswing, and it might be a reason for the selection of the absolute volume of the dominant ES as a significant influencing factor on the CHS.

4-2-4. Contribution of the PM muscularity to CHS from the view of kinematic and kinetic profiles of the trunk and hip joint during golf swing

In the early phase of downswing, right-handed golf players rotate their trunk to their non-dominant side (Figure 4-1a), flex their non-dominant hip, and extend their dominant hip (Figure 4-4c). The torques of the non-dominant and dominant hip joints were mutually generated in the opposite directions during the early phase of downswing: flexor and adductor torque in the non-dominant hip joint and extensor and abductor torque in the dominant hip joint (Figure 4-6). These results agree with previous findings (Foxworth et al., 2013; Takagi et al., 2019). Takagi et al. (2019) showed that flexor and adductor torque in the non-dominant hip and extensor and abductor torque in the dominant hip contribute to pelvis rotation during golf swing. These aspects imply that golf players are required to flex their non-dominant hip while rotating their trunk to the non-dominant side in the early phase of the downswing. As shown in Figure 4-4e and -4f, however, for the non-dominant hip, the angular velocity of internal rotation and extension peaked in the late phase of the downswing. The external rotator and extensor torques during the late phase of the downswing were generated from the non-dominant hip (Figure 4-6), indicating that these hip motions prevent pelvis rotation before ball impact. The PM is the muscle connecting the lower extremities with the trunk, and functions to produce hip flexion on the ipsilateral side, as well as hip external rotation on the ipsilateral side (Schunke, 2014). All golf players who participated in this study had a larger volume of the PM on the non-dominant than on the dominant side. Considering these profiles of hip motion and action of the PM during golf swing, it seems that the non-dominant PM would be stretched and internally rotated during the latter phase of the downswing and consequently obliged to eccentrically contract. If so, the profiles of hip motion during the golf swing might be a factor that induces greater hypertrophic change on the non-dominant side compared to the dominant side of the PM. Moreover, the action of hip motion prevents pelvis rotation and leads to angular momentum transfer from the pelvis to the upper body segment through reciprocal action and reaction. Taking these into account with the kinematic and kinetic profile of the hip joint during the downswing (Figure 4-4, and 4-5), it is assumed that the non-dominant PM would contribute to the appearance of hip motion and play a role in continuously transferring the angular momentum from the lower extremities to the trunk through the downswing. Thus, the relatively greater volume of PM in the non-dominant side compared to the dominant side might have been selected as an influential factor in CHS.

4-3. Comparison of kinetic profiles of the trunk and hip joint with other sport types

As in the golf swing, the bat swing in baseball and softball (Ae et al., 2018; Iino et al., 2014) and the two-handed tennis stroke (Akutagawa & Kojima, 2005) require trunk rotation and holding the tools with both hands. During both a bat swing and a two-handed tennis stroke, changes in adductor/abductor, flexor/extensor, and internal/external rotator torques at the hip joint from the start of pelvis rotation towards the ball impact are similar to those observed in the downswing of a golf swing. Changes in the torque contributing to trunk rotation are also similar to the lumbar joint torque during the golf swing. Considering these aspects, the kinematics and kinetics of the hip joint in the golf swing are similar to those in the two-handed swing motions of the bat swing and the two-handed tennis stroke. However, because the previous studies cited here have discussed only the component of trunk axial rotation (Akutagawa et al., 2005; Iino et al., 2014), the kinematic and kinetic profile of the trunk lateral flexion and forward flexion cannot be compared between the golf swing and other sports types. Unlike in the bat swing and two-handed tennis stroke, swinging a golf club requires not only trunk axial rotation but also lateral flexion and forward flexion due to the initial position of the golf ball on the ground. In golf, therefore, the trunk rotation about the triaxial direction must be discussed to understand the mechanism of the golf swing.

4-4. Mechanical properties of trunk rotation during a golf swing

Figure 4-7 indicates the changes in segment torque power (STP) and joint torque power (JTP) during the downswing. STP values of the thigh, pelvis, and upper trunk were calculated using the joint torque and angular velocity of each segment, which were determined in Section 4-2 ("Contribution of trunk muscularity to CHS"). JTP was also calculated as the dot product of the joint torque and joint angular velocity, which was the relative angular velocity of the adjacent segments. As shown in Figure 4-7a and 4-7b, the thigh and pelvis STP, exerted by the hip joint torques, were positive during the downswing (Figure 4-7a, b). The upper trunk and pelvis STP, exerted by the lumbar joint torque, were positive and negative, respectively, through the downswing (Figure 4-7c). The hip JTP, exerted by the hip joint torque, was positive through the downswing (Figure 4-7a, b). The lumbar JTP, exerted by the lumbar joint torque, was negative in 0-29% of the downswing and positive in 30-100% of the downswing (Figure 4-7c). Positive and negative JTP can be integrated as parameters representing the mechanical energy generation and absorption, respectively. Calculation of the mechanical energy provided evidence suggesting that the mechanical energy generated during the downswing is greater than the mechanical energy absorption in the hip and lumbar joints (Table 4-1).

The mechanical power exerted by the joint torque to the adjacent segments is positive for one segment and negative for the other segment, if the two adjacent segments rotate in the same direction (Robertson et al., 1980). Positive STP implies that mechanical power is transferred from the adjacent segment to the segment, and negative STP implies that mechanical power is transferred from the segment to the adjacent segment by the joint torque. Thus, the current results indicate that during the downswing, mechanical power at the lumbar joint was transferred from the pelvis to the upper trunk by the lumbar joint torque. In addition, mechanical energy is generated or absorbed to the segment with a larger angular velocity by the joint torque, if two adjacent segments rotate in the same direction with different angular velocities (Robertson et al., 1980). As shown in Figure 4-7c, when the upper trunk angular velocity was greater than the pelvis angular velocity, the lumbar JTP at the lumber joint was positive. Considering these aspects, it is speculated that, during the downswing, mechanical energy would be generated by the hip and lumber joint torque and transferred from the pelvis to the upper trunk segment.

4-5. Practical application of the present findings

This thesis summarizes the results obtained from a study of the influence of trunk muscularity and motion strategy on the CHS of skilled golf players. The findings demonstrated here are useful for golf players and their coaches to better understand optimal trunk motion strategy for performing an effective golf swing and develop training programs for improving golf performance. Previous studies show that a resistance training program targeting the trunk muscles, consisting of exercises such as the crunch, lateral flexion, improve trunk muscle strength as well as golf performance (Kim, 2010; Sung et al., 2016). The present findings regarding the relationship between trunk muscularity and CHS support the results of previous research and highlight the importance of resistance training to strengthen the trunk muscles for golf performance. Additionally, the present findings on the motion strategy of the trunk (upper body) during the golf swing support the terms used in coaching term, in which a typical upper body rotation during the golf swing is explained as a swinging motion of the arm segment "synchronously" with trunk (shoulder) rotation (Hogan et al., 2014; Leadbetter et al., 2015). However, the findings presented in this thesis were obtained from cross-sectional observations. Further study involving longitudinal experimental design is needed to clarify the aforementioned aspects.

4-6. Conclusions of this thesis

The findings of this thesis indicate that, in skilled golf players, 1) the club head during the downswing is accelerated by transferring the external moment so it is sufficient for increasing the club and trunk angular momentum, 2) trunk muscularity of the players is specific to their own training and competitive activities, and 3) a large absolute volume of the ES on the dominant side and bilateral asymmetry of the PM (relatively greater volume on the non-dominant side) positively associate with the CHS at ball impact.

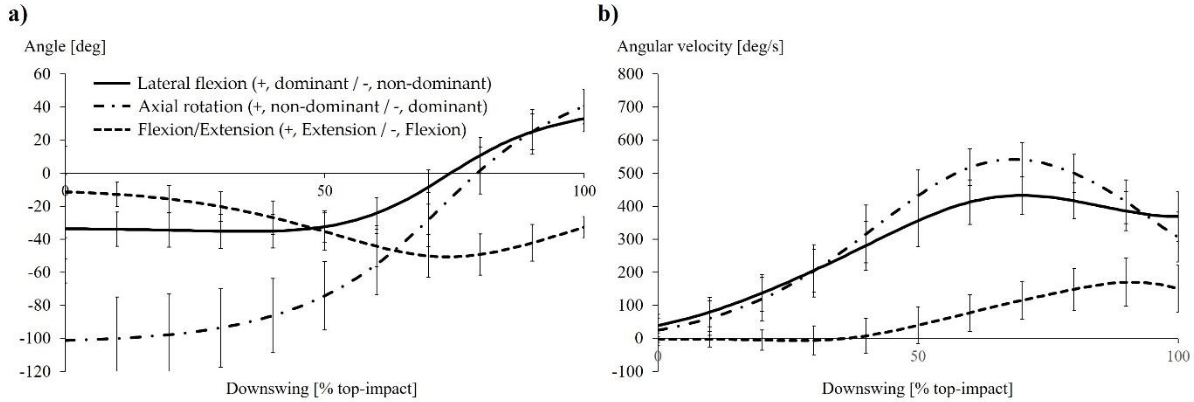

Figure 4-1. Kinematic profile of the trunk from the top of the backswing (0%) to the point of ball impact (100%): a) the angle and b) angular velocity. Solid lines, lateral flexion; dashed lines, axial rotation; broken lines, flexion/extension. The lines and error bars drawn for both sides of the hip joint indicate the mean values for all participants (n = 17) and the standard deviations of each kinematic value at every 10% of the downswing, respectively.

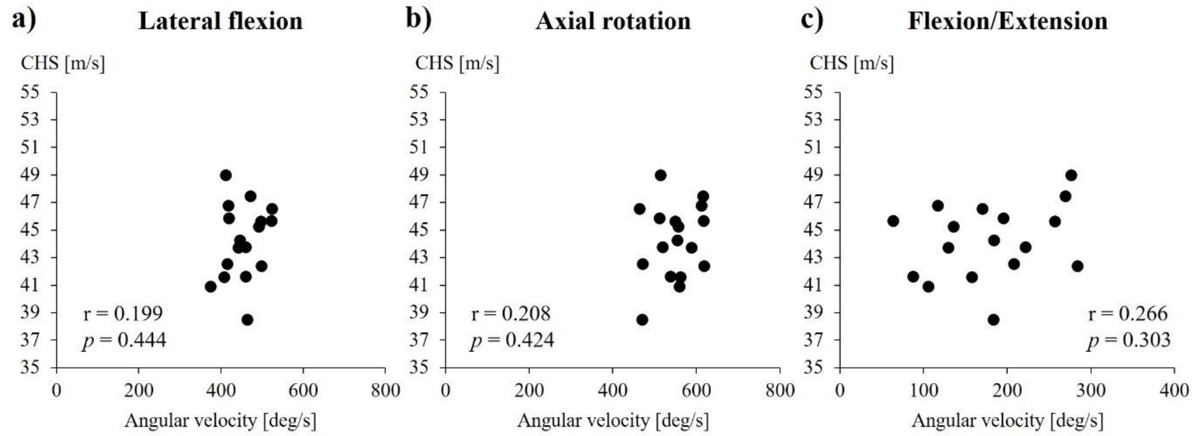

Figure 4-2. Relationship between the club head speed (CHS) and maximum angular velocity: a) lateral flexion; b) axial rotation; c) flexion/extension. n = 17.

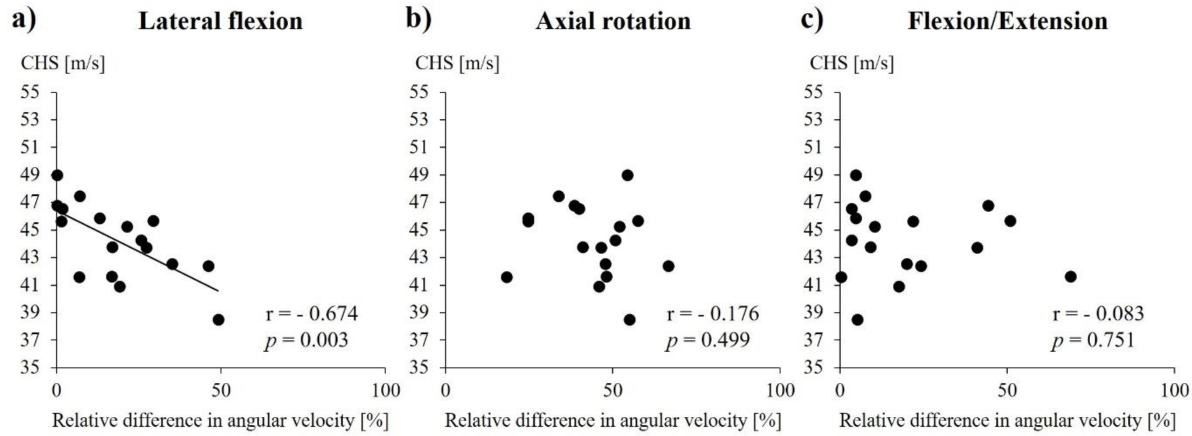

Figure 4-3. Relationship between the club head speed (CHS) and the relative difference in the maximum angular velocity and angular velocity at ball impact: a) lateral flexion; b) axial rotation; c) flexion/extension. n = 17.

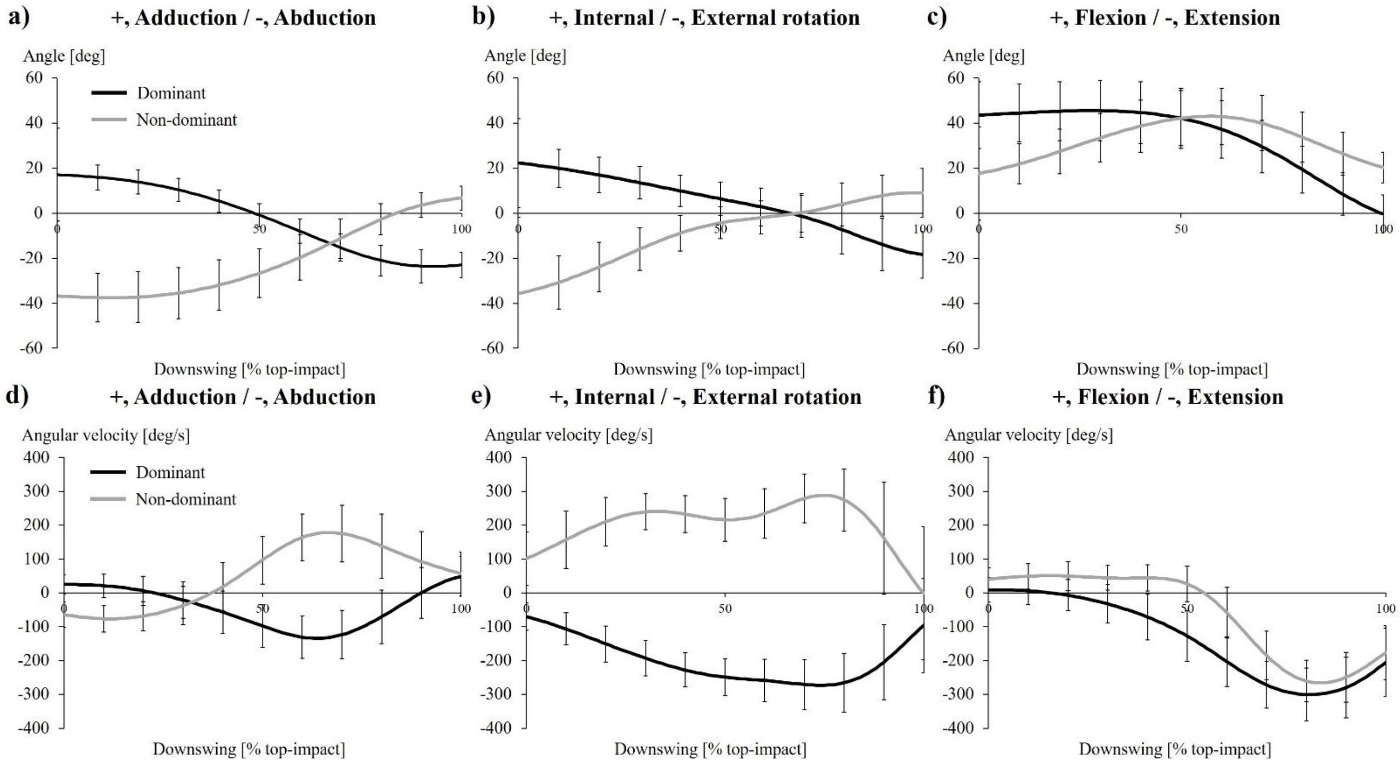

Figure 4-4. Kinematic profile of the dominant and non-dominant hip joint from the top of the backswing (0%) to the point of ball impact (100%): a) the angle of adduction/abduction; b) angle of internal/external rotation; c) angle of flexion/extension; d) angular velocity of adduction/abduction; e) angular velocity of internal/external rotation; f) angular velocity of flexion/extension. Black line, dominant side; gray line, non-dominant side. The lines and error bars drawn for both sides of the hip joint indicate the mean values for all participants (n = 17) and the standard deviations of each kinematic value at every 10% of the downswing, respectively.

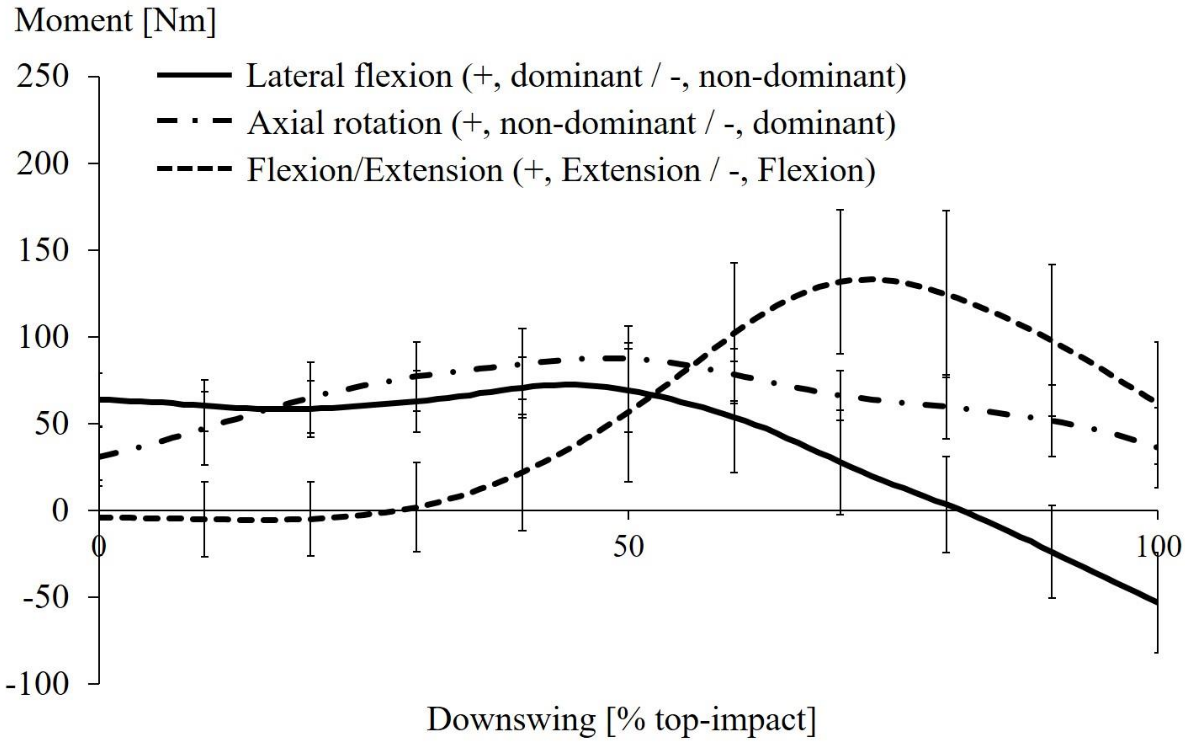

Figure 4-5. Kinetic profile of the trunk from the top of the backswing (0%) to the point of ball impact (100%): Solid lines, lateral flexion; dashed lines, axial rotation; broken lines, flexion/extension. The lines and error bars drawn for both sides of the hip joint indicate the mean values for all participants (n = 17) and the standard deviations of each kinematic value at every 10% of the downswing, respectively.

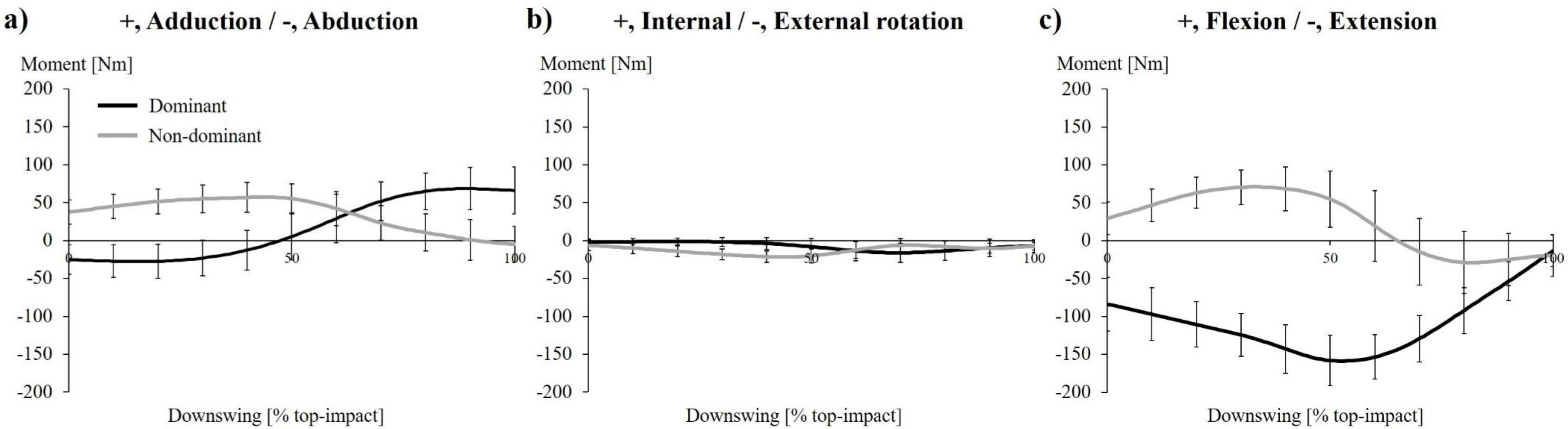

Figure 4-6. Kinetic profile of the dominant and non-dominant hip joint from the top of the backswing (0%) to the point of ball impact (100%): Black line, dominant side; gray line, non-dominant side. The lines and error bars drawn for both sides of the hip joint indicate the mean values for all participants (n = 17) and the standard deviations of each kinematic value at every 10% of the downswing, respectively.

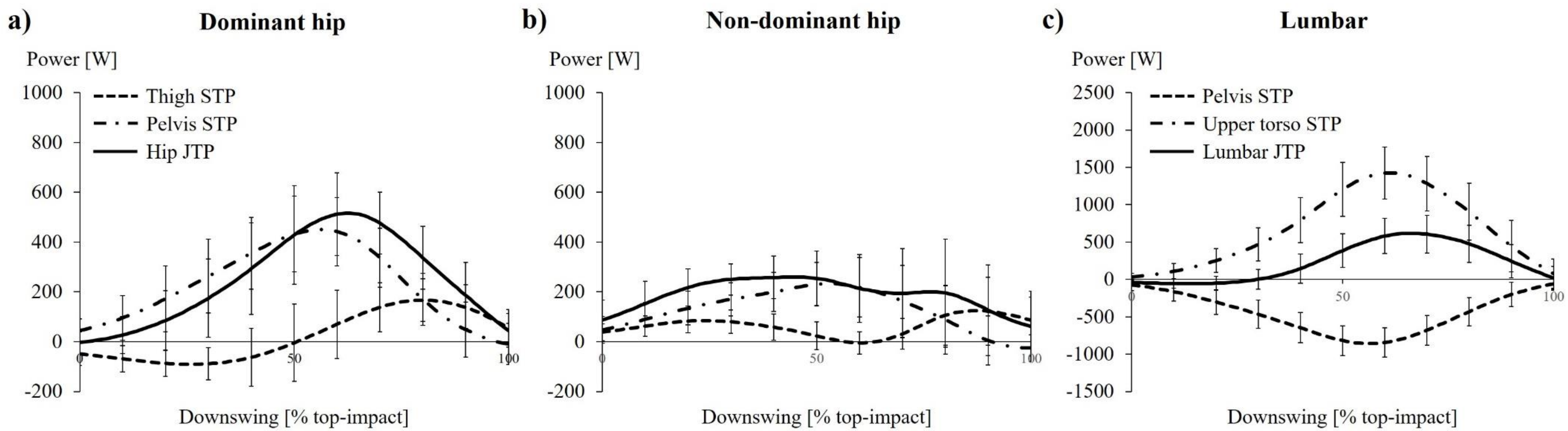

Figure 4-7. Changes in the power of the hip and lumbar joint from the top of the backswing (0%) to the point of ball impact (100%): a) thigh STP (broken line), pelvis STP (dash line) and hip JTP (solid line) exerted by hip joint torque of the dominant hip joint; b) thigh STP (broken line), pelvis STP (dash line) and hip JTP (solid line) exerted by hip joint torque of the non-dominant hip joint; c) pelvis STP (broken line) and upper trunk STP (dash line) and lumbar JTP (solid line) exerted by lumbar joint torque of the lumber joint. The lines and error bars drawn for both sides of the hip joint indicate the mean values for all participants (n = 17) and the standard deviations of each kinematic value at every 10% of the downswing, respectively.

Table 4-1. The average of mechanical energy generation and absorption exerted by the hip and lumbar joint torque.

	Generation [J]	Absorption [J]
Dominant hip joint	71.8 ± 16.4	- 1.1 ± 1.2
Non-dominant hip joint	55.9 ± 21.2	- 1.2 ± 2.1
Lumbar joint	72.2 ± 21.4	- 8.1 ± 6.2

Notes: Mean ± SD.

References

Ae, K., Koike, S., Fujii, N., Ae, M., Kawamura, T., & Kanahori, T. (2018). A comparison of kinetics in the lower limbs between baseball tee and pitched ball batting. *Hum Mov Sci, 61*, 126-134. doi:10.1016/j.humov.2018.07.010

Ae, M., Tang, H., and Yokoi, T. (1992). Estimation of inertia properties of the body segments in Japanese athletes [in Japanese]. *Biomechanisms, 11*, 23-33.

Akutagawa, S., & Kojima, T. (2005). Trunk rotation torques through the hip joints during the one- and two-handed backhand tennis strokes. *Journal of Sports Sciences, 23*(8), 781-793. doi:10.1080/02640410400021609

Bae, J. H., Kim, D. K., Seo, K. M., Kang, S. H., & Hwang, J. (2012). Asymmetry of the isokinetic trunk rotation strength of korean male professional golf players. *Ann Rehabil Med, 36*(6), 821-827. doi:10.5535/arm.2012.36.6.821

Bahamonde, R. E. (2000). Changes in angular momentum during the tennis serve. *Journal of Sports Sciences, 18*(8), 579-592. doi:10.1080/02640410050082297

Bechler, J. R., Jobe, F. W., Pink, M., Perry, J., & Ruwe, P. A. (1995). Electromyographic Analysis of the Hip and Knee During the Golf Swing. *Clinical Journal of Sport Medicine, 5*(3), 162-166.

Broadie, M. (2008). Assessing Golfer Performance Using Golfmetrics. *Science and golf V: Proceedings of the world scientific congress of golf*, 253-262.

Broadie, M. (2012). Assessing Golfer Performance on the PGA TOUR. *Interfaces, 42*(2), 146-165. doi:10.1287/inte.1120.0626

Bulbulian, R., Ball, K. A., & Seaman, D. R. (2001). The short golf backswing: effects on performance and spinal health implications. *Journal of Manipulative and Physiological Therapeutics, 24*(9), 569-575. doi:10.1067/mmt.2001.118982

References

Cheetham, P. J., Martin, P. E., Mottram, R. E., & St Laurent, B. F. (2001). The Importance of Stretching the X-Factor in the Golf Downswing of Golf :The X-factor Stretch. *Optimising performance in golf*, 192-199.

Cheetham, P. J., Rose, G., Hinrichs, R., Neal, R., Mottram, R., Hurrion, P., et al. (2008). Comparison of kinematic sequence parameters between amateur and professional golfers. *Science and golf V: Proceedings of the world scientific congress of golf.*

Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences, 28*(11), 1251-1259. doi:10.1080/02640414.2010.507249

Cole, M. H., & Grimshaw, P. N. (2008). Electromyography of the trunk and abdominal muscles in golfers with and without low back pain. *Journal of Science and Medicine in Sport, 11*(2), 174-181. doi:10.1016/j.jsams.2007.02.006

Dapena, J. (1978). A method to determine the angular momentum of a human body about three orthogonal axes passing through its center of gravity. *Journal of Biomechanics, 11*(5), 251-256.

Dumas, R., Cheze, L., & Verriest, J. P. (2007a). Adjustments to McConville et al. and Young et al. body segment inertial parameters. *Journal of Biomechanics, 40*(3), 543-553. doi:10.1016/j.jbiomech.2006.02.013

Dumas, R., Chèze, L., & Verriest, J. P. (2007b). Corrigendum to "Adjustments to McConville et al. and Young et al. body segment inertial parameters" [J. Biomech. 40 (2007) 543–553]. *Journal of Biomechanics, 40*(7), 1651-1652. doi:10.1016/j.jbiomech.2006.07.016

Ehara, Y., Tanabe, K., Shiraki, H., & Kuno, S. (2017). Relationship between club head speed and physical fitness factors in Japanese male professional golfers [in Japanese]. *Journal of Japanese Society of Clinical Sports Medicine, 25*(1), 68-74.

Fletcher, I. M., & Hartwell, M. (2004). Effect of an 8-week combined weights and plyometrics training program on golf drive performance. *Journal of Strength and Conditioning Research, 18*(1), 59-62.

References

Foxworth, J. L., Millar, A. L., Long, B. L., Way, M., Vellucci, M. W., & Vogler, J. D. (2013). Hip joint torques during the golf swing of young and senior healthy males. *Journal of Orthopaedic and Sports Physical Therapy, 43*(9), 660-665. doi:10.2519/jospt.2013.4417

Fuchs, P. X., Lindinger, S. J., & Schwameder, H. (2018). Kinematic analysis of proximal-to-distal and simultaneous motion sequencing of straight punches. *Sports Biomechanics, 17*(4), 512-530. doi:10.1080/14763141.2017.1365928

Fukunaga, T., Miyatani, M., Tachi, M., Kouzaki, M., Kawakami, Y., & Kanehisa, H. (2001). Muscle volume is a major determinant of joint torque in humans. *Acta Physiologica Scandinavica, 172*(4), 249-255. doi:DOI 10.1046/j.1365-201x.2001.00867.x

Han, K. H., Como, C., Kim, J., Hung, C. J., Hasan, M., & Kwon, Y. H. (2019). Effects of pelvis-shoulders torsional separation style on kinematic sequence in golf driving. *Sports Biomechanics, 18*(6), 663-685. doi:10.1080/14763141.2019.1629617

Han, K. H., Como, C., Kim, J., Lee, S., Kim, J., Kim, D. K., et al. (2019). Effects of the golfer-ground interaction on clubhead speed in skilled male golfers. *Sports Biomechanics, 18*(2), 115-134. doi:10.1080/14763141.2019.1586983

Harriss, D., Macsween, A., & Atkinson, G. (2017). Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *International Journal of Sports Medicine, 38*(14), 1126-1131. doi:10.1055/s-0043-124001

Hasegawa, S., & Ono, T. (2012). The relationship between asymmetric characteristics of muscle thickness and ball speed in baseball pitchers [in Japanese]. *Japanese Journal of Physical Fitness and Sports Medicine, 61*(2), 227-235.

Hellstrom, J. (2009). Competitive Elite Golf A Review of the Relationships between Playing Results, Technique and Physique. *Sports Medicine, 39*(9), 723-741. doi:Doi 10.2165/11315200-000000000-00000

Hellström, J. (2008). The Relation between Physical Tests, Measures, and Clubhead Speed in Elite Golfers. *International Journal of Sports Science & Coaching, 3*(1_suppl), 85-92. doi:10.1260/174795408785024207

References

Hellstrom, J., Nilsson, J., & Isberg, L. (2014). Drive for dough. PGA Tour Golfers' tee shot functional accuracy, distance and hole score. *Journal of Sports Sciences, 32*(5), 462-469. doi:10.1080/02640414.2013.832353

Hides, J., Fan, T., Stanton, W., Stanton, P., McMahon, K., & Wilson, S. (2010). Psoas and quadratus lumborum muscle asymmetry among elite Australian Football League players. *British Journal of Sports Medicine, 44*(8), 563-567. doi:10.1136/bjsm.2008.048751

Hogan, S., Smeltz, K., Richardson, A. F., & Leadbetter, D. (2014). *The Leadbetter Golf Academy Handbook: Techniques and Strategies from the World's Greatest Coaches*. Chicago, USA: Triumph Books.

Horan, S. A., Evans, K., Morris, N. R., & Kavanagh, J. J. (2010). Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *Journal of Biomechanics, 43*(8), 1456-1462. doi:10.1016/j.jbiomech.2010.02.005

Horan, S. A., & Kavanagh, J. J. (2012). The control of upper body segment speed and velocity during the golf swing. *Sports Biomechanics, 11*(2), 165-174. doi:10.1080/14763141.2011.638390

Hume, P. A., Keogh, J., & Reid, D. (2005). The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Medicine, 35*(5), 429-449.

Iino, Y., Fukushima, A., & Kojima, T. (2014). Pelvic rotation torque during fast-pitch softball hitting under three ball height conditions. *Journal of Applied Biomechanics, 30*(4), 563-573. doi:10.1123/jab.2013-0304

Ishiguro, N., Kanehisa, H., Miyatani, M., Masuo, Y., & Fukunaga, T. (2006). Applicability of segmental bioelectrical impedance analysis for predicting trunk skeletal muscle volume. *Journal of Applied Physiology, 100*(2), 572-578. doi:10.1152/japplphysiol.00094.2005

Izumoto, Y., Kurihara, T., Suga, T., & Isaka, T. (2019). Bilateral differences in the trunk muscle volume of skilled golfers. *PloS One, 14*(4), e0214752. doi:10.1371/journal.pone.0214752

Joyce, C. (2017). The most important "factor" in producing clubhead speed in golf. *Hum Mov Sci, 55*, 138-144. doi:10.1016/j.humov.2017.08.007

References

Joyce, C., Burnett, A., Cochrane, J., & Ball, K. (2013). Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics, 12*(2), 108-120. doi:10.1080/14763141.2012.728244

Keogh, J. W., Marnewick, M. C., Maulder, P. S., Nortje, J. P., Hume, P. A., & Bradshaw, E. J. (2009). Are anthropometric, flexibility, muscular strength, and endurance variables related to clubhead velocity in low- and high-handicap golfers? *Journal of Strength and Conditioning Research, 23*(6), 1841-1850. doi:10.1519/JSC.0b013e3181b73cb3

Kim, K.-J. (2010). Effects of Core Muscle Strengthening Training on Flexibility, Muscular Strength and Driver Shot Performance in Female Professional Golfers. *International Journal of Applied Sports Sciences, 22*(1), 111-127.

Kwon, Y. H., Como, C. S., Singhal, K., Lee, S., & Han, K. H. (2012). Assessment of planarity of the golf swing based on the functional swing plane of the clubhead and motion planes of the body points. *Sports Biomechanics, 11*(2), 127-148. doi:10.1080/14763141.2012.660799

Kwon, Y. H., Han, K. H., Como, C., Lee, S., & Singhal, K. (2013). Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers. *Sports Biomechanics, 12*(3), 231-246. doi:10.1080/14763141.2013.771896

Leadbetter, D., & Kaspriske, R. (2015). *The A Swing: The Alternative Approach to Great Golf* (First ed.). New York, NY, USA: St. Martin's Press.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. S. (2007). An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *Journal of Strength and Conditioning Research, 21*(3), 860-869. doi:10.1519/R-20606.1

Lewis, A. L., Ward, N., Bishop, C., Maloney, S., & Turner, A. N. (2016). Determinants of Club Head Speed in PGA Professional Golfers. *Journal of Strength and Conditioning Research, 30*(8), 2266-2270. doi:10.1519/JSC.0000000000001362

Lim, Y. T., Chow, J. W., & Chae, W. S. (2012). Lumbar spinal loads and muscle activity during a golf swing. *Sports Biomechanics, 11*(2), 197-211. doi:10.1080/14763141.2012.670662

References

Lin, H. T., Su, F. C., Nakamura, M., & Chao, E. Y. S. (2003). Complex chain of momentum transfer of body segments in the baseball pitching motion. *Journal of the Chinese Institute of Engineers, 26*(6), 861-868. doi:10.1080/02533839.2003.9670841

Marshall, R. N., & Elliott, B. C. (2000). Long-axis rotation: the missing link in proximal-to-distal segmental sequencing. *Journal of Sports Sciences, 18*(4), 247-254. doi:10.1080/026404100364983

Marta, S., Silva, L., Vaz, J., Bruno, P., & Pezarat-Correia, P. (2013). Electromyographic Analysis of Trunk Muscles during the Golf Swing Performed with Two Different Clubs. *International Journal of Sports Science & Coaching, 8*(4), 779-787. doi:10.1260/1747-9541.8.4.779

Marta, S., Silva, L., Vaz, J. R., Castro, M. A., Reinaldo, G., & Pezarat-Correia, P. (2016a). Electromyographic analysis of lower limb muscles during the golf swing performed with three different clubs. *Journal of Sports Sciences, 34*(8), 713-720. doi:10.1080/02640414.2015.1069376

Marta, S., Silva, L., Vaz, J. R., Castro, M. A., Reinaldo, G., & Pezarat-Correia, P. (2016b). Electromyographic Analysis of the Lower Limb Muscles in Low- and High-Handicap Golfers. *Research Quarterly for Exercise and Sport, 87*(3), 318-324. doi:10.1080/02701367.2016.1177634

Martin, C., Kulpa, R., Delamarche, P., & Bideau, B. (2013). Professional tennis players' serve: correlation between segmental angular momentums and ball velocity. *Sports Biomechanics, 12*(1), 2-14. doi:10.1080/14763141.2012.734321

Maughan, R. J., Watson, J. S., & Weir, J. (1983). Relationships between Muscle Strength and Muscle Cross-Sectional Area in Male Sprinters and Endurance Runners. *European Journal of Applied Physiology and Occupational Physiology, 50*(3), 309-318. doi:Doi 10.1007/Bf00423237

McNitt-Gray, J. L., Munaretto, J., Zaferiou, A., Requejo, P. S., & Flashner, H. (2013). Regulation of reaction forces during the golf swing. *Sports Biomechanics, 12*(2), 121-131. doi:10.1080/14763141.2012.738699

Morrison, A., McGrath, D., & Wallace, E. (2014). Changes in Club Head Trajectory and Planarity Throughout the Golf Swing. *Procedia Engineering, 72*, 144-149. doi:10.1016/j.proeng.2014.06.083

References

Morrison, A., McGrath, D., & Wallace, E. (2018). The relationship between the golf swing plane and ball impact characteristics using trajectory ellipse fitting. *Journal of Sports Sciences, 36*(3), 303-310. doi:10.1080/02640414.2017.1303187

Mun, F., Suh, S. W., Park, H. J., & Choi, A. (2015). Kinematic relationship between rotation of lumbar spine and hip joints during golf swing in professional golfers. *Biomedical Engineering Online, 14*, 41. doi:10.1186/s12938-015-0041-5

Muramatsu, M., Hoshikawa, Y., Iida, T., Ii, N., & Nakajima, H. (2010). Trunk muscle size of high school athletes in relation to gender and event differences [in Japanese]. *Japanese Journal of Physical Education, Health and Sport Sciences, 55*(2), 577-590.

Myers, J., Lephart, S., Tsai, Y. S., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports Sciences, 26*(2), 181-188. doi:10.1080/02640410701373543

Narici, M. V., Hoppeler, H., Kayser, B., Landoni, L., Claassen, H., Gavardi, C., et al. (1996). Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiologica Scandinavica, 157*(2), 175-186. doi:10.1046/j.1365-201X.1996.483230000.x

Narici, M. V., Roi, G. S., Landoni, L., Minetti, A. E., & Cerretelli, P. (1989). Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *European Journal of Applied Physiology and Occupational Physiology, 59*(4), 310-319. doi:10.1007/bf02388334

Neal, R., Lumsden, R., Holland, M., & Mason, B. (2007). Body segment sequencing and timing in golf. *International Journal of Sports Science & Coaching, 2*(1_suppl), 25-36.

Neal, R., Lumsden, R. G., Holland, M., & Mason, B. (2008). Segment Interactions: Sequencing and timing in the downswing. *Science and golf V: Proceedings of the world scientific congress of golf*, 21-29.

Nesbit, S. M., & Serrano, M. (2005). Work and power analysis of the golf swing. *Journal of Sports Science & Medicine, 4*(4), 520-533.

References

Ohkawa, M., Sugawara, I., & Sakurai, T. (2004). Cross-sectional MRI areas of the trunk muscles, and capacity test of student javelin throwers compared with other throwers [in Japanese]. *Japanese Journal of Physical Fitness and Sports Medicine, 53*(4), 411-423. doi:DOI 10.7600/jspfsm1949.53.411

Okuda, I., Gribble, P., & Armstrong, C. (2010). Trunk rotation and weight transfer patterns between skilled and low skilled golfers. *Journal of Sports Science and Medicine, 9*(1), 127-133.

Peterson, T. J., Wilcox, R. R., & McNitt-Gray, J. L. (2016). Angular Impulse and Balance Regulation During the Golf Swing. *Journal of Applied Biomechanics, 32*(4), 342-349. doi:10.1123/jab.2015-0131

Pickering, W., & Vickers, G. (1999). On the double pendulum model of the golf swing. *Sports Engineering, 2*(3), 161-172.

Pink, M., Perry, J., & Jobe, F. W. (1993). Electromyographic analysis of the trunk in golfers. *American Journal of Sports Medicine, 21*(3), 385-388. doi:10.1177/036354659302100310

Putnam, C. A. (1993). Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *Journal of Biomechanics, 26 Suppl 1*, 125-135. doi:10.1016/0021-9290(93)90084-r

Rankin, G., Stokes, M., & Newham, D. J. (2006). Abdominal muscle size and symmetry in normal subjects. *Muscle and Nerve, 34*(3), 320-326. doi:10.1002/mus.20589

Read, P. J., Lloyd, R. S., De Ste Croix, M., & Oliver, J. L. (2013). Relationships between Field-Based Measures of Strength and Power and Golf Club Head Speed. *Journal of Strength and Conditioning Research, 27*(10), 2708-2713. doi:10.1519/JSC.0b013e318280ca00

Reed, M. P., Manary, M. A., & Schneider, L. W. (1999). *Methods for measuring and representing automobile occupant posture* (0148-7191). Retrieved from

Robertson, D. G., & Winter, D. A. (1980). Mechanical energy generation, absorption and transfer amongst segments during walking. *Journal of Biomechanics, 13*(10), 845-854. doi:10.1016/0021-9290(80)90172-4

References

Robertson, G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. (2004). *Research methods in biomechanics*: Human kinetics.

Sanchis-Moysi, J., Idoate, F., Dorado, C., Alayon, S., & Calbet, J. A. (2010). Large asymmetric hypertrophy of rectus abdominis muscle in professional tennis players. *PloS One, 5*(12), e15858. doi:10.1371/journal.pone.0015858

Sanchis-Moysi, J., Idoate, F., Izquierdo, M., Calbet, J. A., & Dorado, C. (2011). Iliopsoas and gluteal muscles are asymmetric in tennis players but not in soccer players. *PloS One, 6*(7), e22858. doi:10.1371/journal.pone.0022858

Sanchis-Moysi, J., Idoate, F., Izquierdo, M., Calbet, J. A., & Dorado, C. (2013). The hypertrophy of the lateral abdominal wall and quadratus lumborum is sport-specific: an MRI segmental study in professional tennis and soccer players. *Sports Biomechanics, 12*(1), 54-67. doi:10.1080/14763141.2012.725087

Schunke, M., Schulte E, Schumacher U. (2014). PROMETHEUS LernAtlas der Anatomie: Allgemeine Anatomie und Bewegungssystem. Auflage 4. In: Rumpfwand. In (pp. 100-188): Thieme.

Sell, T. C., Tsai, Y. S., Smoliga, J. M., Myers, J. B., & Lephart, S. M. (2007). Strength, flexibility, and balance characteristics of highly proficient golfers. *Journal of Strength and Conditioning Research, 21*(4), 1166-1171. doi:10.1519/R-21826.1

Sorbie, G. G., Grace, F. M., Gu, Y., Baker, J. S., & Ugbolue, U. C. (2018). Electromyographic analyses of the erector spinae muscles during golf swings using four different clubs. *Journal of Sports Sciences, 36*(7), 717-723. doi:10.1080/02640414.2017.1334956

Sprigings, E. J., & Mackenzie, S. J. (2002). Examining the delayed release in the golf swing using computer simulation. *Sports Engineering, 5*(1), 23-32.

Stewart, S., Stanton, W., Wilson, S., & Hides, J. (2010). Consistency in size and asymmetry of the psoas major muscle among elite footballers. *British Journal of Sports Medicine, 44*(16), 1173-1177. doi:10.1136/bjsm.2009.058909

References

Sung, D. J., Park, S. J., Kim, S., Kwon, M. S., & Lim, Y.-T. (2016). Effects of core and non-dominant arm strength training on drive distance in elite golfers. *Journal of Sport and Health Science, 5*(2), 219-225. doi:10.1016/j.jshs.2014.12.006

Takagi, T., Murata, M., Yokozawa, T., & Shiraki, H. (2019). Dynamics of pelvis rotation about its longitudinal axis during the golf swing. *Sports Biomechanics*, 1-20. doi:10.1080/14763141.2019.1585472

Tanaka, N. I., Komuro, T., Tsunoda, N., Aoyama, T., Okada, M., & Kanehisa, H. (2013). Trunk muscularity in throwers. *International Journal of Sports Medicine, 34*(1), 56-61. doi:10.1055/s-0032-1316316

Tinmark, F., Hellstrom, J., Halvorsen, K., & Thorstensson, A. (2010). Elite golfers' kinematic sequence in full-swing and partial-swing shots. *Sports Biomechanics, 9*(4), 236-244. doi:10.1080/14763141.2010.535842

Tsuchikane, R., Higuchi, T., Suga, T., Wachi, M., Misaki, J., Tanaka, D., et al. (2017). Relationships between Bat Swing Speed and Muscle Thickness and Asymmetry in Collegiate Baseball Players. *Sports, 5*(2), 33-40. doi:10.3390/sports5020033

Wagner, H., Pfusterschmied, J., Tilp, M., Landlinger, J., von Duvillard, S. P., & Muller, E. (2014). Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scandinavian Journal of Medicine and Science in Sports, 24*(2), 345-354. doi:10.1111/j.1600-0838.2012.01503.x

Wakahara, T., Miyamoto, N., Sugisaki, N., Murata, K., Kanehisa, H., Kawakami, Y., et al. (2012). Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance training. *European Journal of Applied Physiology, 112*(4), 1569-1576. doi:10.1007/s00421-011-2121-y

Wang, L. H., Lin, H. T., Lo, K. C., Hsieh, Y. C., & Su, F. C. (2010). Comparison of segmental linear and angular momentum transfers in two-handed backhand stroke stances for different skill level tennis players. *Journal of Science and Medicine in Sport, 13*(4), 452-459. doi:10.1016/j.jsams.2009.06.002

Watkins, R. G., Uppal, G. S., Perry, J., Pink, M., & Dinsay, J. M. (1996). Dynamic electromyographic analysis of trunk musculature in professional golfers. *American Journal of Sports Medicine, 24*(4), 535-538. doi:10.1177/036354659602400420

References

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. New Tork, NY: John Wiley & Sons.

Wiseman, F., & Chatterjee, S. (2006). Comprehensive analysis of golf performance on the PGA Tour: 1990-2004. *Perceptual and Motor Skills, 102*(1), 109-117. doi:10.2466/pms.102.1.109-117

Zheng, N., Barrentine, S. W., Fleisig, G. S., & Andrews, J. R. (2008). Kinematic analysis of swing in pro and amateur golfers. *International Journal of Sports Medicine, 29*(6), 487-493. doi:10.1055/s-2007-989229

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