January 12 & 13, 2005

The brain and brawn of athletic performance

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To a sports fan there is nothing better than having the opportunity to directly watch an elite athlete in action. Not only are their motor skills phenomenal, the movements themselves exhibit a combination of strength, confidence and smoothness that seem so different from our own efforts. What is it that distinguishes the star athlete from their teammates and competitors? Is it simply their brawn, i.e. are they just bigger, stronger and more fit than their competitors? Certainly these factors are necessary pre-requisites to enable athletes to compete at high levels. However, today's athletes are so remarkably homogeneous in their physical abilities, coaching and background that clearly these properties alone are not sufficient to distinguish the star from members of the supporting cast (Siff, 2000). Thus the seat of elite performance must lie between the ears of the athlete, i.e. in the brain. This chapter examines the neural contributions for elite athletic performance.

Studies of athletes have provided major insights into how the brain performs skilled motor activities ranging from planning a golf shot (Milton, et al, 2003, 2004b; Ross, et al, 2003) to catching a fly ball (McLeod, et al, 2003). A number of observations suggest that the voluntary, highly skilled movements performed by athletes are learned through the computational, or cognitive, activities of the cortex (Milton, et al, 2004a). First, acquired motor skills exhibit specificity, i.e. the skill level is not transferable to other activities. Second, practice is required to both attain and to maintain the skill level. Finally, even with extensive practice, few are able to become skilled at expert levels (e.g. Halverson, et al, 1982). Thus what makes movements in sports so interesting is that they do not simply reflect activities of "hard-wired" innate reflexes and central pattern generators.

Neural contributions to muscle strength and power

Strength refers to the ability of a muscle to produce force. The maximal strength generated by a muscle is proportional to its cross-sectional area (Semmler and Enoka, 2000; Roy and Edgerton, 1992). The cross-sectional area of a muscle is determined by genetic factors (sex, height, lean body weight), hormonal factors (e.g. androgens) and environmental factors. The relative importance of these components to the development of superior athletes is the subject of ongoing debate (Entine, 2000; Gabbard, 2000; Siff, 2000).

The neural contribution to muscle strength is most clear in situations in which the athlete is able to increase strength independent of changes in muscle size. An example is the increase in strength that individuals experience when they participate in a strength-training program lasting, for example, 8-12 weeks (Semmler and Enoka, 2000). It is well established that the accompanying change in muscle strength precedes and exceeds the change in muscle size (Häkkinen, et al., 1985; Natici, et al., 1989; Staron, et al., 1994). In addition, the improvement depends on the similarity between the training and testing procedures and not on the size of the muscle. For example, subjects who practice can increase their maximal knee extensions by over 200%, but isometric strength using the same muscles increases by only 10-20% (Rutherford and Jones, 1986). Finally, it is possible to increase muscle strength even without subjecting the muscle to physical training! For example, when muscles in one limb participate in a strength-training program, the homologous muscles in the un-exercised limb typically also show an increase in strength (Ploutz, et al., 1994; Yue and Cole, 1992). Indeed it has even been suggested that subjects who practice sets of imagined maximal voluntary contractions experience a significant increase in the strength of a hand muscle (Yue and Cole, 1992), although this effect has not been re-produced by other laboratories (Herbert, et al., 1998).

The force required to move from one position to another is defined as work; work per unit time as power. Muscle power can be increased either by increasing the activity of a single motor unit[1] or by increasing the total number of motor units that are activated. In the latter case motor units are recruited in an order that is based on properties of the motoneuron that covary with its size ("size principle"): smaller motoneurons are recruited before larger ones (Binder and Mendell, 1990; Cope and Pinter, 1995; Denny-Brown and Pennybacher, 1938; Heckman and Binder, 1993; Henneman, 1957, 1977). Over most of the normal operating range of muscles the above mechanisms act concurrently (Person and Kudina, 1972; Seyffarth, 1940). Although it may be possible to increase motor strength by increasing motor unit synchronization (Milner-Brown, et al., 1973, 1975; Semmler and Nordstrom, 1998; Yao, et al., 2000), synchronization alone does not result in an increase in power (Miller, et al, 1981).

All movements in sports involve the coordination of the activity of many muscles and, in particular, involve rotation of body segments about their respective joints axes (Zatsiorsky, 1998, 2002). Muscles that act across a given joint are typically organized as an agonistic-antagonistic pair: increases in strength can result from either increased activation of an agonist or reduced activation of an antagonist muscle (Carolan and Cafarelli, 1992; Herzog, 2000). Moreover, contraction of a muscle across a joint rarely produces a pure movement in one direction, e.g. extension (Lawrence, et al., 1993), but typically produces rotations and displacements about all three axes (Zhang, et al., 1998). The capability of a force to produce rotation is given by the torque. The torque is

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[1] The term 'motor unit' refers to the number of muscle fibers that are innervated by a single motoneuron (range 5-2000). Most human muscles are composed of a few hundred motor units.

equal to the force times the moment arm, i.e. the perpendicular distance between the line of action of the force and the axis of rotation. Torque is always determined with respect to a specific axis. Consequently the coordinates for the equations of motion are the joint angles (Zatsiorsky, 2002) and considerations such as the length of the bones on either side of the joint and the geometry of the attachment of muscles to the bone become important parameters.

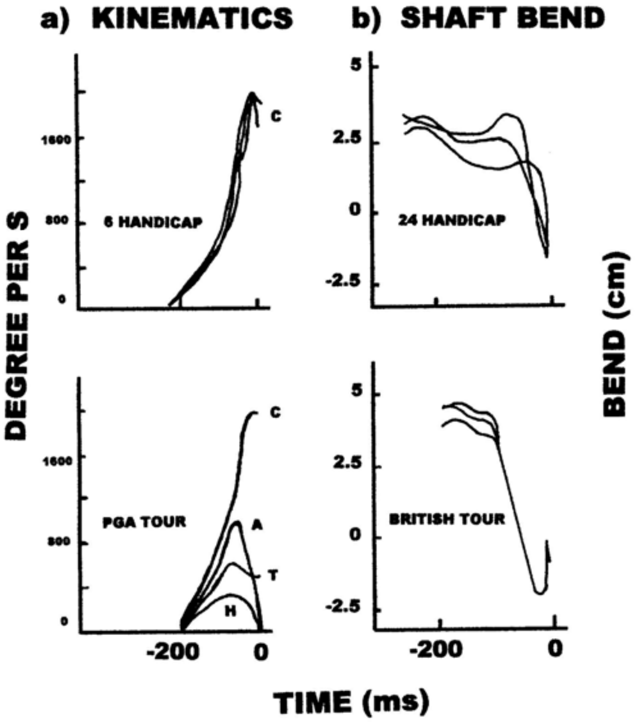

Figure 1: Swing-to-swing variability in the golf swing for amateur and professional golfers measured either from shaft bend or kinematic measurements. Kinetic measurements are for three consecutive swings. For the PGA tour golfers the variation in the kinematic measurements for three consecutive swings was of the order of the thickness of the plotted line. Data for shaft bend is from Cochran and Stobbs (1968). C: club, A: arm, T: torso, H: hip

The observation that movement depends on the tightly interwoven interplay between neural activity and the biomechanical properties of the body (Chiel and Beer, 1997; Perry, 1998; Zajac, 1993) explains the importance of proper technique for optimal performance in sports. A striking characteristic of a skilled athlete is their attention to maintaining the correct position of their limbs and joint angles during the movement (Figure 1). The importance of this attention to detail follows directly from the fact that the mechanical advantage of a muscle is a function of the joint angle and the response of the whole body to its contraction is a complex function of the geometric relationships and positions of the other muscles and joints (Zajac, 1993). An obvious corollary is that there is not an optimal way to perform a movement, but likely as many optimal ways to move as there are different people. Thus it would seem to be self-evident that the best approach to teach a sports-related motor skill would be to use an approach based on the biomechanical characteristics of the individual. Yet few sporting skills are taught in this manner.

The biomechanical properties of muscle and tendon explain the importance of proper warm-up for optimal sports performance. The musculoskeletal system exhibits a number of history-dependent properties including thixotropy (Prosk, et al., 1993), force depression following muscle shortening (De Ruiter, et al., 1998; Lee, et al., 1999), force enhancement following muscle elongation (Edman and Tsuchiya, 1996), and the nonlinear viscoelastic properties of joints and tendons (Esteki and Mansour, 1996; Jenkins and Little, 1974). Thus the compliance and stiffness of the tendons that attach the muscle to the bone as well as the properties of the muscles themselves depend on past history.

Coordination: The kinematic sequence

Optimal performance in sports requires the production of “just the right amount of force at the right time”. For example, it takes 3-4 horsepower to hit a golf ball over 183 m (i.e. 200 yards) (Cochran and Stobbs, 1968). This power is applied to the golf ball in just 0.5-0.8 ms (Cochran and Stobbs, 1968; Jones, 2002). A useful rule of thumb is that each 0.45 kg (i.e. one pound) of contracting muscle generates one-eighth of a horsepower. Thus, 10.9 – 14.5 kg of contracting muscle are required. Where are muscles of this size located on your body? You’re right! You are sitting on them.

The problem is how to transfer the power generated in our lower body (thighs, buttock, lower back) to the projectile. There are two possibilities:

1. through the temporal coincidence of the trunk and arm movements;
2. through a sequential activation of body segments: typically from proximal to distal, i.e. legs → pelvis → back → shoulders → arm → shot.

Figure 2 shows a cinematographic analysis of a golf swing. Clearly there is not a coincidence of muscle activation. Rather, there is a sequential transfer of power from proximal to distal body segments: the legs and hips are the engine, the arms and hands the transmission system. This sequential transfer of power is referred to as the kinetic sequence.

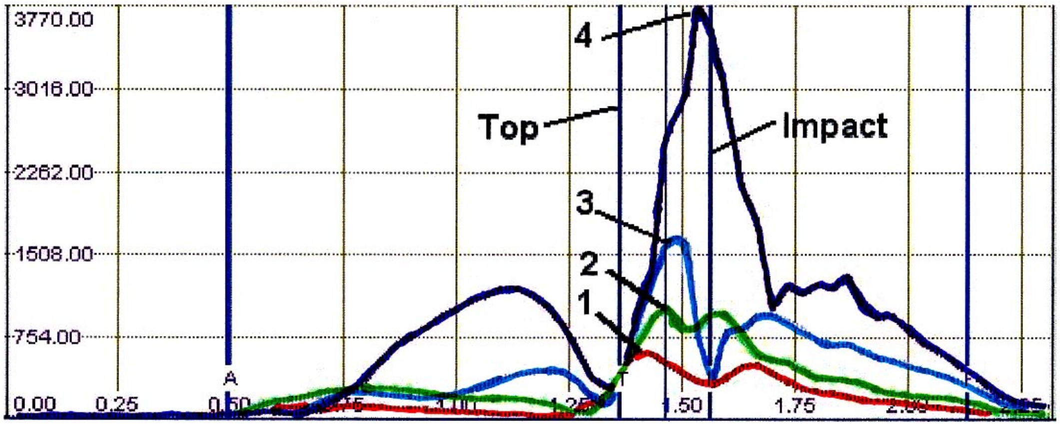

Figure 2: Kinematic sequence for a good golf swing (PGA professional). 1) hips; 2) upper torso; 3) arms; 4) club head. Note that before impact the hips first reach maximal speed, followed in order by upper torso, arms and club. 'Top' refers to the top of the back-swing and 'Impact' is the instance at which the ball is struck.

This same kinematic sequence is a feature of all sporting activities that combine speed of movement with power (Broer, 1960), including pitching and hitting a baseball, throwing a discus or javelin, and so on. The contribution of the kinetic sequence to performance can be illustrated by a consideration of Olympic shot putters. Today's top shot putters can push a shot from a standing position to a distance of 19-20 m. The current world outdoor record for putting a 7.5 kg shot is 23.12 m (Randy Barnes USA, Los Angeles, May 20, 1990) and the indoor record is 22.66 m (Randy Barnes USA, Los Angeles, Jan. 20, 1989). Thus the contribution of technique is to add another 3-4 m to the distance that the shot is put.

A precisely coordinated kinetic sequence is one of the main features that distinguish the performance of an elite athlete from that of a novice (Lanka, 2000). For example, the pitching prowess of hall-of-famer, Sandy Koufax, has been attributed in part to his studious attention to the proper kinematic sequence for pitching (Leavy, 2002). However, despite the paramount importance of the kinematic sequence for elite athletic performance very little in known about how it develops. It is known that the basic building blocks of the kinematic sequences for sports related motor skills, such as throwing, catching, hitting and kicking, are acquired by most children by ages 5-6 (for a useful review see Gabbard, 2000). The advanced adjustments to these kinematic sequences required for specific sports, e.g. pitching in baseball, wrist shot in hockey, begin to develop between ages 6-12 (Wickstrom, 1983) and are continually refined by experience and practice throughout adolescence and early adulthood. The acquisition of these motor skills is not hard-wired into the developing nervous system but is driven by the preferences and motivations of the child towards a specific sport and the opportunities provided by the home and school environment. Consequently many never acquire high levels of motor skill. For example, the over arm throwing pattern is a motor skill that has a relatively high incidence of individuals who do not accomplish this skill, especially among females (Halverson, et al., 1982). Another example is the golf swing!

It's all about timing!

Although considerations of strength, power and kinematic sequence dominate the preparation of an athlete, playing the game itself is all about timing. For example, an absolutely necessary requirement to be able to strike a ball with a hand, foot, racket, bat or club, is that the ball and striking implement be at the same spatial location at the same time. However, it takes time for a ball to move from one position to a second. It also takes time for the nervous system to detect the direction and speed that the ball moves, plan the response, and then execute the movements of the body that enable the ball to be struck. Considerations of these two time scales, the neural and physical, provide important insights into the fundamental nature of the problems faced by an athlete. To illustrate, let us consider the interaction between a batter and a pitcher during a baseball game from the perspective of these two time scales (Adair, 2002).

The time, T_P, that it takes a baseball to travel the distance from the pitchers hands to home plate is

$$T_P \approx \frac{16.46}{V_P}$$

where V_P is the speed (meters per second) of the baseball as it crosses home plate (Banks, 1998) and in which we have taken into account the length of the outstretched arm of the pitcher when delivering the pitch. For major league baseball pitches V_P ranges from 26.82-44.81 m/sec (i.e. 60-100 mph) and hence

$$T_p \approx 367 - 614 \text{ ms} \qquad (1)$$

The response time, T_S, of the batter is equal to the sum of the reaction time, T_R, plus the movement time, T_M, i.e.

$$T_S = T_R + T_M$$

The movement time, T_M, is the time required to complete the swing. Estimates are of the order of 250 ms (Science of Baseball website). By comparison a good golf swing takes 190-250 ms (Cochran and Stobbs, 1968). If the delivered pitch is a fastball traveling 153 km/hr (i.e. 95 mph), then 250 ms is approximately the time it takes the ball to travel the last 7.6-9.1 m.

During the first half of the pitch the brain of the batter must identify the target (i.e. the ball), plan the action, and then produce the neural output that will coordinate the muscle activity that generates the swing and maintains balance during the swing. These steps must be completed before the batter can swing the bat. The total time required is the reaction time, T_R. These processes are performed by three physically distinct regions of cortex (Figure 3): respectively, posterior parietal cortex, pre-motor cortical areas, such as supplementary and pre-supplementary cortex, and primary motor cortex. Under optimal conditions of attention, adults age 28-29 (i.e. the years of peak hitting performance (Schultz, et al., 1994), can respond to a sensory stimulus, such as randomly flashing light, within 150 ms (mean $\approx$ 200 ms (Gabbard, 2000).

The above observations suggest that

$$T_S \approx 400 - 450 \text{ ms}$$

Thus baseball is a game that is played at the limits of a human's ability to react to a stimulus.

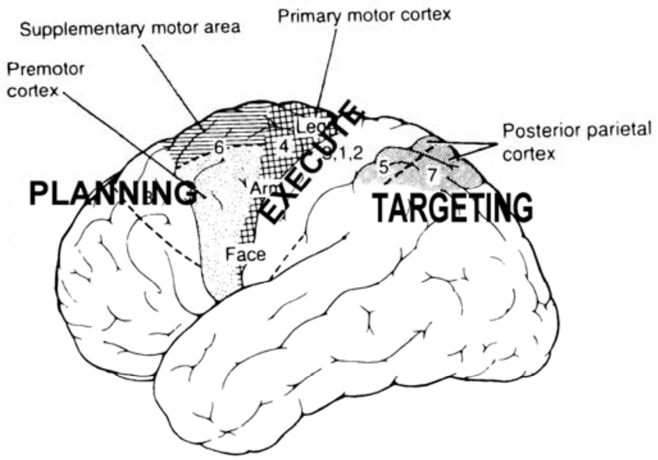

Figure 3: Schematic representation to show the relative positions of the targeting, planning and motor execution regions of the cortex. The numbers refer to the Brodman areas.

However, baseball is much more that a game of stimulus and response. It is also a mind game between pitcher and batter. This is because T_R, and hence T_S, is a function of the complexity of the task (Hick, 1952). Certainly it is clear that T_R can be increased by an effective wind-up that makes it difficult for the batter to determine exactly when the pitch left the pitcher's hand, how fast and where it was going. More importantly T_R can be increased by the “inner game” of baseball, i.e. the difficulty of the game situation (i.e. the pressure), distractions, and even over-coaching. The oft-cited wisdom “keep it simple” can be very hard to follow in a game situation.

Surprisingly, measurements of elite professional baseball hitters suggest that it is possible that (Techna Sport, LLC, 2003)

$$T_S \approx 300 - 350 \text{ ms}$$

Now it is unlikely that T_M could be faster than a golf swing and hence it is likely T_M could be improved upon more than a few milliseconds. Thus this means that T_R for an elite athlete can be 50 - 100 ms, i.e. much shorter than for average adults. Moreover, since it takes ≈ 43 ms for information concerning the velocity and trajectory of the baseball to be sent from the retina of the eye to higher areas of visual cortex, we have that the motor planning activities of the cortex for these batters only takes 7 - 50 ms! Reductions of T_R of this magnitude come from years of practice and experience (Fitts and Posner, 1973).

Inside the mind of skilled performance

In contrast to baseball, the game of golf is played at the limits of the ability of the nervous system to reproducibly make precise, ballistic movements (see Figure 1). To paraphrase golfing legend Sam Snead, an important difference between golf and baseball is that golfers have to play their foul balls! Pre-programming of the motor cortex for voluntary movements, such as the golf swing, takes much longer than for movements that occur in response to a stimulus. For example, neurons in the lateral premotor area begin firing ≈ 800 ms before a voluntary finger movement (Deeke, et al., 1969). However, in highly skilled aiming sports such as putting and the golf swing, archery, and rifle shooting, the period of mental preparation before the movements occur, referred to as the pre-shot routine, is surprisingly much longer, e.g. 8-15 s (Crews and Landers, 1993; Hatfield and Hillman, 2001; Milton, et al, 2003, 2004b). Behavioral studies emphasize that consistency and reproducibility of this preshot routine is a major feature that distinguishes novice from expert (Feltz & Landers, 1983; Hatfield & Hillman, 2001; Crews and Landers, 1993).

Magnetic resonance imaging techniques, i.e. fMRI, provide a way to measure the functional neuroanatomy of the preshot routine. Recent emphasis has been focused on the preshot routine of golfers (Milton, et al, 2003, 2004b; Ross, et al, 2003). Golfers are particularly good candidates for such studies since their motor skills are complex, their acquisition both difficult and lengthy, and they are naturally motionless during their preshot routine. These studies have shown that professional golfers have less activation in critical cortical motor planning and execution regions than novices. Similar findings have been obtained in studies involving musicians (Jancke, et al., 2000). These observations suggest that the neural networks for expert performers are more efficiently organized than for novices.

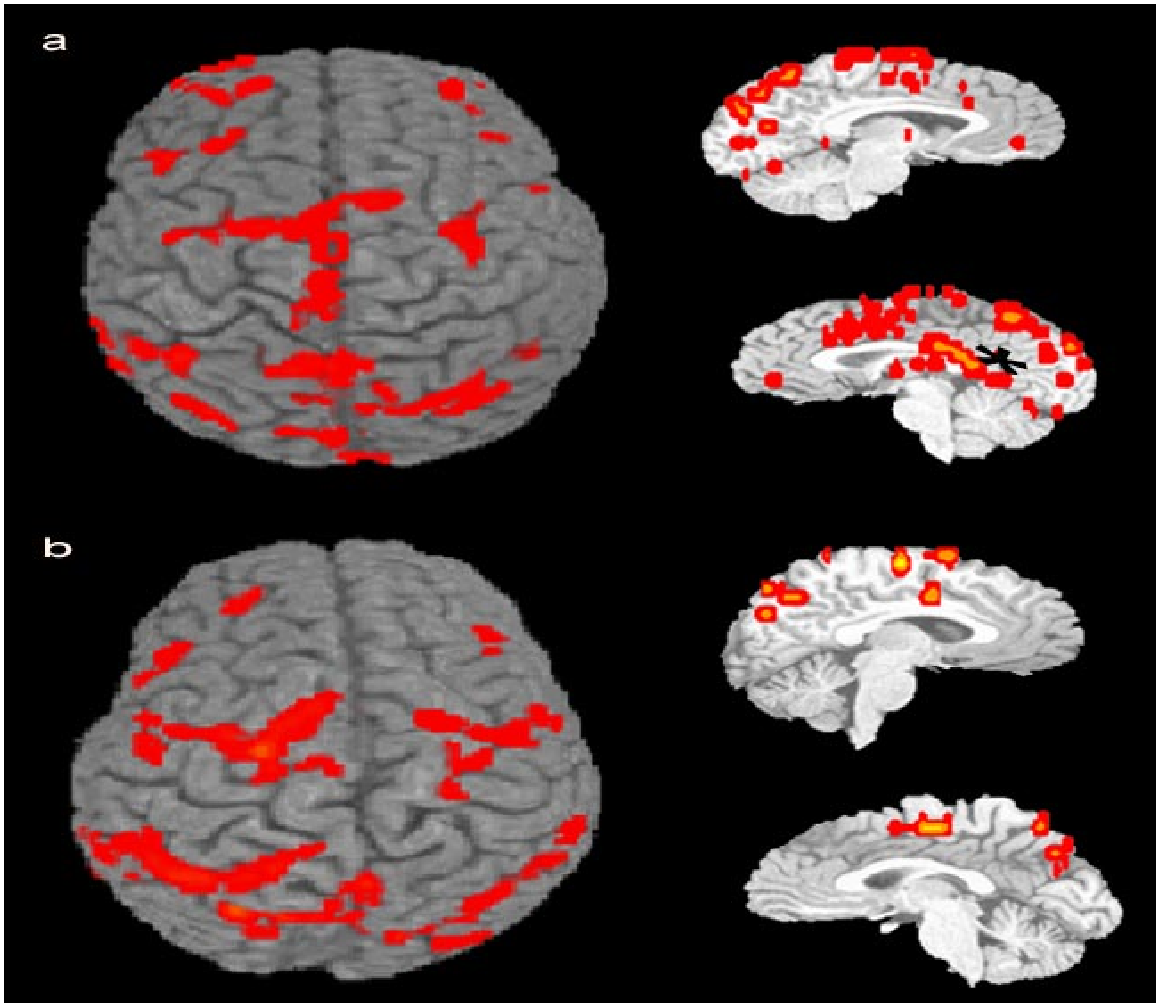

Figure 4: fMRI images obtained during the preshot routine of a) beginner and b) professional golfer. In each case, the golfer shown represents the one for whom the number of regions of interest activated and the total brain activation was closest to the group's mean. The color code gives the values of the F test: red ($6.63 < F < 10$), orange ($10 \leq F < 25$) and yellow ($F \geq 25$), where $F = 6.63$ corresponds to significance at the $P = 0.05$ level. Reproduced from Milton, et al (2004b) with permission.

Equally important has been the observation that neural networks of elite performers may also be structurally different that those just beginning to learn a skill (Leveroni et al, 2000; Milton, et al., 2003, 2004b; Mundel et al 2003; Tracy, et al., 2003). Milton, et al (2003, 2004b) used fMRI to compare the functional neuroanatomy of professional and novice golfers during the preshot routine. In this study, the golfers were asked to go through their preshot for a 100-yard golf shot to a green and pin viewed on a screen while they were lying in an fMRI scanner. It was observed that in addition to the decreased overall brain activation of the professionals, there were also differences in the topology of the involved neural networks.

First, professional golfers had significantly more activation in the parietal lobe, occipital cortex and dorsal lateral premotor cortex. Preferential activation of these regions has been observed previously in subjects who perform goal-directed movement tasks that are visually triggered (e.g. Humphrey, 1979). Thus the brain of the professional golfers is much more focused on the task than the brains of beginners. Second, in the beginner's brain regions were activated that did not activate in the brain of the professional golfers. The two regions activated in beginners, but not the professionals, were the basal ganglia and the limbic system (Figure 4). The regions of the limbic system that were activated were 1) the posterior cingulate region (* in Figure 4a), a region involved in learning of visuospatial tasks (e.g. Vogt, et al, 1992); and 2) the basal forebrain-amygdala, regions often related to the control of stressful and fearful responses.

An intriguing explanation for the inverse relationship and skill level is suggested by the work of Fitts and Posner (1973). In their view an important step in the acquisition of a motor skill occurs when the individual no longer is consciously aware of the control of the movement. Thus, once the nervous system has sufficiently learned a motor skill, control depends more on the inherent properties of the movement as a whole and less on learning mechanisms and the conscious efforts of the individual to control the movement. Moreover, as is clear from everyday experience, directing conscious attention to the control of the movement is generally detrimental (e.g. Csikszentmihalyi, 1990). Since activation of limbic regions increases the awareness or attention of the individual to the environment and the presented task (e.g. Damasio, 1999), deactivation of these regions would be expected to increase motor skill (Pochon, et al, 2002). Surprisingly this interpretation resonates strongly with recent concepts on the neural control of skilled manual tasks, including juggling (Beek and Turvey, 1992; Polster, 2003), ball bouncing with a racket (Dijkstra, et al, 2003; Sternad, et al, 2000) and stick balancing at the fingertip (Cabrera and Milton, 2002, 2004).

The "inner game"

Learning a motor skill is not the same as being able to perform a motor skill under "game conditions" (Linden, et al 2002). Focus conscious attention on a movement and invariably skill level deteriorates. Examples include asking a golfer whether they breathe in or out when they hit the ball or asking a patient to walk normally during their medical examination. And, of course, many of us have experienced the negative impact of those "little voices in our head".

The important concept is the difference between active and passive feedback control (see, for example, Sternad, et al, 1996). The concepts of active and passive feedback control should not be confused with the older ideas of closed-loop and open-loop feedback control. These latter terms distinguish neural control mechanisms that are dependent on current sensory feedback (closed-loop) from those that are less dependent on sensory input (open-loop). Active and passive feedback control arises in situations that involve a hierarchy of feedback loops, such as occurs in motor control (Bernstein, 1967), in which the higher loops actively tune the performance of lower ones: the role of the higher loop becomes passive once the performance of the lower loops in the hierarchy has been optimized.

A simple example that illustrates the difference between active and passive feedback control is the thermostatic control of room temperature. Typically, thermostats operate as so-called “bang-bang” controllers, i.e. the furnace is either on or off (Flügge-Lotz, 1968). Two thresholds are chosen, one higher than the other. The furnace is turned on whenever room temperature falls below the first threshold and off when room temperature exceeds the upper threshold. Once the thresholds have been set, room temperature is self-controlled: no further changes in the thresholds are required to ensure that room temperature stays within the desired range (passive feedback control). In fact, by definition, any attempt to further change the thresholds would result in a deterioration of the control of room temperature! Active feedback control corresponds to the ‘trial and error’ process of changing the thresholds until the appropriate operating range is determined.

A close analogy can be drawn between active and passive feedback control on the one hand and, respectively, conscious and subconscious movement control on the other. However, in contrast to mechanical systems, it is not always possible for a human to turn off conscious interventions into motor control, even though once the task is well learned, such interventions are almost always detrimental to performance! From the nervous system’s point of view, the most important requirement for a passive feedback control mechanism is that it minimizes the role of consciously directed corrective movements. The reason that this is so important is that conscious control by the nervous system behaves as a resource limited quantity, i.e. the nervous system has a very limited ability to consciously control multiple tasks simultaneously (Just, et al., 2001; Miller, 1956; Rubinstein, et al., 2001). Consequently, any strategy that minimizes the demands placed on conscious control it is of great benefit. To overcome this problem, the nervous system manages multiple tasks serially in an intermittent fashion, i.e. every so often it checks to see whether or not a corrective movement is necessary (Bergen and Julescz, 1983; Crick, 1984; Krose and Julesz, 1989; Treisman, 1977).

The above observations also provide insights into the states of very high athletic performance referred to as “being in the zone” (Hatfield and Hillman, 2001). Although little work has appeared on the functional neuroanatomy of such states, our observations suggest that they may be related to keeping the limbic system inactive, i.e. to performing under game conditions with no feelings of stress or anxiety.

Practice

The three most important factors for sports achievement are practice, practice, and more practice. Log-log plots of motor skill versus practice time are linear (Fitts and Posner, 1973): each incremental improvement in skill requires progressively more practice. Thus, a novice typically experiences larger improvement in skill following a focused period of practice than a more skilled performer. These observations are consistent with suggestions that learning is on a ‘trial and error’ basis (Chialvo and Bak, 1999), possibly influenced by mimicry of the movements of more skilled individuals, such as sports heroes (Billard, 2001).

One mechanism for skill acquisition is repetition. However, by itself, repetition is a very slow and inefficient method to perfect a motor skill. Estimates of the numbers of repetitions to acquire elite levels of performance are in the range of 1-3 x 10^6 repetitions (Fitts and Posner, 1973). Thus, attainment of expert skill levels requires years of practice. There is also a dark side to repetition as a method to refine motor skills. Repetition of stereotyped movements with poor techniques and improperly designed equipment leads to the development of overuse injuries, such as back pain and entrapment neuropathies (Sahrmann, 2002). Consequently, research has begun to focus on the development of new teaching strategies that enable skill to be acquired with less physical practice time and hence less risk of injury.

Three novel concepts have gradually emerged. First variability in practice and problem solving during the early years is more important for the later acquirement of a sports skill than is specific instruction in the sports skill (Carson and Wiegand, 1979; Schmidt, 1988; Yan, et al, 1998). Thus the motor programs that are stored in memory are not specific records of the movements to be preformed, but a set of general rules, concepts, and relationships that can be called upon to solve situations as they arise. These findings have important implications for how practice sessions should be structured, especially for children.

Second, neuro-psychological studies emphasize that mental rehearsal of skilled movements is at least as important as practice for the development of expertise (Herbert, et al., 1998; Yue and Cole, 1992). Several studies have shown that motor imagery parallels motor planning and execution (Jeannerod, 1994). For example, muscle excitation levels increase during imagery in precisely those muscles that are implicated in the imagined movements (Bakker, et al., 1996; Hale, 1982; Harris and Robinson, 1986). In fact mental imagery alone is sufficient to reproduce all of the autonomic changes, i.e. changes in breathing, heart rate, sweating, that are associated with the physical performance of the activity (Oishi, et al., 2000).

Finally, performance, particularly in stressful game situations, depends critically on the "inner game" (Linden, et al., 2002). At every skill level, performance can be enhanced by teaching programs that include techniques from sports psychology, such as goal setting, positive self-talk, relaxation, and imagery (Lutz, 1999).

Discussion

The "modern philosophy" for training athletes, especially for the so-called strength and body contact sports, is that brawn is better than brain. This philosophy has driven the development of industries devoted to producing strength-training equipment, a fixation on the use of anabolic steroids to increase muscle mass, and produced predictable changes into how the game is played (Gerdy, 2002). However, elite performance clearly reflects a synergy of all of the biomechanical, physiological, neurological and psychological processes that make up an individual that are relevant to the sport and that can be applied to the sport in a given situation at a given time (Siff, 2000).

Directly assessing the activity of the nervous system of an athlete during competition is problematic. Currently available techniques for monitoring neural activity are not well suited for this task. Measurements of electro-physiological activity, for example, electromyography (EMG) and electro-encephalography (EEG), and regional changes in cortical metabolism and blood flow, for example, positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), require the individual to remain motionless and typically to be confined to a laboratory setting. In all cases the very thing we wish to study, i.e. movement, can introduce serious artifacts that can obscure the underlying changes in the activity of the nervous system. On the other hand there is also a danger of extrapolating from findings obtained far from the playing field to athletes in competition (Herzog, 2000). Thus, at present, there is no single laboratory test that is predictive of stardom: the only measure of star performance is the performance itself!

Little attention has been given in this discussion to the factors that determine team performance. All sports fan are aware of teams of less gifted athletes that consistently beat teams of super stars. A number of observations suggest that there are also neurobiological aspects to team performance. Team strategy clearly evolves with maturity of children. For example, soccer teams composed of six-year olds typically chase the ball en mass around the field. Despite the efforts of good coaching, positional play does not appear until the players are much older. It has been suggested that the cyclical nature of the win-loss records of professional football teams reflects the maturation time required before rookies can make meaningful contributions to overall team performance (Banks, 1998). Team performance is known to deteriorate because of jet lag (Recht , et al, 1995).

The importance of determining the neural contributions to elite athletic performance is the clues provided into how the nervous system learns to perform at high skill levels (Milton, et al, 2004a). Even though professional and novice have in common the activation of some cortical areas, the relative roles played by these areas for the control of motor skill may be very different. It is possible that fMRI studies in concert with a controlled teaching protocol would be ideally suited to objectively determine the impact of each of the proposed cognitive strategies on the functional neuroanatomy. In this way it is possible that even more effective strategies for improving performance could be devised. These strategies could be applicable even to those who are trying to regain motor skills lost because of the results of a stroke or other neurological diseases. Thus these observations have implications for increasing sport performance and teaching motor skills to both healthy and neurologically impaired individuals.

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