Dynamic determinants of the upper torso angular velocity in golf swing

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The purpose of this study was to clarify the dynamic components of the upper torso angular velocity about its longitudinal axis during golf swing. Six right-handed golfers hit a golf ball to the net. Three dimensional kinematic data of swing motions were collected using motion capture system. The dynamic components of the upper torso angular acceleration during swing were calculated as a function of 1) joint torque, 2) gravity, 3) gyro-moment, 4) motion-dependent force, and 5) ground reaction forces. The present study found that the torso joint torque most contributed to the upper torso angular acceleration about its longitudinal axis. On the other hand, the shoulder joint torque and the motion-dependent force of the left arm negatively contributed to the angular acceleration of the upper torso about its longitudinal axis.

KEY WORDS: joint torque, gravity, gyro, motion dependent force, ground reaction force

INTRODUCTION:

The torso twist motion (the differential between the lower and upper torso turn) is known as the important motions for increasing the ball velocity during golf swing (Chu et al., 2010). The torso twist motion is required to increase the angular velocity of the upper torso utilizing the stretch-shortening cycle of the trunk muscles (Hume et al., 2005). Teu et al. (2006) reported that the upper torso angular velocity most contribute to the clubhead speed. Therefore, it is thought that the increasing the angular velocity of the upper torso (in particular about its longitudinal axis) is required for increasing the clubhead speed. Although a variety of the studies have investigated the kinematic characteristics of the upper torso (Teu et al., 2006; Horan et al., 2010), the kinetics of the upper torso has hardly been investigated. Furthermore, because most studies which investigated the kinetics of the upper torso measured (or simulated) only the torque acted on the shoulder and/or the joint between the upper and the lower torso (i.e. torso joint) (Nesbit, 2007), the kinetic mechanism generating the angular velocity of the upper torso about its longitudinal axis is poorly understood. Not only the torque but also the motion-dependent forces (e.g. the centripetal force) between segments affect the accelerations of each segment (Putnam, 1993). However, the dynamic determinants of the upper torso have not yet been explored. The purpose of this study is to clarify the dynamic components of the upper torso angular velocity about its longitudinal axis and to investigate the mechanism generating the angular velocity of the upper torso.

METHODS:

Six right-handed golfers (three men and three women; handicap, 2.6 ± 2.0) participated in the experiment. Written informed consent was obtained prior to data collection. Subjects hit a golf ball to the net. Subjects repeated seven trials with their own driver. Three dimensional kinematic data of the club were collected using motion capture system (VICON, 500 Hz). The reflective markers were attached to the club and the body. The ground reaction forces of the both feet were collected using two force platforms (Kistler, 1000 Hz). Global coordinate system was defined as follows. Vertical axis was defined as the **Z**-axis, the hit ball direction in the horizontal plane was defined as the **Y**-axis, the orthogonal axis to **Z**-and **Y**-axes was defined as the **X**-axis. Upper torso coordinate system was defined as follows. The longitudinal axis of the upper torso was defined as **s**-axis, the vector pointed from the left shoulder to the right shoulder was defined as the **x**-axis, the cross product between the **s**-axis and the **x**-axis was defined as the **y**-axis, the cross product between the **x**-axis and the **y**-axis was defined as the **z**-axis. The coordinate data were smoothed with a Butterworth low-pass digital filter of optimal cut-off frequencies which were determined by the residual error method. The left arm was defined as the vector pointed from the left shoulder to the midpoint of the both hand. The full-body model was defined with the 11 segments (i.e. club, left arm, head, upper torso, lower torso, both feet, both legs, and both thighs). The club was assumed to be a rigid body. The equation of full-body motion during the golf swing is expressed as follows (Koike and Harada, 2014). First, the equation is explained using two segments for simplicity. The equation of motion of two segments can be expressed as,

$$\boldsymbol{M\dot{V}} = \boldsymbol{PF} + \boldsymbol{QT} + \boldsymbol{G} + \boldsymbol{H} \quad (1)$$

Where, $\boldsymbol{M} = \begin{bmatrix} \boldsymbol{E}\mathrm{m}_{1\mathrm{cg}} & \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{I}_1 & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{E}\mathrm{m}_{2\mathrm{cg}} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{I}_2 \end{bmatrix}$, $\boldsymbol{\dot{V}} = \begin{bmatrix} \ddot{\boldsymbol{x}}_{1\mathrm{cg}} \\ \dot{\boldsymbol{\omega}}_{1\mathrm{cg}} \\ \ddot{\boldsymbol{x}}_{2\mathrm{cg}} \\ \dot{\boldsymbol{\omega}}_{2\mathrm{cg}} \end{bmatrix}$, $\boldsymbol{P} = \begin{bmatrix} \boldsymbol{E} & -\boldsymbol{E} & \boldsymbol{o} & \boldsymbol{o} \\ [\boldsymbol{r}_\mathrm{p}\times] & -[\boldsymbol{r}_\mathrm{d}\times] & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{E} & -\boldsymbol{E} \\ \boldsymbol{o} & \boldsymbol{o} & [\boldsymbol{r}_\mathrm{p}\times] & -[\boldsymbol{r}_\mathrm{d}\times] \end{bmatrix}$

$\boldsymbol{F} = \begin{bmatrix} \boldsymbol{F}_{1\mathrm{p}} \\ \boldsymbol{F}_{1\mathrm{d}} \\ \boldsymbol{F}_{2\mathrm{p}} \\ \boldsymbol{F}_{2\mathrm{d}} \end{bmatrix}$, $\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{E} & -\boldsymbol{E} & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{o} \\ \boldsymbol{o} & \boldsymbol{o} & \boldsymbol{E} & -\boldsymbol{E} \end{bmatrix}$, $\boldsymbol{T} = \begin{bmatrix} \boldsymbol{T}_{1\mathrm{p}} \\ \boldsymbol{T}_{1\mathrm{d}} \\ \boldsymbol{T}_{2\mathrm{p}} \\ \boldsymbol{T}_{2\mathrm{d}} \end{bmatrix}$, $\boldsymbol{G} = \begin{bmatrix} \boldsymbol{E}\mathrm{m}_{1\mathrm{cg}} \\ \boldsymbol{o} \\ \boldsymbol{E}\mathrm{m}_{2\mathrm{cg}} \\ \boldsymbol{o} \end{bmatrix}\boldsymbol{g}$, $\boldsymbol{H} = \begin{bmatrix} \boldsymbol{o} \\ -\boldsymbol{\omega}_{1\mathrm{cg}} \times \boldsymbol{I}_1 \boldsymbol{\omega}_{1\mathrm{cg}} \\ \boldsymbol{o} \\ -\boldsymbol{\omega}_{2\mathrm{cg}} \times \boldsymbol{I}_2 \boldsymbol{\omega}_{2\mathrm{cg}} \end{bmatrix}$

where, the numbers of lower case express the segment numbers. $\boldsymbol{E}$: 3×3 identity matrix, $\boldsymbol{g}$: gravity, $\boldsymbol{o}$: 3×3 zero matrix. m_{cg}: the mass of a segment, $\boldsymbol{I}$: inertial tensor of a segment, $\ddot{\boldsymbol{x}}_{\mathrm{cg}}$: acceleration of the center of gravity of a segment, $\boldsymbol{\omega}_{\mathrm{cg}}$,: angular velocity of a segment, $\boldsymbol{r}_\mathrm{p}$and $\boldsymbol{r}_\mathrm{d}$: the vector pointed from the center of gravity to the proximal and distal end, respectively, $\boldsymbol{F}_\mathrm{p}$and $\boldsymbol{F}_\mathrm{d}$: the force acted on the proximal and distal end, respectively, $\boldsymbol{T}_\mathrm{p}$and $\boldsymbol{T}_\mathrm{d}$: the torque acted on the proximal and distal end, respectively. The equation of the connection of the two segments can be expressed as,

$$\boldsymbol{CV} = \boldsymbol{0} \quad (2)$$

where, $\boldsymbol{C} = [\boldsymbol{E} \quad -[\boldsymbol{r}_{1\mathrm{p}}\times] \quad -\boldsymbol{E} \quad [\boldsymbol{r}_{2\mathrm{d}}\times]]$, $\boldsymbol{V} = [\dot{\boldsymbol{x}}_{1\mathrm{cg}} \quad \boldsymbol{\omega}_{1\mathrm{cg}} \quad \dot{\boldsymbol{x}}_{2\mathrm{cg}} \quad \boldsymbol{\omega}_{2\mathrm{cg}}]^{\boldsymbol{t}}$
The differential of the equation (2) is,

$$\boldsymbol{C\dot{V}} + \boldsymbol{D} = 0 \quad (3)$$

Where, $\boldsymbol{D} = \boldsymbol{\dot{C}V}$. When x-axis of the segment ($\boldsymbol{e_{1x}}$) is orthogonal to the y-axis of the adjacent segment ($\boldsymbol{e_{2y}}$), the cross product of the both axes equal zero.

$$\boldsymbol{e_{1x}}^{\boldsymbol{t}}\, \boldsymbol{e_{2y}} = 0 \quad (4)$$

The differential of the equation (4) can be expressed as,

$$\boldsymbol{AV} = 0 \quad (5)$$

Where, $\boldsymbol{A} = [\boldsymbol{o} \quad \boldsymbol{e}_{2y}[\boldsymbol{e}_{1x}\times] \quad \boldsymbol{o} \quad \boldsymbol{e}_{1x}[\boldsymbol{e}_{2y}\times]]$
Therefore, the differential of the equation (5) is

$$\boldsymbol{\dot{A}V} + \boldsymbol{A\dot{V}} = 0 \quad (6)$$

By solving simultaneous equations of (1), (3), (6) about $\boldsymbol{\dot{V}}$, the equation of the motion is derived as,

$$\boldsymbol{\dot{V}} = \boldsymbol{K_1QT} + \boldsymbol{K_1G} + \boldsymbol{K_1H} + \boldsymbol{K_2D} \quad (7)$$

Where, $\boldsymbol{K_1} = \boldsymbol{M^{-1}}[\boldsymbol{E} + \boldsymbol{P}\{-(\boldsymbol{CM^{-1}P})^{-1}\boldsymbol{CM^{-1}}\}]$, $\boldsymbol{K_2} = -\boldsymbol{M^{-1}P}(\boldsymbol{CM^{-1}P})^{-1}$.

The equation (7) indicate that the $\dot{\boldsymbol{V}}$ can be described as a function of the terms of Torque ($\boldsymbol{T}$), Gravity ($\boldsymbol{G}$), Gyro-moment ($\boldsymbol{H}$), and Motion-dependent force ($\boldsymbol{D}$). In this study, the parameters of the 11 segment are inserted in each matrixes of the equation and the terms of the ground reaction forces are added to the equation (1). The terms of the error caused from the expansion/contraction of the segment and the motion about the constraint joint and are added to the equation (3), (6), respectively. The joint torque and the force which calculated from the lower limbs differ from that calculated from the upper limbs. The term of the error caused from the difference is also added to the equation (1). The dynamic components (i.e. Torque, Gravity, Gyro-moment, and Motion-dependent) of the upper torso angular velocity were calculated by integrating each term of the equation (7) about the upper torso angular acceleration. To validate the equation, the upper torso angular velocity was also calculated using the unit vectors of the upper torso coordinate system (i.e. unit vector method) (Feltner & Nelson, 1996).

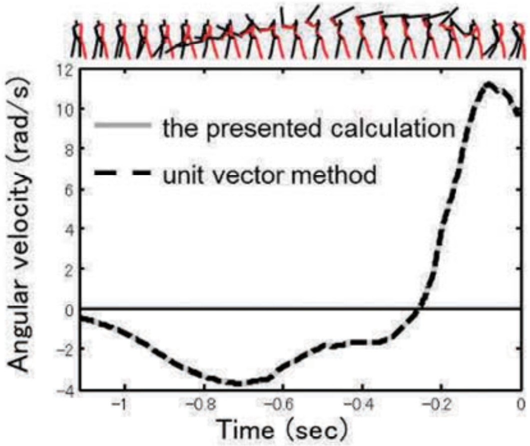

Figure 1: Comparison of the upper torso angular velocity about its longitudinal axis between two methods.

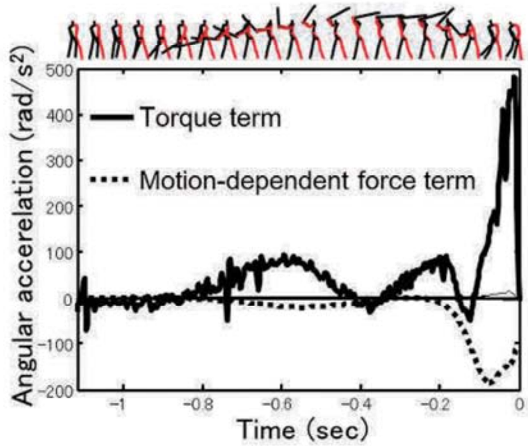

Figure 2: Dynamic components of the upper torso angular acceleration about its longitudinal axis.

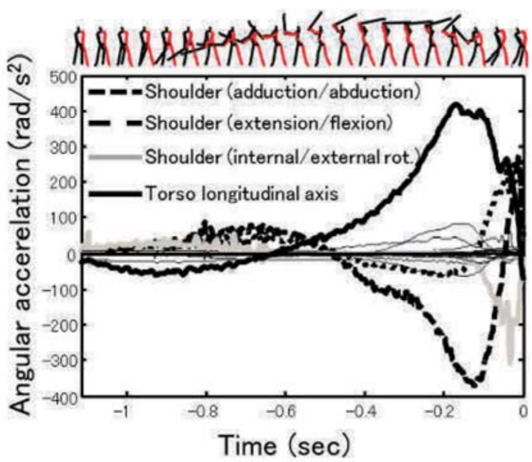

Figure 3: The components of the Torque term contributing to the angular acceleration of the upper torso about its longitudinal axis.

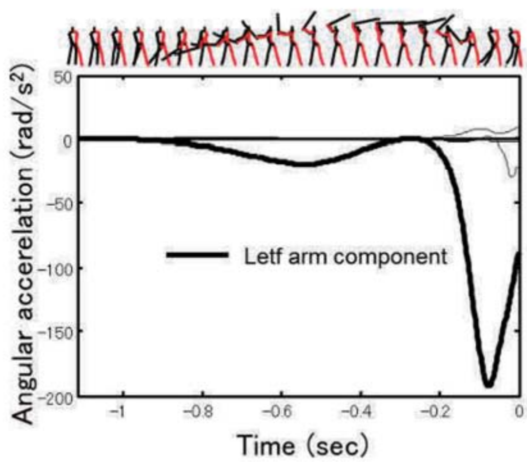

Figure 4: The components of the centripetal acceleration contributing to the angular acceleration of the upper torso about its longitudinal axis.

RESULTS AND DISCUSSION:

The angular velocity calculated by the presented calculation was coincident with that calculated using the unit vector method (Figure 1), indicating that the presented calculation is valid. Figure 2 shows the dynamic components contributing to the upper torso angular acceleration about its longitudinal axis during a typical driver shot (the terms of the errors are excluded from the Figure). The Torque positively largely contributed, while the Motion-dependent term negatively contributed to the upper torso angular acceleration during swing. The torso joint torque was the main component of the Torque term contributing to the upper torso angular acceleration about its longitudinal axis (Figure 3). On the other hand, the shoulder joint torque about its extension/flexion axis negatively contributed to the upper torso angular acceleration (Figure 3). Golfers rotate not only their upper torso but also their arms during the swing. Therefore, it was thought that the shoulder joint torque (especially extension torque) decelerates the upper torso rotation about its longitudinal axis during swing. The Motion-dependent term of the left arm also negatively contributed to the angular acceleration of the upper torso about its longitudinal axis (Figure 4). The centripetal force (the component of Motion-dependent term) of the left arm increases as the left arm angular velocity increases. Therefore, it was suggested that the centripetal force of the left arm decelerated the upper torso angular velocity about its longitudinal axis.

CONCLUSION:

The present study revealed the dynamic components of the upper torso angular velocity about its longitudinal axis. While the torso joint torque positively contributed to the angular acceleration of the upper torso about its longitudinal axis, the shoulder joint torque about its extension/flexion axis and the motion-dependent force of the left arm negatively contributed to the upper torso angular acceleration.

REFERENCES:

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*, 1251–1259.

Feltner, M.E & Nelson, S.T.(1996). Three-dimensional kinematics of the throwing arm during the penalty throw in water polo. *Journal of Applied Biomechanics, 12*, 359–382.

Horan, S.A., Evans, K., Morris, N.R., Kavanagh, J.J. (2010). Thorax and pelvis kinematics during the downswing of the male and female skilled golfers. *Journal of Biomechanics, 43*, 1456–1462.

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

Koike, S. & Harada, Y. (2014). Dynamic contribution analysis of tennis-serve-motion in consideration of torque generation mode. *Procedia Engineering, 72*, 97-102

Neal, R.J. & Wilson, B.D. (1985). 3D kinematics and kinetics of the golf swing. *International Journal of Sports Biomechanics, 1*, 221–232.

Nesbit, S.M. (2007). Development of the full-body mechanical model of the golf swing. *International Journal of Modelling and Simulation, 27*, 392–404.

Putnam, C.A. (1993). Sequential motions of body segments in striking and throwing skills: descriptions and explanations. *Journal of Biomechanics, 26*, 125–135.

Teu, K.K., Kimb, W., Fussa, F.K., Tan, J. (2006). The analysis of golf swing as a kinematic chain using dual Euler angle algorithm. *Journal of Biomechanics, 39*, 1227–1238.