A new golf-swing robot model emulating golfer's skill

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Abstract

Conventional golf-swing robots are generally used to evaluate the performance of golf clubs and balls. Most of the robots have two or three joints with completely interrelated motion. This interrelation only allows the user of the robot to specify the initial posture and swing velocity, and therefore the subtle adjustments in swing motion that advanced golfers make according to the characteristics of individual golf clubs are not possible. Consequently, golf-swing robots cannot accurately emulate the performance of advanced golfers, which is a problem for the evaluation of golf club performance. In this study, a new golf-swing robot that can adjust its motion to both a specified value of swing velocity and the specific characteristics of individual golf clubs was analytically investigated. This robot utilizes the dynamic interference force produced by swing motion and shaft vibration like advanced golfers. Thus, this new robot can emulate the performance of advanced golfers and can therefore be used for accurate evaluation of golf clubs.

Keywords: golf-swing robot, golfer's skill, interference drive, release of wrist, shaft elasticity, torque planning

Nomenclature

M_1, M_2 Mass of the arm and grip, respectively
M_p, R_p Mass and radius of the club head, respectively
L_1, L_2 Length of the arm and grip, respectively
L_3 Length of the shaft
I_1 Moment of inertia of the arm around the shoulder joint
I_2 Moment of inertia of the grip around the wrist joint
I_3 Moment of inertia of the shaft around the grip
I_p Moment of inertia of the club head
E, I Young's modulus and second moment of area of the shaft, respectively
P_3, A_3 Density and cross section of the shaft, respectively
λ_{sm} Efficiency index of golf-swing motion

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Introduction

The dynamics of golf-swing motion have been studied for many years in an effort to improve the performance of golf clubs and to optimize the swing motions of golf players (e.g. Budney & Bellow, 1982; Jorgensen, 1970; Lampsa, 1975; Milburn, 1982; Neal & Wilson, 1985). Most of these analytical studies have focused on the double pendulum model of golf-swing motion and have taken into consideration only the shoulder and wrist joint movements of a golfer, while regarding the golfer's arms and golf club shaft as rigid rods. However, the vibration of the club shaft during the swing is also closely related to the golfer's motion, and the displacement of shaft vibration at impact greatly affects the trajectory of a hit ball. Therefore, advanced golfers pay a lot of attention to the flexural and torsional rigidity of the shaft. A few recent studies have considered shaft vibration during the swing in order to optimize the design of a club shaft (Iwatsubo *et al.*, 1990) and to examine the relationship between the golfer's motion and shaft deformation during the swing (Brylawsky, 1994; Butler & Winfield, 1994; Milne & Davis, 1992). However, the golfer's skill in wrist turn and the accompanying interference drive of the golfer's joints have not been examined in these studies.

In the evaluation of golf club performance for the development of new golf clubs, professional golfers usually hit a ball with a test club, and the distance of the hit ball is measured directly. This evaluation technique requires many trials because weather conditions and physical conditions of the golfer at the time of testing greatly affect the distance. The measurements are therefore statistically analysed, and this process requires considerable time and resources. For these reasons, it is hoped that golf-swing robots can be used instead of professional golfers for the evaluation of golf club performance.

Many of the golf-swing robots currently on the market have only two or three joints, which are connected by gears and belts with completely interrelated motion. In addition, the joints are always controlled during the swing according to the specified head velocity. Therefore, although the user can adjust the initial posture and swing velocity of the robot, the swing motion cannot be adjusted according to the dynamic characteristics of individual golf clubs. Consequently, the results obtained by using robots to evaluate golf club performance are frequently different from those obtained by the advanced golfers. Ming *et al.* (1995) applied the analytical results of hammer-swing motion to the down swing in order to examine the interference drive of a wrist joint using centrifugal force, Corioli's force and gravity. However, the dynamic interference force due to shaft vibration, which may produce a comparatively large amount of interference and greatly affect the trajectory of a hit ball, was not considered.

In the present study, a golf-swing robot that can emulate the performance of advanced golfers by effectively utilizing the dynamic interference force produced by shaft vibration was analytically investigated. In this investigation, it was assumed that a skilful golfer can achieve fast head speed with less power by utilizing the dynamic interference force. The robot used in this study allows the swing motion to be planned according to the specific characteristics of a given golf club, such as the moment of inertia with respect to the grip of the club and the flexural rigidity of the shaft. By using a simplified dynamic model, we also investigated whether the torque-input at the shoulder can be determined when the head velocity at impact is specified for different types of clubs. Finally, the reliability of swing motion and the contribution of this new golf-swing robot to the development of new golf clubs were evaluated.

Modelling

Dynamic model

As shown in Fig. 1, the entire golf-swing motion is assumed to occur in one plane. In fixed coordinate system O–XYZ, the swing plane is inclined at an angle α to the X–Z plane. Usually, the value of α differs according to the golfer's physique and the club number. In the present study, the value of α was set at $\pi/3$ rad. The arm, club grip, and grip-holding fingers are regarded as independent rigid rods. Hereafter, the grip refers to the club grip, including the grip-holding fingers, and impact means that a club head hits a ball. The shoulder

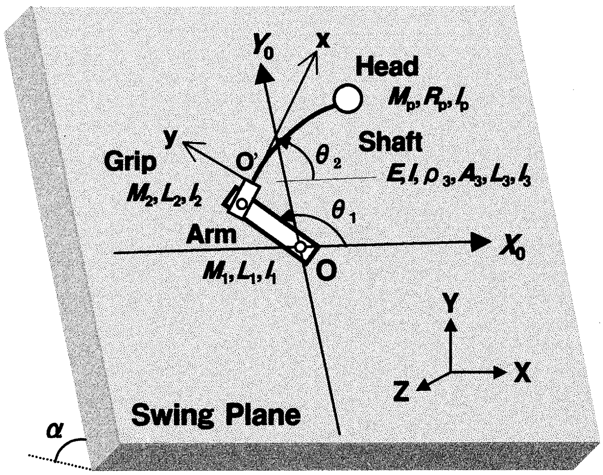

Figure 1 Dynamic model of a golf-swing robot.

joint rotates around the origin O of the coordinate system fixed on the swing plane. The rotational coordinate system o′–*xy* is set using the end of the grip as the origin. The displacement of the shaft vibration is represented as $y(x, t)$. The angle of the arm with the X_0 axis is θ_1 and the angle of the grip with the X_0 axis is θ_2.

Equations of motion

The equations of motion can be derived by applying Hamilton's principle to the dynamic model. Here, the friction of each section is ignored. The centre of gravity of the club head is assumed to be on the central axis of the shaft; therefore, only the flexural vibration of the shaft on the swing plane is considered. If the torque-inputs at the shoulder and wrist are expressed by Q_1 and Q_2, respectively, the equations of motion are given as balancing equations of moment at the shoulder (1) and at the wrist (2), and an equation of flexural vibration of the shaft (3).

$$\begin{aligned} &C_1\ddot{\theta}_1 + (C_2L_C + D_1L_S)\ddot{\theta}_2 \\ &\quad + (C_2L_S - D_1L_C)\dot{\theta}_2^2 + 2\dot{D}_1L_S\dot{\theta}_2 \\ &\quad + \ddot{D}_1L_C + G_1\cos\theta_1 - Q_1 = 0, \end{aligned} \tag{1}$$

$$\begin{aligned} &(C_2L_C + D_1L_S)\ddot{\theta}_1 + (C_3 + D_2)\ddot{\theta}_2 \\ &\quad - (C_2L_S - D_1L_C)\dot{\theta}_1^2 + 2D_3\dot{\theta}_2 + D_4 \\ &\quad + G_2\cos\theta_2 - S_1\sin\theta_2 - Q_1 = 0, \end{aligned} \tag{2}$$

$$\begin{aligned} &\rho_3A_3L_C\ddot{\theta}_1 + \rho_3A_3(L_2 + x)\ddot{\theta}_2 - \rho_3A_3L_S\dot{\theta}_1^2 \\ &\quad - \rho_3A_3y\dot{\theta}_2^2 + \rho_3A_3\ddot{y} + EIy'''' = 0. \end{aligned} \tag{3}$$

The boundary conditions at the head of the golf club are

$$\begin{aligned} &M_PL_C\ddot{\theta}_1 + M_PL_R\ddot{\theta}_2 - M_PL_S\dot{\theta}_1^2 - M_Py_P\dot{\theta}_2^2 \\ &\quad + M_P\ddot{y} - EIy'''_{L_3} = 0, \end{aligned} \tag{4}$$

$$\begin{aligned} &M_PR_PL_C\ddot{\theta}_1 + (M_PR_PL_R + I_P)\ddot{\theta}_2 \\ &\quad - M_PR_PL_S\dot{\theta}_1^2 - M_PR_Py_P\dot{\theta}_2^2 \\ &\quad + M_PR_P\ddot{y}_p + I_P\ddot{y}'_{L_3} + EIy''_{L_3} = 0. \end{aligned} \tag{5}$$

Here, $\ddot{\theta} \equiv \mathrm{d}^2\theta/\mathrm{d}t^2$, $\ddot{y}' \equiv \partial^3 y/\partial t^2\partial x$, and so on. The symbols used in the equations are defined as

$$\begin{aligned} &L_C = L_1\cos(\theta_1 - \theta_2),\ L_S = L_1\sin(\theta_1 - \theta_2), \\ &L_R = L_2 + L_3 + R_P, \\ &y_{L_3} = y(L_3, t),\ M_3 = \rho_3A_3L_3, \\ &C_1 = I_1 + (M_2 + M_3 + M_P)L_1^2, \\ &C_2 = \frac{1}{2}M_2L_2 + M_3\left(L_2 + \frac{1}{2}L_3\right) + M_PL_R, \\ &C_3 = I_2 + I_3 + I_P + M_3L_2(L_2 + L_3) + M_PL_R^2, \\ &D_1 = \rho_3A_3\int_0^{L_3} y\ \mathrm{d}x + M_Py_P, \\ &D_2 = \rho_3A_3\int_0^{L_3} y^2\ \mathrm{d}x + M_Py_P^2, \\ &D_3 = \rho_3A_3\int_0^{L_3} y\dot{y}\ \mathrm{d}x + M_Py_P\dot{y}_P, \\ &D_4 = \rho_3A_3\int_0^{L_3} (L_2 + x)\ddot{y}\ \mathrm{d}x + M_PL_R\ddot{y}_P + I_P\ddot{y}'_{L_3}, \\ &G_1 = \left(\frac{1}{2}M_1 + M_2 + M_3 + M_P\right)L_1g\sin\alpha, \\ &G_2 = \left(\frac{1}{2}M_2L_2 + M_3L_2 + M_PL_R + \frac{1}{2}\rho_3A_3L_3^2\right) \\ &\qquad \times g\sin\alpha, \\ &S_1 = \left(\rho_3A_3\int_0^{L_3} y\ \mathrm{d}x + M_Py_P\right)g\sin\alpha. \end{aligned}$$

Using the eigen function of a cantilever $\varphi_i(x)$ that has a mass at the tip with no damping and the time function $q_i(t)$, the displacement of the shaft vibration can be approximated as

$$y(x,t) = \sum_{i=1}^{\infty} \varphi_i(x) q_i(t). \quad (6)$$

The expression describing orthogonal conditions between modes with Kronecker's symbol is

$$\rho_3 A_3 \int_0^{L_3} \varphi_i(x)\varphi_j(x)\,\mathrm{d}x + M_\mathrm{p}\Big[\varphi_i(L_3)\varphi_j(L_3) + R_\mathrm{p}\Big\{\varphi_i(L_3)\varphi_j'(L_3) + \varphi_i'(L_3)\varphi_j(L_3)\Big\}\Big] + \Big(M_\mathrm{p}R_\mathrm{p}^2 + I_\mathrm{p}\Big)\varphi_i'(L_3)\varphi_j'(L_3) = \delta_{ij} \times M_3. \quad (7)$$

By applying this expression to equations (1)–(6) and by approximating the displacement of shaft vibration to the secondary mode, the equation of motion becomes

$$\mathbf{J}\ddot{\mathbf{v}} + \mathbf{h} + \mathbf{g} = \mathbf{pu},$$

where

$$\mathbf{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} \\ J_{12} & J_{22} & J_{23} & J_{24} \\ J_{13} & J_{23} & M_3 & 0 \\ J_{14} & J_{24} & 0 & M_3 \end{bmatrix}, \quad \mathbf{v} = [\theta_1\ \theta_2\ q_1\ q_2]^T,$$

$$\mathbf{h} = [h_1\ h_2\ h_3\ h_4]^T, \quad \mathbf{g} = [g_1\ g_2\ g_3\ g_4]^T,$$

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T, \quad \mathbf{u} = [Q_1\ Q_2]^T.$$

where **J** is the inertia matrix, **h** is the non-linear force vector, **g** is the gravity vector, and **u** is the input vector.

In order to simplify the calculation of swing motion, all the values of L_S concerning the non-linear force are ignored. Using the derived equations of motion, the robotic swing motion is analysed numerically using the fourth-degree Runge–Kutta method at intervals of 1.0×10^{-8} s.

Motion setting

Posture at start and impact

In general, golfers twist the upper half of their bodies around the backbone during the swing motion. However, the dynamic model requires that these motions are substituted by rotation of the shoulder joint. Therefore, θ_1 is initially set at $\pi/2$ rad and θ_2 at 0. Because the central axes of the arm and grip are expected to point downward along the Y_0 axis at impact, both θ_1 and θ_2 are set at $3\pi/2$ rad.

Golfer's skill

In order to investigate the possibility of a robot being able to emulate the performance of advanced golfers, it was assumed, by referring to guide books on golf and to the opinions of professional golfers, that the golfer is able to: (a) adjust the swing motion to the characteristics of the golf club; (b) effectively utilize dynamic interference force; (c) effectively utilize elasticity of the club shaft; (d) achieve fast head speed with less power; (e) release the wrist freely.

Many guide books on golf state that free release of the wrist is very important for making progress and for maximizing the distance of a hit ball. Since advanced golfers pay much attention to the rigidity of a club shaft, golfer's skill was investigated by examining the relationship between shaft vibration and release point of the wrist. The release point is called 'uncock' in the golf terms and is realized by setting $Q_2 = 0$ immediately in the numerical simulation of the swing motion.

In Fig. 2, the numbers of release points from one to four are based on shaft vibration expressed as displacement at the tip (y_{L3}) during swing motion.

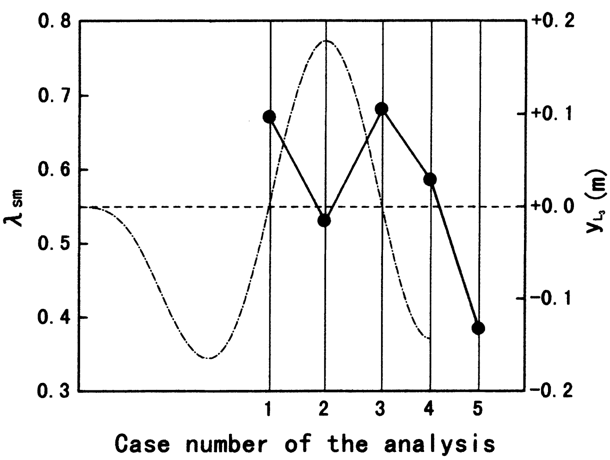

Figure 2 Comparison of λ_{sm} for various release points of the wrist.

Number five represents swing motion without release of the wrist. In order to examine the conditions of advanced swing motion, the efficiency index of swing motion (λ_{sm}) represented by the ratio of kinetic energy of a club head, when the arm and grip become straight, to the work produced at the shoulder joint was analysed in a horizontal plane. By representing kinetic energy of a club head at impact as E_P, the expression describing λ_{sm} is

$$\lambda_{sm} = \frac{E_P}{\int_{\theta_1} Q_1(t)\ d\theta_1}. \quad (8)$$

Work at the shoulder was set to 19.7 J in the analyses. Because the posture at start and at impact during golf swing motion does not change, λ_{sm} shows the same tendency as λ_{sm} in a horizontal plane.

It was found that the value of λ_{sm} in releases number one and three is larger than those in other cases. At these release points, elastic strain energy of the shaft decreases after the release of the wrist. The kinetic energy of the system inversely increases as much. In addition, λ_{sm} is reduced to a minimum when the wrist joint is not released throughout the swing motion. These results suggest that the effective transformation of strain energy into kinetic energy accelerates rotation of the wrist joint at the release and that the interference drive of the wrist due to utilization of shaft elasticity leads to fast head speed.

Consequently, adjusting the release of the wrist to the zero-cross point of shaft vibration is very important for improving the golfer's skill.

Release of wrist joint

As shown in Fig. 3, the wrist joint of the robot is fixed at the beginning of the swing and is released during the swing motion. In the robotic golf swing, the timing of the release of the wrist joint was varied and the subsequent head velocity at impact analysed. The head velocity refers to the velocity at the centre of gravity of the club head with respect to the fixed co-ordinate system O–*XYZ*.

The basic timing of the release was set to 140 ms after the start of the swing, when the displacement of shaft vibration zero-crosses the positive direction for the first time as explained in the section on golfer's skill. Two more release intervals were set to 20 ms before and after the basic release time. The maximum torque-input at the shoulder joint was set to 100 N · m for 50 ms. The acceleration time from the start of the swing was set to 116 ms. Figure 4 shows comparative values of the head

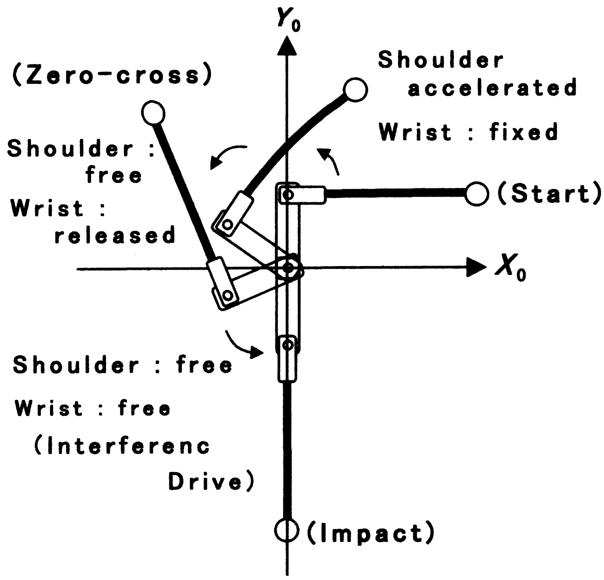

Figure 3 Institution of golf-swing motion.

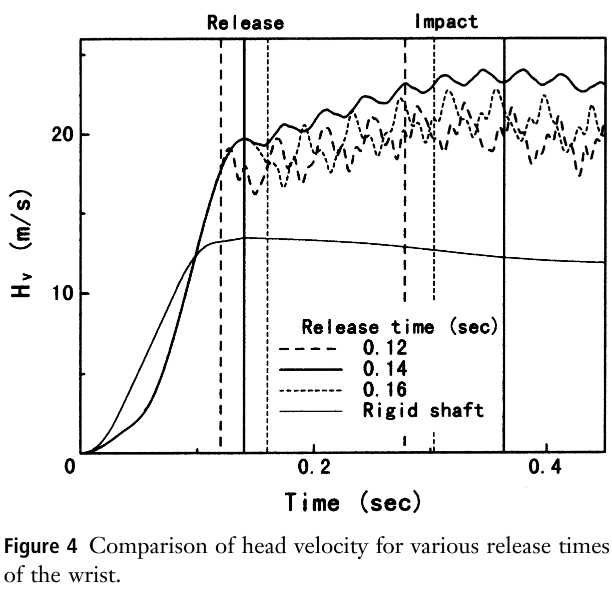

Figure 4 Comparison of head velocity for various release times of the wrist.

velocity (H_V) for various release times of the wrist joint. Releasing the wrist joint at the positive zero-cross point of the shaft vibration maximized H_V. The posture at impact satisfied the conditions described in the section on posture at start and impact only when the release time was 140 ms after the start of the swing. With respect to other release times, the impact time refers to the time when the centre of the club head passes the Y_0 axis. The H_V curves show that even a difference of only 20 ms in the release time greatly affects H_V.

H_V curves were also obtained for the case of a rigid shaft, and the results are shown in Fig. 4. The same settings as those described above were used in this analysis. The thin solid line in Fig. 4 shows the H_V of a club with a rigid shaft under the conditions of the same torque-input at the shoulder as that in the case of a flexible shaft. The results of this analysis show that the same amount of torque at the shoulder accelerates the rotation of the shoulder joint only slightly in the case of a rigid shaft because there is no elasticity available to reduce the torque. Consequently, H_V becomes very slow. In this analysis, the arm goes ahead of the shaft during the swing (i.e. θ_1 is always larger than θ_2). Thus, in order to correctly adjust the posture at impact, the shoulder joint would need to decelerate before impact, as was also described in another report (Ming *et al.* 1995). However, such an action does not occur when golfers use maximum power for their swing motion. These results indicate that shaft vibration is an important factor to consider when studying golf-swing robots. The condition of wrist release should reduce the differences when evaluating golf club performance using advanced golfers and golf-swing robots.

The shaft vibration expressed as displacement greatly affects the trajectory of a hit ball because it determines the face-angle of the club head at impact. This can affect the reliability of the evaluation of golf clubs using conventional robots. In this regard, the proposed golf-swing robot, the performance of which is thought to be similar to that of an advanced golfer, is different from the conventional type of robot. If this new robot can accurately emulate the performance of an advanced golfer, then the trajectory of a ball hit by this robot will differ from that hit by the conventional type of robot. For this purpose, the displacements due to shaft vibration at impact for the new and conventional robot were compared. The conventional type of robot has servo motors and reducers at each joint. It is assumed that this robot correctly maintains path planning without being affected by dynamic interference because the reduction ratio at each joint is large. The paths of θ_1 and θ_2 are planned as linear expressions. H_V at impact is set to 35 m s^{-1} and the value of the flexural rigidity of the shaft in the swing plane (*EI*) varies from 70 to 110 N m^2 at intervals of 10 N m^2. As shown in Fig. 5, the displacement at impact in the case of the new robot changes independently of the value of *EI*. However, in the case of the conventional type of robot, displacement is almost constant because the wrist joint requires a large amount of torque-input at the start of the rotation of the wrist. Consequently, the trajectories of balls hit by the new robot and the conventional type of robot will be different even if the value of H_V at impact is the same. This seems to be the reason for the differences in the evaluation of the golf club performance between an advanced golfer and the robot. Therefore, since the wrist joint should be released or fixed, the wrist joint does not need an actuator but only a brake mechanism or stopper.

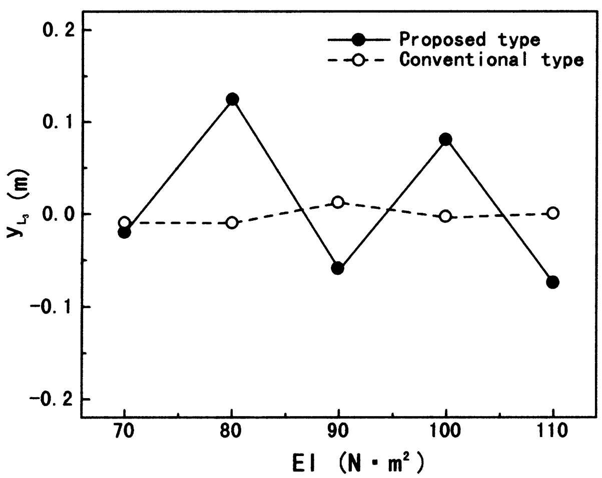

Figure 5 Comparison of y_{L3} between two types of the robot.

Torque planning

Torque function

Golf-swing robots are usually commanded to maintain a specified head velocity at impact. However, the proposed robot is driven only by the dynamic interference force after acceleration of the shoulder. Consequently, if many torque function variables need to be considered, torque planning is difficult. Thus, the torque function was set as a trapezoid (Fig. 6). The swing motion was adjusted according to the moment inertia with respect to the grip of the club and flexural rigidity of the shaft by adjusting the height (T_{max}) and the bottom length (T_u) of the trapezoid. T_u determines the acceleration time of the shoulder joint and T_{max} corresponds to the maximum muscular strength of the shoulder. The top length (T_e) is fixed at 50 ms because the duration of the human golf swing is comparatively short and does not differ greatly among individuals.

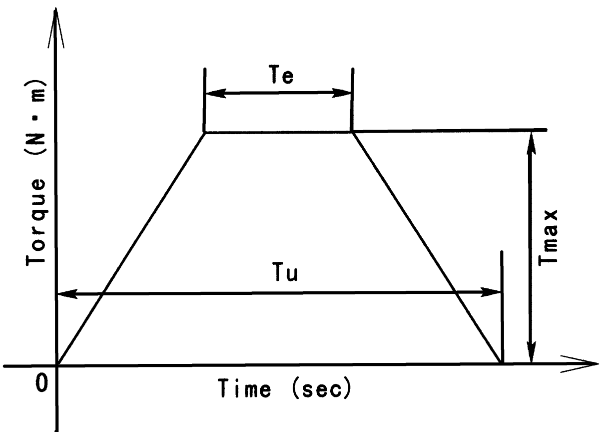

Figure 6 Torque function of the shoulder joint.

Determination of torque function parameters

Table 1 shows the specifications of the dynamic model. The golf club has a spherical head of 5.0×10^{-2} m diameter and a 1.0-m-long shaft that has uniform flexural rigidity along its entire length. EI is set to a range of 70–110 $N \cdot m^2$. The moment of inertia of the club around the grip (I_c) is set to a range of 2.27×10^{-1} to 2.78×10^{-1} kg m^2. For setting the I_c range, the mass is assumed to be 7.5×10^{-2} to 1.2×10^{-1} kg for the shaft and 2.0×10^{-1} to 2.5×10^{-1} kg for the head. When a head velocity is specified using the above conditions, the torque function is determined as explained below.

Fig. 7 shows the relationship between H_V and T_{max} for three types of clubs. For this analysis, I_c was fixed at 2.27×10^{-1} kg m^2 and T_u was adjusted accurately to satisfy the conditions of motion. The relationship between H_V and T_{max} is approximately linear for all of the clubs. Using these relationships, T_{max} can be defined for a specified head velocity using EI and I_c of the club. It was found that the greater the EI value is, the higher are the ranges of H_V and T_{max}. This confirms the popular view that a stiff shaft is suitable for a muscular golfer who attains a fast head velocity.

Next, the relationship between the rotation of joints and the value of T_u was examined. For this analysis, T_{max} was fixed at 100 $N \cdot m$ and I_c at 2.27×10^{-1} kg m^2. Figure 8 shows the relationship between T_u and θ_{im} for three types of clubs. Here θ_{im} is the joint angle when θ_1 and θ_2 become equal during a swing. The horizontal dashed line in the figure indicates the downward direction of the Y_0 axis. At impact, θ_{im} must satisfy this angle. This result shows that precise adjustment of T_u is very important to satisfy the conditions of motion because T_u greatly affects θ_{im}.

Table 1 Specifications of the dynamic model

Parameter	Arm	Grip	Shaft	Head
L_1, L_2, L_3, R_P (m)	0.4	0.1	1.0	2.5×10^{-2}
M_1, M_2, M_3, M_P (kg)	5.0	1.0	$7.5 \sim 12 \times 10^{-2}$	$2.0 \sim 2.5 \times 10^{-1}$
I_1, I_2, I_3, I_P (kg·m^2)	2.7×10^{-1}	3.3×10^{-3}	2.5×10^{-2}	7.5×10^{-6}

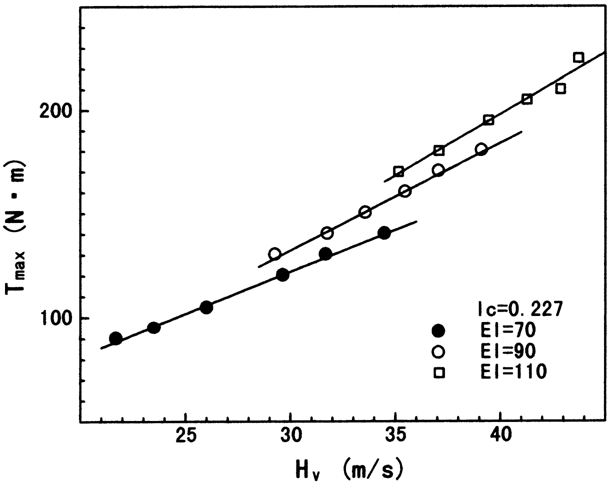

Figure 7 Relationship between H_V and T_{max} for three types of clubs ($EI = 70, 90, 110, I_c = 2.27 \times 10^{-1}$).

The relationship between H_V and T_u also became approximately linear. However, because the inclination of the plot is very small, changing the specified head velocity will not greatly affect T_u.

Algorithm

According to the section on the determination of torque function parameters T_{max} and T_u can be defined by linear approximation. However, a relationship between T_{max} and T_u has yet to be established. Therefore, an approximate value of T_u was tentatively determined. By repeating the calculation at regular intervals using this value of T_u as the middle value, the value of T_u that satisfies the conditions of posture at impact was finally determined. This method is effective for adjusting the posture and is expected to reduce off-line calculation costs, because the inclination of any plot of the relationship between H_V and T_u becomes small. Thus, the associated algorithm is determined as follows.

1. Two linear expressions for T_u and T_{max} are selected from the *EI* and I_c of a given golf club.
2. A specified value of H_V is substituted into these linear expressions in order to determine T_{max} and to calculate the tentative value of T_u.
3. The calculation of swing motion is repeated five times at 1.0-ms intervals using the tentative value of T_u for the middle calculation.
4. The final T_u value is determined to maintain the error of θ_{im} to within $\pm 3.0 \times 10^{-2}$ rad.

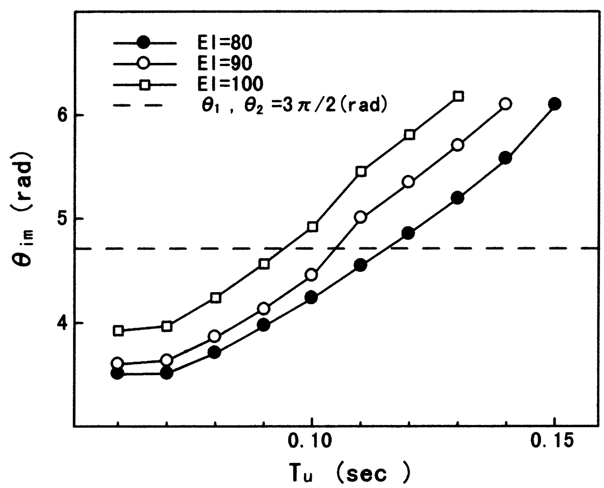

Figure 8 Relationship between T_u and θ_{im} for three types of clubs ($EI = 80, 90, 100, T_{max} = 100, I_c = 2.27 \times 10^{-1}$).

Simulation of robotic swing motion

Reliability of swing motions

The algorithm shown in the last section gives priority to the setting of θ_{im} and thus an error may occur in the specified head velocity. Therefore, the reliability of the evaluation with regard to H_V at impact must be examined. In this investigation, *EI* was fixed at 100 N m^2 and I_c was fixed at 2.27×10^{-1} kg m^2. The specified head velocity at impact was represented as H_{VS}, which was varied at intervals of 1.0 m/s in the range of 33 to 42 m/s. The expression below represents the value of $\mathbf{e}_{HV}$ (%), which indicates the error factor between H_V and H_{VS} at impact.

$$\mathbf{e}_{HV} = 100 \times (H_V - H_{VS})/H_{VS}. \quad (9)$$

Figure 9 shows the results of this analysis. Because the error due to H_{VS} is always within ±3.0%, highly reliable evaluations can be expected. If the identification of specific characteristics of individ-

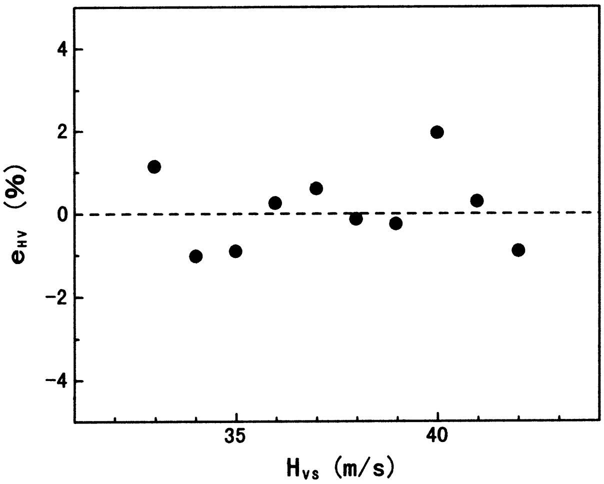

Figure 9 Error factor between head velocity and specified head velocity at impact ($EI = 100$, $I_c = 2.27 \times 10^{-1}$).

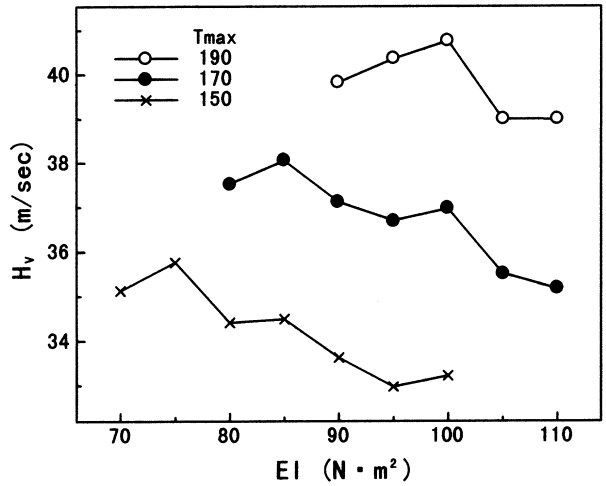

Figure 10 Relationship between H_V and EI ($I_{max} = 150$, 170, 190; $I_c = 2.27 \times 10^{-1}$)

ual golf clubs can be automated, the autonomous golf-swing motion can be adjusted correspondingly.

Application to the development of new golf clubs

In the evaluation of golf club performance, the performance indicator of test clubs is the distance of a ball's flight when hit by robots and golfers. The conventional type of robot can examine only the relationship between the distance of a hit ball and H_{VS} commanded by the operator with a given golf club. Therefore, the robot hits a ball at almost the same H_{VS} with any golf club. On the other hand, advanced golfers regard the harmony between their swing motion and dynamic characteristics of a golf club to be important. Thus the H_V at impact becomes different by changing test clubs in their swing motion. The proposed robot can determine the optimum design of a golf club for the assumed physical strength of a golfer by emulating the golfer's actual skill.

Figure 10 shows the simulation results of head velocity at impact during robotic swing motion for various degrees of flexural rigidity of a shaft when maximum muscular strength at the shoulder is set to 150, 170 and 190 N · m. It was found that H_V has a maximum value when EI is set to 75, 85 or 100 N m^2. Consequently, this new type of robot can determine the most suitable shaft for a golfer.

Conclusions

The following points summarize the results of an investigation of a golf-swing robot capable of a adjusting the swing motion according to the characteristics of any given golf club and which can emulate the performance of an advanced golfer when evaluating the performance of a specific golf club.

In this model, releasing the wrist joint at the positive zero-cross point of the displacement due to shaft vibration maximizes the head velocity. This motion setting is expected to reduce the differences between the evaluations of golf club performance by an advanced golfer and robot.

In the usual evaluation technique, once the torque function of the shoulder joint is set as a trapezoid, the height and the bottom length can be determined easily by off-line calculations. This trapezoid enables the swing motion to be easily adjusted to a specified head velocity according to the characteristics of the club. Although the algorithm for torque planning gives priority to the setting of posture at impact, the error in head velocity does not exceed ±3%. Thus, highly reliable evaluation of the performance of a golf club can be expected.

The proposed robot can be used not only to evaluate the performance of a golf club using conventional technique with a specified head velocity at impact but also to determine the most suitable characteristics of a golf club for an assumed golfer's swing motion by adjusting the trapezoid.

Future research will focus on the verification of these results through experiments. It is expected that the dynamic model developed will be further enhanced and that the effects of twisting motion of the wrist joint and torsional vibration of the shaft will be clarified.

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