# Examining the delayed release in the golf swing using computer simulation

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## Abstract

The objectives of this study were first to examine whether, in theory, a delayed release technique that used resistive wrist torque provided an advantage in clubhead speed; and second, to identify the mechanical sources of power that are responsible for increasing clubhead speed. A 2-D, three-segment model comprising torso, arm, and golfclub was used to model the downward phase of the golf swing. Muscle torque generators, constrained by the activation rates and force–velocity properties of human muscle, were inserted at the proximal end of each segment. Three separate optimized simulation conditions were examined. The first, SIM-1, made no attempt to constrain the natural release of the clubshaft. Optimally activated muscular wrist torque was used to accelerate the clubhead. The second, SIM-2, delayed the release point of the clubshaft by means of a resistive muscular wrist torque. This was followed by active wrist torque to accelerate the clubhead. The third, SIM-3, was similar to SIM-2 except no wrist torque was used to accelerate the clubhead following the release point. The results indicated that there was a small advantage in employing the delayed release technique using resistive wrist torque, but significantly less than had been previously reported by other simulation studies. The use of an active wrist torque following the delayed release was found to be advantageous. The main source of power delivered to the golfclub originated from the passive joint forces created at the wrist joint during the swing. In terms of muscle power contributions to the swing, the torque generator at the shoulder joint produced the highest value (800 W), followed by the wrist torque generator (600 W), followed by the torso torque generator (390 W).

*Keywords*: energy flow, optimization, power, simulation

## Introduction

Accuracy and distance off the tee are what all golfers strive for. Accuracy is a function of both clubhead path and clubface angle at impact. Assuming solid contact is made with the centre of percussion of the clubface, distance is primarily a function of the clubhead speed at impact (Daish 1972), although other factors such as launch-angle and spin on the ball also play an important role. High clubhead speed at impact requires exquisite coordination of the sequential segment velocities of the chain link comprising the golf swing. Timing errors of as little as ± 50 ms can decrease clubhead speed by approximately 5% (Sprigings & Neal 2000). It has been suggested that, in theory, delaying the uncocking of the wrists during the downswing (henceforth referred to as a delayed release) will enhance clubhead speed at impact (Jorgensen 1970; Lampsa 1975; Pickering &

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Vickers 1999). The delayed release magnitudes used in these earlier simulation experiments were in the order of 100 ms. Such a short duration time means that it is imperative that the models used to examine this technique take into consideration those elements that might affect the outcome. To date, all of the mathematical models used to study the delayed release phenomenon have been limited to two segments (combined torso-arm, and club), and have made no allowance for the properties of human muscle in generating the joint torques. In addition, none of the previous studies has thoroughly examined whether there is any advantage in employing active wrist torque after the moment of clubhead release.

One of the primary energy generators for the chain link sequence employed in the golf swing is the rotation of the torso (Cochran & Stobbs 1968), yet most simulation models that have been used to examine the golf swing have been composed of just two segments, the combined torso-arm, and the club, and thus have effectively ignored the torso's interaction with the arm segment (Jorgensen 1970; Lampsa 1975; Budney & Bellow 1979; Pickering 1998; Pickering & Vickers 1999). In addition, little attempt has been made by earlier researchers to identify the sources of power that produce the energy flow through the chain link system.

The primary purpose of this paper was to re-examine the delayed release phenomenon in the golf swing using a three-segment model that incorporated the properties of human muscle into the simulation. A second objective of this paper was to identify the mechanical sources of power that are responsible for increasing clubhead speed.

## Methods

A representative mathematical model for a golfer was formulated using a three-segment, two-dimensional (2-D), linked system with the golfclub, arm, and torso segments moving in a plane tilted 60° to the ground (Fig. 1) (Sprigings & Neal 2000). The assumption of planar movement of these segments during the downward swing is well supported in golf literature (Cochran & Stobbs 1968; Jorgensen 1994). The golfclub was modelled as a rigid segment which is consistent with the conclusion of Milne & Davis (1992) that, contrary to popular belief, shaft bending flexibility plays only a minor dynamic role in the golf swing. The arm segment was modelled as a rigid rod and reflects the inertial properties and mass of the left arm. For the purposes of the 2-D representation, the torso segment was collapsed along its longitudinal axis so that it lay in the movement plane as a rigid rod with a length equal to the distance from the sternal notch of the sternum to the glenoid fossa of the scapula. Torque generators that adhered to the activation rates and force–velocity properties of human muscle were inserted at the proximal end of each segment, and provided the model with the capability of controlling energy to the system. A complete description of these muscle torque generators can be found in Sprigings & Neal (2000).

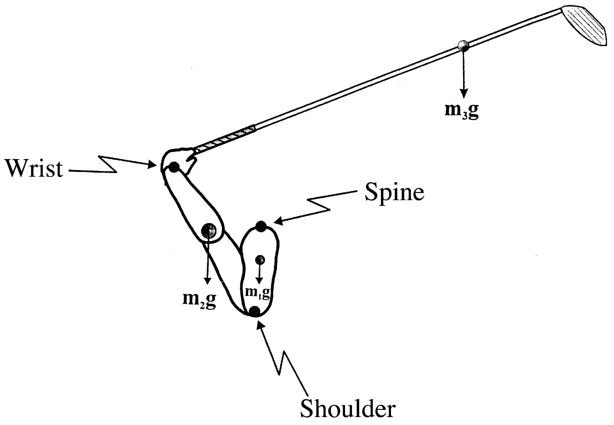

**Figure 1** Two-dimensional model, with muscle torque generators inserted at the spine, shoulder, and wrist, used in the simulation of the golfswing. The swing plane was assumed to be at an angle of 60° to the ground.

Parameter values for segment length, moment of inertia, and mass for a representative golfer with a body mass of 80 kg, and a standing height of 1.83 m, were calculated using the values of De Leva (1996). The value used for the moment of inertia of the model's torso segment about its proximal end was that of the anatomical torso's moment of inertia about its longitudinal axis. Parameter values for a standard driver, 43.5 in. in length, were taken from the work of Cochran & Stobbs (1968).

To simulate a late release, a wrist-cock angle of 90° was maintained between the arm and the club during the initial phase of the downward swing. This was achieved by employing wrist torque values that were calculated dynamically in accordance with the constraint that the angular velocities of the club and arm segments had to be the same value. At the optimized moment of release, the restraining wrist torque was terminated, and depending on the experiment, either a positive (i.e. counter-clockwise) generation of wrist torque commenced, or zero wrist torque was used until impact.

The equations of motion for the three-segment system were written using a Newtonian formulation in combination with the known equations of constraint for a system linked with pin joints (Sprigings *et al.* 1998; Sprigings & Neal 2000).

### Newtonian equations of motion for the three-segment model

$$F_{xn} = \sum_{\mathrm{i}=n}^{3} (m_{\mathrm{i}} a_{\mathrm{xi}}) \tag{1}$$

$$F_{yn} = \sum_{\mathrm{i}=n}^{3} (m_{\mathrm{i}} (a_{\mathrm{yi}} + g)) \tag{2}$$

$$\begin{aligned} l_n \alpha_n = {} & F_{xn} r_{2n-1} \sin(\theta_n) - F_{yn} r_{2n-1} \cos(\theta_n) \\ & + F_{xn+1} r\mathrm{SUB}2n \sin(\theta_{n+1}) \\ & - F_{yn+1r2n} \cos(\theta_n) + C_n - C_{n+1} \end{aligned} \tag{3}$$

### Equations of constraint for linked segment model

$$\begin{aligned} a_{xn} = {} & \left[ \sum_{\mathrm{i}=1}^{n-1} (-\alpha_{\mathrm{i}} L_{\mathrm{i}} \sin(\theta_{\mathrm{i}}) - \omega_{\mathrm{i}}^2 L_{\mathrm{i}} \cos(\theta_{\mathrm{i}})) \right] \\ & - \alpha_n r_{2n-1} \sin(\theta_n) - \omega_n^2 r_{2n-1} \cos(\theta_n) \end{aligned} \tag{4}$$

$$\begin{aligned} a_{yn} = {} & \left[ \sum_{\mathrm{i}=1}^{n-1} (+\alpha_{\mathrm{i}} L_{\mathrm{i}} \cos(\theta_{\mathrm{i}}) - \omega_{\mathrm{i}}^2 L_{\mathrm{i}} \sin(\theta_{\mathrm{i}})) \right] \\ & + \alpha_n r_{2n-1} \cos(\theta_n) - \omega_n^2 r_{2n-1} \sin(\theta_n) \end{aligned} \tag{5}$$

where $F$ is the external component of force on segment, $n = 1$–3 (where 1 is the torso segment, 2 is the arm segment, 3 is the club segment), $a$ the linear acceleration of CM of segment, m the segment mass, $g$ the gravitational acceleration, I the moment of inertia of segment about its CM, α the absolute angular acceleration of the segment, r the length between segment's proximal or distal end and its CM, θ the absolute orientation angle of the segment as defined counter-clockwise from a right horizontal axis attached to the proximal end of the segment, $C$ the internally generated muscle torque, $L$ the total length of segment, and ω the absolute angular velocity of segment.

The computer simulation required that separate expressions be derived for $\alpha_1$, $\alpha_2$, and $\alpha_3$ that were functions only of the variables $\theta_1$, $\theta_2$, $\theta_3$, $\omega_1$, $\omega_2$, $\omega_3$, $C_1$, $C_2$, $C_3$. This was accomplished by substituting Eqs (4) and (5) into Eqs (1) and (2), and then substituting the new expressions for the values of $F_x$ and $F_y$ into Eq. (3). The software package MATHEMATICA (Wolfram Research, Inc. Champaign, IL, USA) was used to generate the lengthy equations for $\alpha_1$, $\alpha_2$, and $\alpha_3$ so as to reduce the possibility of bookkeeping errors. Although the resulting equations contained the muscle torque terms $C_1$, $C_2$, and $C_3$, these were not unknown variables in that, once activated, their magnitude was governed by the muscle model. A fifth-order Runge–Kutta–Fehlberg algorithm (Burden *et al.* 1981) with variable step size was programmed and used to drive the simulation model.

The simulation process commenced with the assumption that the golfer had just completed his back swing and was just about to initiate his down swing. It was assumed that at time zero the golfer's torso segment was rotated 90° clockwise (top view) from the address position, with the arm and club segments positioned 60° and 30°, respectively, above a horizontal line through their proximal end, which is a typical configuration for an elite golfer (Yun 1996) (Fig. 1). The acute 90° of wrist-cock angle that corresponds to this starting configuration agrees with that observed for top players (e.g. Woods, Els) during the early stages of the downswing.

The optimization scheme employed a single activation muscular control strategy where the onset of voluntary torque at each joint was controlled separately. The time of onset, as well as the length of time that the joint torques acted, provided six control variables for the optimization. The optimization search engine was based on Powell's algorithm (Press *et al.* 1992). The objective function was the clubhead speed at impact, along with penalty variables that reflected inappropriate behaviour by the model during the simulated golf swing. For example, the position of the shaft at impact was constrained using a penalty variable to be within $\pm 0.5°$ of a vertical alignment on the computer screen. This impact position constraint is consistent with the observation made by internationally acclaimed professional golf instructor, Jim McLean, that the greatest drivers of the modern era (Nicklaus, Norman, Hogan, Nelson, Snead, Price, Woods, Lietzke, Peete, Sutton) when viewed face on, all had their clubshaft vertical at impact (McLean 1999). The simulation sequence was terminated when the clubhead reached a position 0.2 m horizontally past the proximal end of the torso segment. This termination point corresponds to striking a ball positioned off the inside of the left heel. Although a maximum time-step of 0.002 s was used during the simulation runs, the exact time of impact was determined by means of interpolation. To reduce the chance of arriving at a local instead of a global minimum during the optimization process, 400 randomly generated starting conditions for each of the six control variables were examined for each optimization trial. The set of 'best' starting conditions, as determined by the magnitude of the penalty summation that accrued during each simulation, was then used as the starting conditions for the POWELL optimization process. At the termination of the POWELL optimization process, the optimized set of control variables was stored in memory. This entire procedure was repeated 50 times with the 'best' set of optimized control variables being saved as a permanent file. For each simulation run, the magnitudes of the torso and shoulder generators were set to zero until activated by the optimization process. As mentioned previously, the required torque at the wrist joint to maintain the wrist-cock angle during the early phase of the downswing was computed dynamically.

Three simulation conditions for the downward phase of the golf swing were optimized. The first simulation condition (SIM-1) provided for the presence of voluntary wrist torque during the optimization search for maximum clubhead speed at impact, but did not employ a delayed release strategy. The second simulation condition (SIM-2) employed a delayed release strategy where an active wrist torque was used to restrain any change in the relative angle of the wrist joint until that time deemed to be optimal by the search method. At the precise moment when the release point was reached, the torque generator at the wrist was actively recruited to develop torque that aided the release process. The third simulation condition (SIM-3) was similar to SIM-2 except that, following the moment of release, the muscular wrist torque was set to zero which effectively reduced the wrist to a free hinge during the point of release up until the point of impact with the imaginary ball.

The energy flow through the three segments was computed by first calculating (Quanbury *et al.* 1975), and then integrating with respect to time, the two power sources at both the proximal and distal ends of the segments. The first source of power (muscle power), is the power generated by the muscles crossing the joint, and was calculated using: $P_{\mathrm{m}} = T\omega$; where $T$ is the active muscular torque and $\omega$ is the absolute angular velocity of the segment. The second source of power (joint-force power) is a passive mechanism which simply transfers energy between segments via the joint itself, and is a function of the linear reaction forces ($\mathbf{F}_j$) acting at the joint centre and the linear velocity ($\mathbf{V}_j$) of the joint centre ($P_j = \mathbf{F}_j \cdot \mathbf{V}_j$).

A qualitative validation test was performed on the simulation results by comparing the corresponding image sequences for the three-segment model with a real-life photographic sequence of an elite professional golfer during his downswing.

## Results

The simulation results indicated that the delayed release technique (SIM-2) provided a slight advantage in clubhead speed at impact (44.7 vs. 44.0 m $\mathrm{s}^{-1}$)

when compared with a normal swing (Fig. 2). However, to be effective, the delayed release technique required that the wrist-joint muscle torque generator had to be activated following the moment of release, and kept activated up until the point of impact with the ball. Without this active wrist torque following the delayed release (SIM-3), the clubhead reached a maximum speed at impact of only 38.9 m $s^{-1}$ (Fig. 2). The sensitivity of the simulation to the timing of the wrist torque has been previously reported (Sprigings & Neal 2000). It was found that for SIM-1, activating the wrist torque 50 ms prematurely reduced the clubhead speed at impact by approximately 2%, whereas activating the wrist torque late resulted in a 4.6% reduction.

The length of time to complete the downswing was longer for SIM-1 (0.36 s) when no delay was used, than for SIM-2 (0.34 s) where a delayed release was used. These values are comparable with a value of 0.34 s measured from video for professional golfer, Nick Faldo, whose clubhead speed at impact was approximately 5 m $s^{-1}$ faster. As previously reported (Sprigings & Neal 2000), the sequence of segment positions during Faldo's downswing were markedly similar to those produced during both SIM-1 and SIM-2. In the current study, the longer swing time required for the non-delayed release technique was a result of greater torso rotation being used (Δ96.5° vs. Δ78.2°) during the downward swing by the optimization process in order to satisfy the penalty constraint that the clubshaft be vertical at impact.

The muscular torque histories associated with the energy flow pattern in SIM-2 reflect the force–velocity properties of human muscle (Fig. 3). The muscles responsible for positive wrist torque were activated initially (0.0–0.19 s) to maintain the wrist joint angle at 90° as the torso and arm accelerated the club. This was followed by a brief time interval (0.19–0.24 s) where a restraining negative torque at the wrist joint was used to resist the normal straightening of the wrist joint resulting from the linear momentum in the clubhead. It is this 0.05 s period that is actually the delayed or late release in the simulation. Following the moment of release, the contributing wrist torque built up to a peak magnitude of 22 N m before diminishing back to 15 N m at impact. The maximum muscular torque generated for the torso was 112 N m, and for the shoulder joint, 87 N m. These values agree favourably with the upper values of torque for the torso, shoulder, and wrist (110, 90, 30 N m) measured directly from a low handicap amateur golfer using inverse dynamics (Neal *et al.* 1999).

For the delayed release technique (SIM-2), the maximum muscle power (800 W) generated during the downswing was produced by the muscles crossing the shoulder joint (Fig. 4). The next highest muscle power recorded (600 W) was

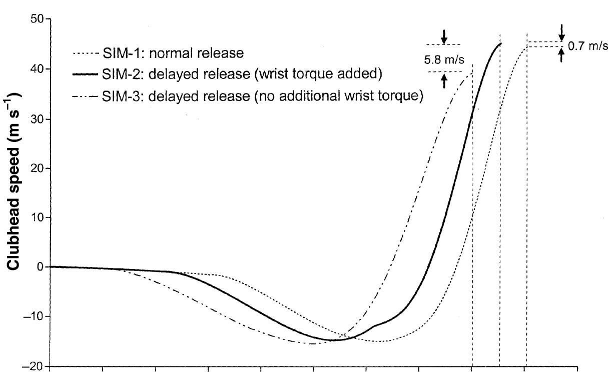

**Figure 2** Comparison of clubhead speeds reached using the three simulation conditions: SIM-1, SIM-2, and SIM-3.

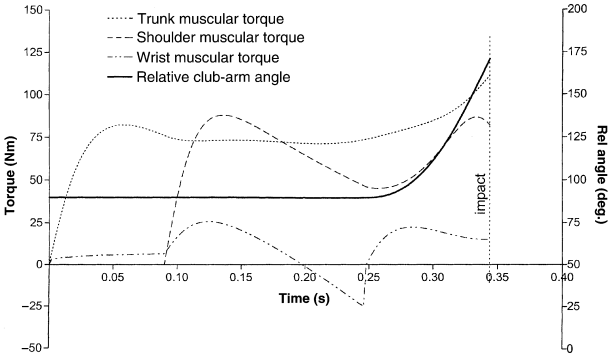

**Figure 3** Optimal torque histories from the three muscle torque generators used in SIM-2. The relative angle between the arm and club segments remains constant until just after the release point is reached.

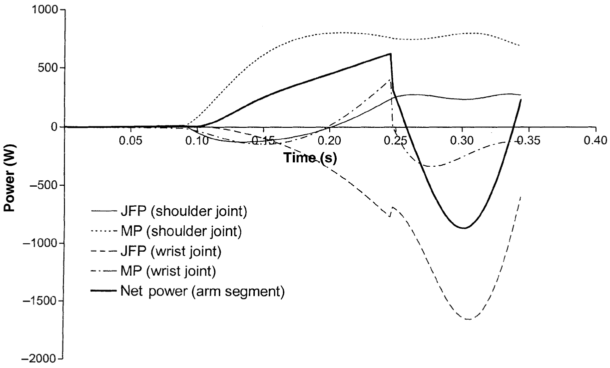

**Figure 4** Components of muscle power (MP) and joint-force power (JFP) acting at the proximal and distal ends of the arm segment.

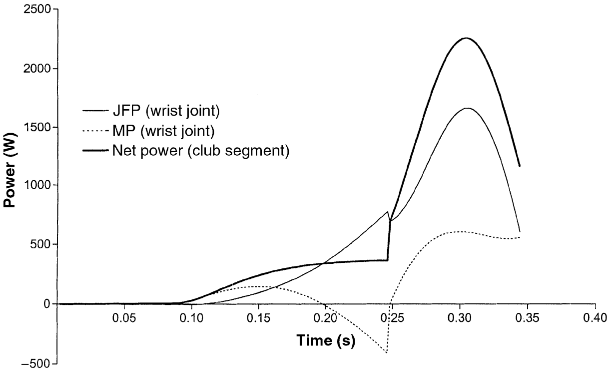

**Figure 5** Components of muscle power (MP) and joint-force power (JFP) acting at the proximal end of the club segment.

produced by the muscles crossing the wrist joint (Fig. 5). The lowest peak muscle power (390 W) was recorded for the muscles creating torso rotation (Fig. 6). The maximum instantaneous component of joint power (1650 W) recorded for any segment during the entire downward swing emanated from the joint forces created at the wrist joint as a result of the proximal to distal whip-like kinematics of the three-segment system (Fig. 5).

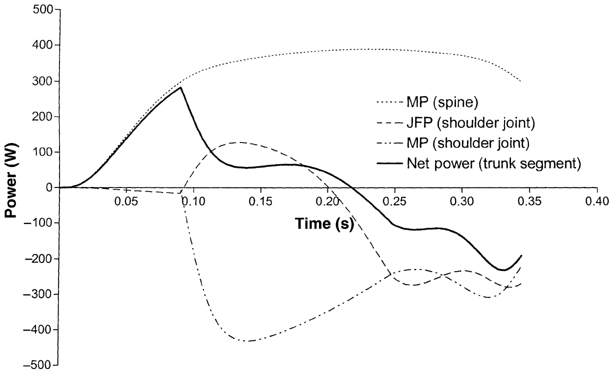

**Figure 6** Components of muscle power (MP) and joint-force power (JFP) acting at the proximal and distal ends of the torso segment. There is no proximal component of JFP as the model assumed that the proximal end was stationary.

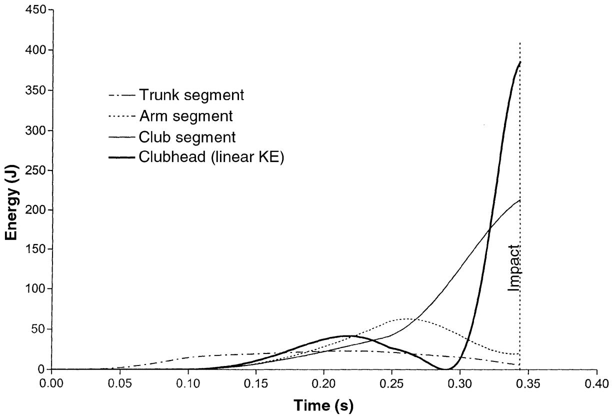

**Figure 7** Net energy histories of the three segments, as well as for the clubhead itself. The energy for the clubhead reflects only its linear kinetic energy as any rotational energy possessed by the clubhead was expected to be insignificant.

For SIM-2, the net energy histories for the three segments, as well as for the clubhead itself, indicate that there was an overall proximal to distal transference of energy from the torso and arm segments through to the clubhead at the moment of impact (Fig. 7). The same conclusion was reached for SIM-1. In SIM-2, a breakdown of the club's energy history into its sources by mathematically integrating the resultant joint-force power and resultant muscle power history curves at the grip end of the club revealed that the primary energy source (157 J) originated from the passive joint-forces created at the wrist joint by the kinematics of the swing (Fig. 8). However, one must remember that these seemingly passive joint forces are actually a consequence of the dynamic movements of the torso and arm segments that are themselves dependent on muscle power. The muscle power, created by active wrist torque following the release, supplied an additional 48 J of energy to the swing (Fig. 8). It is evident that the energy contribution

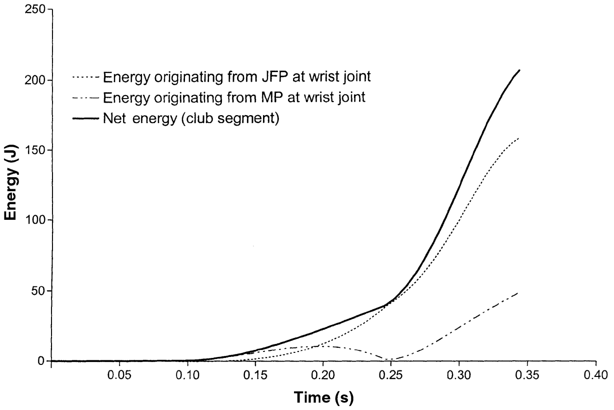

**Figure 8** Components of energy for the club segment as determined by integrating the respective power histories shown in Fig. 5. (JFP and MP refer to joint-force power and muscle power, respectively.)

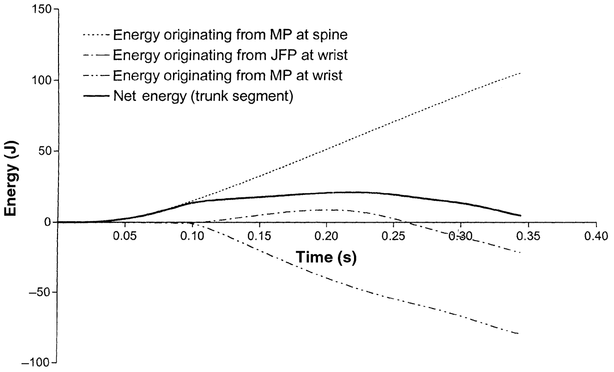

**Figure 9** Components of energy for the torso segment as determined by integrating the respective power histories shown in Fig. 6. (JFP and MP refer to joint-force power and muscle power, respectively.)

from the wrist muscular torque began before the instant that wrist-cock release was initiated (0.24 s). Because the relative wrist angle was being maintained during this pre-release phase, the muscles associated with providing wrist torque were actually transferring, rather than generating, energy through to the club from the arm segment during this pre-release stage (Winter 1987).

Examining the energy flow from the torso, to the arm, and finally to the club, it was observed that initially energy entered the torso via its muscle torque generators which produce torso rotation (Fig. 9). At approximately 0.09 s, when the shoulder torque muscular generator was activated, energy began to leave the torso, as a result of the opposing shoulder torque on the distal end of the torso segment, and flowed into the proximal end of the arm. Externally, this was observed as a slowing down of the torso's rotation as the arm picked up rotational speed. At 0.24 s, when the positive wrist torque was activated, it was observed externally that the increase in speed of the clubshaft coincided with a reduction in rotational speed of the arm segment (Fig. 10). In terms of energy flow, this corresponds to energy leaving the distal end of the arm segment via the wrist musculature and flowing into the club segment via the same muscle system (Winter 1990).

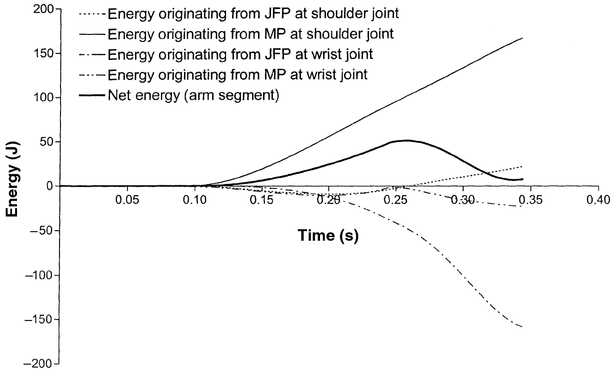

**Figure 10** Components of energy for the arm segment as determined by integrating the respective power histories shown in Fig. 4. (JFP and MP refer to joint-force power and muscle power, respectively.)

## Discussion

The purpose of a simulation model is to provide insight into the phenomenon under investigation, not to simply reproduce the movement pattern being studied. Alexander (1990, 1992) and Hubbard (1993) have cautioned against the use of complex mathematical models whose results become impossible to interpret because of the large number of inextricably intertwined independent variables. The three-segment model used in the present simulation study provides a reasonable compromise in the level of possible complexity required to examine the delayed release phenomenon. This model does take into account the activation rate and force–velocity properties of human muscle which constrain the torque generation capabilities of the torso, shoulder, and wrist joints. The model does not examine the role of the legs, nor does it account for any lateral shift of the torso during the downswing. In addition, no attempt was made to model the flexion and extension of the right arm or the longitudinal rotation (i.e. supination) of the left arm segment itself. In the present study, it was assumed that none of these additional factors would affect the conclusions reached as to the benefit, if any, of using a delayed release. As previously reported by Lampsa (1975), the clubhead speeds reached during the different simulations were relatively insensitive for up to 10% changes in the parameter values selected for the segments.

The present paper has examined the delayed release technique using a three-segment simulation model. The major advancements in this paper over earlier papers that have examined the delayed release (Jorgensen 1970; Lampsa 1975; Pickering & Vickers 1999) are that a torso segment was incorporated into the mathematical model, and that the active joint torques employed by the model were constrained by the force–velocity and activation rates of human muscle (Epstein & Herzog 1998). The results from the present simulation study support the findings of previous researchers that a slight improvement in clubhead speed (1.6%) can be achieved using a delayed release. However, the percentage gain in clubhead speed obtained is approximately 40% less than the increases reported by Pickering & Vickers (1999) (2.5%), and Jorgensen (1994) (2.9%). The most likely reason for the smaller gain in performance found for the delayed release in the present study is that previous studies had used constant torque generators that could be switched on instantaneously. In addition, these previous studies employed upper segment torques of unrealistic magnitude (≥200 N m) to reach reasonable clubhead speeds at impact as they did not have a torso segment to aid in the rotational acceleration sequence (Neal *et al.* 1999). Lampsa (1975), using a two-segment optimal control study, suggested that the upper segment's torque should increase linearly in time from 0 to 400 N m. Lampsa was aware that muscles could not be activated to their full torque potential instantaneously, and although his linear activation rate was physiologically incorrect (Epstein & Herzog 1998), it was a reasonable approximation for the model. However, the upper segment torque maximum used by Lampsa was approximately twice the magnitude of muscular torque that an exceptionally strong gymnast would be required to generate at the shoulder joint to hold a front lever on rings – needless to say, this is not a realistic torque value for a golfer who has to generate torque dynamically where the force–velocity properties of muscle come into play.

It is important to note that the point of 'natural' release of the clubshaft in a golf swing is a function of the angular acceleration of the segments proximal to the wrist joint. A low handicap golfer may be able to delay the natural release point of the club past that of a high hand golfer by employing a highly coordinated sequence of torso and arm segment accelerations. However, in the present paper, we have addressed the use of a delayed release technique that strictly relies on a resistive wrist torque to delay the natural uncocking of the wrist joint. In SIM-1, the optimization procedure activated a counter-clockwise wrist torque when the arm segment reached an angle of 22° below a horizontal reference line through the shoulder joint. For SIM-2 the optimization procedure activated a counter-clockwise wrist torque 0.05 s later when the arm segment had rotated counter-clockwise through an additional 3.25°. Thus, the duration of a forced delayed release is very small and would, most likely, be difficult to measure in actual practice.

Earlier researchers who have examined the delayed release technique concluded that at the moment of release there is little, if any, value in supplementing the release with active wrist torque (Jorgensen 1994; Pickering & Vickers 1999). The results from the present optimized simulation study provides theoretical evidence to the contrary. It was found that if the model, using a delayed release, did not employ active muscular torque at the wrist joint at the instant of release (SIM-3), the maximum clubhead speed reached was approximately 13% lower than if muscle torque was used (SIM-2) (Fig. 2). It is also apparent from the energy flow into the club that the wrist torque generators supply approximately 48 J of energy to the club by the time that impact with the ball is reached. This is approximately 24% of the total energy that goes into the club segment itself.

In the past, the main source of power for the golf swing had been attributed to the large muscles of the legs and torso (Cochran & Stobbs 1968). They had reasoned that a good golfer would be required to generate up to four horsepower (3040 W) to reach clubhead speeds in excess of 100 mph (44 m $s^{-1}$), and the only way of accomplishing this was to recruit approximately 13.6 kg of muscle mass, working flat out. They had neglected to take into consideration the role that the linear reaction forces at the joint centres play in transferring energy through to the clubhead via joint-force power (Fig. 8). Although muscle torques developed at the torso and shoulder are ultimately responsible for the linear reaction forces at the wrist joint, the peak magnitudes of muscle power never exceeded 800 W for any of the three joints. The highest maximum muscle power value (800 W) was recorded for the shoulder joint, with the next highest occurring at the wrist joint (600 W), and the smallest at the torso (390 W). The higher peak power value recorded for wrist torque when compared with the larger torso segment is a consequence of the force–velocity properties of muscle. The larger torso muscles are predominately composed of slow twitch fibres, while the muscles associated with wrist torque are known to have a higher ratio of fast twitch fibres (Johnson *et al.* 1973). This means that in the model the wrist torque generators had the capacity during the simulation to exert torque magnitudes in excess of 20 N m while the club was simultaneously reaching angular speeds approaching 30 rad. $s^{-1}$, generating maximum power of approximately 600 W. On the other hand, the maximum torques developed by the torso segment (120 N m) were greater in magnitude than that at the wrist, but were exerted on the torso segment that was rotating relatively slowly (3.25 rad. $s^{-1}$) as impact approached, thus generating lower maximum power (390 W). Although the peak power provided by the torso was the lowest of the three segments, its contribution in terms of energy production was significant because of the magnitude of power being maintained near its peak for most of the downswing (Fig. 6). Inspection of Figs 9 and 10 reveal that energy leaves the distal end of the torso segment (Fig. 9, Emd1) and enters the proximal end of the arm segment (Fig. 10, Emp2). This is a result of the same shoulder muscle torque acting on both segments simultaneously, but in opposite directions. The same shoulder torque that helps to speed up the rotation of the arm segment slows down the rotation of the torso.

The results produced using SIM-2 revealed that energy increased in both the torso and arm segments to a maximum during the middle phase of the downswing, but then decreased as impact approached (Fig. 7). At the same time, the energy of the club increased slowly until the release point (0.24 s), and then preceded to increase at an exponential rate until impact was reached. The observed exponential increase in energy delivered to the actual clubhead itself was delayed another 0.05 s past the release point which corresponded to the time when the clubhead actually began to travel forward towards the point of impact (Fig. 7). As impact approached, the gain in energy displayed by the clubhead coincided with the loss of energy in both the torso and arm segments, which lends support to the proximal to distal energy flow observed in throwing and striking activities (Herring & Chapman 1992).

In summary, this paper examined the theoretical benefit to clubhead speed that a delayed release technique, using resistive wrist torque, would produce. This delayed release technique is not to be confused with the 'natural' delay in clubshaft release that is introduced into the system by the rotational accelerations of the trunk–arm system itself. In this study, it was found that the delayed release technique, using a resistive wrist torque, provided a small benefit in terms of increasing clubhead speed at impact, but the percentage gain in clubhead speed was approximately half that previously reported by other researchers. Whether the additional gains in clubhead speed are worth the additional complexity introduced into the timing of the swing is left up to the golfer to decide. In the simulated golf swing, the main source of power delivered to the golfclub originated from the passive joint forces created at the wrist joint as result of the whip-like kinematics produced by the torso and arms.

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