Impedance Control for a Golf Swing Robot to Emulate Different-Arm-Mass Golfers

Various golfers can play different golf swing motions even if they hold the same golf club. This phenomenon casts light on the significance of the dynamic interaction between the golfer’s arm and golf club. The dynamic interaction results in different swing motions, even if the robot has the same input torque of the shoulder joint as that of a golfer. Unfortunately, such influence has not been considered in the conventional control of a golf swing robot. An impedance control method is proposed for a golf swing robot to emulate different-arm-mass golfers in consideration of the dynamic interaction between human arm and golf club. Based on the Euler–Lagrange principle and assumed modes technique, a mathematical model of golf swing considering the shaft bending flexibility is established to simulate the swing motions of different-arm-mass golfers. The impedance control method is implemented to a prototype of golf swing robot composed of one actuated joint and one passive joint. The comparison of the swing motions of the robot and different-arm-mass golfers is made and the results show that the proposed golf swing robot with the impedance control method can emulate different-arm-mass golfers.

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Keywords: impedance control, mechanical impedance, golf swing robot, swing motion

1 Introduction

A large amount of research has been devoted to improve golfers’ swing skills and golf club performance for decades. Among these studies, golf swing robots have formed a large body of literature [1–5]. In their work, professional golfers’ swing motions were expected to be emulated by robots and the evaluation of golf club performance was replaced by robots instead of golfers.

Though much progress has been achieved in this area, there still remains a long-standing challenge for a golf swing robot to accurately emulate the fast swing motions of professional golfers. It has been noticed that conventional golf swing robots on the market are usually controlled by the swing trajectory functions of joints or of the club head directly measured from professional golfers’ swings. The swing motions of these robots, unfortunately, are not completely the same as those of the advanced golfers, in that they do not involve the dynamic features featured by different characteristics of human arms and golf clubs. Hunt and Wiens [1] developed a parallel mechanism robotic testing machine that captures the human golfer dynamics during golf club testing. Suzuki and Inooka [2] proposed a new golf swing robot model consisting of one actuated joint and one passive joint. In their model, the robot like professional golfers was able to utilize the interference forces resulting from the dynamic features of individual golf clubs on the arms, and the resulting optimal control torques of the shoulder joint were obtained. Ming and Kajitani [3] gave a new motion planning method for this type of robot, using different cost functions to gain the optimal control torques. In their work, the control input for the robot was the torque function of the shoulder joint instead of the general ones such as the trajectory functions of joints or of club head. The change of the control input mainly results from the special dynamical characteristics of this new type of robot: The swing motion of the wrist joint is generated by the dynamic coupling drive of the shoulder joint. This point was specifically explained in the work of Ming and Kajitani [3]. In their research, however, the difference between the golfer’s arm and the robot’s arm in mass (or the moment of inertia of the arm) was not considered. Therefore, if the optimal control torque from their work is applied to other golfers who own different-mass arms, various swing motions would be gained. In other words, the robots proposed by them can only emulate one kind of golfers who have the same arm mass as that of the robot. The limitation of the golf swing robots promotes us to investigate a new control method to make the robots emulate more general golfers.

In our study, an impedance control method based on velocity instruction is proposed for a golf swing robot to emulate different-arm-mass golfers. A model of a golfer’s swing considering the shaft bending is given by using the Euler–Lagrange principle and assumed modes method. A prototype of golf swing robot with one actuated joint and one passive joint is developed using the impedance control method. The comparison of swing motion is carried out between golfers and the golf swing robot. The results demonstrate that our golf swing robot can simulate different-arm-mass golfers.

2 Dynamic Modeling of Golf Swing

In order to demonstrate the validity of the impedance control method, the swing motions of different-arm-mass golfers should be obtained so that the motions can be compared with those from the proposed golf swing robot using the impedance control method. Therefore, a dynamic model has been developed to emulate the swing motions of different-arm-mass golfers under the given input torques of the shoulder joint. The detailed derivation of the model is shown as follows.

2.1 Dynamic Model and Assumptions. The dynamic model of golf swing is shown in Fig. 1. Here, the rotations of the arm and golf club are assumed to occur in one plane during the downswing and follow-through, and this plane is inclined with an angle \( \theta \) to the horizontal plane. The assumption of the planar movement of the arm and golf club is well supported in the early work of...
Cochran and Stobbs [6] and Jorgensen [7]. Therefore, the gravity acceleration vector in the swing plane can be expressed as $g = [0 \ -g_0]^T$, $\gamma_0 = g \sin \theta$. The arm and handgrip are considered as the rigid rods and the club head as a tip mass. The shaft is treated as an Euler– Bernoulli beam, in which the elastic modulus, density, inertia, and cross-sectional area are constant along the beam length. Two coordinate systems in the swing plane are introduced to describe the dynamics of the golf swing: a fixed reference frame $XY$ and a rotational reference frame $xy$ attached to the end of the handgrip where its $x$ axis is along the undeformed configuration of the beam. The torque $\tau_1$ is applied at the shoulder joint $O$ to drive the swing. The torque $\tau_2$ is employed at the wrist joint $s$ to hold the golf club. Since the center of gravity of the club head is regarded as on the central axis of the shaft, the twisting of the shaft is neglected and the bending flexibility of the shaft in the swing plane is only considered. The bending displacement of the shaft is expressed as $y(x,t)$ in the rotational coordinate system $o-xy$. The rotational angle of the arm with the $X$ axis is $\alpha$ and the rotational angle of the club grip with the $x$ axis is $\beta$.

### 2.2 Dynamic Equations of Motion

The Euler–Lagrange approach is used to derive the dynamic equations of motion for a golfer’s swing. In the coordinate system $O-XY$, $\mathbf{r}_2$ and $\mathbf{r}_3$ are defined as the position vectors of the centers of gravity of the handgrip and the club head, respectively; $\mathbf{r}_p$ is the position vector of a point $p$ on the shaft; $\gamma_p$ is the bending displacement of a point $p$ on the shaft with respect to the coordinate system $o-xy$; $J_1$ is the moment of inertia of the arm about the shoulder joint $O$; $J_2$ and $J_R$ are the moments of inertia of the handgrip and the club head, respectively; $m_1, m_2, m_3,$ and $m_g$ are the masses of the arm, the handgrip, the shaft, and the club head, respectively; $a_1, a_2,$ and $a_3$ are the lengths of the arm, the handgrip, and the shaft, respectively; $R$ is the radius of the club head; $\rho$ is the mass per unit length of the shaft; $E$ is Young’s modulus of the shaft material; and $I$ is the area moment of inertia of the shaft.

The following operators are defined:

\[
(\gamma) = \frac{\partial}{\partial t}(\gamma) \quad \text{and} \quad (\gamma)’ = \frac{\partial}{\partial x}(\gamma)
\]

The total kinetic energy of the system is given by

\[
T = T_1 + T_2 + T_3 + T_4
\]

where $T_1$, $T_2$, $T_3$, and $T_4$ are the kinetic energies associated with the arm, the handgrip, the shaft, and the club head, respectively. They are

\[
T_1 = \frac{1}{2} J_1 \dot{\alpha}^2
\]

\[
T_2 = \frac{1}{2} J_2 (\dot{\alpha} + \dot{\beta})^2 + \frac{1}{2} m_2 \dot{\mathbf{r}}_2^2
\]

\[
T_3 = \frac{1}{2} m_p \dot{\mathbf{r}}_p^2
\]

\[
T_4 = \frac{1}{2} m_g \dot{\mathbf{r}}_g^2 + \frac{1}{2} J_R (\dot{\alpha} + \dot{\beta} + \gamma’|_{(s=0)})^2
\]

The total potential energy of this system can be written as

\[
U = U_1 + U_2 + U_3 + U_4
\]

where $U_1$, $U_2$, and $U_4$ are the potential energies resulting from the gravitational forces of the arm, the handgrip, and the club head, respectively, and $U_3$ is the potential energy of the shaft.

\[
U_1 = -m_1 g \mathbf{r}_1
\]

\[
U_2 = -m_2 g \mathbf{r}_2
\]

\[
U_3 = m_3 + U_3
\]

\[
U_4 = -m_g \mathbf{r}_g^2
\]

Therefore, the Lagrangian $L$ of the system can be obtained as

\[
L = T - U
\]

The internal structural damping in the golf shaft should also be considered. By using Rayleigh’s dissipation function, the dissipation energy for the golf shaft is written as

\[
E_D = \sum_{i=1}^{m} \frac{1}{2} \frac{d}{dt} q_i^2
\]

where $d_i$ and $q_i$ are the damping coefficient and the mode amplitude associated with the $i$th mode of the shaft bending vibration, respectively.

According to the assumed modes technique of Theodore and Ghosal [8], a finite-dimensional model of the shaft bending displacement is written as

\[
y(x,t) = \sum_{i=1}^{m} \phi_i(x) q_i(t)
\]

where $\phi_i(x)$ and $q_i(t)$ are the $i$th assumed mode eigenfunction and $i$th time-varying mode amplitude, respectively. Since the golf shaft is modeled as an Euler–Bernoulli beam with uniform density and constant flexural rigidity ($EI$), it satisfies the following partial differential equation:

\[
EI \frac{d^2 y(x,t)}{dx^2} + \rho \frac{d^2 y(x,t)}{dt^2} = 0
\]

We can obtain the general solution of Eq. (14)

\[
q_i(t) = \exp(j \omega_i t)
\]

where $\omega_i$ is the $i$th natural angular frequency.

Furthermore, $\phi_i(x)$ can be expressed as

\[
\phi_i(x) = C_{i1} \sin(e_i x) + C_{i2} \cos(e_i x) + C_{i3} \sinh(e_i x) + C_{i4} \cosh(e_i x)
\]

where $e_i = \omega_i^2 / EI$.

We consider the golf club as a cantilever that has a tip mass; the following four expressions associated with the boundary conditions can be obtained [9]:

\[
y|_{x=0} = 0
\]

\[
y’|_{x=0} = 0
\]
\[ EI \gamma''_{l=5} = -J_R \gamma''_{l=3} \quad (19) \]
\[ EI \gamma''_{l=3} = m_R \gamma''_{l=3} \quad (20) \]

From these boundary conditions, the following results are given:
\[ C_{1i} = C_{3i} \quad \text{and} \quad C_{2i} = -C_{4i} \quad (21) \]
\[
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
C_{10} \\
C_{20}
\end{bmatrix} = 0 \quad (22)
\]

The \(i\)th natural angular frequency \(w_i\) can be obtained by solving the eigenvalue problem of the matrix equation (22) and the coefficients \(C_{1i}\) and \(C_{2i}\) are chosen by normalizing the mode eigenfunctions \(\phi_i(x)\) such that
\[ \rho \int_0^a \phi_i^2(x) dx = m_i, \quad i = 1, 2, \ldots, m \quad (23) \]

The impedance of the wrist joint is also considered in our simulation. The wrist impedance function is written as
\[ \tau_f = c \beta \quad (24) \]
where \(c\) is the viscous damping constant of the wrist joint and \(\tau_f\) is the wrist retarding torque due to the impedance of the wrist joint.

Since professional golfers such as Jones [10] turned the wrist joint freely and felt that the golf club was free at the wrist at the end of the downswing, the value of \(c\) used here is relatively small compared to that from Milne and Davis [11]. Here, it is assumed that the value of \(c\) is equivalent to that of the golf swing robot. On the basis of the Euler–Lagrange equation
\[ \frac{\partial}{\partial t} \left( \frac{\partial L}{\partial \dot{Q}_i} \right) - \frac{\partial L}{\partial Q_i} + \frac{\partial E_D}{\partial Q_i} = f_i \quad (25) \]
with the Lagrangian \(L\), the dissipation energy of the shaft \(E_D\), the generalized coordinates \(Q_i\), and the corresponding generalized forces \(f_i\), the dynamic equations of motion of the golf swing can be obtained. Since the amplitudes of the lower modes of the bending vibration of the golf club are significantly larger than those of the higher ones, \(m\) is simplified to 2 in this paper. As a result, the equations of motion of the golf swing can be written as
\[ B(\dot{\theta}) \dot{\theta} + h(\theta, \theta) + K \theta + G(\theta) + D \theta = \tau \quad (26) \]

where
\[
B = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & 0 \\ B_{41} & B_{42} & 0 & B_{44} \end{bmatrix}, \quad \theta = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}, \quad h = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix}, \quad \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}, \quad \alpha = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \quad \beta = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}
\]
\[
K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & K_{33} & K_{34} \\ 0 & K_{34} & K_{44} \end{bmatrix}, \quad G = \begin{bmatrix} G_1 \\ G_2 \\ G_3 \\ G_4 \end{bmatrix}
\]
\[
D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & c & 0 & 0 \\ 0 & 0 & d_1 & 0 \\ 0 & 0 & 0 & d_2 \end{bmatrix}, \quad \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}, \quad \alpha = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}
\]

\(B, K, \text{and } D\) are the inertia, stiffness, and damping matrices; \(h\) is the vector of Coriolis and centrifugal forces; \(G\) is the gravity vector and \(\tau\) is the input vector; \(q_1\) and \(q_2\) are the first and second time-varying mode amplitudes of the shaft bending vibration, respectively; \(c\) is the wrist viscous coefficient; and \(d_1\) and \(d_2\) are the damping coefficients of the first and second modes of the bending vibration of the shaft, respectively.

3 Impedance Control Design

The dynamic equation of a mechanical system is always expressed as
\[ \mathbf{Mx} + \mathbf{Cx} + \mathbf{Kx} = \mathbf{F} \quad (27) \]
where \(\mathbf{F}\) is the external force and \(\mathbf{M}, \mathbf{C}, \text{and } \mathbf{K}\) are denoted as the inertia, viscosity, and stiffness, respectively. These parameters were called mechanical impedance in the work of Hogan [12]. In this paper, the golfer’s arm as a mechanical system is investigated. Since it has been found that a golfer’s hands move in a circular arc about the shoulder joint during the golf swing, the golfer’s arm is assumed to be a rigid body and the stretch reflex of the arm muscle is neglected. The fact that the swing motions obtained from the numerical simulation using the rigid arm link [6,7,11,13–15] agree well with those from the swing photographs of professional golfers have assured the above assumption. Therefore, the dynamic equation of the golfer’s arm can be given as
\[ \mathbf{Mx} = \mathbf{F} \quad (28) \]

where the viscous damping and stiffness of the golfer’s arm are ignored and the moment of inertia of the arm about the shoulder joint \(\mathbf{M}\) is defined as the mechanical impedance. The virtual system representing the dynamic model of a golfer’s arm and the robot system expressing the dynamic model of a robot’s arm are shown in Figs. 2 and 3, respectively.

The equations of motion of the virtual and robot systems are written as Eqs. (29) and (30).
\[
J_{1\text{h}} \ddot{\alpha}_h = \tau_{1h} + F_h L_{1\text{h}} + f_g h(\alpha_h) + N_h \quad (29)
\]
\[
J_{1\text{r}} \ddot{\alpha}_r = \tau_{1r} + F_h L_{1\text{r}} + f_g h(\alpha_r) + N_r \quad (30)
\]

where the subscripts \(h\) and \(r\) denote the golfer and robot, respectively; \(f_g(\alpha) = -F_g l(\cos \alpha); F_g\) is the gravitational force of the arm; \(F\) is the reaction force from the club to arm, and the direction...
is perpendicular to the arm; and \( N \) is the reaction torque from the club to the arm. Here, we assume \( L_{1h}=L_{1r} \).

In our control method, the dynamic parameters \( J_{1h} \) and \( J_{1r} \) in Eqs. (29) and (30) are defined as the mechanical impedance. With the various arm masses for the golfer and robot, the mechanical impedances \( J_{1h} \) and \( J_{1r} \) are varied. Consequently, the swing motion of the robot is not the same as that of the golfer, even if the input torques of the shoulder joints are equal. In order to realize the dynamic swing motion of the virtual system, the following control algorithm is proposed for the robot.

According to the Euler method, angular acceleration of the arm can approximate the following expressions:

\[
\ddot{\alpha}_{n} = \frac{\alpha_{n} - \alpha_{n-1}}{\Delta t}, \quad n = 1, \ldots, M \tag{31}
\]

In the impedance control method, the arm angular velocity of the golfer is regarded as the control input reference for the robot. As shown in Eq. (33), the reaction force \( F_{h} \) and reaction torque \( N_{h} \) should be known in advance, if we expect to acquire the control input reference \( \alpha_{n} \). Since the PI control in the velocity loop for the robot is used to assure that the arm angular velocity of the robot is equivalent to that of the golfer, \( \alpha_{n} = \dot{\alpha}_{n} \). The reaction torques of the same golf club used by the golfer and robot are the same. Therefore, the reaction force and reaction torque from the same golf club to the arms of the golfer and robot are equal, that is, \( F_{h} = F_{r} \) and \( N_{h} = N_{r} \). Note that the reaction force \( F_{r} \) and reaction torque \( N_{r} \) can be obtained by a six-dimensional force sensor and a one-dimensional force sensor installed on the robot’s arm, respectively. Substituting the above results into Eq. (33), the control input reference \( \alpha_{n} \) for the swing golf robot can be calculated from the following equation:

\[
\ddot{\alpha}_{n} = \frac{\alpha_{n} - \alpha_{n-1}}{\Delta t} + \frac{\Delta t}{J_{1h}}(\tau_{1h}^{n-1} + F_{h}^{n-1}L_{1h} + f_{gh}(\alpha_{n-1}^{r}) + N_{h}^{n-1}) \tag{35}
\]

where \( \Delta t \) is the sampling time, \( M \) is an integer, and \( \ddot{\alpha}_{n} \) and \( \ddot{\alpha}_{n} \) are the angular acceleration and velocity in the \( n \)-th sampling period.

Substituting Eq. (31) into Eq. (29), and Eq. (32) into Eq. (30), and after some manipulations, Eqs. (33) and (34) are obtained.

\[
\ddot{\alpha}_{n} = \alpha_{n} - \alpha_{n-1} + \frac{\Delta t}{J_{1h}}(\tau_{1h}^{n-1} + F_{h}^{n-1}L_{1h} + f_{gh}(\alpha_{n-1}^{r}) + N_{h}^{n-1}) \tag{33}
\]

\[
\ddot{\alpha}_{n} = \alpha_{n} - \alpha_{n-1} + \frac{\Delta t}{J_{1r}}(\tau_{1r}^{n-1} + F_{r}^{n-1}L_{1r} + f_{gh}(\alpha_{n-1}^{r}) + N_{r}^{n-1}) \tag{34}
\]

In the impedance control method, the arm angular velocity of the golfer is regarded as the control input reference for the robot.

<table>
<thead>
<tr>
<th>Table 1 Parameters of the robot system</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Mass of arm</td>
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<tr>
<td>Moment of inertia of arm about shoulder Joint O</td>
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<tr>
<td>Length of arm</td>
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<tr>
<td>Mass of handgrip</td>
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<tr>
<td>Moment of inertia of handgrip</td>
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<tr>
<td>Length of handgrip</td>
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<tr>
<td>Mass per unit length of shaft</td>
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<tr>
<td>Length of shaft</td>
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<tr>
<td>Area moment of inertia of shaft</td>
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<tr>
<td>Young’s modulus of shaft material</td>
</tr>
<tr>
<td>Mass of club head</td>
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<tr>
<td>Moment of inertia of club head</td>
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<tr>
<td>Radius of club head</td>
</tr>
<tr>
<td>Wrist viscous damping coefficient</td>
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<tr>
<td>Damping coefficient of first mode of club</td>
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<td>Damping coefficient of second mode of club</td>
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The experiment was implemented by a prototype of golf swing robot composed of an actuated joint driven by a direct drive motor (NSK MEGATORQUE) and a passive joint with a mechanical stopper. The stopper carries out the wrist cock action. A mechanical brake is used to stop the golf club after impact. An absolute
resolver (feedback signal of 51,200 pulse/rev) and an incremental encoder (9000 pulse/rev) situated at the actuated and passive joints are utilized to measure the arm and club rotational angles, respectively. A one-dimensional force sensor (KYOWA LCN-A-500N) and a six-dimensional force sensor (NITTA IFS-67M25A50-I40) are adopted to obtain the reaction torque $N_r$ and reaction force $F_r$ from the club to the arm, respectively. A flexible solid beam made of aluminum is used to replace the shaft, and it is clamped at the grip. The natural frequencies and vibration mode shapes of the golf club are obtained by numerical calculation and experimental modal analysis. The photograph of the robot system is shown in Fig. 5. Table 1 gives the parameters of the robot system. The experimental control system is indicated schematically in Fig. 6. A personal computer is used to implement the impedance control program and its sampling rate is 1 kHz. By using the velocity control mode of motor driver, the DD motor is controlled by the velocity (voltage) reference from the D/A converter. Here, JR3 is a DSP-based signal receiver for the six-dimensional force sensor.

The obtainment of the reaction torque $N_r$ is shown in Fig. 7. Based on the figure, the reaction torque $N_r$ can be calculated by

$$N_r = -F_n b$$  \hspace{1cm} (36)

where $F_n$ is the force measured from the one-dimensional force sensor and $b$ is the distance between the force contact point of the sensor and the wrist joint of the robot.

It is noted that not only the force measured from the six-dimensional force sensor is needed to calculate the reaction force $F_r$ but also the inertia force of the sensor $f_s$ caused by the arm angular acceleration $\ddot{\alpha}$, should be considered because the sensor is regarded as a part of handgrip. The specific force analysis of the handgrip is shown in Fig. 8.

According to Fig. 8, the following equations are obtained:

$$\hat{F}_r = f_t + f_s$$  \hspace{1cm} (37)

$$f_s = m_s \ddot{\alpha} L_{1r}$$  \hspace{1cm} (38)

$$F_r = -\hat{F}_r$$  \hspace{1cm} (39)

where $m_s$ is the sensor mass; $\hat{F}_r$ is the reaction force from the arm to the club; and $f_s$ is the force obtained from the sensor, and its direction is perpendicular to the arm, as shown in Fig. 9. The force $f_s$ can be calculated by

$$f_s = -TX \sin(\beta) + TY \cos(\beta)$$  \hspace{1cm} (40)

where $TX$ and $TY$ are the forces measured from the six-dimensional force sensor, and they are perpendicular to each other.

Therefore, the reaction force $F_r$ from the club to the arm is obtained as

$$F_r = -m_s \ddot{\alpha} L_{1r} + TX \sin(\beta) - TY \cos(\beta)$$  \hspace{1cm} (41)

In Eq. (41), the arm angular acceleration $\ddot{\alpha}$ should be known in order to calculate the reaction force $F_r$. Here, a constant-coefficient Kalman filter is used to obtain the arm angular velocity to reject undesirable position measurement noise, and then $\ddot{\alpha}$ is acquired by the filtered velocity using the difference method.

Lampa [14] thought that a pause usually occurs at the moment when a golfer completes his backswing and is just about to begin his downswing, indicating that the angular velocities of the arm and club are equal to zero at the start of the downswing. Therefore, in this paper, it is assumed that the swing commences with $\dot{\alpha}=0$, $\dot{\beta}=0$ and also the bending of the shaft at the start of the downswing is ignored. The posture values of the arm and club at
the start of the downswing are taken with $\alpha=120$ deg, $\beta=-90$ deg, which were regarded as the general initial configuration for professional golfers in the work of Sprigings and Mackenzie [15]. The simulation and experiment are terminated when the club head hits the golf ball, and the ball is placed at the center of the width of golfer’s stance (the same golf ball position is shown in Figs. 7 and 8 of Ref. [16]), that is, the test result of up to impact is all that is of concern. The gravity effect is neglected because of the horizontal positioning of the direct drive motor. The golf swing robot is defined as $R$, and three golfers, labeled by $H1$, $H2$, and $H3$, own the same arm length as that of the robot but with different arm masses, 7 kg, 5 kg, and 3 kg, respectively. It has been noted that there are many kinds of torque input functions of the shoulder joint applied in the previous research work of golf swing, and here these functions are referred as $\tau_1$ employed to the shoulder Joint $O$. Jorgensen [7] thought that the shoulder input torque was constant during the swing. Milne and Davis [11] used a ramp as the torque function and Suzuki and Inooka [2] set the torque function as a trapezoid. Here, the trapezoid-shaped torques (Fig. 10) are employed at the shoulder joint for the golfers. The torques are linearly increased with the rise time of 0.12 s and then up to the corresponding maximum values, which are maintained 0.05 s, and finally are terminated at the time of 0.29 s. Here, the maximum torque values for $H1$, $H2$, and $H3$ are 25 N m, 20 N m, and 17 N m, respectively.

Figure 11 illustrates a simulation comparison of the swing motions of different-arm-mass golfers. It should be noted that the swing motions of $H1$, $H2$, and $H3$ plotted in Fig. 11 are generated by the model developed in Sec. 2. From Fig. 11, it is evident that the arm rotational motions of these different-arm-mass golfers are not the same and the club rotational motions of $H3$ are different from those of $H1$ and $H2$. However, we note that the club rotational motions of $H1$ are almost the same as those of $H2$ even if the input torques of shoulder joint for them are different. It clearly demonstrates that dissimilar torque profiles of shoulder joint can generate very similar looking club rotational motions for different-arm-mass golfers. Figures 12–14 show the results of the errors of the swing motions by the proposed golf swing robot to emulate different-arm-mass golfers. From Figs. 12(a), 12(c), 13(a), 13(c), 14(a), and 14(c), it can be seen that the motion errors of the arm of the robot are very small. As for the swing motions of the club, it is clear that no substantial differences are found between the robot and different-arm-mass golfers from Figs. 12(b), 12(d), 13(b), 13(d), 14(b), and 14(d). It is noteworthy to mention that the club swing motion differences between the robot and golfers are clearly larger than the arm swing motion differences. We note that there are two forces retarding the club during the downswing: one is the wrist retarding force due to the mechanical impedance of the wrist joint; the other is the air retarding force due to the high-speed rotational motion of the club. As for obtaining the club swing motions of different-arm-mass golfers in simulation, the air retarding force of the club was neglected due to the complex dynamical modeling and practical measurement difficulty for this air retarding force despite that it works in the experiment for the robot. Therefore, the club swing motion differences between the robot and golfers become relatively large as compared with the arm swing motion differences.

5 Conclusions

An impedance control method based on the velocity instruction was proposed to control a golf swing robot. By this method, the interference forces from the club to the arm were considered, and the influence of different human arms on the golf swing motion was also involved.

Simulation of the swing motions of the different-arm-mass golfers was carried out by a mathematical model of golf swing considering the shaft bending flexibility. This model was derived
Fig. 12 The errors in the swing motions of the 7 kg arm-mass golfer (H1): (a) error in arm rotational angle, (b) error in club rotational angle, (c) error in arm angular velocity, and (d) error in club angular velocity.

Fig. 13 The errors in the swing motions of the 5 kg arm-mass golfer (H2): (a) error in arm rotational angle, (b) error in club rotational angle, (c) error in arm angular velocity, and (d) error in club angular velocity.
by the Euler–Lagrange principle and assumed modes method. A prototype of golf swing robot consisting of one actuated joint and one passive joint was developed to verify the impedance control method. The simulational and experimental results showed that the robot with the impedance control method could emulate the swing motions of different-arm-mass golfers.

References


