

Proposal of Golf Swing Analysis Method Using Singular Value Decomposition [†]

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[†] Presented at the 13th conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Published: 15 June 2020

Abstract: We analyzed the relationship between the cooperative actions of golf swings and the differences in swing trajectory. To extract cooperative actions from different swings, we acquired swing data in an experiment on an experienced golfer who swung with two different trajectories. We measured the swings with motion capture system (VICON). We built an observance matrix from the collected positional data and conducted singular value decomposition (SVD) on it. The SVD yielded the cooperative actions as independent modes. Next, we compared the cooperative actions of different swing trajectories in the main mode. The results indicate that the analysis of the golf swing could be divided into a dominant behavior and an accompanying behavior.

Keywords: golf swing; singular value decomposition (SVD); swing trajectory; motion capture system; cooperative action

1. Introduction

To improve golfing skills, the most appropriate clubs must be selected for each kind of swing [1,2]. Here, custom-made clubs tailored to each kind of swing are designed by conducting simulations of their behavior. The authors have modeled clubs by using the finite element method and reproduced the deformation behavior of actual clubs [3]. However, to reproduce deformation in clubs that have not been used with this model, the swing must be simulated in accordance with the corresponding changes in the club's characteristics.

A previous study that analyzed the relationship between a club's characteristics and a swing expressed the golfer's body by a segment model. It analyzed the torque of each joint [4,5] and analyzed the myoelectric potential during a swing [1,2]. The results clarified the relationship between club movements and individual body parts, such as the wrists, shoulders, and hips. In addition, in a study of club design based on the relationship between club characteristics and swings, swing changes were found to depend on club characteristics [6]. However, in a swing, the individual parts of the body cooperate to form the whole movement, and directly correlating the motions of the individual parts with those of the club is difficult. Therefore, the movement of the body must be regarded as a combination of several cooperative actions, and the relationship between the cooperative actions and the club characteristics must be clarified.

A study was conducted on joint coordination in a 2D plane for walking motions; it divided the body motions into several cooperative actions. The results suggested that walking motions can be expressed in terms of three cooperative actions [7,8]. Another study expressed golf-swing behavior on a 2D plane and classified the swing behavior into multiple cooperative actions by using the singular value decomposition (SVD) method [9]. However, a swing is a 3D motion, so the relationship between the club characteristics and the swing should be clarified by determining the cooperative actions in 3D. Here, the authors have constructed a 3D cooperative action extraction method that uses SVD to analyze cooperative actions in golf swings [10]. We used it to analyze cooperative actions and clarified the characteristic behaviors of golf swings. In addition, we analyzed the relationship between the weight of the club and the cooperative actions and found that the cooperative actions change depending on the weight of the club [10]. In this study, we confirm the effectiveness of our swing analysis method using SVD by focusing on differences between trajectories and analyzing cooperative actions in different trajectories. We measured the outside-in trajectory (referred to as “fade”) and the inside-out trajectory (referred to as “draw”) of a skilled golfer by using 3D motion capture and performed SVD on the collected data [11]. The swing was divided into characteristic behaviors, and the role of each behavior was revealed. We then clarified the characteristic behavior of each trajectory by reconstructing the decomposed characteristic behaviors and comparing the behaviors of different swings.

2. Experiment to Measure Golf Swings

2.1. Preparations

We recruited one expert golfer to be the subject of the measurements. Table 1 shows the subject’s height, weight, and average score of one hall. We prepared a club that the subject could swing comfortably. We measured his golf swings using 46 infrared cameras (VICON) at a sampling rate of 500 Hz. Markers were attached to the subject’s body and to the club (Figures 1 and 2). In particular, we placed 53 markers on the subject’s body and 4 on the club. The coordinate system used for the measurements denoted the back-front direction of the body as the x-axis for, the target line direction as the y-axis, and the upward vertical direction as the z-axis. Figure 1 shows this coordinate system together with the body marker arrangement.

Table 1. Subject data.

Height [cm]	Weight [kg]	Average Score
171	70	75

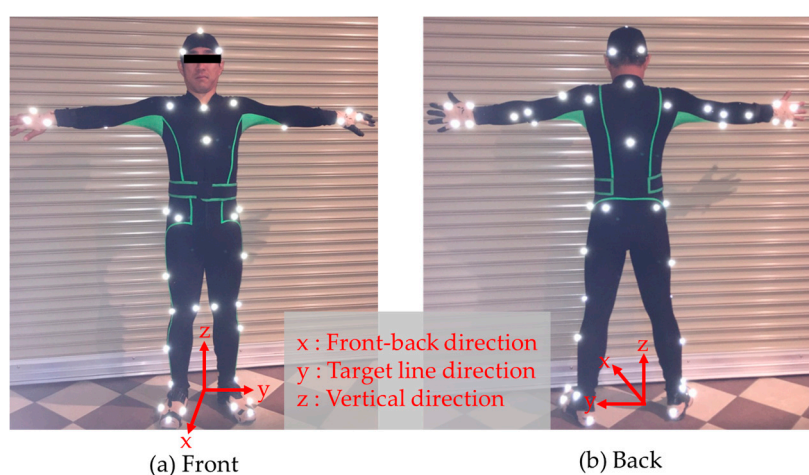


Figure 1. Locations of markers on the subject: (a) front, (b) back. The x-axis is in the front-back direction, the y-axis is along the target line, and the z-axis is in the vertical direction.



Figure 2. Marker locations on club.

2.2. Experiment Method

We measured the swing behavior of the subject as he swung 14 sponge balls (which eliminated the sense of impact of the club hitting the ball) on two different trajectories. The subject was instructed to intentionally change trajectories during the measurements. In addition, the measurements were conducted with the consent of the subject.

3. Motion Data Analysis

We examined the differences in behavior on the different trajectories by collecting motion data. We determined take away (TA), middle of back swing (MB), top of back swing (TB), middle of down swing (MD), ball contact (BC), middle of follow swing (MF), top of follow swing (TF) and analyzed swing behaviors in each of these events. The definitions of these events can be found in Reference [10–12]. We compared the swings in different trajectories by using a stick diagram. The stick diagrams were created for all 14 balls of swing data and the posture data at TA to TF. We averaged the data at redundant markers in order to examine only the characteristic behavior [11]. An example of each trajectory is shown as a representative because that the subject in this study was able to change trajectories intentionally. Change trajectories were visually confirmed with the swings measured. Figure 3 shows the results for representative attitude data. In Figure 3, (a) shows the front view, and (b) shows the side view. The dashed red lines show the fade swing, while the solid blue lines show the draw swing. The left toe positions of each swing in the direction of the target line were aligned in order to reveal only the differences in the swing motions. In particular, the fade swing shows the trajectory of outside to inside from MD to MF and the draw swing shows the trajectory of inside to outside from MD to MF. Consequently, the figure shows the differing attitude data between swings in different trajectories.

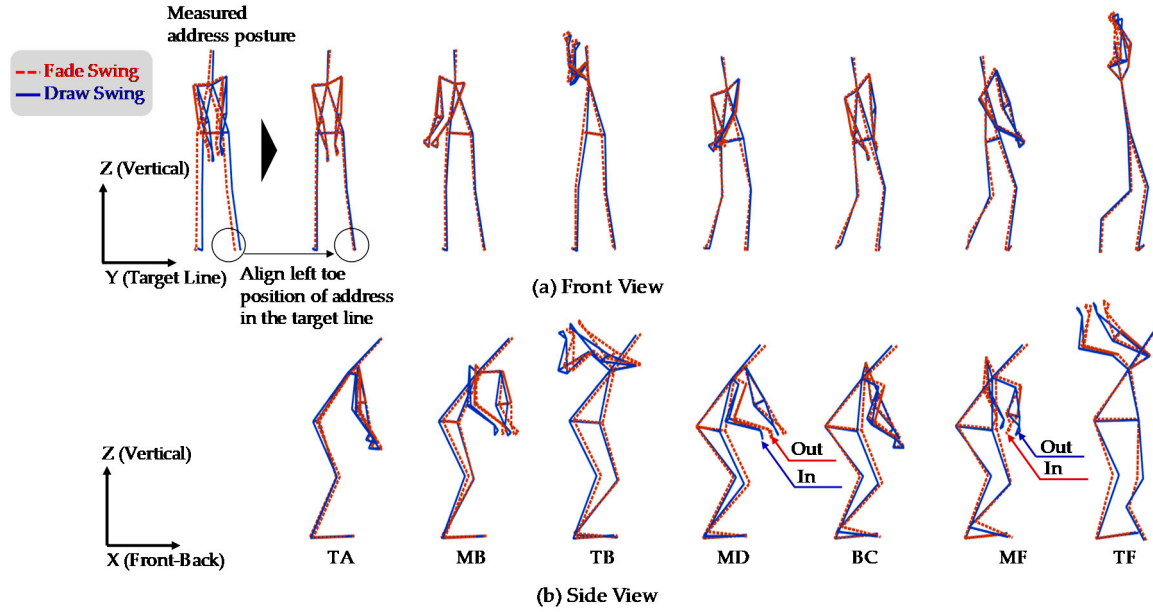


Figure 3. Representative trials of fade swing (red lines) and draw swing (blue lines): (a) front view, (b) side view.

4. Analysis Using Singular Value Decomposition (SVD)

4.1. Construction of Observation Matrix

The observation matrix was constructed using position coordinate data. The data was the swing behavior from TA to TF. TA thus denotes the first point in time and TF the Nth point in time. The position vector of the i -th marker at the n -th time is

$$r_i(n) = [x_i(n) \quad y_i(n) \quad z_i(n)] \quad (1)$$

Here, $x_i(n)$, $y_i(n)$, and $z_i(n)$ mean the components in the x , y , and z directions (Figure 1) of the n -th time point of the i -th marker. The matrix $([r_i] \in \mathbb{R}^{N \times 3})$ of such position vectors arranged in rows was composed for each time. An $[r_i]$ was constructed for each characteristic behavior. Then, a matrix $([R] \in \mathbb{R}^{N \times 66})$ was composed that consisted of matrixes $[r_i]$ as its columns:

$$[R] = [[r_1] \quad \cdots \quad [r_i] \quad \cdots \quad [r_{22}]] \quad (2)$$

The matrix of Equation (2) aligns the reference point of SVD closer to the posture at TA. To clarify the behavioral differences in the different trajectories, we extended it to be a common standard for all trials. For each marker, the position vector at TA was obtained from Equation (1), all the trials were averaged, and the matrix $([\bar{r}_i(1)] \in \mathbb{R}^{10 \times 3})$ was formed for each row [10]. Then the matrix $([\bar{R}(1)] \in \mathbb{R}^{10 \times 66})$ was formed from $[\bar{r}_i(1)]$ for all markers [11]. To increase the number of data points of the observation matrix and improve the resolution, the inverse of Equation (2) ($[R_t] \in \mathbb{R}^{N \times 66}$) in the time series direction was calculated. To extract only the cooperative actions, $[R]$ and $[R_t]$ were translated so that the left toe coincided with the target line ball direction, and the observation matrix $([R_a] \in \mathbb{R}^{22N \times 66})$ was formed as follows [10]:

$$[R_a] = \begin{bmatrix} [\bar{R}(1)] \\ [R] \\ [R_t] \\ [\bar{R}(1)] \end{bmatrix} \quad (3)$$

4.2. Singular Value Decomposition (SVD)

For the observation matrix of Equation (3), the average in the time direction (row direction) of $[R_a]$ was taken and the average for each row was defined as $[R_0]$. $[R_a]$ was expanded into modes as follows:

$$[R_a] = [R_0] + \sum_{j=1}^{66} \lambda_j v_j z_j^T \quad (4)$$

In Equation (4), λ_j indicates the singular value of the j -th mode, $v_j \in \mathbb{R}^N$ is the left singular vector of $[R_a] - [R_0]$, and $z_j \in \mathbb{R}^{66}$ is the right singular vector of $[R_a] - [R_0]$. z_j indicates the posture of each body part, and v_j represents the time information of z_j . λ_j represents the ratio of each mode to $[R_a]$ [8,10].

4.3. Analysis of Swing Behavior Reconstructed from Modes

The method described in the previous section was used to perform SVD. The main behaviors up to the fifth mode were analyzed [10,11]. Table 2 shows the behaviors of each mode [10,11]. From Equation (4), the swing behavior $[R_5]$ in the first to fifth modes is expressed by the following equation.

$$[R_5] = [R_0] + \sum_{j=1}^5 \lambda_j v_j z_j^T \quad (5)$$

We extracted the behavior during each event defined in the previous section (i.e., TA, MB, TB, MD, BC, MF, and TF) and compared the behaviors of fade and draw swings. Figure 4 shows the results. Here, the reconfigured swings constructed in the first to fifth modes show the differences due to the different trajectories [11]. However, the side view at BC shows no differences in the knee or hip. We believe that this is because the behavior after the fifth mode affects high-speed behavior such as impact. On the other hand, considering the behaviors up to the fifth mode, the behaviors of the whole body in each event can be compared with the differences between the fade and draw trajectories.

Table 2. Relationship between each swing composed mode and each action [10,11].

Action	
First mode	Steady rotation of legs, waist and rotation of arms in a swing as a whole
Second mode	Rotation of shoulders in a swing as a whole
Third mode	Extrusion and rotation of legs and waist from TB to TF
Forth mode	Rotation of shoulders and arms around BC
Fifth mode	Extension of arms from BC to TF

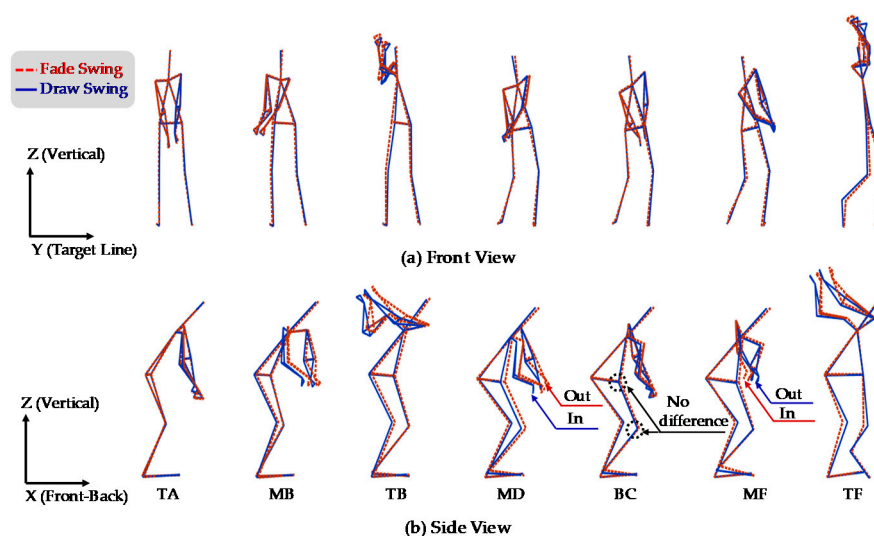


Figure 4. Stick pictures comparing sums of first to fifth mode swing: (a) front view (b) side view. Red pictures show a fade swing and blue pictures show a draw swing.

4.4. Comparison of Temporal Behaviors

To analyze the role of the mode in each event, the temporal behavior of each mode can be expressed as follows:

$$\mathbf{w}_j = \lambda_j \mathbf{v}_j \quad (6)$$

In Equation (6), \mathbf{w}_j indicates the temporal behavior of the j -th mode. Figure 5 shows the temporal behaviors of the first to fifth modes obtained by substituting 1 to 5 for j in Equation (6). Figure 5a shows the results for a fade, while (b) shows the results for a draw. The dominant behavior in each event is circled. The first to third modes are the dominant behavior at each timing in (a) and (b). The fourth and fifth modes are the behaviors after BC. These results show that the first to third modes indicate when the whole body swings, while the fourth and fifth modes show linking or compensating behavior. Accordingly, the proposed SVD method shows that a golf-swing analysis can be divided into dominant behavior and accompanying behavior.

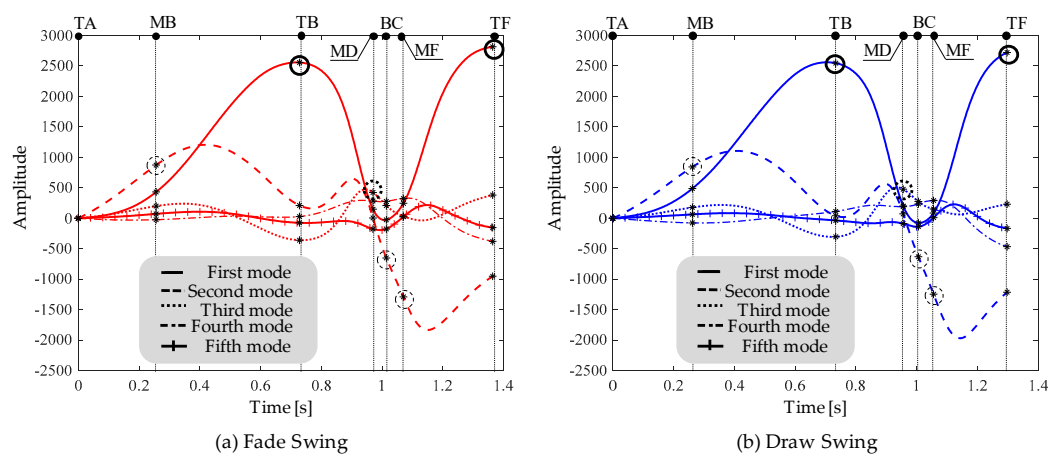


Figure 5. Comparison of temporal behaviors up to fifth mode: (a) draw swing, (b) fade swing.

5. Conclusions

- (1) Golf swings can now be analyzed in terms of independent modes which are in each role.
- (2) The SVD method can divide the analysis into dominant and accompanying motions.

Author Contributions: All authors have read and agree to the published version of the manuscript. Conceptualization K.M., N.T., I.A., H.K., M.U. and K.O.; methodology, K.M. and K.O.; software K.M.; validation K.M. and K.O.; formal analysis K.M. and K.O.; investigation K.M., M.U., and K.O., resources M.U. and K.O.; data curation K.O.; writing-original draft preparation K.M. and H.K.; writing – review and editing K.M., N.T., A.I., H.K. and K.O.; visualization K.M. and K.O.; supervision N.T. and U.M.; project administration M.K. and K.O.; funding acquisition K.M., N.T., U.M. and K.O.

Funding: This research received no external funding.

Conflicts of Interest: This research does not conflict of interest.

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