Neuromotor issues in the learning and control of golf skill.(Special Topics)

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Theoretical and practical issues related to the neuromotor control of a golf swing are presented in this paper. The typical strategy for golf training consists of high volume repetition with an emphasis on a large variety of isolated swing characteristics. The student is frequently instructed to maintain consistent performance in each swing with absolute invariance. Based on dynamical systems and motor control schema perspectives, it is argued that golfers can learn a more reliable swing by exploring swing parameters and focusing on higher order control principles that reduce the vast number of degrees of freedom. Some candidate training practices are proposed for applying these theoretical issues into practice.

Key words: degrees of freedom, kinesthesis, variability

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Compared to the simple objective of the golf swing, the control problem the aspiring golfer faces is highly complex. Throughout the history of golf, the swing kinematics of successful players have been passed from one golfing generation to the next. Tradition and model learning have, therefore, shaped the modern golf swing. Based on the kinematics of today's best players, motion analysis technology has contributed a model of what is believed to be the optimal golf swing (CompuSport International, Las Vegas, NV).

While kinematic analysis details the movement patterns of elite players, developing and controlling a golf swing are motor learning and motor control problems. Accordingly, acquiring an effective golf swing will be considered from a motor control and motor learning perspective. The effective golf swing is sought under the premise that if reduced variability in ball contact conditions is prioritized throughout learning, the resulting kinematics that create these conditions will follow. A swing that evolves according to this strategy might present subtle yet important differences from a swing modeled on an elite player. Furthermore, the flexibility afforded by redundant degrees of freedom will be favored in training rather than the traditional approach toward absolute invariance in a golf swing through strict repetition. Accordingly, while developing an effective golf swing is based on minimizing variability in the outcome performance, the stability of the swing rests in the ability to solve this complex motor problem rather than in a single solution (Bernstein, 1967). The improved ability to solve this motor problem provides a more flexible control strategy than the alternative, which is based on training of a single, wholly invariant solution. A flexible control strategy is hypothesized to be more successful amid the certain physiological and environmental inconsistencies.

Representation of the Swing in the Motor Domain

The objective of a golf swing is to translate the head of the golf club through the point of ball contact in a path in line with the target and a club face that is either perpendicular to this path or oriented to produce the intended trajectory. The intended trajectory is a consideration for a more advanced player and would typically include a draw or a fade and sometimes the height of the bali's flight. Any issue of a popular golf magazine will present photos of the key body positions throughout a swing that are deemed necessary to meet the objective. Although frame-by-frame swing sequences are helpful, the reader may be left with the notion that controlling these discrete body positions creates the swing path. Rather, a systems perspective suggests that these body positions are byproducts of the swing path, and because this perspective recognizes the possibility of several correct solutions, the resulting positions may vary considerably (Bernstein, 1967; Sporns, & Edelman, 1993). Anatomical differences alone might promote different landmark positions that are more optimal for one player than the corresponding positions of an elite player.

Rather than emphasizing discrete positions throughout a swing, a more complete approach is to understand the swing for what it actually is: a path. One representation of the swing consists of the club head's trajectory. Although a position trajectory is most comprehensible (see Figure 1A), a phase portrait (see Figure 1 B) could also contain valuable information regarding control mechanisms. Figure 1A depicts the position of the club head as viewed while lacing a tight-handed golfer. Beginning with a wide takeaway, the club head progresses left and to the top of the backswing. With a weight shift toward the tight, the club head takes a steeper approach toward the ball in the downswing. Although the contact conditions have already been achieved, the final position at the top of the follow through has important beating on the shape of the swing in all three spatial dimensions.

[FIGURE 1 OMITTED]

Figure 1B is a phase portrait of the club head's horizontal velocity on the ordinate and club head horizontal position on the abscissa for each time point throughout a movement. From the bottom center of this plot, the trajectory progresses to the left through a loop and back to the central position at the point of peak velocity. The loop in the lower left represents the region near the top of the backswing, where the club head slows and changes direction. Such a plot might be useful tot examining swing characteristics, such as tempo throughout the swing or the relationship between the width of a backswing and the velocity of the club head at ball contact.

Degrees of Freedom and Coordinative Structures

Individual control of the many degrees of freedom is a cumbersome solution to the complex motor problem of the golf swing. Because we are aware of our limited capacity for attention that diminishes as the velocity and complexity of the task increases, attending to a minimum set of "swing thoughts" is widely promoted in the golf media. We often hear expert golf commentators praising a player's swing due to its simplicity or because it has fewer moving parts. Even after great achievements as a professional, a golfer named Nick Price worked with a leading coach, David Ledbetter, to simplify his swing by eliminating unnecessary leg movement (Price & Rubenstein, 1999). The prolonged duration of his competitive success supports this intervention, even with swing characteristics and a tempo some analysts might consider atypical on the PGA tour.

Aside from reducing the number of degrees of freedom, another strategy is to learn control at levels of the control hierarchy in which several temporal and spatial components of the golf swing are affected together (Bernstein, 1967; Gallistel, 1980). A coordinative structure is a group of muscles, often spanning several joints, that is constrained to act as a single functional unit (Tuller, Turvey, & Fitch, 1982). As demonstrated in other complex tasks, learning a new motor skill involves the organization of independent degrees of freedom into control via coordinative structures (Vereijken, Whiting, & Newell, 1992). It is believed that the coupling of movements across multiple segments simplifies the challenge of controlling several independent units (Bernstein, 1967). The notion of a coordinative structure is easy to find in golf instruction. In Harvey Penick's Little Red Book, for example, the magic move of golf is described as a coupled movement in which the player initiates the downswing toward the ball by shifting weight to the left foot while bringing the right elbow down toward the body (Penick & Shrake, 1992). This coordinative structure results in combined transport of the arms, hands, and club caused by moving the tight elbow to the hip. By attending to control at the hip and elbow as one unit, controlling each of the component degrees of freedom is substantially simplified.

Although the "magic move" is intended to establish the major components of proper body position at contact as well as an appropriate swing path through contact, the precise orientation of the club head at contact also depends on the forearm and wrist action through contact. This requires the ability to coordinate the correct action of the distal upper extremities with the major turn of the torso. In a study of reaching movements that involve the trunk, degrees of freedom from the arm and trunk were coupled in a compensatory system to achieve invariance in reaching a target (Adamovich et al., 2001). Similarly, to achieve invariance at ball contact the golfer must combine the transport action of pelvis rotation with precise control of club face orientation by the wrist and hand motion. Therefore, the appropriate combination of movements is solved by control systems based on the predicted status of the transport mechanisms.

Attractors

Although we do not fully understand what parameters complex human movements control (Latash, 1993; Bizzi, Hogan, Mussa-Ivaldi, & Giszter, 1992; van Ingen Schenau, van Soest, Gabreels, & Horstink, 1995), new perspectives that consider control of a control hierarchy at various levels may present new information for solving the golf swing problem. One such perspective is to view the many types of swings a golfer may use as attractors. There are different types of attractors, such as point attractors and limit cycles, but the term is used here generically as a conceptual illustration. An attractor's basin of attraction is a region within state space toward which a behavior converges. The depth of a basin of attraction reflects its relative strength (Kelso, 1995). Each attractor in Figure 2A represents the hypothetical combination of the unknown control parameters for a particular type of swing a player might use (low draw, straight shot, high fade, etc). Panels B and C depict two swings that can be caused by similar or overlapping sets of control parameters, a draw and hook, for a beginner (B) and an elite player (C). A draw is typically desirable, whereas a hook is often the penalty for motor errors. Each arrow depicts the convergence of a trajectory from some arbitrary starting point (initial conditions) to the nearest (or strongest) attractor. For the beginner, considerable overlap among the basins of attraction results in hooked shots despite the intended draw. One training strategy is to attempt to reduce the strength of attraction toward the unwanted pattern, making it easier to develop the intended pattern. The trick is to identify some parameter that can diminish the unwanted attraction without fundamentally changing the task (Walter & Swinnen, 1992). For example, a player may modify hand motion to weaken the hook attractor while strengthening the attractor for a draw. These changes are depicted as shrunken and expanded basins of attraction, respectively (see Figure 2C). Consequently, the same initial conditions that allowed a hook for the beginner are more likely to converge on the control parameters for a draw in the expert player.

[FIGURE 2A, 2C OMITTED]

A potential landscape is a schematic representation that depicts the relative strength of movement patterns with different sets of control parameters, such as speed or force. Based on the number of control parameters of interest in), the potential landscape exists in n-dimensional space. Figure 3A depicts a simple potential landscape with one hypothetical control parameter for the hook and draw for a beginner (top) and an expert (bottom). Deep wells indicate sets of control parameters that promote stability. This stability is represented by the relative difficulty a marble might have in leaving a well. These wells are similar to the basins of attraction discussed earlier. The relatively deeper well for the expert's draw indicates that the associated coordination pattern is less likely to be perturbed toward the hook with this set of control parameters.

[FIGURE 3A OMITTED]

A beginner could be characterized as having few attractors with little stability (see Figure 3B). Each attempt at a swing could use different control parameters, resulting in highly variable outcomes. Perhaps a beginner may develop an inappropriate attractor for a big slice. The player's difficulty in preventing the slice would indicate too much strength in this attractor. An elite golfer will have command over a number of different swings that are each useful, depending on the task requirements (see Figure 3C). Depending on how the swings are trained, stronger attractors will make the successful outcome of one type of swing more likely than others. Golfers typically develop one preferred swing that has the greatest probability for successful results (b). Other swings such as c and d are stable, with respect to a, b, mad e, but less stable with respect to each other. The proximity of these two attractors could reflect similarity in the control parameters for straight shot and a slight fade. Noise from various possible sources is present in each well, and this noise can perturb a behavior such that it migrates to a nearby attractor. This event depends on the stability of the attractor and the energy of the noise. For example, it would not require much noise to produce a slight fade rather than the intended straight shot (c-d), whereas it would require substantial noise to perturb the swing away from the default swing in b. Research based in information theory has demonstrated that noise may be a modifiable characteristic and the consequences of noise are jointly determined by the relative strength of the motor signal (Slifkin & Newell, 1999; van Galen & van Huygevoort, 2000).

[FIGURE 3B-3C OMITTED]

In addition to developing stable swings, a second objective is to train flexibility within these swings to allow recovery from internal or external perturbations (Walter, Swinnen, & Franz, 1993). Such perturbations include the effects of a side-hill stance on the player's center of mass or the effects of reflex responses altered by anxiety (Andrew & Cadden, 1996). Increased stability of the attractor means that the club head trajectory would be more likely to fall on the preferred swing path despite perturbations. Increased flexibility of an attractor may be associated with more possible solutions to the control problem as specified in the combination of control parameters. Figure 4 illustrates the advantage of increased flexibility in control strategies. Assume that the parabola represents the optimal relationship between one hypothetical control parameter (CP1) and another (CP2). The shape of this function and the definitions of the control parameters are irrelevant here. If a golfer only practiced the combinations represented by Xs he or she may only learn successful combinations of CP1 and CP2 within a narrow range. Consequently, when faced with alternate values of CP1, either by choice or motor errors or the environment, the golfer's selection of the corresponding CP2 value may fall off of the function representing optimal performance (Y). However, if the golfer learned a more complete range of combinations, including both Xs and Os, he or she would develop more flexibility in control strategies. Deviant values for CP1 would more likely be paired with appropriate values of CP2, thus improving the overall performance. This is sought when a player strives for a swing that will not break down under pressure. The task of learning flexible combinations of control parameters, as described in the dynamical systems context, could also be explained as formulating a more complete rule relating the two control parameters according to a Schema approach. These theories on motor control and learning are not mutually exclusive.

[FIGURE 4 OMITTED]

Learning a flexible relationship between CP1 and CP2 can be likened to expert marksmen using coordinative structures in their endpoint control strategies (Tuller et al., 1982). Whereas a beginner's uncompensated movement of one joint will throw a gun off target, multiple joints act as a compensatory unit in an expert marksman to keep a gun on target. In this example, multiple possible solutions to the problem of endpoint control provide the flexibility characterized in Figure 4. Such compensatory synergies would certainly be beneficial to train within a golf swing. Perhaps a selected control parameter could be manipulated while focusing on a likely compensatory parameter. A simple example would be manipulating swing or pelvic rotation speeds throughout the full range while learning the appropriate hand and arm movements that result in good contact conditions. Similarly, the golfer could practice extreme manipulations of the swing path that progress either inside out or outside in across the contact area. By exploring component movements that are usually not intentional, the golfer may be better equipped to produce a reasonable compensatory motion when faced with aberrant motions. Again, both the dynamical systems account and the schema account support these efforts.

Initial Conditions

After developing swing attractors through practice, a golfer must learn how to consistently select the preferred swing. Initial conditions are starting points known to influence the evolving dynamics of some systems. In golf, some examples include the tilt of the shoulders or orientation of the club face at address. By specifying initial conditions that favor a given attractor, convergence toward the appropriate swing is more likely. In Figure 3C, the arrows depict two possible sets of initial conditions (IC1 and IC2). The conditions at IC1 are more likely to find the swing designated as c, whereas the conditions at IC2 may find either c or d.

Some initial conditions may promote convergence on a selected attractor by imparting anatomical constraints. For example, the position of the feet at set-up can influence the shape of a swing path. If a right-handed player places the right foot in an open or toe-out position, this will allow greater pelvic rotation away from the target during the backswing. If the fight foot is closed, this will limit the rotation. The extent of pelvic rotation into the follow-through can be increased by an open left-foot position or constrained by a closed left-foot position. By manipulating the extent of pelvic rotation, the player modifies the shape and orientation of the swing path without muscular activity. These passive control sources simplify the challenges of the golf swing.

Variable Control Solutions to Promote Reliable Performance

Absolute invariance in a golf swing appears to be the norm in instruction. However, our many redundant degrees of freedom afford several possible solutions to the golf swing problem. Given the certainty of physiological and environmental variability, training absolute invariance in a golf swing may be unnecessay or even counterproductive. An alternate approach would be to train flexibility in the golf swing such that the golfer's control systems have access to a greater number of viable solutions. Indeed, by increasing variability among the practiced control strategies, performance variability may be decreased.

If any invariance is to be sought, it should be at the point of ball contact, where the outcome is determined. There may be other critical swing components that require minimal variance to promote contact invariance, but there are certainly parts of the golf swing at which variability is allowable or even beneficial. A practical solution is a strategy that minimizes variability only in the swing components that have the greatest influence on variability of the shot's outcome. However, the task of identifying these components could be monumental. Some component analysis of variability has been discussed in other applications, with examples from variability in force production and timing (Ivry & Corcos, 1993).

Greater Emphasis on Sensation

In popular golf media, the control of the golf swing is approached primarily as a motor problem, although it is more appropriately described as a problem of sensory-motor integration. For the golfer, correct sensory information is required for control and learning purposes. Although details regarding the tinting, volume, and nature of feedback vary depending on the context and individual (Guadagnoli, Dornier, & Tandy, 1996), it is widely accepted that feedback is a requirement for motor learning (c.f., Adams, 1987). This poses a substantial problem for a novice golfer, because, in the absence of external feedback, the golfer may not be able to determine what he or she did correctly or incorrectly. Perhaps similar to expert jugglers, elite golfers can effectively use sensory feedback from the swing, while novices depend on visual information (Beek & Lewbel, 1995).

The kinesthetic sense is a topic that seldom appears in popular golf media, even though golf poses a special kinesthetic challenge compared to many other sport situations. The golf club is a nonphysiological extension of the player, about which the player needs to know position and velocity information. As instructed by Dave Pelz, partial swings of different lengths but at the same relative tempo provide the basis for effective distance control (Pelz & Frank, 1999). To exploit this strategy, the player needs a good kinesthetic awareness for partial swings. The sense of swing length is typically trained implicitly as a player focuses on the ability to hit shots of various distances. However, the rate of learning and the effectiveness of control may both benefit, if the player makes a more deliberate effort to develop this golf-specific sensation.

Conclusion

Some training methods are actually consistent with the proposed approach, such as practicing a golf swing under challenged balance or in the absence of visual information. If a single recommendation is derived from this paper it is to reevaluate the manner in which one approaches development of an effective golf swing. Rather than focusing on individual details in the swing, as prescribed by much of the popular golf media, more attention should be given to higher order control strategies, with greater allowance for individual differences. Golf is a sport that requires substantial cognitive involvement in addition to motor proficiency. To explore the topics presented in this paper, a golfer must use systematic analysis of individual movement to solve the sensorymotor problems of the effective swing. The lessons from our predecessors are precious, and modern golf has gained much from a continuum of model learning that originated in Scotland. However, even for elite players, variability in performance is still the primary challenge.

There are many possible training methods with this alternate approach. A player should use exploratory training methods to find the most stable attractors. In other words, rather than only modeling the swings of the pros, a player might be better served to seek one's own most stable swings. The resulting swing, even flit has atypical characteristics, might be more reliable than a swing learned solely from emulation. In pursuit of higher order control strategies, a player could benefit from learning the details of a swing path outside of the visual field during its execution. Deliberate kinesthetic training should be used to help the player learn how various initial conditions can modify the swing path and what effective synergies emerge from swing paths with different characteristics. Deliberate sensory training will likely yield the greatest benefits early in a player's experience.

Because the only objective of the swing is to produce the desired contact conditions, the ability to solve this problem should be trained through attempts to achieve these conditions from various positions in the workspace of the golf swing and amid perturbations that simulate environmental influences or possible motor errors. Generally, a player should consider alternatives to the most popular training method, which is repetition. In addition to practicing with different clubs, the player should practice with different swings. However, the reader might be well served to accept the content of this paper with caution. Although some experimentation during practice would likely do little harm, further research on individual development of a golf swing is merited before these propositions can be considered anything but speculative. Presently, there may be no a priori reason why acquiring the appropriate compensatory strategy preserving a given movement output is any simpler than lowering variability at each joint; the control problem is simply shifted to another level.

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