Age-related Differences in Rhythmic Coordination in Golf

Dissertation

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Abstract

Analyzing coordinative patterns among limb segments can be a cornerstone in studying human movement and the underlying structure of motor coordination. However, there is much unknown about multi-limb movements, such as how the upper and lower parts of the body move together. Sports which involve hitting a ball with some manipulandum (e.g., a bat, golf club, or tennis racket) offer ecologically valid tasks for exploring multi-limb coordination. Observing golf swings can provide important information about coordination patterns for hitting tasks, and is useful because golf is a popular sport regardless of age.

This study addresses the three following issues: (1) the timing invariance of the clubhead force pattern and the weight shift, and adaptive capability for different task demands depending on age and skill level; (2) the predominance of an independent timing structure for upper and lower body coordination and change of this predominance with age; (3) the generalizability of previous research findings for chip shots to more
forceful shots. In this study, two groups of older and younger golfers of two different
skill levels were compared, using a golf swing as the primary task. Participants attempted
two different shots with the same club, requiring the ball to travel different distances of
80-yards and 40-yards.

Across golfers, the timing of the force pattern applied to the clubhead changed with
the required distances but the weight shift timing was approximately invariant. This
dissociation was the complement of the temporal adjustment found for chip shots, in
which the clubhead timing was relatively invariant and the weight shift timing was
adjusted. Analysis of the temporal variations across repeated attempts at the same shot for
each golfer showed that temporal variations in the clubhead force pattern were
independent or only weakly correlated with temporal variations of the weight shift for
most golfers, similar to previous findings for chip shots. These two findings provide
evidence for the presence of two separable, relatively independent rhythmic units in this
hitting task.

The predominance of this independent temporal structure decreased with age. The
older adults also used an additional front foot weight shift to begin most of their shots,
and this additional movement may simplify the overall rhythmic structure of their golf swings. The poorer balance capability in older adults was accompanied by more limited trunk rotation during their golf shots. This latter limitation may constrain the efficient transfer of force from the lower body to the trunk and in turn to the clubhead.

Meta analysis of a previous chip shot study and the present study demonstrated that the applied backswing force magnitude as a function of trunk rotation was approximated by a non-linear spring characteristic. The effects of skill level were limited to decreased variability in some of the timing and force magnitudes.

Overall, these findings may guide more detailed quantitative modeling of golf skill, and the methodology may be applicable to other hitting tasks for the analysis of swing components and whole body coordination.
Dedication

Dedicated to my parents who have provided all the support
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Chapter 1: Introduction

Patterns of Coordination

Just as coordination among the various parts in an orchestra is required for a good performance, coordination between the parts of the body is essential in human movement. The issue of how humans coordinate the many degrees of freedom associated with a great number of body joints has been discussed since Bernstein (1967), and there is still much to understand about the coordination among various limbs. For example, attempts to reproduce the very basic task of human bipedal walking in walking robots have thus far been unsuccessful (Vaughan, 2003). According to Turvey (1990), coordination is the patterning of body and limb motions relative to the patterning of environmental objects and events. In other words, depending on the relationship between environmental constraints and task demands, various kinds of coordination are possible. Components which are involved in the same task mutually constrain each other, and throughout these processes, a coupling between components occurs, reducing the number of possible stable relations between components (Haken, Kelso & Bunz, 1985).
Various kinds of inter-limb coordination have interested researchers, such as bimanual tapping (Summers, 2002), head and body coordination (Berthoz & Pozzo, 1994; Kavanagh, Barrett, & Morrison, 2005), hand and foot coordination (Salesse & Temprado, 2005), and upper and lower body coordination (Jeka, Kelso, & Kiemel, 1993). Among the various kinds of inter-limb coordination which occur during voluntary action, bimanual tapping has received a great deal of attention.

Research has focused on how people reduce coordinative complexity by constraining the components required for a certain movement in order to overcome a large number of degrees of freedom (Bernstein, 1967). Attraction to simple coordination modes such as in-phase and anti-phase has been shown in rhythmically coordinated finger movements and two-handed movements. The performance of in-phase coordination is more stable than that of the anti-phase, and the coordination stability decreases as movement frequency increases. At higher velocities, the stability of the anti-phase coordination is lost and there is an abrupt transition to the in-phase coordination (Haken et al., 1985).

Additional studies of the coordination of the two hands have demonstrated that the synchronized rotation of limb segments in the same direction is easily achieved,
whereas movement in opposite directions proves more difficult (Baldissera, Cavallari, & Civaschi, 1982). A preference for iso-directional, in-phase movements has been observed for movement combination besides two handed movement as well. For example, coordinated movements of the upper and lower limbs such as an axial rotation of arm and leg, a prono-supination of hand and foot, and flexion-extension of hand and foot tend to be easier than movements in the opposite direction (Salesse, Temprado, & Swinnen, 2005).

Studies of coordinated movements have focused on bimanual tapping and other two-handed movements, but there is a considerable difference between bimanual tapping studies and other studies of inter-limb coordination, such as hand and foot pairs and head and trunk pairs; that is, the former studies are about homologous limb pairs, while the latter generally focus on non-homologous limb pairs. Various studies have investigated the coordination of non-homologous limb pairs, but unified control principles have not yet been identified. Of particular interest among these non-homologous limb pair movements is the coordination of upper and lower body movement.

Kelso and his colleagues (Kelso & Jeka, 1992, Jeka et al., 1993, Jeka & Kelso, 1995) attempted to apply findings from bimanual tapping studies to inter-limb
movements such as arm and leg movements. They had participants sit in a reclining chair and asked them to make coordinated movements with their arms and legs with their feet off of the ground. Two coordination modes were manipulated: in-phase and anti-phase using flexion and extension of elbow and knee joints, which created different kinds of “gait” patterns similar to those of four-limbed animals. In other words, the movements of subjects’ forearms and lower legs produced an effect similar to four-limbed animals’ trotting, galloping, and walking.

The results showed that dynamical principles derived from bimanual movements applied; these included the presence of two simple coordination patterns and the abrupt transition from anti-phase to in-phase movement. In addition, more variability appeared in the non-homologous limb pairs (arm and leg) than homologous limb pairs (arm and arm, and leg and leg). One of the interesting results was that subjects had difficulty in performing 1:1 frequency matching, which is quite an easy task in bimanual tapping. In other words, they had trouble coordinating non-homologous limb pairs. The authors asserted that the asymmetry of non-homologous limb pairs occurred due to the physical constraints, the natural frequency differences between two limbs. In other words, the difficulty of coordinating the upper and lower body may be caused by the intrinsic
frequency differences between limb pairs in the four-limb coordination task. The
differential coupling among the limbs rendered all patterns of four-limb coordination not
equally stable, showing a phase drift between non-homologous limb pairs as the required
movement frequency increased.

Serrien and Swinnen (1998) further examined the finding of natural frequency
differences by adding weight to the wrist. They modulated the arm’s inertial
characteristics, so that homologous limb pairs (arm and arm) were more dissimilar and
non-homologous limb pairs were more similar in terms of natural frequency. They used
experimental settings similar to Jeka and Kelso’s (1995), where participants were seated
in a chair with their feet off of the ground. Subjects were asked to make coordinated
movements using flexion and extension of elbow and knee joints. Loading weight to the
limb decreased relative phase stability, but did not affect the mean phase accuracy, which
depended more on the type of limb pairs (homologous vs. non-homologous). Indeed,
change of inertial characteristics deteriorated the stability of non-homologous limb pairs,
which suggests a tighter synchronization of homologous limb pairs.

However, the studies conducted by Jeka and Kelso (1995) and Serrien and
Swinnen (1998) did not consider the role of dynamic balance by the lower body, which is
one of its key roles in movement. Kelso and Jeka (1992) argued that the aim of investigating pattern formation led them to have subjects perform various movement patterns in a reclining chair. However, as they mentioned, locomotory function such as weight bearing and balance is one of the most important roles for hind-limbs (legs). Thus, it is not appropriate or ecologically valid to explore coordination patterns between upper and lower body without any consideration of balance.

Donker, Beek, Wagenaar, & Mulder (2001) analyzed arm and leg movements during walking in order to explore the differential stability of in-phase and anti-phase coordination which was found in bimanual tasks. They found no significant differences in coordinative stability between ipsilateral arm and leg movements (anti-phase) and contralateral arm and leg movements (in-phase).

This approach was further developed by Donker, Daffertshofer, and Beek (2005). In their experiment, participants were instructed to walk on a treadmill at different velocities between 0.5 and 5.0 km/hr (in steps of 0.5 km/h). They compared walking with or without additional loading on the arm in order to test the natural frequency hypothesis. The results showed that the frequency coordination between arm and leg movements was 2:1 at the lower velocities (lower than 3.0 km/h) and 1:1 at the higher velocities (higher
than 3.0 km/h), and the stability of the leg movements was greater than that of the arm movements. While individual limb movements were affected by the mass manipulation, the coordination between limbs was preserved. Their results contradicted previous findings which showed a change in coordination of the arm and leg by adding a mass to the arm (Serrien et al., 1998), presumably because dynamic balance maintenance by the lower body is required during walking.

This finding suggests that mechanical, functional constraints rather than physiological constraints play an even more prominent role in walking, and must be considered when examining the coordination of non-homologous limb pairs. This hypothesis agrees with Schöner’s (1995) assertion, which states that the nervous system is organized in a functional task-related way rather than in a structural, anatomy-related fashion.

Forner-Cordero, Levin, Li, and Swinnen (2007) investigated the stability of the lower body in terms of postural sway. Participants were asked to do 6 different bimanual multi-joint coordination tasks while their ground reaction forces were measured by force plates. The results showed that the performance of complex tasks disrupts postural control; larger variability in the center of pressure was found. They asserted that
attentional resources need to be redistributed depending on the complexity of the task.

When people are performing complex bimanual multi-joint coordinative tasks, their postural sway is affected, resulting in an increase in sway.

The debate between physiological and mechanical constraints for the non-homologous limb movements is still progressing. Thus, it is imperative to develop experimental settings in which the functional roles for each limb are considered.

**Golf Movements and Force Patterns**

While there are various ways of investigating upper and lower body coordination, the golf swing can be considered an especially good experimental task. Golf is one of the sports that involves hitting a ball with some manipulandum (e.g., a bat, golf club, or tennis racket); even though each sport has its own manipulandum, the fundamental qualitative mechanism of force generation and transfer applies to most hitting tasks. Performers generate force from their lower body by pressing against the ground, and they transfer force to the swing manipulandum by shifting their weight and then rotating their trunks as a swing progresses (e.g., Bootsma & van Wieringen, 1990 for the table tennis; Katsumata, 2007 for the baseball). In other words, performers need to adjust themselves
in coordinating their upper and lower body for efficient force generation and transfer. However, some sports pose severe challenges to experimental study: performers may need to change their location in order to chase the ball (for example, in tennis), or adjust their position depending on the types of a thrown ball (for example, in baseball). Contrary to these sports, golfers stand on the ground and hit a ball which is stationary at address. Thus, research on golf can perhaps provide advantages for investigating fundamental mechanisms of force generation and transfer and the associated coordination pattern.

Research on golf in psychology has focused mainly on how mental activities affect the performance of a golfer such as performance under pressure (Beilock & Carr, 2001), the effect of arousal (Molander & Bäckman, 1996), and the relationship with memory and attention (Beilock, Wierenga, & Carr, 2002); the analysis of the coordination involved in the swing itself, another building block of golf research, has received less attention. Other disciplines such as biomechanics and physical education have taken different approaches, emphasizing physiological correlates of the swing and the effectiveness of various training techniques. By combining these lines of study, the present research seeks to identify how people manage those physiological properties in
terms of coordinative strategies that may vary by age and skill level.

A growing body of developmental research has addressed many important features of the golf swing, but attention has been paid mostly to the control of putting and golfers’ competitiveness in relation to the level of anxiety and/or pressure, factors that tend to change with age. In fact, there have been relatively few attempts to analyze the golf swing itself from the psychological perspective of inter-limb coordination.

However, Jagacinski, Kim, and Lavender (2005; in press) have proposed a conceptual framework of polyrhythmic movement to discuss possible coordination strategies. Their analysis of the golf swing in terms of force emphasized three events for the upper body movement and two events for the lower body movement: the peak forces for backswing, downswing, and follow-through in the upper body movements, labeled $F_1$, $F_2$, and $F_3$, and the peak forces of weight shift to the back foot and front foot in the lower body movements, labeled $W_1$ and $W_2$ (right and left feet for a right-handed golfer, respectively) (Figure 1). Under this framework, golfers have to coordinate a 3:2 polyrhythmic movement pattern between their upper and lower bodies, which is a rhythmic ratio found to be difficult to achieve in bimanual tapping.
Figure 1. The skeleton figures show the approximate positions of the golfer corresponding to each peak force event in the time histories for clubhead force pattern and weight shift. The middle graph shows the force pattern applied to the clubhead during a golf shot. $F_1$, $F_2$, and $F_3$ are, respectively, the peak forces during the backswing, downswing, and follow-through. Impact was accompanied by a sudden, large spike in the force pattern. The bottom graph shows the weight shift pattern, the difference of vertical forces against the ground between the back (right) foot and the front (left) foot. $W_1$ and $W_2$ are, respectively, the peak weight shift to the back foot and the front foot.


The attention paid to polyrhythmic performance, especially bimanual tapping, can illustrate how the coordination of two different limbs is achieved when each limb produces different beats simultaneously (for a review, see Jagacinski, Peper, & Beek,
Temporal variability of within- and between-hand movements has been used to assess the difficulty of polyrhythmic tapping. As rhythm becomes more complicated (e.g., 5:3 compared to 3:2) and/or basic frequency increases, phase transitions to simpler rhythms appear.

![Diagram of bimanual tapping](image)

**Figure 2.** Two rhythmic structures of bimanual tapping: R₁, R₂, and R₃ correspond to three taps with the right hand, and L₁ and L₂ correspond to two taps with the left hand in a 3:2 musical polyrhythm. The curved lines correspond to time intervals between two events that constitute the temporal organization of the behavior. The top graph (A) illustrates an integrated control structure, in which left hand movements are nested into the sequence of right hand movements, and the bottom graph (B) demonstrates an independent control structure, in which the two hands proceed in separate streams of events that have only one initial event in common.


Correlational analysis between time intervals revealed the underlying organization of polyrhythmic performance; an integrated control structure and an
independent control structure. As shown in Figure 2, the sequences of each hand
movement are integrated into one sequence in the integrated control structure, while the
sequence of each hand is independent in the independent control structure. An integrated
control structure for both hands was exhibited in most of the studies (Jagacinski,
Marshburn, Klapp, & Jones, 1988; Summers, Ford, & Todd, 1993); however, when
performing very rapidly, advanced skilled pianists showed an independent control
structure for each hand (Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000).

The golf swing is different from two-handed polyrhythmic tapping, in that it has
clear beginning and end points. No continuously repeated performance of a polyrhythmic
pattern occurs in golf, where each swing is a discrete action. It may not be possible to see
phase drift or phase transitions as in bimanual tapping. However, assuming that there is
an invariant temporal pattern in a golf swing, over the course of a game golfers have to
attempt the same pattern repeatedly. For example, a professional golfer will repeat a
swing more than 50 times per round. Different amounts of force are applied depending
on the kinds of shots, and the force difference may cause qualitative changes in the
stability of swing performance.
One of the possible patterns is a transition from anti-phase to in-phase movement in terms of the relative timing of the lateral shift in the center of pressure with arm movement; namely, in-phase movement is the shift of the center of pressure toward the back foot during the backswing and toward the front foot during the downswing and follow-through, and anti-phase movement is the opposite way of shifting the center of pressure. A transition from anti-phase movement to in-phase movement would be expected as skill level increases.

In the present investigation, the coordination of movements between the upper and lower body was of interest. Golf-swing-like tasks were executed in a laboratory setting to explore golfers’ adaptive strategies for adjusting the polyrhythmic force patterns in the golf swing when they were required to use the same club for different target distances. To regulate distance using the same club, either the force magnitude or the timing of swing, or both, need to be adjusted. Given that the lower body is the primary source of force generation, its movement will be different depending on the shot distance. Further, the different coordination strategies employed by intermediate and relatively advanced players and by older and younger players were compared. Various analyses were performed to investigate the two competing roles of the lower body:
balance maintenance and force generation.

Among the many relevant variables, timing, force and velocity are of particular interest. First of all, the magnitude of the force is one of the important variables. Because there is a complex relationship between the mechanical factors producing the movement and the movement itself (Bernstein, 1967), the same amount of force may produce very different patterns of movement for each successive repetition depending on the initial positions and velocities of the limbs. Analyses of the force alone are insufficient to explain all possible movement patterns. In the present study, information about the timing of specific events (e.g., the backswing, downswing, and follow-through) and the clubhead velocity at a certain event (e.g., impact with the ball) coupled with analyses of force produced more precise information about the golf swing.

In simple movements toward a stationary target, an increased force output can be obtained by increasing movement amplitude while keeping the required movement time constant (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), or by maintaining constant movement amplitude while decreasing movement time (Newell et al., 1980). Namely, the movement amplitude and movement time are two critical parameters influencing force generation. In the golf swing, however, golfers generally do not vary
their movement time to adjust their force when they are using the same club to hit shots of different distances. Rather, they tend to attune the amplitude of their backswing and downswing (Leadbetter, 2007). Delay, Nougier, Orliaguet and Coello (1997) showed that when attempting longer putts, subjects generally increased the downswing amplitude while maintaining constant downswing movement time, thereby increasing clubhead velocity at the moment of contact with the ball.

In comparing the amplitudes of the downswing and follow-through in putting, Delay et al. (1997) showed that for advanced players, the ratio of downswing to follow-through was about 1:2, while for novice players the ratio was closer to 1:1. In other words, the amplitude of the follow-through of expert players was twice the amplitude of the downswing, regardless of the target distance. Delay and his colleagues argued that this is because advanced players were trained and planned to hit the ball during the acceleration phase of the club. If advanced players also employ a larger amplitude of follow-through in an iron shot, a question the present study seeks to answer, then the difference between the peak forces of the downswing and the follow-through would be larger for advanced players than for intermediate players.
The present study addresses issues of timing invariance and coordinative structure of the upper and lower body. It is hypothesized that the rhythm of the golf swing does not change with the magnitude of the swing, despite force changes. In other words, golfers employ the same rhythmic pattern for forceful shots as they do for weaker shots in terms of kinetic timing of events of the upper body. In studies by Jagacinski et al. (2008; in press), the force patterns of chip shots showed timing invariance of the F1-F2 and F2-F3 intervals, regardless of the exerted force. If timing invariance is a key factor in maintaining rhythmic patterns in a golf swing, more forceful shots should exhibit the same pattern of timing invariance. The present study investigated whether golfers, using an eight iron, demonstrate timing invariance of the F1-F2 and F2-F3 intervals with 40-yard and 80-yard approach shots.

In a study of chip shots (Jagacinski et al., in press), the time interval and magnitude of weight shift were adjusted in order to generate and transmit different amounts of force with chip shots. Golfers shifted more of their weight more quickly to produce more force. In the present study, the experimental task – more forceful iron shots – requires that much more force be generated. It is hypothesized that the timing and magnitude of golfers’ weight shifts will be adjusted even more with these shots than with
Contrary to the typical coordination structure found in most bimanual tapping studies, independent temporal covariance patterns of the upper and lower body forces have been found in studies of chip shots for highly-skilled golfers (handicap 5-10 strokes; Jagacinski et al., in press). The timing of force patterns by the upper body and the lower body do not covary, suggesting that there is an independent timing regulation of the upper and lower body movement. If this is a general coordination pattern in a golf swing, the same pattern should be apparent in more forceful iron shots. Thus, the coordination pattern of the upper and lower body movement in the golf swing is hypothesized to be independent. This hypothesis is investigated in this study.

Several variables may influence the predominance of independent timing. Just as skill level plays a role in bimanual tapping (Krampe et al., 2000), it is hypothesized that independent temporal structure is employed more by highly-skilled golfers, while less-skilled players utilize an integrated temporal structure between the clubhead force pattern and weight shift. Another factor which may affect this structure is age. Older adults have worse balance capability than do younger adults (Menz, Lord, and Fitzpatrick, 2003). This difference in balance capability may affect force generation by the lower body in the
golf swing. A comparison between age groups may show how balance maintenance capability is related to the selection of a coordinative pattern. Thus, in the present study, the effects of age and skill level on the coordinative strategy were examined in order to determine whether the degrees of constraint on the force patterns of the upper and lower body vary with golfers’ age or skill level.

**Upper vs. Lower Body Movement**

A great number of movement components have to be coordinated in the golf swing, but it is the coordination of the upper and lower body that is most often mentioned by many professional golfers (e.g., Woods, 2007; Watson, 2008). In describing a high-performance golf swing, many professional golfers emphasize the use of bigger muscles, such as in the lower body, torso, and shoulders muscles, rather than the smaller muscles of the hands and wrists. Of interest is the pattern or strategy by which golfers coordinate these larger muscles.

In studies of bimanual tapping, novice or less experienced subjects had considerably more trouble performing anti-phase tapping than in-phase tapping than did expert or more experienced subjects. However, that may not be the case for upper and
lower body coordination in a golf swing since forces have to be generated by medial/lateral shifts of the appropriate body parts. Unlike in conventional laboratory tasks which require upper and lower body coordination (Kelso and Jeka, 1992), the golf swing requires that the lower body should take charge of maintaining balance as well as generating force through movement as is the case in tasks such as lifting a package or throwing a ball. Contralateral support is naturally used to maintain balance in activities such as walking, which is an anti-phase movement in terms of a lateral shift of the upper and lower body. In other words, the lateral shift (leftward) in the center of pressure with a forward movement of the left foot is partially compensated by an accompanying forward movement of the right arm, and vice versa; balance is therefore achieved.

On the other hand, Cockell, Carnahan, and McFadyen (1995) showed a change in preference to ipsilateral limb pairs for some tasks. These results were the product of a grasping and walking study, in which subjects were asked to grasp a certain object from a distance of about an arm’s length. In a grasping condition, when the left hand was being stretched out to grasp an object, subjects could locate their center of pressure either on the left foot or on the right foot. They showed a preference for ipsilateral support during grasping, which supposedly encourages balance maintenance by locating the center of
pressure around the center of mass. This pattern of balance is opposite to the contralateral support pattern found in a walking only condition. The strategy of stabilizing by the coordination of the upper and lower body was appropriately modified to accommodate the task. In other words, depending on the task at hand, the coordinative pattern may be modified to ensure stability and/or maintain balance.

In a golf swing, golfers need to transfer their weight to their back foot during the backswing, with the center of pressure moving in the same direction as the clubhead; this is similar to the ipsilateral support pattern found in the grasping study (Cockell et al., 1995). However, it has been reported frequently that novice golfers have trouble transferring their weight to their back foot, possibly due to an insufficient capability for balance maintenance. Therefore, novice players or those with balance problems may show more of a tendency to shift the center of the pressure to the lateral part of their front foot during the backswing (Brown, Best, Ball, and Dowlan, 2002).

Contrary to naturally preferred contralateral support, ipsilateral support of a leg is suggested in order for golfers to efficiently transfer force from the lower body to the upper body (Nicklaus, 1974). As mentioned before, this type of support may not be very effective in maintaining balance because the center of pressure can be over-shifted to the
right side during the backswing. This problem may be especially present for the beginner who has not yet received enough training to command the ipsilateral support pattern. Therefore, in-phase movement of the club and the center of pressure is expected for advanced players; anti-phase movement of the club and the center of pressure, or an unstable movement pattern of the center of the pressure, is expected for novice or less-skilled players in golf swing-like tasks. An anti-phase pattern or unstable pattern is also expected for those players who experience greater difficulty with balance, as may be the case with older golfers. These differences may be due to the fact that balance maintenance has been established through training and automatically activated for advanced players, but not for less-skilled players.

The movement pattern of the center of pressure in a golf swing has been focused on in the previous studies: a greater mean lateral deviation of the center of pressure is found in the highest skill group (Jacobson, Stemm, and Redus, 2005); a reduced range of the center of pressure is found in older golfers along with a negative correlation between the range of the center of pressure and the velocity at impact (Brown et al., 2002). However, few studies investigated the relationship between balance capability and the movement of center of pressure (Mason, McGann, & Herbert, 1995; Ball, Best, Dowlan,
& Brown, 2002). Therefore, the present study explores the role of balance capability and the effect of balance on the lower body movement.

**Balance Maintenance in a Golf Swing**

It should not be overlooked that balance maintenance is a critical issue when investigating the role the lower body plays in the generation and transfer of power to the upper body. As mentioned before, the lower body is not responsible solely for force generation: it is also instrumental in keeping balance during the whole swing. In fact, balance maintenance is an important issue in many tasks besides golf swings. Every movement which involves the lower body, like walking, running, kicking, etc., requires that the lower body satisfy the competing demands of balance and guided movement (Kavanagh et al., 2005). Unlike other movements though, a golf swing has a unique feature regarding balance maintenance. Because golfers have to generate force from the lower body without moving their feet and transmit that force via the rotatory power of the upper body, it is especially critical to distribute and adjust the exertion of the lower body toward balance maintenance and force generation.
This additional role of the lower body can change the conventional coordinative pattern often employed in two-handed movements. Voluntary movements of the hand showed an immediate and natural coupling with the same direction of foot movement (Baldissera et al., 1982). Transition pathways or routes between patterns, as in bimanual tapping, turn out to be governed by pattern stability. That is, it is much easier to switch from a less stable to a more stable pattern than vice versa. Great care and attention are required to move the two limbs in opposite directions, a difficulty which often leads subjects to revert spontaneously to the easy pattern (in-phase).

Jagacinski et al. (2008) argued that, contrary to bimanual coordination which integrates a single temporal schema, different temporal schemas are used in a golf swing for the upper body and the weight shift. The intrinsic frequency differences between the large limbs of the lower body and relatively smaller limbs of the upper body could be one possible explanation for the deviation from bimanual coordination. However, it should be considered how balance maintenance affects this strategy, since the lower body has two functions in a golf swing. Depending on the degree of attention given to each role, different coordinative patterns will appear; for example, more emphasis on balance maintenance may lead to a reverse weight transfer pattern in which weight shift towards
the front foot compensates for the movement of upper body towards the back foot during the backswing. Thus, golfers with low balance capability may have a limited magnitude of weight shift, so that a negative correlation is expected between balance capability and weight shift magnitude: the more stable balance capability golfers have, the larger magnitude of weight shift.

Many components in the movement of the lower body affect balance maintenance such as the weight distribution in the anterior/posterior plane and the medial/lateral plane in terms of the center of pressure and the rotational force of each foot (Barrentine, Fleisig, Johnson, and Woolley, 1994). Of special interest among these components is the movement pattern of the center of the pressure in the medial/lateral plane. In order to fully exploit resources for force generation, the center of pressure needs to have maximal displacement in the same direction that the clubhead is traveling; during the backswing, for example, the center of pressure should move toward the back foot.

This, however, could disrupt balance if the center of pressure moves too far to the right (toward the back foot) during the backswing or to the left (toward the front foot) during the downswing and follow-through. Thus, golfers adjust their lower body
movement and distribute their force against the ground in an appropriate manner to avoid falling or an awkward swing. It is hypothesized that golfers with special concern for balance do not shift their center of pressure laterally sufficiently.

**Coordinative strategies in a golf swing**

Many strategies exist for adapting the hitting movement employed in the task at hand. One such strategy involves adjusting the weight shift (Jagacinski et al., in press). Note that this strategy does not change the movement time of the swing. The force to the clubhead is primarily generated from the lower body and transferred to the clubhead through the upper body. Increased force to the clubhead can be obtained by adjusting the lower body movement. For example, decreasing movement time of the lower body results in a quicker weight shift, which produces more ground reaction force. The linkage between lower body movement time and clubhead force is not direct, but with the assumption that the lower body is a primary source of force generation, this linkage can be considered an example of how shorter lower body movement time can increase force.

Of particular interest is the predominance of an independent control structure in a golf swing. Contrary to the bimanual tapping studies, the study by Jagacinski et al. (in
press) showed that the time intervals of the clubhead (primarily controlled by the upper body) and of the weight shift (primarily controlled by lower body) were at best very weakly correlated. However, this finding may not be generalizable, because the experimental tasks in their study were relatively short chip shots. Also, participants were limited to younger players with a relatively advanced skill level (handicap 5-10 strokes). Replication of the study using more forceful shots with different age groups and skill levels will provide more information about coordinative patterns of the upper and lower body in a golf swing.

In addition, the same demographic group of participants (aged 18-25 and handicap 5-10 strokes) as in the chip shot study was included in the present study. Combining the results of chip shot study by Jagacinski et al. (in press) and the present study will demonstrate whether or not the temporal invariance of the clubhead force pattern and the adjustment of the weight shift for chip shots are maintained for the more forceful shots.

The theory of spring-like movement dynamics offers one explanation of the observed temporal invariance of the swing time intervals for chip shots requiring different amounts of force (Jagacinski et al., in press). Grober and Cholewicki (2008)
investigated the relationship between the applied torque and maximum torso rotation
during the backswing. They found it to be approximately linear for low to intermediate
levels of torque in accordance with a linear spring characteristic, which they
approximated with a simple harmonic oscillator. The magnitude of torque changes
without varying the timing pattern in this linear spring model. In contrast, for higher
levels of the torque, participants showed non-linear spring characteristics in their rotary
dynamics. In other words, the spring becomes stiffer as the torso rotation increases.

Similar non-linear spring characteristics are expected in the present study, a
prediction which is further justified by the study by Jagacinski et al. (in press). The
authors asked participants to attempt chip shots at a low target and at a high target using
a standard eight iron. The experimental setting employed in the present study is
comparable to that employed by Jagacinski et al.: 40-yard and 80-yard approach shots
were attempted using a standard eight iron. One can predict that as the force magnitude
increases (from a chip shot to a low target to a chip shot to a high target to a 40-yard
approach shot to an 80-yard approach shot), the maximum trunk rotation will change
from a linear-spring characteristic for the less forceful shots to a non-linear spring
characteristic for the more forceful shots.
**Age-related differences in a golf swing**

Studies of perceptual-motor tasks have shown that people become slower as they age (Welford, 1982). Such slowing might result from an age-related decline of fundamental physiological processes (Birren, 1974), and/or a strategic compensation for the decreased physiological signal-to-noise ratio (Myerson, Hale, Wagstaff, Poon, & Smith, 1990). However, studies of the golf swing did not show an age-related slowing for older golfers (Redanty, 1975; Jagacinski, Greenberg, & Liao, 1997). This may be because golfers hit a ball which is stationary at address, without re-locating or adjusting their positions, thus they do not have to deal with above-mentioned differences. However, physical limitations such as stiffness of the trunk (Taylor & Johnson, 2008) may constrain the movement of body segments in older golfers. Therefore, the comparison between younger and older golfers should reveal age-related similarities and differences between a golf swing and other perceptual-motor tasks.

The hypothetical limitation of using lower body movement due to a concern for balance might lead older adults to focus more on upper body movement for force generation. This may, sometimes, prevent them from making a strong, long distance shot since a tendency of reverse weight shift or relatively smaller weight shift than required
disturbs the forward motion of the swing; if such a shot is attempted with a reverse weight shift in extreme cases, golfers may struggle to maintain their balance due to the conflict between the forward movement of the upper body and weight shift to the back foot. It is possible that older adults lose the coordinative ability to transmit power from the lower body to the upper body, consequently causing them to use their upper bodies to hit the ball forward. In this case, the trunk would not efficiently transfer vertical forces generated from the lower body to rotational forces. It is hypothesized that older adults with more concern for balance may show less usage of the trunk rotation.

Older adults tend to lean backward while standing, which is not efficient for transitioning to other movements such as walking. They try to compensate for balance problems by shortening step length to ensure gait stability. Similarly, for balance maintenance, older golfers might have a tendency to lessen their lateral weight shift during a swing, possibly with a wider stance (Cromwell & Newton, 2004). Also, the tendency to lean backwards affects the displacement of the center of pressure in the anterior/posterior plane and in the medial/lateral plane. In other words, older golfers may try to hold their center of pressure near the middle of the stance. Thompson (2002) showed that movement of the center of pressure decreased in older golfers. This could
mean that older players intend to use their lower body for balance maintenance rather than power generation, which may be a primary difference between older and younger golfers.

The concern for balance maintenance might also lead older golfers to secure their posture before attempting their swing. Thus, older golfers may lean backward more than younger golfers in order to keep from falling over toward the ball during the swing. Leaning backwards might be an anticipatory postural adjustment whose main goal is to minimize the postural disturbance created by the movement (Bouisset & Zattara, 1987). In training, golfers are typically instructed to put their weight on the balls of their feet, and to locate their foot centers of the pressure at about two-thirds of the distance from the heel toward the toes (Harmon, 2003); this adjustment allows them to generate substantial power from the lower body, without overly disturbing their balance maintenance. However, this method may not be very appropriate for older golfers who tend to lean backward in order to avoid tumbling down. Therefore, older golfers might have a different presetting of their centers of pressure prior to the shot.

Assuming that older golfers lean backwards to avoid falling down, it is also of interest how this anticipatory adjustment affects the swing. For example, the clubhead
speed and the amount of movement of the center of pressure were suggested to change with age (Brown et al., 2002). Yet, general fitness was not found to affect clubhead speed (Thompson, 2002), which indicates that differences in muscular strength were not a primary reason for differences in the clubhead speed. Instead, the more the center of pressure moves in the medial/lateral plane, the faster the swing. The range of the center of pressure was correlated positively with the clubhead speed and negatively with age (Ball et al., 2002; Mason et al., 1995). A smaller range of the center of pressure may correspond to less weight transfer and a slower swing.

Golfers who tend to use the upper body as the primary means of force generation may experience two possible patterns of weight shift. First, the pattern of weight shift may not largely differ with increased shot distance when force generation is adjusted only by the upper body movement. In this case, the correlation between the weight shift magnitude or velocity and the force applied to clubhead will be near zero. The other possibility is that a reverse weight transfer increases with longer shot distance, in which the lower body leans more toward the front foot during the backswing and more toward the back foot during the downswing and follow-through. In this case, a negative correlation between the weight shift and the force applied to the clubhead will appear.
It has been demonstrated that a bigger weight shift is used for more forceful chip shots by younger adults (Jagacinski et al., 2008). The difference in weight shift between shots can be further investigated by comparing 80-yard and 40-yard approach shots. 80-yard shots require more force than 40-yard shots which would be generated by larger and/or quicker weight shift. However, this pattern may not hold for older golfers, assuming they depend more on their upper bodies for force generation. Thus, it is hypothesized that the ratio of $W_2 - W_1$ for the 80-yard shots to $W_2 - W_1$ for the 40-yard shots will be larger for younger golfers than for older golfers.

In summary, in a hitting task such as a golf swing, the rhythm golfers are using in their swing in terms of timing should not change; more specifically, when golfers have to adjust their swings for different force magnitudes, they should not change their rhythms, but instead adjust their weight transfer. With regard to the coordinative movement of the upper and lower body, the additional constraint on the lower body, balance maintenance, must be considered, since to some extent balance maintenance interferes with lower body force generation. These expectations lead to the following hypotheses for hitting a golf ball.
Concerning the relationship between the force generation and balance maintenance capability, increased concern with balance will lead older golfers to rely more heavily on the upper body for force generation, with relatively less movement of the lower body. If this is the case, the range of the center of pressure should be more limited for older golfers than for younger ones. This contrast is heightened depending on the needed force. Thus, the difference between the ranges of the center of pressure for older and younger golfers will be larger for the 80-yard shots than for the 40-yard shots.

Consequently, the weight shift timing of the lower body will be slower for older golfers. In other words, if the lower body is used less for force generation, the time interval between \( W_1 \) and \( W_2 \) will increase; this slow weight shift leads to a smaller amount of force generation. Also, the force difference between \( W_1 \) and \( W_2 \) may be less for older golfers than for younger ones. Finally, if the upper body has to generate most of the force, then the movement of the upper body will be quicker. This may explain why older golfers showed a tendency for a relatively quicker swing for chip shots (Jagacinski et al., 1997).

The purposes of the present study can be classified into three major categories. The first goal is to test if the coordination pattern in chip shots is generalizable to more
forceful shots, and consequently to help develop the definition of the overall rhythm of
the golf swing. The second goal is to measure the covariance timing pattern of multi-limb
coordination, specifically between the upper and lower body coordination with a more
naturalistic task than has been used in past studies. The third aim of this research is to
determine the effects of age and skill level on the upper and lower body coordination. In
other words, this study is designed to investigate how age and skill level affect the
adaptive capability for different task demands, and to characterize the difference in
coordination patterns of the upper and lower body depending on age and skill level.
Chapter 2: Experimental Design

The present study investigates the golf swing, a task that involves coordinated movement of the upper and lower body. The golf swing has features in common with many tasks involving upper and lower body movements, such as balance maintenance. This study also explores golfers’ adaptive strategies for adjusting the polyrhythmic force patterns in the golf swing when golfers are required to use the same club for different target distances.

<table>
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<th><strong>Experimental Design</strong></th>
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| **Between Subject Variables** | Age: Younger (18-25 years), Older (60-69 years)  
|                          | Skill level: Advanced (handicap 5-10 strokes), Intermediate (handicap 15-20 strokes)  
|                          | 10 male subjects for each combination of age and skill level  
|                          | (a total of 40 subjects) |
| **Within Subject Variable** | Force level: 40-yard shot and 80-yard shot, both with an 8 iron  
|                          | 10 practice shots and 60 data shots for each distance per data day  
|                          | 1 practice day and 2 data days (120 total data shots per condition) |

Table 1. Experimental Design
Golfers of different age groups and skill levels were investigated. Subjects were divided into four groups corresponding to the various combinations of age (older and younger golfers) and skill level (advanced and intermediate). Each golfer attempted approach shots for two different distances, 40 yards and 80 yards. By using two different distances, it was possible to test how the coordination pattern is affected by changes of force. It was also helpful to determine the role of the lower body with regard to the maintenance of balance as well as force generation. To sum up, there were two between-subject variables (age and skill level) and one within-subject variable (force level), as seen in Table 1.

In addition, individual differences in balance maintenance were an important topic in this study. As mentioned before, older adults tend to be more concerned with balance than younger adults, but the effects of individual differences in balance on swing skill is not yet clearly established. Balance maintenance capability is expected to covary with the degree of involvement of the lower body movement in force generation. In other words, those with better balance capability should be better at generating and transferring force from the lower body.
Individual differences in balance capability may occur in the medial/lateral plane and/or the anterior/posterior plane. A pretest measure of balance capability in both dimensions was expected to covary with the degree of involvement by the lower body in balance maintenance and accordingly, how individual golfers adjust their upper and lower body coordinative strategies.

There were four types of balance pretest, all conducted with eyes open. First, subjects’ general balance capability was measured by their regular standing posture on two legs and one leg without a golf club. Second, subjects were asked to assume two positions in a golf swing in order to assess their task-related balance capability. Subjects were initially asked to stand at the address position while holding the club, the posture golfers assume just before a shot is made. This position demonstrates balance capability primarily in the anterior/posterior plane. Then subjects were asked to commence their swing, but to stop halfway through the downswing, when the club is nearly parallel to the ground; this position demonstrates balance capability primarily in the medial/lateral plane.

The hypotheses of the present study can be recapitulated and classified into three categories: generalization of the coordination pattern found previously in chip shots, the
upper and lower body movement pattern, and the effect of balance maintenance. First, would findings from chip shots generalize to more forceful shots such as the 40-yard and 80-yard approach shot? It was expected that timing invariance of clubhead movement (F1-F2 and F2-F3 time intervals) would be demonstrated regardless of the exerted force. In contrast, the time interval of the weight shift (W1-W2 time interval) would be adjusted to achieve more forceful shots; in other words, more forceful shots require a quicker weight shift in the lower body, and greater force is then transferred through the upper body to the clubhead.

Regarding upper and lower body timing patterns, it was expected that the covariance timing pattern would differ depending on the skill level and age. An independent timing structure was expected for younger golfers and for more skilled golfers, while an integrated timing structure was expected for older golfers and for less skilled golfers.

Second, does the role the lower body plays in force generation differ between two different approach shots? It was expected that more force would be generated and transferred from the lower body to the upper body for the longer 80-yard shot. This pattern should be especially apparent for younger golfers, rather than for older golfers,
who rely more on the upper body for force generation. Thus, the ratio of the magnitude of \( W_2-W_1 \) for the two shot distances would be larger for younger golfers than for older golfers; for younger golfers, the difference would be greater depending on their skill level.

Third, how does balance capability affect the degree to which the lower body is being used for force generation? For those with more concern for balance, the lower body may be primarily used for balance maintenance rather than for force generation. With less use of the lower body for power transfer, the range of the center of pressure was expected to be smaller for older golfers, regardless of shot distance. Also, the weight shift pattern of older golfers was expected to be different from that of younger golfers. Older golfers were expected to neglect adjustment of the time interval \((W_2-W_1)\) because they underutilize their lower bodies in the golf swing. Therefore, the difference in the weight shift timing for the 80-yard shots and 40-yard shots was expected to be relatively smaller for older golfers than for younger ones. Also, the magnitude of weight shift was expected to be smaller for older golfers.

Balance capability may also affect the covariance of the force magnitudes of the upper and lower body depending on age group. Less use of the lower body by older
golfers who have a concern for balance should result in a positive correlation of balance
capability with the range of the center of pressure. Further, this study should help
determine how younger and older golfers at different skill levels are distinct in terms of
their coordination strategies.
Chapter 3: Method

Participants

Participants were drawn from two age categories. Twenty male students, ranging in age from 18 to 25, comprised the younger age group; they participated in the study as a way of fulfilling a research experience assignment in an introductory psychology course. Similarly, twenty older adults ranging in age from 60 to 69 participated as older age group; they were paid $20 per one and a half hour session. Each group was then sub-divided into two groups based on their handicap scores for the previous year; golfers with handicaps of 5 to 10 strokes were considered an advanced skill level group, while those with handicaps of 15 to 20 strokes were considered an intermediate skill level group. One younger golfer with advanced skill level was replaced because he showed very inconsistent performance over the two data days and did not pass a statistical test for stationary performance.

All participants were right-handed and had a hand size corresponding to a medium size golf glove. They reported having no painful arthritis or heart problems,
exercised at least twice per week, and reported not taking any medication that might impair performance. Participants were tested to assure they had at least 20/25 corrected vision at a distance of 5 ft. All participants reported having played 18 holes of golf at least 20 times per year over the previous five years, which was a prerequisite for inclusion in the experiment.

**Apparatus**

A modified eight iron (Titliest Tour Model) was used to test clubhead force. A miniature strain-gauge accelerometer (Entran Model EGAXT-F*-25) was mounted on the rear of the clubhead after the removal of an approximately equal mass of metal. The accelerometer was placed at the approximate center of gravity of the clubhead and provided an estimate of the applied force perpendicular to the face of the clubhead. The accelerometer signal was sampled at 720 Hz.

As reviewed in more detail by Jagacinski et al. (1997, pp. 161-162), except at the brief instant of ball contact when there is an additional impulsive force, the force applied to the ball is given by:

\[
ma = F + mg
\]  

(1)
where \( m \) is the mass of the clubhead, \( a \) is its acceleration, \( F \) is the force applied through the shaft, and \( g \) is the acceleration due to gravity. Rearranging this three-dimensional vector equation:

\[
\frac{F}{m} = a - g
\]  

(2)  

The strain-gauge accelerometer is sensitive to the acceleration of the clubhead (\( a \)) minus gravitational acceleration (\( g \)) (Hayes, Gran, Nagurka, Feldman, & Oatis, 1983), which is proportional to the force applied through the shaft (\( F \)) (Equation 2).

A swing analyzer (P3Pro Swing) was placed under the tee to measure the velocity of the clubhead at impact and provided an estimate of the distance and angular deviation of ball flight. These measurements were displayed on a screen located 14 feet (427 cm) away from the tee, and were provided to the subjects as feedback.

Participants wore 13 magnetic sensors (Ascension Technology) that were attached to the back of the head, the upper and lower spine, the backs of their hands via right and left golf gloves, the forearms, the upper arms, and the upper and lower legs. The calibration procedure consisted of measuring the positions of the top of the head, fingers, wrists, elbows, shoulders, spine (T12/L1), hips, knees, and ankles. The participants stood on a green mat of artificial turf, below which two force plates (Bertec)
were placed and sampled at 720 Hz. White tape demarcated two adjacent regions, each approximately 22 x 14 inches (56 x 36 cm); these regions indicated where participants should place their feet such that they would be directly over the force plates. The magnetic sensor signals were sampled at 120 Hz. The magnetic sensor data provided an initial real-time estimate of when the clubhead made contact with the ball. Measurements were taken between 3 seconds prior to and 2 seconds after impact.

**Procedure**

Four different types of pretests for balance measure were executed. Subjects were asked to stand in four different postures, all with eyes open – on two feet without the golf club; on one foot without the golf club; at the address position holding the golf club as they would just before a shot; and at the moment halfway through the downswing while holding the club. The force exerted against the ground was recorded for 10 seconds in each position.

Each block of trials consisted of 10 consecutive shots that the participant attempted to land in the target region. Prior to each shot, the experimenter placed a golf ball on the tee and gave the golfer a ready signal, after which the golfer could swing
whenever ready. Subjects were instructed to make an approach shot with a distance of around 80 yards to the hole and another approach shot of around 40 yards to the hole, which was displayed on the video screen. On Day 1 there was one practice block with a non-instrumented eight-iron followed by six data blocks with the instrumented eight-iron for each distance. There was a brief 1-2 minute break between data blocks.

Participants who landed at least 20% of their non-practice shots in the target circles on Day 1 were permitted to continue (no participant was excluded due to this criterion). The target circles had diameters of 8 yards for the 80-yard shots and 4 yards for the 40-yard shots; the diameters were thus 10% of the total shot distance. The procedure on Days 2 and 3 consisted of one 10-trial practice block and six data blocks per each distance, for a total of 10 practice shots and 60 data shots per condition per day, and a total of 120 data shots across two days. Half of the participants attempted the 80-yard approach shot first, and the other half attempted 40-yard approach shot first. The order of the two different distances was counter-balanced across days.

**Dependent Measures**

The forces applied to the clubhead and against the ground were measured during
each trial: the weight shift pattern and the range of the center of pressure were calculated from the force against the ground. The clubhead velocity at impact was measured from the launch monitor. In addition, the amount of pelvic and trunk rotation were measured from the sensors on the participant’s body.
Chapter 4: Results

The data collected on Day 1 were considered practice, and therefore were not included in the analysis. For 17 of the golfers, some of the trials were excluded from the analysis because of significant electronic noise, so that the total number of analyzable shots per distance was reduced; however, there were never fewer than 100 analyzable shots out of 120 shots. The lost time histories amounted to 4.5% of the total data set. The shots landing in the target regions (the 8-yard and 4-yard circles) for each shot were considered made shots, while the shots landing outside of those regions were considered missed shots. In other words, ± 10% of the total shot distance was allowed as deviation from the targeted point, resulting in 80 ± 8 yards for the 80-yard shot and 40 ± 4 yards for the 40-yard shot.

Across 40 golfers, the percent of shots landing in the target region ranged from 31% to 93%; overall, the mean percentage of shots on target was 69%. In more detail, it ranged from 53% to 92% for the 40-yard shot (mean = 73%) and from 31% to 93% for
the 80-yard shot (mean = 65%). Overall, a larger number of shots were landed in the target region for the 40-yard shot than for the 80-yard shot, $F(1, 36) = 17.93, p < .01$. The two age groups did not show differences in the number of shots on target, but the performance of the advanced level group (mean = 74%, SD = 11%) was significantly better than that of the intermediate level group (mean = 53%, SD = 12%), $F(1, 36) = 11.62, p < .01$.

Mean Clubhead Force Patterns for Different Target Distances

The peaks for three events in the clubhead force pattern, $F_1$, $F_2$, and $F_3$ (the backswing, downswing, and follow-through, respectively, as seen in Figure 3) were identified from the accelerometer signal for each shot. $F_2$ was identified as a global minimum in the time history of the force pattern; $F_1$ was identified as the maximum in the preceding time history; $F_3$ was identified as the maximum in the subsequent 1 s of time history after $F_2$ (for more details of pattern recognition, see Jagacinski et al., in press). The times at which these peak forces respectively occurred ($T_{F1}$, $T_{F2}$, and $T_{F3}$) were also identified.
Figure 3. The skeleton figures at the top show the approximate positions of a golfer corresponding to peaks in the time histories for clubhead force and weight shift. The middle graph shows the force pattern applied to the clubhead during a golf shot with peaks, $F_1$ (backswing), $F_2$ (downswing), $F_3$ (follow-through), and impact. The bottom graph shows the weight shift pattern with peaks, $W_1$ (shift to back foot) and $W_2$ (shift to front foot). $W_0$ corresponds to a forward press at the beginning of the shot.

A three-way analysis of variance (distance, age, skill level) was conducted on the mean force magnitudes differences ($F_1-F_2$) and also on the mean time intervals ($T_{F2}-T_{F1}$) of the clubhead force pattern between the peak backswing and downswing forces for the 80-yard and 40-yard shots. A larger force magnitude difference was observed for the 80-
yard shot than for the 40-yard shot: 18.92 N/mg (80-yard) vs. 6.66 N/mg (40-yard),

\[ F(1, 36) = 3405.90, \ p < .01. \]

Similarly, a longer time interval was observed for the 80-yard than for the 40-yard shot: 0.97 s (80-yard) vs. 0.80 s (40-yard), \( F(1, 36) = 64.49, \ p < .01 \). However, age and skill level differences were not statistically significant in either analysis of variance.

The ratio of mean time intervals between the peak backswing and downswing forces for the 80-yard and 40-yard shots, \( \frac{(T_{F2}-T_{F1})_{80yds}}{(T_{F2}-T_{F1})_{40yds}} \), was calculated for each golfer in order to understand the pattern of adjustment for two different target distances. The magnitudes of the mean force differences were compared in the same way; \( \frac{(F_1-F_2)_{80yds}}{(F_1-F_2)_{40yds}} \) was calculated for the force differences between the backswing and downswing. These timing and force magnitude ratios for the backswing and downswing interval are cross-plotted on each axis of the four graphs in Figure 4, where each number (1-10) corresponds to a different participant.

As shown in Figure 4, golfers adjusted the time interval and force magnitude. Comparing the 40-yard and 80-yard shots across all four groups, golfers changed their timing a relatively small amount (by a factor of 1.20); median ratios are 1.15, 1.26, 1.20, and 1.21 for (A), (B), (C), and (D) in Figure 4, respectively. When comparing
Younger Golfers

Advanced Skill Level

Older Golfers

Intermediate Skill Level

Figure 4. The ratios of the time intervals and force differences between the backswing and downswing for the 80-yard to 40-yard shots are cross-plotted. The horizontal axis displays the ratio for the time interval (T_{F2}-T_{F1}) between the peak forces, and the vertical axis displays the ratio for the peak force difference (F_1-F_2) between the downswing and follow-through. The graphs (A), (B), (C), and (D) represent younger golfers with advanced skill level, older golfers with advanced skill level, younger golfers with intermediate skill level, and older golfers with intermediate skill level, respectively. Again, in all four graphs, each number (1-10) corresponds to a single individual golfer. The point (1.0, 1.0) corresponds to no change between the 80-yard and 40-yard shots.
the 40-yard and 80-yard shots in terms of force magnitude, a larger adjustment by a factor of 2.8 is seen; median ratios are 3.09, 2.69, 2.79, and 2.68 for (A), (B), (C), and (D) in Figure 4, respectively. In addition, the data points are quite tightly clustered in terms of the time interval; the standard deviations range from 0.11 to 0.21. Two-way analyses of variance (age, skill level) revealed no statistically significant differences across the four groups of golfers for either the timing ratios or the magnitude ratios of the clubhead force pattern during the backswing-downswing.

Additionally, a two-way analysis of variance (age, skill level) was conducted on the standard deviations of the time intervals and also on the standard deviations of the force magnitude differences for each shot distance during the backswing-downswing. Golfers with intermediate skill level showed larger variability than did those with advanced skill level in both force magnitude differences ($F_1 - F_2$) and time intervals ($T_{F1} - T_{F2}$): for the 40-yard shot, $F (1, 36) = 8.43, p < .01$ for the force magnitude (mean standard deviations were 0.127 N/mg and 0.173 N/mg for advanced and intermediate skill levels, respectively), and $F (1, 36) = 6.06, p < .05$ for the time intervals (mean standard deviations were 0.052 s and 0.075 s for advanced and intermediate skill levels, respectively). For the 80-yard shot, a significant difference was observed for the force
magnitude differences (mean standard deviations were 0.360 N/mg and 0.422 N/mg for advanced and intermediate skill levels, respectively), \( F (1, 36) = 5.41, p < .05 \), but not the time intervals. Overall, as skill level increases, performance becomes more consistent (Schmidt & Lee, 2005). There was no significant age effect in any of these analyses.

Similarly, the mean force magnitude differences \((F_3-F_2)\) and the mean time intervals \((T_{F3}-T_{F2})\) between the peak downswing and follow-through forces were analyzed for the 80-yard and 40-yard shots. Two three-way analyses of variance (distance, age, skill level) showed a larger force magnitude difference and a longer time interval for the 80-yard shot than for the 40-yard shot: 18.86 N/mg (80-yard) vs. 7.14 N/mg (40-yard), \( F (1, 36) = 2317.67, p < .01 \), and 0.52 s (80-yard) vs. 0.32 s (40-yard), \( F (1, 36) = 47.00, p < .01 \) for the force magnitude and time interval, respectively. Once again, no significant differences were observed for age and skill level.

Also, the ratios of mean time intervals and mean force magnitude differences between the peak downswing and follow-through forces were calculated for each golfer, \((T_{F3}-T_{F2})_{80yds}/(T_{F3}-T_{F2})_{40yds}\), and \((F_3-F_2)_{80yds}/(F_3-F_2)_{40yds}\), respectively. These ratios are cross-plotted in Figure 5, and once again, each of the numbers (1-10) corresponds to a single golfer.
Figure 5. The ratios of the time intervals and force differences between the downswing and follow-through for the 80-yard to 40-yard shots are cross-plotted. The horizontal axis displays the ratio for the time interval ($T_{F3} - T_{F2}$) between the peak forces, and the vertical axis displays the ratio for the peak force difference ($F_{3} - F_{2}$) between the downswing and follow-through. The graphs (A), (B), (C), and (D) represent younger golfers with advanced skill level, older golfers with advanced skill level, younger golfers with intermediate skill level, and older golfers with intermediate skill level, respectively. Again, in all four graphs, each number (1-10) corresponds to a single individual golfer. The point (1.0, 1.0) corresponds to no change between the 80-yard and 40-yard shots.
In comparison with the backswing-downswing force ratios (Figure 4), Figure 5 shows that a similar adjustment occurred for the magnitude of force differences by a factor of 2.7 from the 40-yard to 80-yard shot. The median ratios are 2.91, 2.48, 2.67, and 2.59 for (A), (B), (C), and (D) in Figure 5, respectively. However, in comparison with the backswing-downswing interval, the downswing-follow-through interval displayed a relatively larger adjustment for the time interval (overall mean ratio = 1.54; the median ratios are 1.37, 1.63, 1.47, and 1.69 for (A), (B), (C), and (D) in Figure 5, respectively). More importantly, the time interval ratios do not show a consistent pattern across golfers; the standard deviations range from 0.42 to 0.89. Two two-way analyses of variance (age, skill level) showed that the timing ratios and force magnitude ratios did not differ significantly across the four groups of golfers.

Additionally, a two-way analysis of variance (age, skill level) was conducted on the standard deviations of the time intervals and also on the standard deviations of the force magnitude differences for each shot distance during the downswing-follow-through. In contrast to the skill level effects found for the backswing-downswing, no significant difference was observed in the variability of the time intervals and force magnitude differences with age or skill level.
Overall, these data show that the golfers adjusted their swings for the more forceful 80-yard shot by increasing the magnitude of force applied to the clubhead and through a proportionately smaller change of the timing pattern for the backswing and downswing. Given that the time interval between the downswing and follow-through \((T_{f3}-T_{f2})\) is not consistent across golfers, the backswing-downswing interval \((T_{f2}-T_{f1})\) seems to play a more important role in controlling the timing pattern of the shot.

**Mean Weight Shift Patterns for Different Target Distances**

Golfers shift their vertical force against the ground initially to the back foot during the backswing and subsequently to the front foot as their swing progresses (e.g., Barrentine et al., 1994; Carlsoo, 1967). As the measure of the weight shift, the difference between the vertical forces on the force plates for each foot was used. A negative difference indicates that the weight is primarily on the back foot, and a positive difference indicates that the weight is primarily on the front foot (the bottom graph in Figure 3). The peak forces for the two events of the weight shift, \(W_1\), and \(W_2\), (the peak forces for back foot and front foot, respectively) were identified from the time histories of the weight shift pattern. The peak back foot weight shift, \(W_1\), was identified as the
local minimum in the time history between $F_1$ and $F_2$. The peak front foot weight shift, $W_2$, was identified as the maximum in the subsequent 1.25 s of time history after $W_1$ (the search window for $W_2$ was adjusted in 3.5% of the trials; for more details of pattern recognition, see Jagacinski et al., in press). The times at which these peak forces respectively occurred ($T_{W1}$ and $T_{W2}$) were also identified.

Given that older participants were heavier than younger participants by an average of 30 pounds (133 N), the magnitude of the weight shift needed to be normalized.

In a hitting task, forces are generated initially by the reaction against the ground and transferred to the trunk for the rotational force. Generally, heavier people produce larger forces against the ground, which in turn allows proportionately larger rotational force to rotate their heavier bodies. Thus, to compare the weight shift magnitude across age groups, it needed to be normalized by the golfer’s weight: $(W_2-W_1)/\text{Weight}$. Note that if a golfer put 100% of their weight on their back foot, and then 100% of their weight on their front foot, the value of normalized weight shift would equal 2.

A three-way analysis of variance (distance, age, skill level) was conducted on the mean normalized weight shift magnitudes $[(W_2-W_1)/\text{Weight}]$ and also on the mean time intervals $(T_{W2}-T_{W1})$ between the peak back foot and front foot weight shifts for the
different target distances. A larger magnitude was exerted against the ground for the 80-yard shot than for the 40-yard shot: 1.29 (80-yard) vs. 0.89 (40-yard), \( p < .01 \). However, an approximately equal time interval was observed for both distances: 0.73 s (80-yard) and 0.72 s (40-yard), \( p > .10 \). Again, age and skill level differences were not statistically significant in either analysis of variance.

The ratio of mean time intervals between the peak back foot and front foot weight shifts for the different target distances, \( (T_{W2}-T_{W1})_{80\text{yds}}/(T_{W2}-T_{W1})_{40\text{yds}} \), was calculated for each golfer in order to explore the pattern of adjustment by the lower body movement for two difference target distances. Also, differences in the magnitude of weight shift between the back foot and the front foot were compared by calculating the ratio \( (W_2-W_1)_{80\text{yds}}/(W_2-W_1)_{40\text{yds}} \) for each golfer. The ratios of the time intervals and magnitudes of weight shift are cross-plotted for each of the four groups of golfers in Figure 6, where each number (1-10) corresponds to a different participant.

The timing ratios fall close to the value of 1.0, which corresponds to no change in the weight shift timing between the 80-yard and 40-yard shots (median ratios are 0.95, 0.93, 0.99, and 0.99 for (A), (B), (C), and (D) in Figure 6, respectively). The ratio of 80-yard to 40-yard shots for the weight shift magnitudes indicated an increase by a factor of
Figure 6. The ratios of the time intervals and magnitudes of weight shifts for the 80-yard and 40-yard shots are cross-plotted. The horizontal axis displays the ratio of the timing ($T_{W2}/T_{W1}$), and the vertical axis displays the ratio of the weight shift magnitude ($W_{W2}/W_{W1}$). The graphs represent younger golfers with advanced skill level, older golfers with advanced skill level, younger golfers with intermediate skill level, and older golfers with intermediate skill level in (A), (B), (C), and (D), respectively. Again, in all four graphs, each number (1-10) corresponds to a single golfer. The point (1.0, 1.0) corresponds to no change between the 80-yard and 40-yard shots.
1.45 (median ratios are 1.38, 1.39, 1.64, and 1.41 for (A), (B), (C), and (D) in Figure 6, respectively). These data indicate that the golfers adjusted the force magnitude of their weight shift, and the timing pattern of the weight shift was approximately invariant. In general, there is no systematic trend to alter the timing intervals with changes in the force of the shot.

Additionally, a two-way analysis of variance (age, skill level) was conducted on the standard deviations of the time intervals and also on the standard deviations of the normalized weight shift magnitudes for each shot distance. Golfers with intermediate skill level exhibited larger variability in terms of the time interval during the weight shift for the 80-yard shot (mean standard deviations were 0.122 and 0.189 for advanced and intermediate skill levels, respectively), $F(1, 36) = 11.89, p < .01$; there was no significant skill level difference for the 40-yard shots. None of the analyses found significant age effects.

Additionally, a three-way analysis of variance (distance, age, skill level) was conducted on the average velocity of the weight shift, \[\frac{(W_2 - W_1) / \text{Weight}}{(T_{W2} - T_{W1})}\]. There was a significant effect of distance (0.72 s^{-1} (80-yard) vs. 0.55 s^{-1} (40-yard), $F(1, 36) = 56.1, p < .01$), but there were no significant effects of age and skill level.
Of additional interest is the number of subjects who showed a forward press, $W_0$, a weight shift toward the front foot immediately before the initiation of the swing. Many older golfers (17 out of 20 subjects) exhibited a forward press, $W_0$, on more than two-thirds of their shots; comparably fewer younger golfers (4 out of 20 subjects) exhibited $W_0$ on more than two-thirds of their shots, ($\chi^2 (1) = 16.94, p < .01$). This forward press, $W_0$, may function as a triggering event for the shot (Nicklaus, 1974), especially for older adults.

**Balance Capability and Weight Shift**

The pretest measures of balance capability identified how well participants maintain their balance in various positions. Participants performed 4 types of balance pretest, all with eyes open, where they were required to maintain the following positions for 10 s each: (1) standing on two feet without a golf club, (2) standing on the right foot without a golf club, (3) standing at the address position at the start of a golf shot, and (4) stopping about halfway through the downswing while holding a golf club. The standard deviation of the vertical forces exerted against the ground over the 10 s period was selected as a stability measure; the measure was converted to a log scale because of...
its wide range with a skew toward large values across all of the balance pretests (from 2 N to 42 N).

**Figure 7.** Balance pretest while standing on the right foot without a golf club. The vertical axis displays the logarithm of the standard deviation of the vertical forces exerted against the ground over 10 s.

A two-way analysis of variance (age, skill level) was conducted on each of the 4 balance measures. Only the second measure (standing on the right foot without a golf club) showed significant differences among groups (see Figure 7). Younger participants had a smaller standard deviation than did older participants (means of the logs of the standard deviation in N are 0.58 and 1.04 for younger and older golfers, respectively, $F$
participants with advanced skill level had a lower
standard deviation than did participants with intermediate skill level (means of the logs
of the standard deviation in N are 0.73 and 0.90 for advanced and intermediate skill
levels, respectively, $F(1, 36) = 6.35, p < .05$). This pattern was pronounced only for the
older participants as indicated by a significant interaction, $F(1, 36) = 4.58, p < .05$. A test
of the simple effect for the advanced skill level showed that younger golfers had a better
balance capability than did older golfers (means of the logs of the standard deviation in
N are 0.57 and 0.89 for younger and older golfers with advanced skill level, respectively,
$F(1, 19) = 13.978, p < .01$).

Golfers with unsteady balance may have their lower body focus more on the
balance maintenance. This may lead to relatively less usage of lower body for force
generation, and a smaller magnitude of weight shift. A correlational analysis was
conducted to examine the relationship between balance capability and the weight shift.
However, this balance pretest measure was not significantly correlated with the
magnitude of normalized weight shift across all 40 golfers, either for the 40-yard shot
($r = 0.20, p > .05$) or the 80-yard shot ($r = 0.17, p > .05$).
Range of the Center of Pressure and Mean Velocity at Impact for Different Target Distances

Past studies have found variations in the range of the center of pressure during a driver shot to be correlated with the clubhead velocity at impact and with age (Brown, Best, Ball, & Dowlan, 2002; Mason, McGann, & Herbert, 1995). However, it is unclear which plane of the center of pressure is most important for generating high clubhead velocity, and in what way the three factors (range of the center of pressure, clubhead velocity, and age) are related to one another.

Previous findings have shown different patterns of correlation with the clubhead velocity for driver shots: clubhead velocity has been found to be significantly correlated with the range of the center of pressure in the anterior/posterior plane, but not with the range of the center of pressure in the medial/lateral plane by Mason et al. (1995). However, Brown et al. (2002) maintained that golfers reduce the movement of their center of pressure in the medial/lateral plane as they become older, and this reduction leads to lower velocity of the clubhead. Note that the range of the center of pressure for a driver shot is expected to be substantially larger than that of the less-than-full-force iron shots in the present study; for the shots in the present study, the effects of age might
exhibit a different pattern.

The range of the center of pressure was calculated by observing the range in each plane over 3 seconds (from 1.5 s before to 1.5 s after impact), and then was normalized by the stance of each golfer. A three-way analysis of variance (distance, age, skill level) was conducted on the normalized range of the center of pressure in the medial/lateral plane and also in the anterior/posterior plane. No significant difference was observed for age and skill level.

The clubhead velocity at impact was recorded by a launch monitor located in front of the participants. A three-way analysis of variance (distance, age, skill level) was conducted on this measure; the swing velocity for the longer shot was twice the velocity exhibited for the shorter shot (Figure 8) (mean velocities were 22.44 mph and 44.82 mph for the 40-yard and 80-yard shots, respectively, $F(1, 36) = 9730.44, p < .01$). This result is consistent with Daish’s (1972) report that distance is approximately proportional to impact velocity due to the effects of gravity and air resistance. Also, there was a significant interaction between target distance and age, $F(1, 36) = 4.79, p < .05$. Tests of simple effects revealed that the clubhead velocity at impact produced by younger golfers was not different from that produced by older golfers for the 80-yard shot, but for the 40-
yard shot, younger golfers made slightly slower shots than did older golfers (mean clubhead velocities were 22.29 mph for the younger golfers and 22.60 mph for the older golfers).

**Figure 8.** Mean clubhead velocity at impact for older and younger golfers for different target distances.

A test of correlation was performed between the normalized range of the center of pressure and the mean clubhead velocity at impact. The mean clubhead velocity was not correlated with the normalized range of the center of pressure either in the medial/lateral plane or in the anterior/posterior plane. Also, no significant correlation was
found between the clubhead velocity at impact and age.

In contrast to the previous findings (Brown et al., 2002), no significant correlation was found between the normalized range of the center of pressure and the mean clubhead velocity. This difference from previous research may be because golfers pushed their center of pressure to the limit during a driver shot, but not in the approach shot.

**Force Transfer from the Lower Body to the Clubhead by Trunk Rotation**

The ideal swing is based on biomechanical properties. During the swing, the vertical force against the ground generated by the lower body should be transferred to the trunk to be converted into rotational force (torque); then, it should be transmitted through the shoulders and arms to the clubhead. During this process, the lower body including the pelvis functions as an axis of rotation, and should not be laterally shifted much for the efficient transfer of force to the trunk. However, the force transfer from the lower body to the trunk may not be executed efficiently (1) if the pelvis is shifted too much and (2) if the golfer focuses more on balance, having their lower and upper body move as one unit, especially for older golfers. Thus, the magnitude of the maximum trunk rotation was
analyzed because of its role in transmitting force from the lower body to the upper body.

A three-way analysis of variance (distance, age, skill level) was conducted to investigate differences in pelvic rotation. The 80-yard shot had a larger pelvic rotation than the 40-yard shot (46.55° for the 80-yard shot vs. 31.89° for the 40-yard shot, $F(1, 36) = 103.11, p < .01$). Also, intermediate level players had a significantly larger pelvic rotation (44.08° for intermediate level vs. 34.35° for advanced level, $F(1, 36) = 4.41, p < .05$). This difference by skill level implies that advanced players use their lower body as a supporting structure in a more stable way for an efficient force transfer to the trunk.

Similarly, a three-way analysis of variance (distance, age, skill level) was conducted to explore how age and skill level affect trunk rotation. As seen in Figure 9, the 80-yard shot had a larger trunk rotation than the 40-yard shot (47.57° for the 80-yard shot vs. 32.99° for the 40-yard shot, $F(1, 36) = 120.07, p < .01$). Also, younger golfers had a significantly larger trunk rotation than did older golfers (43.4° for younger golfers vs. 37.2° for older golfers, $F(1, 36) = 5.83, p < .05$). This difference suggests a greater transmission of lower body force by the younger golfers. Additionally, younger golfers with advanced skill level showed a trend toward larger maximum trunk rotation than
those with intermediate skill level, while approximately the same amount of trunk rotation was exhibited for two different skill levels in older golfers; however, the interaction between age and skill level did not reach statistical significance ($p < .10$).

**Figure 9.** Maximum trunk rotation for two different distances across golfers

*Correlational Analysis of Rhythmic Units*

A previous study of the golf swing suggests separate, relatively independent rhythmic units of behavior for the weight shift timing and the clubhead timing (Jagacinski et al., in press). Similarly, in the present study, evidence for separable,
relatively independent rhythmic units was found in the different patterns of temporal
adjustment of the clubhead force pattern and weight shift from the 80-yard to the 40-yard
shots. Golfers adjusted their clubhead timing pattern during backswing-downswing
(Figure 4) while the weight shift timing was approximately invariant (Figure 6) for these
two different shots. This dissociation suggests two separate rhythmic units.

Correlational analysis of temporal variability across repeated attempts at the
same shot was performed to find converging evidence for separable rhythmic units.
Figure 10 exemplifies two different rhythmic structures: an integrated structure and an
independent structure in a hitting task. In an integrated structure, the two timing patterns,
the time intervals of the weight shift and the clubhead, may be incorporated into one
sequence (Figure 10A). In other words, the weight shift timing, $W_1 \rightarrow W_2$ is integrated
with the clubhead timing, $F_1 \rightarrow F_2$ and $F_2 \rightarrow F_3$. As the clubhead timing changes, the
weight shift timing varies concomitantly, because they share common timing intervals,
$W_1 \rightarrow F_2$ and $F_2 \rightarrow W_2$. Thus, the two timing patterns should be highly correlated. By
contrast, in an independent structure, each timing pattern may function as an independent
rhythmic unit (Figure 10B). If the two timing patterns are independent, the independent
structure does not allow shared time intervals; only the beginning point of the two
streams of events is shared. In this case, the weight shift timing and the clubhead timing should change independently of each other. Thus, the two timing patterns should be uncorrelated or weakly correlated (Jagacinski et al., 1988; Vorberg & Wing, 1996).

![Diagram](image)

**Figure 10.** The rhythmic structure in a hitting task. F₁, F₂, and F₃ correspond to peak forces for the backswing, downswing, and follow-through, and W₁ and W₂ correspond to the peak weights shifts to the back and front foot, respectively. The curved lines correspond to time intervals between two events that constitute the temporal organization of the behavior. (A) displays an integrated structure and (B) displays an independent structure.


Analysis of the correlation between the clubhead timing and the weight shift timing across repeated shots was performed to test whether the two components are independent units or integrated units. First of all, to test performance stationarity, a chi-
square test was conducted on the number of shots landing on the target region by each
golfer for each target distance over two days. Chi-square tests were not statistically
significant ($p > .05$) for all golfers, except one golfer ($p < .05$) in the younger group, who
was replaced with another participant.

The correlation between $T_{F2} - T_{F1}$ and $T_{W2} - T_{W1}$ and between $T_{F3} - T_{F2}$ and $T_{W2} - T_{W1}$ are shown for each golfer for each shot distance for all four groups in Figure 11. Each number (1-10) corresponds to a single golfer; small font numbers correspond to the
40-yard shot, and large font numbers to the 80-yard shot. Data points encompassed by
the solid square in the center of each graph indicate that both correlations were not
statistically significant ($|r| < .18$, $p > .05$). For the younger golfers with advanced skill
level (Figure 11A), 17 points fall within this solid square out of 20 performances (10
golfers x 2 distances), while the remaining 3 performances fall within the dashed square,
an area of weak correlation ($|r| < .30$). For the older golfers with advanced skill level
(Figure 11B), 12 points fall within the solid square, and 7 out of the remaining 8
performances within the dashed square. For the younger golfers with intermediate skill
level (Figure 11C), 14 points lie within the solid square, and 1 out of the remaining 6
performances falls inside the dashed square. Finally, for the older golfers with
Figure 11. The correlation between $T_{F2} - T_{F1}$ and $T_{W2} - T_{W1}$ across shots is on the horizontal axis, and the correlation between $T_{F3} - T_{F2}$ and $T_{W2} - T_{W1}$ across shots is on the vertical axis in all four graphs. Each number corresponds to a single golfer. Numbers in the small font size correspond to the 40-yard shot, and numbers in the large font size correspond to the 80-yard shot. For data points within the solid square in the center of the graph, both correlations are not statistically significant ($p > .05$). For data points within the dashed square in the center of the graph, both correlations have absolute values less than .30.
intermediate skill level (Figure 11D), 9 points fall within the solid square, and 8 out of
the remaining 11 performances are located inside the dashed square. Overall, 89% of the
performances had non-significant or weak correlations between the clubhead timing and
weight shift timing.

A chi-square test was performed to determine whether the number of non-
significant correlations between the upper and lower body time intervals for the 40-yard
shot and for the 80-yard shot are interrelated across participants. The chi-square test did
not reveal any significant relation, \( \chi^2 (1) = 2.20, p > .13 \). Therefore, the data for the 40-
yard and 80-yard shots were treated as independent observations (n=80) for chi-square
tests of whether there is a difference in coordination structure for age groups and skill
levels. Younger golfers had more data points within the non-significant solid square than
did older golfers (Figure 11): 77.5% (younger golfers) vs. 55.0% (older golfers), \( \chi^2 (1) =
4.63, p < .05 \). More performances made by advanced golfers fell within the non-
significant region are than did those made by intermediate golfers; this difference,
however, did not reach statistical significance: 72.5% (advanced level) vs. 57.5%
(intermediate level), \( \chi^2 (1) = 2.21, p < .14 \).
In sum, most of the performances had no or weak correlation between the clubhead timing and the weight shift timing. This finding provides converging evidence that the two timing patterns constitute relatively independent rhythmic units of behavior. In addition, the independent structure was more prevalent in younger golfers. In other words, there was more temporal decoupling of the upper and lower body movements for younger players.

Meta Analysis of Spring-like Body Movement

The chip shot performance from the study by Jagacinski et al. (in press) was combined with the results of the current study in order to explore the claim by Grober and Cholewicki (2008) that the body exhibits spring-like movement dynamics during the golf shot. Among the four groups of golfers in the present study, only the younger golfers with advanced skill level (age 18-25, and handicap 5-10 strokes) were included in this analysis, because this subgroup of the current participants is comparable to the participants used in the previous study by Jagacinski and his colleagues.

Linear spring-like movement dynamics provided one possible explanation for the previously observed temporal invariance of the clubhead timing when the force of a
chip shot was increased (Jagacinski et al., in press) (Figure 12A). A linear spring permits change in movement amplitude without changing the timing. The larger range of performance obtained by combining data from the two studies reveals a non-linear spring characteristic for the relationship between the applied force and maximum torso rotation during the backswing (Figure 12B): the trunk plays a role of converting the vertical force generated from the lower body into rotational force or torque. This pattern is similar to that found by Grober et al. (2008). The relationship can be approximated as a linear spring for the low levels of forces used for chip shots. The nonlinearity is apparent for the larger forces used in the present study.

This nonlinearity may offer an explanation of the deviation from temporal invariance for the $T_{F2} - T_{F1}$ interval in the present study of the 40-yard and 80-yard shots, which is in contrast with the temporal invariance found for chip shots. Another contributing factor to these two different results may be the range of forces in the two studies. Even though the relation between force and time is approximately linear for the backswing-downswing interval across both studies, the range of forces is much smaller for the chip shots and the slope is quite shallow (Figure 12A). Therefore, the statistical power of the test of temporal invariance would be expected to be less for the chip shots.
Figure 12. (A) Approximate timing invariance as a function of force magnitude during the backswing-downswing. A linear regression line was fit to all four points. (B) Non-linear spring characteristic of body rotation during the backswing. A linear regression line shows a good fit for the initial 3 points, but a cubic regression line is needed for all four points.
Chapter 5: Discussion

Relative Invariance of Clubhead Timing and Weight Shift Timing

Golfers were found to increase the peak forces that they applied to the clubhead to hit the ball a farther distance (80-yard vs. 40-yard shot). Also, the time intervals between these peak forces were adjusted, even though this adjustment during the backswing-downswing interval was relatively small (Figure 4). This finding is consistent with Neal, Abernethy, Moran, and Parker (1990), who found that the backswing-impact interval increased with distance for iron shots of 20-60 m. Interestingly, all groups of participants regardless of age and skill level differences showed remarkably similar patterns for the adjustment of the force magnitude and time intervals for the clubhead movement.

These results are different from previous findings (Jagacinski et al., in press), where the clubhead time intervals stayed approximately invariant when the force magnitude for chip shots was increased. However, combining previous findings for chip shots and the present results demonstrate that the timing of the clubhead force pattern
during backswing-downswing changed relatively little with changes in the force
magnitude, as shown in Figure 12A. Overall, the timing of the clubhead force pattern
increased by only a factor of 1.3 with an increase of force magnitude by a factor of 6.
The slope of the linear regression line relating time and force is 0.00126 N/mg·s (Figure
12A), which is relatively flat. In particular, the slope of a line linking just the 40-yard and
80-yard shots would be flatter than the slope of a line linking just the chip shots for low
and high targets because of the larger range of forces for the longer distances.

Overall, the backswing-downswing interval is not perfectly invariant, but it does
change relatively little. Therefore, the first hypothesis which suggested that the findings
from chip shots during the backswing-downswing could be generalized to more forceful
shots seems to be valid. On the other hand, the inconsistent adjustment across golfers of
the downswing-follow-through timing contrasts with the much more consistent pattern of
timing observed for chip shots, where this interval was approximately invariant. Given
the scattered, relatively inconsistent pattern of adjustment of the downswing-follow-
through timing for the 80-yard and 40-yard shots across golfers (Figure 5), the timing
pattern during the backswing-downswing seems to be a more regulatory component for
more forceful shots.
The weight shift strategies used for more forceful shots may also be different from those used for chip shots. A larger and quicker weight shift was used to generate larger clubhead force for a higher target in the studies with chip shots (Jagacinski et al., in press). However, in the present study, approximately invariant timing of the weight shift was exhibited along with a larger magnitude of weight shift (by a factor of 1.45) for more forceful shot (80-yard vs. 40-yard) (Figures 6). Remarkable similarities were observed between golfers, regardless of age and skill level differences.

The present findings are consistent with the findings of Worsfold, Smith, and Dyson (2008). They compared the time interval of the weight shift using different clubs (driver, 3 iron, and 7 iron). Golfers whose skill level approximately matches the levels of the participants in the present study did not change the time interval of weight shift for different shots. The results of all of these studies may imply that golfers use different weight transfer strategies for different types of shots, and that for shots requiring relatively small amounts of force, they adjust weight shift timing for force generation. However, for shots requiring large amounts of force, golfers may leave weight shift timing invariant and adjust the force of hip and/or trunk rotation, in order to maintain greater control. Thus, the hypothesis which suggested that the findings for chip shots in
terms of weight shift can be generalized to more forceful shots is not supported.

Evidence for Two Rhythmic Units

The presence of two independent rhythmic units in this hitting task can be argued using two types of evidence: (1) the different mean adjustment patterns of the time intervals of clubhead force and weight shift with different shot distances, and (2) the correlational analysis of temporal variability in the clubhead time intervals and the weight shift time intervals across repeated attempts at the same shot. First, in the chip shot study, adjustment of the weight shift timing was observed while the clubhead timing was approximately invariant for shots requiring different amounts of force (Jagacinski et al., in press). The present study demonstrated the complementary pattern of adjustment of the clubhead timing while the weight shift timing was invariant (Figures 4 and 6). These data indicate that the two time intervals are not integrated with each other into a common rhythmic unit. If one common rhythmic unit was utilized by golfers, it would be expected that the adjustment of one time interval would affect the other time interval, leading to concomitant alteration.
Second, the correlational analysis of temporal variations across shots in the clubhead force timing and weight shift timing provided more evidence for independent rhythmic units. As exemplified in Figure 10, the weight shift timing would be incorporated into the clubhead timing between backswing and downswing and between downswing and follow-through in the integrated hitting structure (Figure 10A). As the clubhead timing changes, the weight shift timing also changes concomitantly, thus providing a strong positive correlation between time intervals. On the other hand, the weight shift timing is a separate unit from the clubhead timing in the independent structure (Figure 10B). Therefore, the temporal variations in the weight shift timing would be either uncorrelated or weakly correlated with variations in the clubhead timing in this case. In the present study, 89% of the correlations between clubhead timing and weight shift timing were either non-significant or weak ($|r| < .30$), which is consistent with the independent structure. The findings of the present study support the predominance of the independent structure found in the previous study with chip shots.

The findings of two separable rhythmic units in the present study disagree with findings from studies of other types of inter-limb coordination tasks, which tend to provide evidence for integrated structure (for a review, see Summers, 2000). Given that
in the golf swing, individuals need to manage rhythmic complexities of upper and lower body coordination, an independent structure may have strategic advantages. For example, the lower body has to perform two major roles during a swing, force generation and balance maintenance. If control resources of the lower body are not distributed well enough between the two roles, neither role may be successfully fulfilled. In other words, if the upper and lower body are integrated into a common rhythmic unit to generate and transfer force effectively, golfers may lose their balance maintenance due to upper body constraints on the weight shift. These results provide theoretical support for practice techniques that focus separately on the weight shift and on the clubhead force patterns.

**Differences in Coordination Patterns and Balance by Age**

Older adults tend to have worse balance capability than do younger adults; this affects their coordination pattern in walking (Menz et al., 2003). The relationships among balance capability, the weight shift pattern, the center of pressure, the force transfer to the upper body, and the coordination pattern were explored to see how balance unsteadiness in older adults could affect performance in a hitting task, and how those components are related depending on age in terms of force generation and transfer to the upper body.
Age-related differences in performance are summarized briefly in Table 2.

Overall, younger and older golfers did not show differences in the pattern of adjustment for different task demands in terms of the clubhead force pattern and the weight shift; the
time intervals and magnitudes of the clubhead force pattern and weight shift did not differ systematically.

It is somewhat surprising that age did not play any role in terms of the timing and magnitude of the clubhead force pattern and weight shift; a relatively smaller magnitude of weight shift was predicted for older golfers due to their concern for their balance. This finding contradicts the hypothesis which predicted an age-related difference in the roles the lower body plays in force generation.

One possible explanation is that older participants in the present study are relatively healthier than other older adults generally, in that they reported regular exercise and no health problems. Through their experience and practice, these older golfers may have learned how to compensate for their lessened balance in order to generate larger force magnitudes for more forceful shots, even though detailed strategies would be different at some level from younger adults.

For example, the trunk rotation was less for older golfers; this result implies that the manner of force transfer to the clubhead is somewhat different. Also, the differences in prevalence of independent timing and of the forward press suggest that older golfers may adopt a different coordination structure.
Analysis of variance for the balance pretest measure confirmed that older adults have lower balance capability. Unsteadiness in balance may lead older golfers to concentrate more on balance maintenance, resulting in less transfer of force via the trunk to the clubhead. Positive correlations were initially expected among balance capability, range of the center of pressure, and maximum trunk rotation; however, no significant correlations were observed, perhaps because of large individual differences.

Evidence of differences in force transmission between the lower and upper body is provided by a comparison of maximum trunk rotation. A larger trunk rotation was exhibited by younger golfers, even though no significant difference was observed in the magnitude and timing of the weight shift between younger and older golfers. One possible implication of these data is that the mechanism of force transfer from the lower body to the clubhead via the trunk in older golfers is not very efficient. In other words, the generated magnitude of weight shift is approximately the same between older and younger golfers, but somehow it is not efficiently transferred into rotational force of the trunk in older golfers. This lack of rotational force in the trunk for older golfers may lead to the excessive usage of the shoulders and arms.
In general, differences in balance capability seem to lead to inefficient force transmission. Therefore, to compensate for this unproductive force generation, some larger amount of force may need to be initiated by the upper body. Thus, the temporal coupling of the upper and lower body may be tighter for older golfers, and the time intervals of the upper and lower body may be integrated into a common rhythmic unit, rather than being independent rhythmic units.

Correlational analysis of the time intervals between the upper and lower body illustrated the probable shift toward an integrated coordination structure in some older golfers. As exemplified in Figure 11, the temporal correlations of most of the golfers suggest two separate, relatively independent rhythmic units. This predominance of the independent temporal structure was greater in the younger golfers. How this characteristic is related to force transfer between the lower and upper body needs to be modeled in more detail.

In addition, almost all older golfers (85%) showed the forward press, W₀, on at least in the two-thirds of their shots, while only 25% of the younger golfers exhibited this behavior. This finding provides evidence for a trend of transition from the difficult 3:2 polyrhythmic pattern to a relatively easier 3:3 rhythmic pattern. When using a forward
press, a third event is added to the lower body movement, thereby creating a simpler rhythmic pattern: the three events in the upper body movement are the backswing, downswing, and follow-through, and the three events in the lower body movement are the forward press, the weight shift to back foot, and the weight shift to front foot.

Together, the finding of an age-related difference in the coordination structure along with a greater prevalence of the forward press suggests that as golfers age, they may begin to regress to an integrated temporal structure with a simpler rhythm.

**Differences in Variability by Skill Level**

Differences in performance by skill level are summarized briefly in Table 3. Advanced level golfers showed less variability of the backswing-downswing than intermediate level golfers (except the time interval for the 80-yard shot), but no significant differences were observed between two skill levels in the variability of the downswing-follow-through. Again, these data indicate that the backswing-downswing interval is a more regulatory component, and performance becomes more consistent as skill level increases (Schmidt & Lee, 2005). Also, variability of the weight shift interval was not significantly different, except the time interval for the 80-yard shot.
<table>
<thead>
<tr>
<th></th>
<th>Intermediate Level</th>
<th>Advanced Level</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shots on Target (%)</td>
<td>63</td>
<td>74</td>
<td>17%</td>
</tr>
<tr>
<td>(T_{F2}-T_{F1})<em>{80yds}/(T</em>{F2}-T_{F1})_{40yds}</td>
<td>1.21</td>
<td>1.21</td>
<td>ns</td>
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<tr>
<td>(F_{1}-F_{2})<em>{80yds}/(F</em>{1}-F_{2})_{40yds}</td>
<td>2.74</td>
<td>2.89</td>
<td>ns</td>
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<tr>
<td>(T_{F3}-T_{F2})<em>{80yds}/(T</em>{F3}-T_{F2})_{40yds}</td>
<td>1.58</td>
<td>1.50</td>
<td>ns</td>
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<tr>
<td>(F_{3}-F_{2})<em>{80yds}/(F</em>{3}-F_{2})_{40yds}</td>
<td>2.63</td>
<td>2.70</td>
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<tr>
<td>(T_{W2}-T_{W1})<em>{80yds}/(T</em>{W2}-T_{W1})_{40yds}</td>
<td>0.99</td>
<td>0.94</td>
<td>ns</td>
</tr>
<tr>
<td>(W_{2}-W_{1})<em>{80yds}/(W</em>{2}-W_{1})_{40yds}</td>
<td>1.53</td>
<td>1.39</td>
<td>ns</td>
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</tbody>
</table>

**Variability of Backswing-Downswing**

<table>
<thead>
<tr>
<th></th>
<th>40-yard Shot</th>
<th>80-yard Shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{F2}-T_{F1} (s)</td>
<td>0.08</td>
<td>0.10</td>
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<tr>
<td>F_{1}-F_{2} (N/mg)</td>
<td>0.17</td>
<td>0.42</td>
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</tbody>
</table>

**Variability of Downswing-Follow-through**

<table>
<thead>
<tr>
<th></th>
<th>40-yard Shot</th>
<th>80-yard Shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{F3}-T_{F2} (s)</td>
<td>0.10</td>
<td>0.40</td>
</tr>
<tr>
<td>F_{3}-F_{2} (N/mg)</td>
<td>0.19</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**Variability of Weight Shift**

<table>
<thead>
<tr>
<th></th>
<th>40-yard Shot</th>
<th>80-yard Shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{W2}-T_{W1} (s)</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>W_{2}-W_{1}/Weight</td>
<td>0.16</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>40-yard Shot</th>
<th>80-yard Shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{W2}-T_{W1} (s)</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>W_{2}-W_{1}/Weight</td>
<td>0.14</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Intermediate Level</th>
<th>Advanced Level</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Timing (%)</td>
<td>58</td>
<td>73</td>
<td>ns</td>
</tr>
<tr>
<td>Pelvic Rotation (degrees)</td>
<td>44</td>
<td>32</td>
<td>22%</td>
</tr>
</tbody>
</table>

**Table 3.** Differences in various dependent variables by skill levels. The values represent the average of the older and younger golfers for each skill level. Non-significant differences are indicated by ‘ns.’
It is interesting that intermediate level golfers showed greater pelvic rotation than advanced level golfers. The pelvis functions as an axis for a rotational force, and the axis of rotation should not be shifted laterally for maximum rotational force transfer to the trunk. However, a beginning golfer often shows a pelvic shift and sometimes even the displacement of their back foot during the backswing. Increase in skill level will lead to a reduction in unnecessary pelvic rotation.

It is somewhat surprising that even though advanced level golfers showed more stable patterns in the backswing-downswing, performances of the two skill levels were quite similar in the pattern of adjustment for different task demands, as indicated by similar ratios of the time intervals and force magnitudes differences of the backswing-downswing, downswing-follow-through, and weight shift. This finding contradicts the hypothesis which predicted quicker weight shifts for more forceful shots in advanced level golfers. Quicker weight shifts were previously observed by more advanced players executing more forceful chip shots. However, the weight shift for the 80-yard and 40-yard shots in the present study exhibited approximately invariant timing. The weight shift in the chip shot may be more sensitive to skill level.
Meta analysis revealed a non-linear spring characteristic of the applied backswing force magnitude as a function of upper body rotation (Figure 12B; see Table 4 for the summary). This result agrees with the non-linear spring characteristic found by Grober et al. (2008), who used a different methodology for measuring backswing force. More importantly, the change of applied force magnitude as a function of trunk rotation during the backswing may explain why there was a different pattern of the adjustment of the clubhead timing with force of the shot across the chip shot study and the present study. Namely, clubhead timing was approximately invariant in the study with chip shots, but was adjusted somewhat between the 40-yard shot and the 80-yard shot in the present study. The two chip shots required low levels of force, and the spring characteristic is approximately linear in this region. A linear spring exhibits timing invariance with changes in amplitude. In contrast, the more forceful shots in the present study involved more nonlinear regions of the spring characteristic, where timing variations are more expected. Nevertheless, the relatively small adjustment of the time interval during backswing-downswing across all four shots (28%) is in contrast with the large variations in the clubhead force (609%).
Table 4. Comparison of a chip shot to a low target and an 80-yard shot for younger golfers with advanced skill level

<table>
<thead>
<tr>
<th>Upper Body</th>
<th>Chip shot (low target)</th>
<th>80-yard shot</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{F2}-T_{F1}$ (s)</td>
<td>0.74</td>
<td>0.95</td>
<td>28%</td>
</tr>
<tr>
<td>$F_{1}-F_{2}$ (N/mg)</td>
<td>2.7</td>
<td>19.1</td>
<td>609%</td>
</tr>
<tr>
<td>Max. Backswing force (N/mg)</td>
<td>0.62</td>
<td>1.45</td>
<td>134%</td>
</tr>
<tr>
<td>Max. Trunk Rotation (degrees)</td>
<td>27</td>
<td>52</td>
<td>90%</td>
</tr>
</tbody>
</table>

Summary

The present study demonstrated how people adaptively adjust their movement for different task demands. The clubhead force was adjusted while the weight shift timing was approximately invariant. This pattern of adjustment may occur due to a non-linear spring characteristic of the upper body: the upper body operates as a stiffer spring with a larger force magnitude which may lead to alterations in swing timing. In addition, this pattern of adjustment and the prevalence of relatively independent timing between the upper and lower body imply that the upper body and the lower body function as separable rhythmic units in a golf swing.

The coordination pattern found in the present study may have similar counterparts in other sports using a swing manipulandum. Coordination between the
upper and lower body for a golf swing was accounted for by a 3:2 polyrhythmic
movement pattern for younger adults, and independent timing between the upper and
lower body was prevalent likely due to the double role of the lower body. Mechanisms
for lower body force generation and transfer to the upper body occur in other sports
involving hitting, and similar coordination patterns may also be employed: for
coordinating a force pattern for swinging a manipulandum (backswing, downswing, and
follow-through) and a weight shift between the feet. Further investigations are needed to
address the general question of how the upper and lower body coordinate in sports with a
swing manipulandum.

Remarkable similarities appeared for the time intervals and force magnitudes of
the clubhead force pattern and weight shift for older and younger adults, which is
contrary to the general finding of age-related slowing in perceptual-motor tasks (e.g.,
Salthouse, 1995; Welford, 1982). However, it is perhaps not surprising because golfers
hit a ball which is stationary at address. Apparently, professional golfers reach the peak
of their performance in the age range of 30-40 years, which is already late in life relative
to other sports (Harold and Tauer, 2008). Perhaps age-related slowing observed in other
sports such as baseball and tennis may not appear in the golf swing of 60 year olds
because golfers do not need to respond to a moving target. Thus, age-related differences in the golf swing would appear in the underlying physiological and/or cognitive components, rather than in the time interval of the swing.

Physiological constraints by age were observed in a mechanism of force transfer. The plasticity of joints decreases with age (Taylor et al, 2007), and this loss of flexibility leads to a less use of the trunk rotation (Mitchell, Banks, Morgan, & Sugaya, 2003). In the present study, older golfers exhibited less trunk rotation, and this may lead to an excessive compensatory use of the shoulders and arms for force generation.

Strategic differences by age were also observed: the predominance of an independent timing structure for the upper and lower body was identified again with more forceful shots, and this structure is less prevalent as golfers age. In addition, most of the older golfers initiated their swing with a forward press, suggesting a transition from the more difficult polyrhythm (3:2) to an easier rhythm (3:3). This shift may be due to an age-related decline in a cognitive ability.

The relationships among balance capability, weight shift, movement of the center of pressure, and trunk rotation are not yet clearly delineated, namely, how worse balance in older golfers affects other components for force generation and transmission.
The findings of differences in balance capability and maximum trunk rotation suggest that those with worse balance did not transfer force to the clubhead efficiently. However, questions about how all these variables are interrelated needs to be clarified in future studies.

Meta analysis revealed that timing invariance appeared either in the upper body or lower body movement depending on the type of shot. These different adjustment patterns imply that the approach shots in the present study and the chip shots in Jagacinski et al.’s study (in press) may be qualitatively different shots. Thus, different patterns of adjustment may permit more efficient control of coordination among body parts, although much more detailed modeling of movement control is needed to establish this possibility. Meta analysis also showed that the spring characteristic of the upper body is involved in the transfer of the vertical force by the lower body to the rotational force of the trunk.

Going forward, a broader range of skill levels such as professional level players and novice players should be investigated in order to test whether or not the findings from previous studies generalize. The present study showed remarkable similarities between advanced and intermediate skill level golfers. Further investigation with more
advanced players and novice players may provide more measurement sensitivity for skill level differences. It will also show how golfers develop their adaptive ability and how the pattern of adjustment to different shot distances changes as skill level increases. Furthermore, various training techniques could be developed from the present findings of independent temporal structure and different pattern of adjustments.

Additionally, the results of the present study with approach shots did not completely match the results of the study with chip shots, suggesting that each type of a golf shot could carry a qualitatively different adjustment pattern. More types of shots such as putting, and more forceful shots with different irons and woods should also be studied with the force measurement techniques utilized in the present study in order to investigate the similarities and differences among various types of shots.

More detailed understanding of how each swing component is interrelated to generate different types of swings and why relatively large individual differences appear may be answered by constructing a mathematical model of the golf swing that incorporates the various constraints discovered in the present study. Golf is just one of the sports which involves hitting a ball with some manipulandum (e.g., a bat, golf club, or tennis racket); these sports have structural similarities such as the time intervals of the
force pattern in the swinging of the manipulandum and weight shift. The findings in the present study may provide understandings of fundamental mechanisms of force generation and transfer for other sports. Also, these sports can provide ecologically valid examples of multi-limb coordination, in that the upper and lower body must coordinate for a proper swing. Therefore, this endeavor of constructing a mathematical model for a golf swing may provide a foundation for a coherent model of hitting tasks more generally.


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Leadbetter, D. (Sep. 2007). Stare it down from 100 yards. Golf Digest, 58 (9), 92-98.


