Multiple modulation torque planning for a new golf-swing robot with a skilful wrist turn

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Abstract

A new golf-swing robot that included a feed-forward controller in the shoulder joint and a passive wrist joint was suggested in previous studies to more closely model a skilful golfer. In this study, multiple modulation torque planning for a new golf-swing robot that is capable of modelling a skilful golfer's swing with a delayed wrist turn was analytically examined. The two-step modulation torque included the effects of whole-body motion on shoulder acceleration, which improved the efficiency index of the swing motion and the club head speed at impact with a correctly timed wrist turn. In addition, it was demonstrated that the optimum moment of inertia and optimum design of club shaft rigidity for several types of golfers could be determined by torque planning in a virtual performance test.

Keywords: wrist turn, efficiency index, multiple modulation torque, optimum design

Introduction

Performance tests of new golf club products are typically conducted by measuring the drives of balls hit by skilful golfers on a test course. This technique requires many trials and considerable time, because only statistical results calculated from raw data that include the effects of weather changes and the tester's physical condition are reliable. Therefore, it is advantageous to employ a golf-swing robot, in order to shorten the test time and improve the reliability over tests involving skilful golfers.

Golf swing robots currently used in performance tests can repeatedly swing a test club according to the motion trajectory or impact speed directed by an operator. These robots are appropriate for club shaft, club head, and ball endurance tests, or for measuring the coefficient of restitution between the head and the ball. For example, the actuator of the robot developed by Miyamae (1998) is controlled according to the target path of the joint movement by a feedback controller, which is selected using off-line calculations. For this reason, the robot is unable to perform a smooth swing motion because of the controller compensation, and cannot naturally respond to the properties of each test club like a skilful golfer. As a result, the performance evaluation conducted by a skilful golfer and a robot are sometimes quite different. However, if the robot could naturally adjust itself to the dynamic properties of the club, performance test reliability would be greatly improved.

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In previous studies, Suzuki & Inooka (1998, 1999) suggested a new golf-swing robot that included a feed-forward controller in the shoulder joint and a passive wrist joint in order to more closely model a skilful golfer. This robot's swinging motion was based on the skill analysis of a golfer from the viewpoint of efficiency. The passive joint was naturally fixed or released during the down swing by changing the interaction between the joints. It was found that this robot could adequately match a skilful golfer's smooth and efficient movement by utilizing shaft elasticity. Ming *et al*. (1995, 1999) also developed a robot model that had a passive wrist joint. However, this robot was controlled by a feedback controller, so the robot could not naturally respond to the dynamic properties of the test club to utilize shaft elasticity. The vibration of the club shaft during the down swing seems to be closely related to the golfer's motion, and the deformation of the shaft at the instant of the impact greatly affects the trajectory of the hit ball. Therefore, skilful golfers pay considerable attention to flexural and torsional rigidity of the shaft.

Some recent studies have focused on shaft vibration during the swing. In order to optimize the golf club design, Iwatsubo *et al*. (1990, 1998) and Whitaker (1998) numerically analyzed the shaft deformation using a segmental model. Brylawsky (1994), Butler & Winfield (1994) and Milne & Davis (1992) examined the relationship between a golfer's motion and shaft deformation. These studies, however, did not examine the relationship between a golfer's skill and shaft vibration. The present author's previous study (Suzuki, 2003) analytically and experimentally confirmed that a skilful golfer could drive a ball a long distance by adopting an efficient motion that exploits shaft elasticity and the dynamic interaction between the joints.

This study considers the effect of whole-body motion in order to carry out a more skilful and efficient robotic swing motion. The input torque generation consisted of the weight shift, torso twist and shoulder rotation. It is generally known that skilful golfers can achieve a long drive by initiating the swing motion from the lower half of their body and by delaying their wrist release. Although Springs & Mackenzie (2002) analytically investigated delayed wrist release, an impractical resistive torque was used at the wrist to delay its turn and the deformation of the shaft was ignored. This study analytically demonstrates that the robotic swing's efficiency improved by adding a naturally delayed wrist turn to the torque function. The study also demonstrates that a new golf-swing robot could be employed to determine the optimum shaft rigidity for different types of golfers.

Features of the robot model

Two-dimensional analytical model

The dynamic model for the analysis of the robot control was simplified, as shown in Fig. 1a. The swing motion was assumed to occur in one plane. The tilt

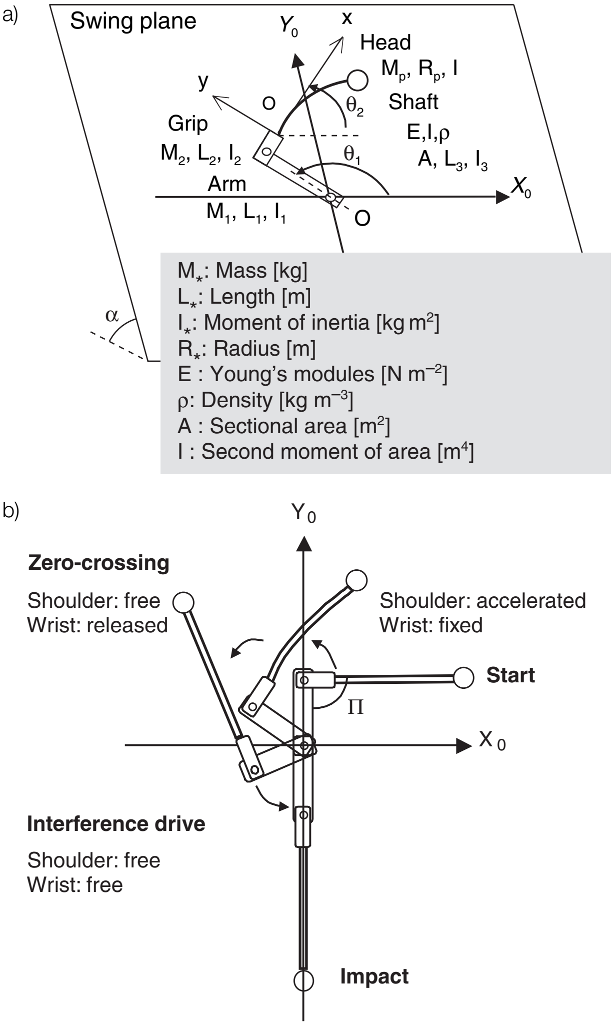


Figure 1 (a) Dynamic model of the golf-swing robot (b) Motion setting of the robotic golf swing.

angle of the swing plane α was set at 60 degrees for the driver shot. In this study, only the rotations of the left shoulder and wrist joints were considered without supination of the forearm. Therefore, the shaft flex was examined only for the in-plane bending vibration using a continuous cantilever beam model. The details of the dynamic model are shown in Table 1. The numerical solution for the robotic swing motion was approximated using the fourth-degree Runge-Kutta method at intervals of 1.0×10^{-8} s.

Control of the wrist

The analytical and experimental results of the previous study (Suzuki, 2003) indicated that a wrist release at the zero-crossing point of the shaft vibration displacement maximized the head speed at impact without an active rotational torque at the wrist. The results also suggested that an advanced golfer had the skill to effectively convert the shaft's elastic strain energy into kinetic energy of the club head. In order for a robot swing to take advantage of this technique, the robot should release the wrist when the displacement of the shaft vibration at the tip zero-crosses in the positive direction for the first time after the start of the swing. At the start of the down swing, the wrist is fixed by geometric boundary conditions. Thereafter, the wrist motion is passive.

Motion setting

The shoulder is initially accelerated by the feed-forward torque, and becomes free after the acceleration is complete. At the start of the swing, θ_1 and the angle between the centre axes of the arm and the grip are set at $\pi/2$ radians. At impact, the centre axes of the arm and the grip should simultaneously point downward along the Y_0 axis, as shown in Fig. 1b. Therefore, the feed-forward torque should maintain the posture at impact, because both joints become free in the latter half of the down swing.

Table 1 Specifications of dynamic model

	Arm	Grip	Shaft	Head
Length (m)	4.0×10^{-1}	1.0×10^{-1}	1.0	5.0×10^{-2}
Weight (kg)	5.0	1.0	7.5×10^{-2}	2.0×10^{-1}
Moment of inertia (kg m^2)	2.7×10^{-2}	3.3×10^{-3}	2.5×10^{-2}	7.5×10^{-7}

Feed-forward torque generation

Acceleration by whole-body motion

In the previous study (Suzuki, 2004) the feed-forward torque at the shoulder joint of the robot was planned as a triangular torque when the effect of the whole-body motion of a golfer is considered. The triangular torque function demonstrated that it could achieve a more efficient swing motion and a delayed wrist turn like a skilful golfer more effectively than the previously implemented trapezoidal function. However, the maximum value and the input time were highly dependent upon the dynamic properties of the golf club, such as the shaft stiffness. Therefore, several types of swing motion could not be freely planned in the virtual performance test of golf clubs by simply modifying these parameters. In this study, the torque function was reconsidered to attempt to improve the planning freedom and to express additional golfer characteristics. It is generally supposed that any advanced sport player utilizes the large work of the large muscles of the lower half of the body for generating the large acceleration of motion. Therefore, this function includes the effect of weight shift and torso twist of a golfer on the acceleration of the shoulder, as shown in Fig. 2a. Fig. 2b shows three variations of torque timing and their effects on the torque function when the maximum values and the whole input time were held constant. In function 1, all acceleration torque starts at the same time. In function 2, the subsequent acceleration is shifted by 50% of each input time. The acceleration is shifted by 75% in function 3. These patterns of torque input were used to analyze the golf club's maximum moment of inertia that could maintain the posture at impact. As shown in Fig. 3, function 3 is capable of rotating a golf club that had the largest moment of inertia around the grip. Therefore, function 3 is most suitable for modelling a skilful swing motion, because a heavier club head produces a longer drive under the same head speed.

Multiple modulation torque

For easy torque function generating, the input pattern of function 3 was modified into the multiple

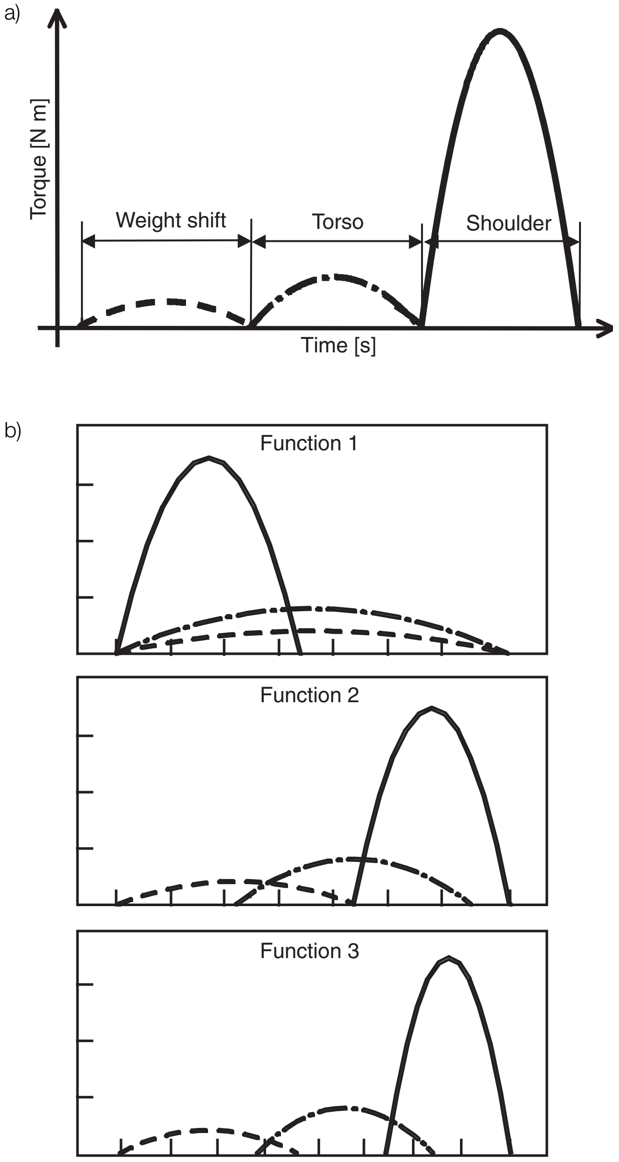


Figure 2 (a) Ingredients of the shoulder acceleration
(b) Composition of the torque input.

modulation torque shown in Fig. 4. Figs. 4a and b show the torque functions for two and three modulation steps, respectively. The effect of weight shift and torso twist can be adjusted separately in three modulation torque steps, while two steps combines these effects. The difference in the head velocity at impact between the two- and three- modulation torque is shown in Fig. 5 under the same effort index τ [N m s] and Q_{MAX} [N m] conditions. τ was calculated using the time integral of the torque function. It was found that there was almost no difference in the head velocity acceleration between the two functions. Therefore, the two-step modulation torque should be employed for easy planning.

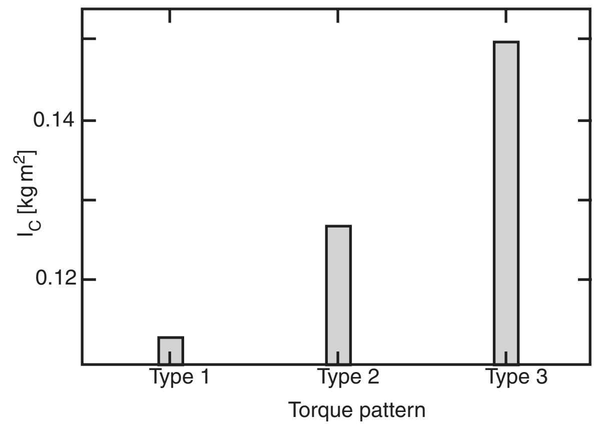
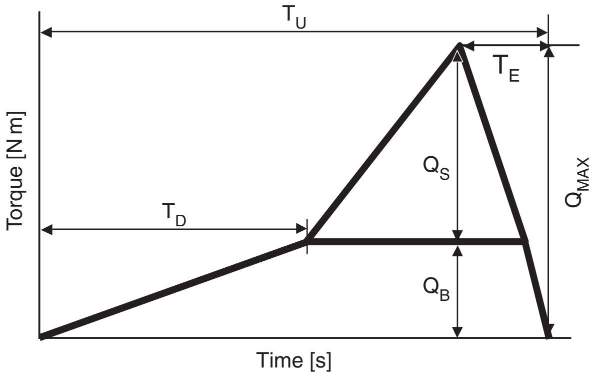
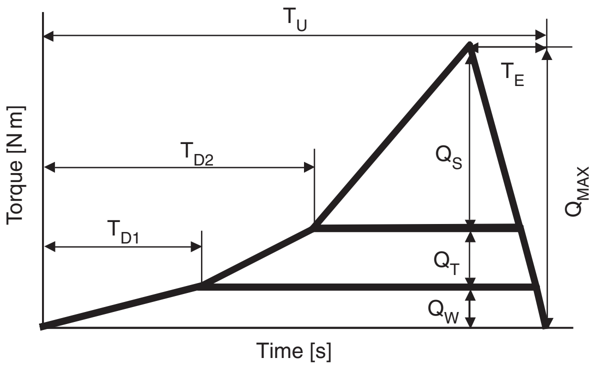


Figure 3 Practical moment of inertia I_C for various torque patterns.



(a) Two-step modulation



(b) Three-step modulation

Figure 4 Torque functions of two and three steps modulation
(a) Two-step modulation (b) Three-step modulation.

Adjustment of the multiple modulation torque

The two-step modulation torque can express a specific golfer's characteristics by adjusting Q_B [N m], Q_S [N m], T_D [s] and T_E [s]. Q_B and Q_S can be determined by the estimation of a golfer's muscular power and the maximum torque value Q_{MAX} is calculated as the sum of Q_B and Q_S. T_D and T_U should be adjusted in order to maintain the impact posture. The duration of T_E strongly affects the zero-crossing of the shaft vibration and was analytically investigated by considering a golfer's skill. Fig. 6b shows a comparison of efficiency index λ among five settings of T_E, which are based on the duration of T_U, as shown in Fig. 6a for three types of shaft rigidity. λ was calculated as the ratio of a club head's kinetic energy at impact to the work of the shoulder joint, as indicated by the following equation.

$$\lambda = \frac{0.5\, M_p V_h^2}{\int_{\theta_1} Torque(t)\, d\theta_1} \tag{1}$$

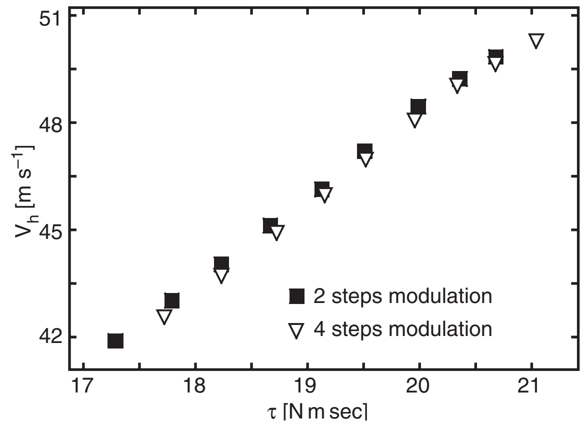


Figure 5 Comparison of head velocity V_h between two- and three-step modulation torque.

It was demonstrated that the shorter $T_{E,}$ the higher λ. When T_E is set to a small value, the zero-crossing of the shaft vibration and wrist release are delayed, thereby increasing the swing motion efficiency (Suzuki, 2003). In the same manner, head velocity at impact was compared in Fig. 6c. The torque input

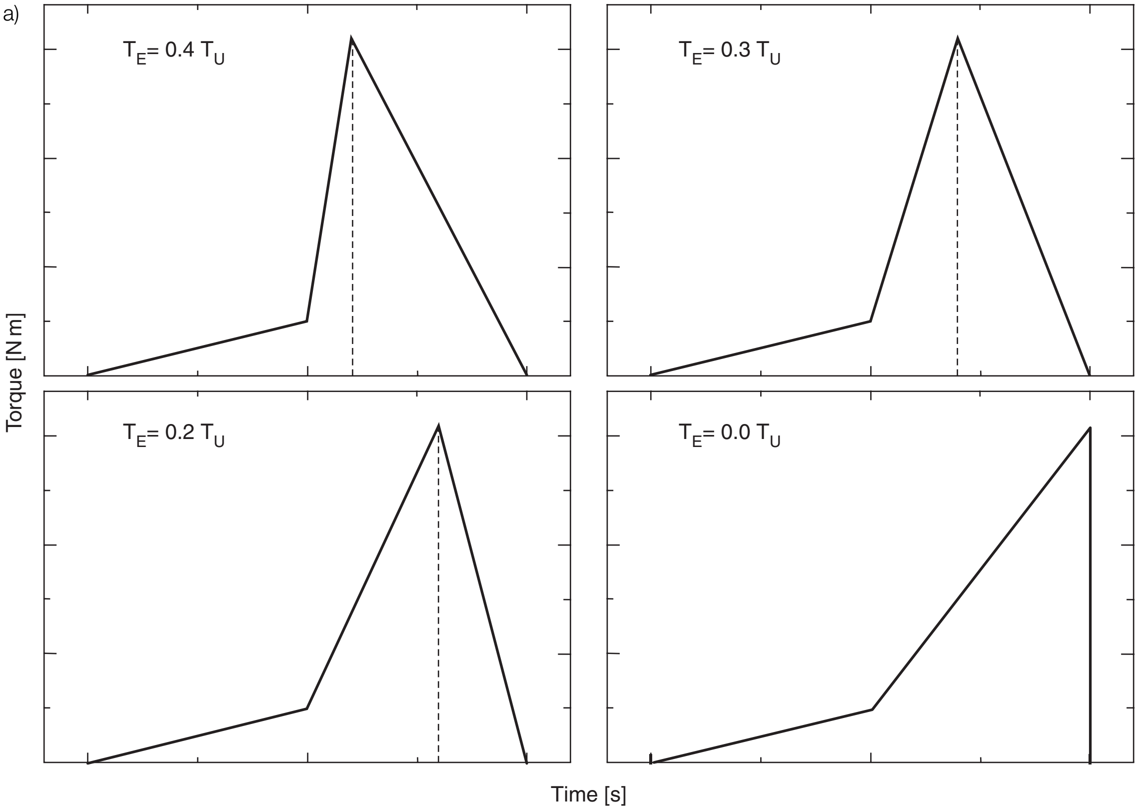


Figure 6 (a) Adjustment of T_E based on the acceleration time

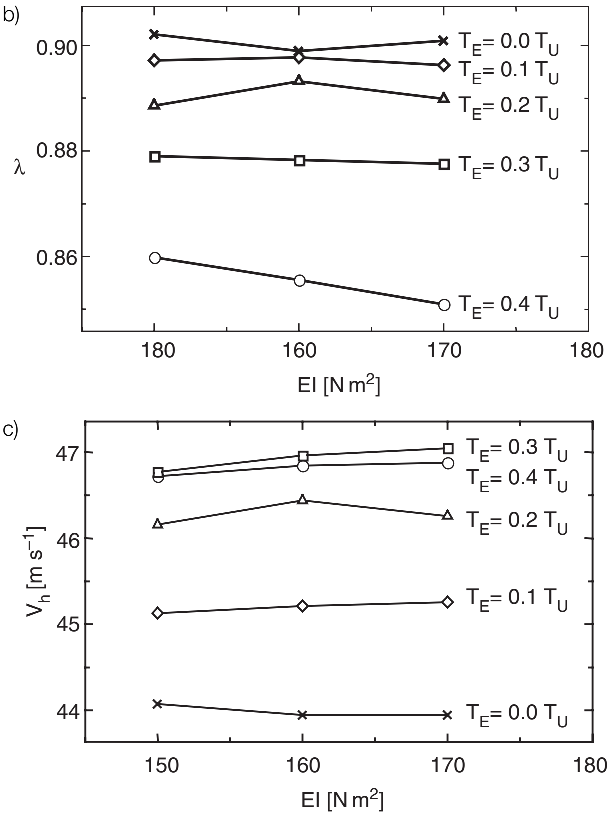


Figure 6 (b) Comparison of efficiency index λ for various T_E
(c) Comparison of head velocity at impact V_h for various T_E.

with a longer T_E accelerates the swing motion faster. This indicates that a longer T_E requires more shoulder work. In general, a skilful golfer can swing a golf club at a high speed with an efficient motion. Therefore, T_E was set to a middle value, 0.2 [s].

Modelling a skilful golf swing

Swing motion comparison

In order to verify the validity of the two-step modulation torque, λ and the shoulder joint angle at the wrist release θ_r [rad] were analyzed by comparing the trapezoidal and triangular torque functions that were investigated in the previous study. Fig. 7a shows the comparison of θ_r for various Q_{MAX} for the three functions. The two-step modulation torque was found to delay the wrist release the longest, like a skilful golfer. λ was also compared with these torque functions for various head speeds at impact, and the results are presented in Fig. 7b. It was shown that λ is larger for every head speed when the swing was accelerated using the two-step modulation torque. The results for the trapezoidal function, however, differ considerably from the other two functions because this function is unable to delay the zero-crossing of the shaft vibration that determines the release point of the wrist. Therefore, the arm is continuously accelerated by gravity until the impact. As a result, the kinetic energy of the arm KE_{ARM} [J] and the head KE_{HEAD} [J] during swing acceleration calculated by the trapezoidal function becomes completely different from the energy of the swings accelerated by the other functions, as shown in Fig. 7c. Consequently, the two-step modulation torque most accurately models the swing of a skilful golfer.

Virtual performance test

The proposed analytical robot model was then used to perform a virtual performance test of golf clubs. The virtual test focused on the mass distribution of a test club and the bending rigidity of the shaft as the static and dynamic properties of the club, respectively. The relationship between the club's moment of inertia around the grip I_C and θ_r for three values of Q_B are shown in Fig. 8. In this figure, T_D is varied in proportion to Q_B, and Q_S was set as a constant. It was demonstrated that when the shoulder was accelerated using a long T_D and a large Q_B, the robot could swing a large I_C club with a more delayed wrist turn. This suggests that a skilful golfer who can utilize whole-body motion with a delayed wrist turn may prefer to use the heavy club head, and this corresponds to observation. In order to examine the relationship between the properties of a golfer and the bending rigidity of the shaft EI [N m^2], the input torque was planned in detail, as shown in Fig. 9a. Table 2 shows the 24 setting patterns that describe the properties of a golfer. The properties were expressed by the effect of the weight shift on shoulder acceleration q_W [N m], the effect of torso twist q_T [N m] and the shoulder rotation q_S [N m], respectively. As shown in Fig. 9b, it was found that the most suitable shaft for maximum head speed could be determined by this test. The so-called 'hard hitter' can swing at a higher impact speed using a higher shaft rigidity. In addition, comparing types 3 and 4 and types 5 and 6 demonstrated that

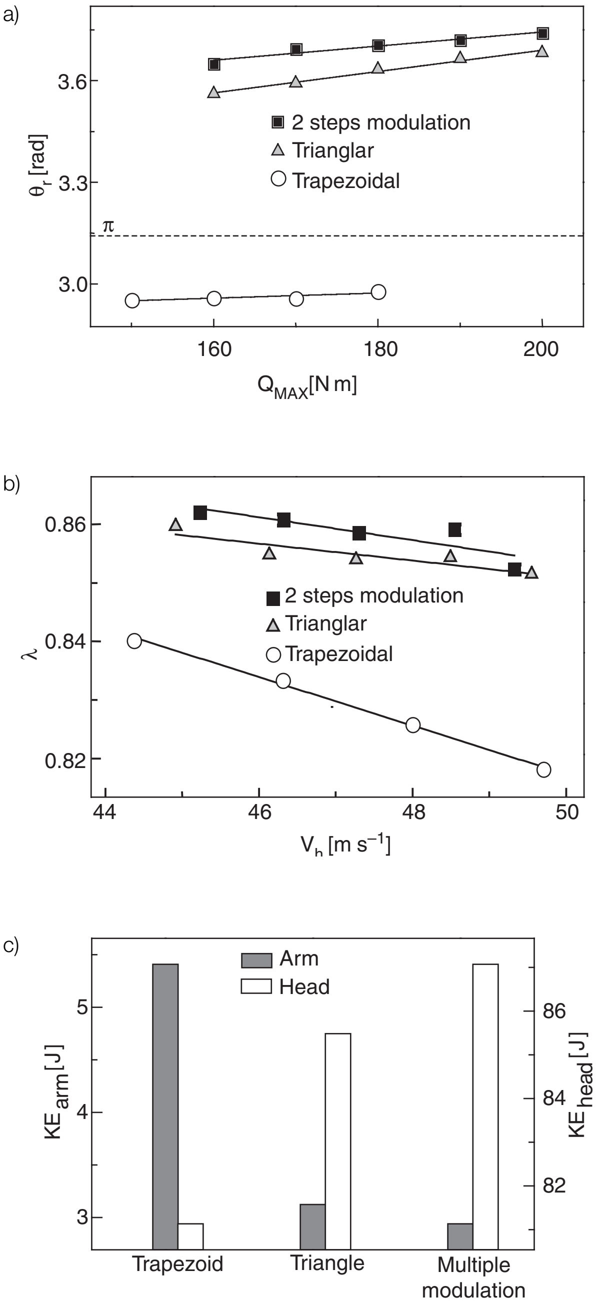


Figure 7 (a) Shoulder angle at the wrist release simulation results for three types of torque functions (b) Efficiency index λ simulation results for three types of torque functions (c) Comparison of kinetic energy of the arm and the head for three types of torque functions.

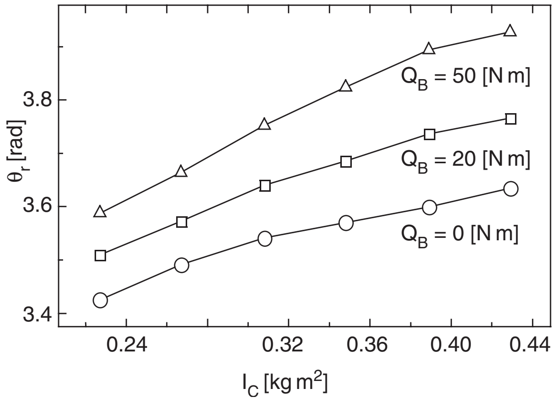
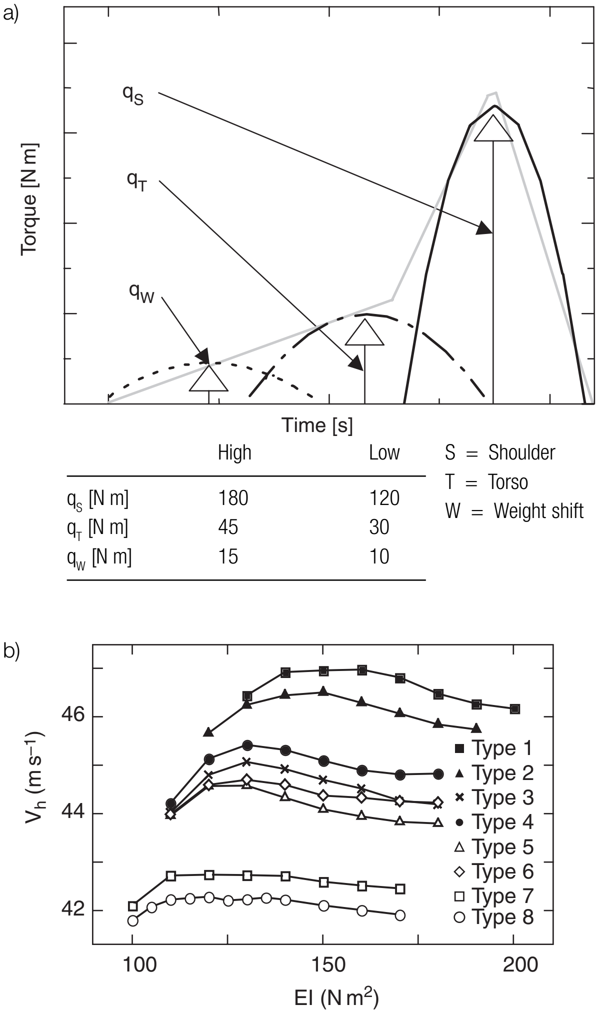


Figure 8 Relationship between the shoulder angle at the wrist release θ_r and moment of inertia I_C.



	High	Low
q_S [N m]	180	120
q_T [N m]	45	30
q_W [N m]	15	10

S = Shoulder
T = Torso
W = Weight shift

Figure 9 (a) Torque planning for the virtual performance test (b) Optimum shaft rigidity for each type of golfer in virtual performance test.

Table 2 Properties of golfers in the virtual performance test

	q_W	q_T	q_S
Type 1	High	High	High
Type 2	Low	High	High
Type 3	High	Low	High
Type 4	High	High	Low
Type 5	Low	Low	High
Type 6	Low	High	Low
Type 7	High	Low	Low
Type 8	Low	Low	Low

torso twist is more influential in accelerating the club head than the shoulder. These performance test experiments suggest that optimum club design settings and various settings of a golfer can be achieved by a robot.

Conclusions

Multiple modulation torque planning for a new golf-swing robot that is capable of modeling a skilful golfer's swing was analytically examined. A two-step modulation torque including the effects of whole-body motion on shoulder acceleration improved the efficiency index of the swing motion and the head speed at impact with a delayed wrist turn. In addition, it was demonstrated that the optimum moment of inertia and optimum design of club shaft rigidity for several muscular types of golfers could be determined by torque planning in a virtual performance test.

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