

THEORIES OF CONTROL

Key Notes

Reflex theory	Stimulus-response explanation of how movement is controlled.
Hierarchical theories	A 'top-down model' of how movements are controlled with the cortical centers responsible for sending motor commands.
Dynamical systems theories	An approach to control from the starting point; how do we control multiple degrees of freedom?
Coordination structures	A group of muscles spanning several joints, which are constrained to work together as a functional unit.
Affordances	Movement possibilities in different contexts within the scope of the performers' individual functional ability.

Related topics

Information processing (E) Theories of motor learning (H)
Sensory contributions to control (G)

To successfully perform a wide variety of skilled actions the performer has to coordinate various muscles and joints to work both effectively and efficiently (*Fig. 1*) Each movement a performer makes has to be planned, constructed and executed. Various theories have evolved to explain the nature and control of movements.



Fig. 1. We can change our posture and muscular involvement to functionally achieve the same end result in different contexts.

Sheridan (1984) outlined four aspects of motor control that have to be considered:

First, that the motor system has the ability to achieve functionally the same end result via different movements, involving different muscles and joints (motor equivalence). Second, that movements are never exactly repeated (uniqueness of action) . . . Third, that despite the apparent uniqueness of each movement the most obvious feature of skilled performance is the consistency and stability of both temporal and spatial structure (stability and consistency of action). Fourth, that not only is skilled action consistent and stable, but it is also capable of amendment as a consequence of changes in information available to the performer (modifiability of action). (Sheridan, 1984, p.60)

The variety of movements available to execute a task is massive. Sheridan's statement indicates the range of motor control problems that the performer has to cope with. Over the years there has been a change in emphasis from reflex theory to an information-processing approach and to a dynamical systems approach of movement control. It must be remembered that any theory of control must be able to account for motor equivalence, uniqueness of action, stability and consistency of action, and modifiability of action. This section will provide an overview of these theories and consider how we control complex movements (it is recommended that this section is read in conjunction with Section H). Theories of control will be considered under the following headings:

1. reflex theories
2. hierarchical theories
3. dynamical systems theories
4. ecological theories.

Reflex theories

Over the years there has been a change in emphasis from an information-processing approach to a dynamical systems approach to movement control. Prior to this, Sherrington (1906) proposed the reflex theory of control. After a series of excellent experiments, Sherrington concluded that with the whole nervous system, the reactions of various parts of that system, and the simple reflexes, are combined into greater actions that constitute the behavior of the individual as a whole (reflex chaining). Put in simple terms a stimulus creates a movement or reflexive response, see Fig. 2. There are a number of limitations to the reflex theory of motor control (Rosenbaum, 1991). It does not adequately explain and predict movement that occurs in the absence of a sensory stimulus. Furthermore, it cannot explain the production of fast movements or the ability to produce novel movements, or how a single stimulus can result in varying responses.

Hierarchical theories

As the term suggests, hierarchical theories of control work from a foundation that all aspects of movement planning and execution are the responsibility of higher orders of the central nervous system (CNS). In this top-down model, higher cortical centers send commands to lower cortical centers and movement then takes place. Feedback enables units within these hierarchies to communicate, and therefore movement can be controlled and adjusted. A starting point for looking at models of control is open- and closed-loop modes of control.

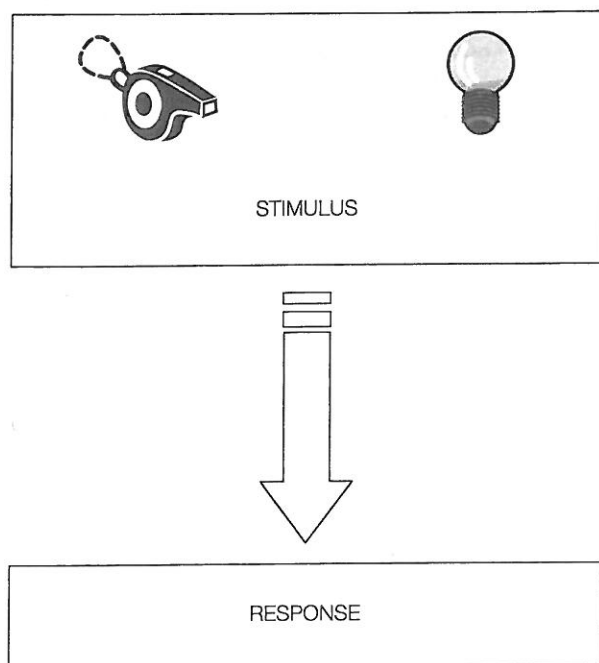


Fig. 2. Model representing reflex theories of control.

Open- and closed-loop modes of control

Adams (1971) proposed two modes of control: open and closed loop. In a closed-loop control system (Fig. 3) the control center issues an initial command to the effectors that is sufficient to initiate the movement. The execution and completion of such movements are however dependent upon feedback as this controls the ongoing movement. In an open-loop system (Fig. 4) feedback is not used in the control of the ongoing movement; the movements are believed to be pre-programmed.

Although more traditional explanations of goal-directed movements propose both open-loop and closed-loop components of movements, more recent theories predict less involvement of feedback (Meyer *et al.*, 1988) and others claim it plays virtually no role in the control of rapid movements (Plamondon, 1995a, b). Plamondon (1995a) suggested that 'sensory feedback is not used to control the trajectory' of aiming movements or reaching movements and that 'feedforward

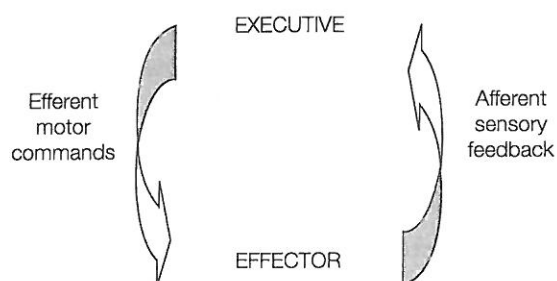


Fig. 3. Closed-loop control.

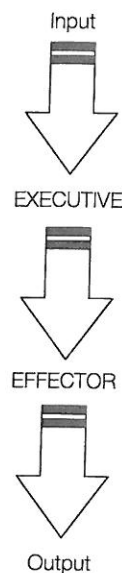


Fig. 4. Open-loop control.

control emerges through practice and learning' (p.216). However, several recent studies still support the two-component model of limb control (Helsen *et al.* 1998a, 2000; Starkes *et al.*, 2002), and this pattern of results has been found regardless of whether one performs aiming with the right or left hand (Helsen *et al.*, 1998b), whether target eccentricity is varied from 10 cm to 40 cm (Helsen *et al.*, 1997) and even when movement complexity is altered (Helsen *et al.*, 1998b).

The speed at which the movement has to be performed has a major influence on the mode of control employed. The most basic distinction in motor control is that between ballistic and controlled movements. Ballistic movements are rapid movements that do not allow for correction during the movement and therefore need to be preprogrammed. Feedback is not used during a ballistic movement, but should the same movement be repeated the performer would make changes as a result of the first trial. Controlled movements are relatively slower and changes are made during the movement. Over one century ago, Woodworth (1899) first explicitly distinguished between the two phases in voluntary goal-directed aiming movement and was the first to compare fast and slow movements. Woodworth (1899) asked subjects to move a pencil back and forth through a slit with the direction reversing once two marks had been passed. The rate of the moving pencil was controlled by a metronome. Subjects performed one set with their eyes open and another set with their eyes closed. He discovered that when subjects had their eyes open, mean absolute error decreased as velocity decreased. Thus, accuracy improved as movements slowed in the eyes-open condition but not in the eyes-closed condition. Woodworth concluded that in the eyes-closed condition subjects' movements were entirely preprogrammed; he referred to this as an initial impulse. In the eyes-open condition he concluded that movements were both preprogrammed and corrected with current control (visual feedback).

Generalized motor program

Taking a hierarchical stance, movements are stored in memory as plans or motor programs for movement. It was Keele (1968, p.387) who defined a motor program

as 'a set of muscle commands that are structured before a movement sequence begins'. However, the idea of a motor program being stored for every movement obviously has storage problems. The work of Keele stimulated a mass of research in this area and a broadening of the definition that took into account sensory feedback and was better able to account for how we were able to store movement memory. The work of Schmidt led to the term generalized motor program (GMP), which indicated that we stored families of movements rather than individual programs. It must be remembered that theories of learning and theories of control are closely related and a full review of the generalized motor program can be found in Section H. The generalized motor program is more adaptable than the motor program and it better explains the control of movement in a more varied and dynamic environment. It also explains how we are able to produce a wide variety of similar movements without the issues of storage. It also better explains motor equivalence and how we are able to produce novel movements.

The next theories of control to be reviewed approach control from a very different stance to previous theories. Both dynamical and ecological theories take into account the role of the environment and its interaction with the individual. These theories are better able to address Sheridan's aspects of control and they provide a more flexible overview of control that considers self-organization of the movement system. Dynamical and ecological theories are better able to explain how we control complex movement in an adaptive and demanding environment regardless of our level of expertise or experience.

Dynamical systems theories

Dynamical systems theories of control approach control in terms of a problem; that is how multiple degrees of freedom are controlled. How a number of units (joints, muscles) are controlled and co-coordinated to produce skilled movement needs further explanation. Bernstein (1967) raised a number of questions about the control and coordination of movements. He tried to characterize the study of movements in terms of the problems of co-coordinating and controlling a complex system of biokinematic links. In particular he worked on the issue of degrees of freedom. In an arm movement there are many structures that could be controlled at any one time. These could be the joints, muscles, alpha-gamma linkages or motor units. If we just consider the joints of the arm there are three degrees of freedom of movement at the shoulder joint, two degrees of freedom of movement at the elbow, and two degrees of freedom of movement at the wrist, this can be seen in Fig. 5.

Kelso (1982) states that if you take into account motor units per muscle (100) and joints in the arm, there are around 2600 degrees of freedom to be regulated at any one time. If these units are being controlled separately this would be a lot for any controlling mechanism. Kelso (1982) uses the example of a system with two elements (Fig. 6) operating in two-dimensional space. As there are two axes each element has a value on each axis, so element A has a y value and an x value, as does element B. As a result in (a) the two elements create a system that has four degrees of freedom of movement. By linking the two together (b), the positions of A and B are now dependent on the position of each other and the degrees of freedom of movement is reduced to three.

However, movement control is not that simple; movement takes place in a variety of different contexts and changing conditions. Bernstein (1967) identified three main sources of context-conditioned variability. Firstly, variability due to anatomical factors; secondly, mechanical variability; and thirdly, physiological variability. Bernstein considered this to be how many degrees of freedom can be

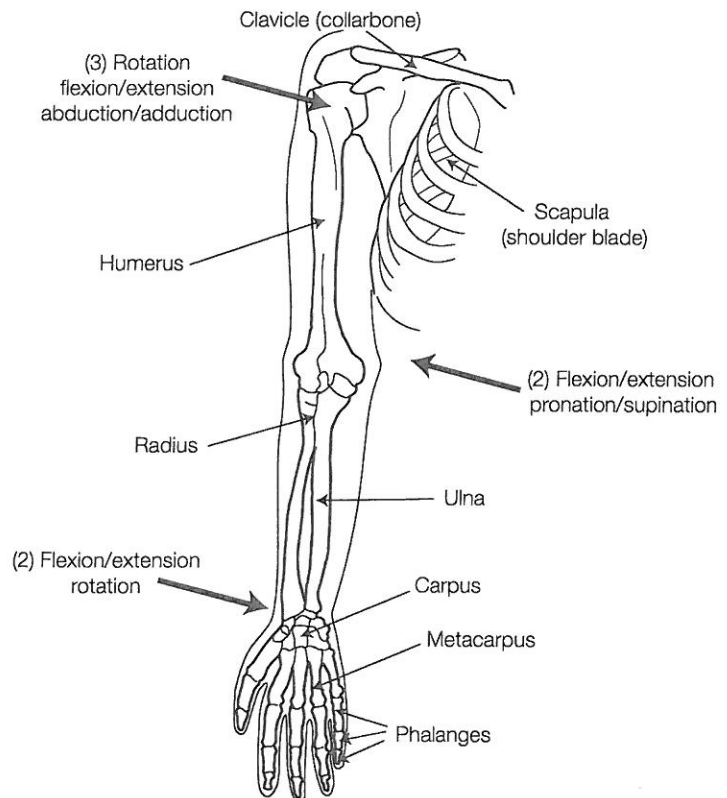


Fig. 5. Degrees of freedom of the joints of the arm (numbers indicate the number of degrees of freedom).

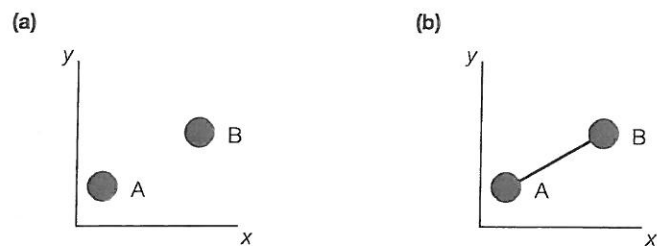


Fig. 6. How linking two elements (a) can reduce the degrees of freedom of movement. (b) demonstrates that by linking elements together control is potentially simpler as fewer degrees of freedom of movement have to be controlled at any one time. Adapted from Kelso (1982).

regulated systematically in varying control contexts without totally overloading the system. He suggested that a given nervous system program will produce different outcomes in different situations. He referred to a 'motor image', a central representation of the movement by the nervous system. The 'motor image' represented the form of movement to be achieved not the impulses needed to achieve it. He believed that proprioception played a vital part as it contributed to the representation of the movement. He also believed that one

way of controlling a large number of degrees of freedom of movement was to organize actions into synergies (Fig. 7).

Turvey (1977) proposed the concept of coordinative structures and this concept helps our understanding of how we control a number of movement variables in varying movement contexts. A coordinative structure is a group of muscles spanning several joints that is constrained to act as a single functional unit. Coordinative structures can be described as groups of muscles, often traversing several joints, which are constrained by the intrinsic structure of the mechanical system to act as a coherent unity (Davids *et al.*, 1994). The formation of coordinative structures assists us with controlling complex movements. Tuller *et al.* (1982) give numerous examples to illustrate this point. They give the example of steering a car where the front wheels are linked together. If the two wheels had to be controlled separately this would cause major problems for the driver. Analysis of the coordinative structures in animals such as the gait of a horse where changes of speed happen instantly promote the argument that there are biomechanical as well as cortical decisions supporting these changes. Other studies (Kugler and Turvey, 1987; Kelso *et al.*, 1991) on rhythmic hand and finger movements have shown how human movement systems can be described through the principle of self-organization.

The concept of coordinative structures can help overcome the problem of controlling innumerable degrees of freedom. However, another movement issue that has to be considered is: how do we control a particular action in different contexts? The coordinative structure must be adjustable. Tuller *et al.* (1982) among others have argued that a coordinative structure is a device that adjusts itself automatically to changing external conditions and achieves the same result. The ability to do this has been compared to a simple mass spring



Fig. 7. Cycling involves the control and coordination of multiple degrees of freedom in a changing environment.

model, which is a spring attached at one end to a fixed support and at the other end to a mass. Whether stretched (pulled) or compressed (pressed), the spring calibrates at a constant length regardless of the initial conditions and comes to rest back at its original starting position. This oscillatory system does not need any controller directing it. There is some evidence that some movements of the biological system exhibit the same properties as oscillatory systems. Movements at the elbow (Feldman, 1966) and finger movements (Kelso, 1977) act in an analogous way to a mass spring system. Kelso (1977) conducted an experiment which tested this theory. Subjects moved their forefinger from side to side over a distance that they selected. Their finger was then passively moved by the experimenter to a different starting position and the subject was asked to produce either the amplitude or the final position of the first movement. Kelso discovered that subjects could return to the same final position of the first movement with a high level of accuracy, but could not produce the same amplitude very accurately. Subjects could also return to the same final position of the first movement without being able to see or feel their finger's location. This research supports the mass-spring theory of control and explains how movement can be adjusted automatically depending on changing initial conditions.

The above theories help our understanding of how we control a number of degrees of freedom of movement, in a number of varying contexts, influenced by many variables. A coordinative structure explains how we control the number of degrees of freedom. The analogy of the mass spring is used to describe how a biological system can be self-regulating.

Ecological theories

The ecological perspective on motor control is based on the fact that the perceptual and motor systems evolved in natural environments, and that a good starting point is the physical task to be performed. An ecological approach to the control of actions considers how information available within the environment supports the coordination of movements.

As we move in the environment, the pattern of light on the retina varies depending on the layout of the environment, the level of illumination and the way in which we are moving. Gibson (1966, 1979) argued that the layout of the environment is specified by the optical array that it omits, that is the light that is perceived by an individual. The color, texture, shape and angle of inclination will affect the light pattern, or optical array in a characteristic way. This provides the performer with the perceptual information that they need to control movements in differing environments and contexts. Information from the environment is used by the performer to regulate motor activity. If a person moves forward in a stable environment, then the optical array will undergo an outward flow pattern. When stationary a person who then rotates the body will experience a local expansion of the optical array. Thus there is an invariant pattern of change for every type of movement. This information is vital to the performer and plays a significant role in the control of actions. Lee and Aronson (1974) and Lee and Lishman (1975) tested Gibson's theory. They constructed a room with a stable floor surrounded by walls which could be moved forwards and backwards. They wanted to see how the subjects reacted when the optical array was manipulated by moving the walls slowly while the subject stood still. They found that subjects swayed and that the direction of the optical illusion influenced the direction of the sway. When the walls moved forward they swayed backwards; as the wall approached the subject the retinal image size

increased as it would if you were walking towards the wall; as a result the subject sways backwards. Further work with children showed that they use visual information in the same way as adults. However, as they do not have the same proprioceptive experience as adults, the effect of moving the room was much more dramatic. When the room was moved forwards or backwards some children actually fell over in the opposite direction or swayed and had to take a step to steady themselves.

Lee and coworkers concluded, as did Gibson, that kinesthesia is not totally directed from within the body (proprioception) but can be controlled by vision (visual kinesthesia). Lee expanded this work in 1976 by calculating a precise relationship between the optical flow and movement in the external environment. He discovered that when an object is approaching the eye, the greater the speed of approach, the higher the rate of retinal image expansion (Lee, 1976). The higher the retinal image expansion rate then the less time there is until contact. Therefore time to contact can be calculated by the visuomotor system and the appropriate response made. Lee named this formula *tau* 'The inverse of the rate of expansion of the retinal image of an object equals the time remaining until contact is made with the object' (Rosenbaum, 1991).

According to Gibson (1979), a lawful account of perceiving and acting in dynamic contexts should be based upon a theory of a mutually constraining relationship between animals and their environments. Gibson (1979) theorized that a lawful relationship exists between the properties of the environment and the structure of surrounding energy distributions. The layout of the environment imposes a rich spatio-temporal order upon the surrounding energy flows (Fig. 8), particularly the crucial source-optical energy. Gibson (1966, 1979) argued that the layout of the environment is specified by the optical array that it

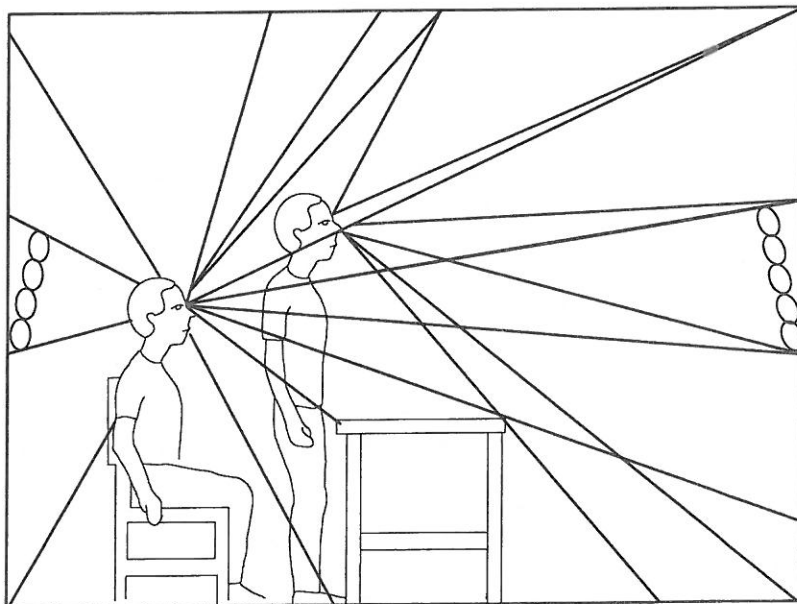


Fig. 8. Changes in the optical array can be caused by variation of the light, and also by the movement of an individual.

emits, that is, the light that is perceived by an individual, providing the performer with the perceptual information they need to control movements in differing contexts. Gibsonian theorists have highlighted the relationship between perception and action as direct and cyclical, in that information from the environment is used to regulate motor activity.

- *Flow field*: includes perceptual information from vision, haptic, proprioception, and auditory systems.
- *Force field*: refers to how we effect change in the environment through action.

The ecological approach to control has two main ideas that distinguish it from other theories. One is the concept of affordances, the other is the concept of invariants or higher-order properties of surrounding energy flow. Gibson (1966, 1979) introduced the idea of affordances. He stated that objects invite a specific action within a specific context. Therefore objects afford certain actions, and a cube, for example, is seen by the performer not as a cube but as an object that affords differing types of manipulation.

The object attributes are represented therein as affordances, that is, to the extent that they trigger specific motor patterns for the hand to achieve the proper grasp. In addition, this function does not seem to imply binding of object attributes into a single entity. Instead, each attribute contributes to the motor configuration of the hand by selecting the relevant degrees of freedom. (Jeannerod, 1994, p.8)

Affordances represent possibilities in different contexts within the scope of the performers' individual functional ability. This is a natural way in which the multiple degrees of freedom can be controlled. Kelso and Tuller (1981) also believe that situational conditions can provide constraints. An object can only 'afford' so much and will have different constraints in differing contexts and vary for each individual. Affordances are invitations to act within specific contexts (Gibson, 1979). For example, the athlete in the 3000 m steeple chase may see a barrier as an object that affords hurdling; another athlete may see it as an object that affords placing a foot on top and pushing off. The style adopted or afforded depends on the interaction between the expertise of the athlete, the task and the context. In Fig. 9 the task influences the grasp used by the performer for example.

Affordances for perception and action

The concept of affordances is the central aspect of the ecological approach. In his ecological approach to perception, Gibson (1979) proposes that from the origins of development what are perceived are the affordances of the environment: '... what it offers the animal, what it provides or furnishes, for ill or for good' (p.127). Hence, an affordance 'refers to the fit between an animal's capabilities and the environmental supports and opportunities (both good and bad) that make possible a given activity' (Gibson and Pick, 2000, p.15). Affordances are therefore possibilities for action; any given task, in a particular context, can be achieved in a number of ways depending upon the individual.

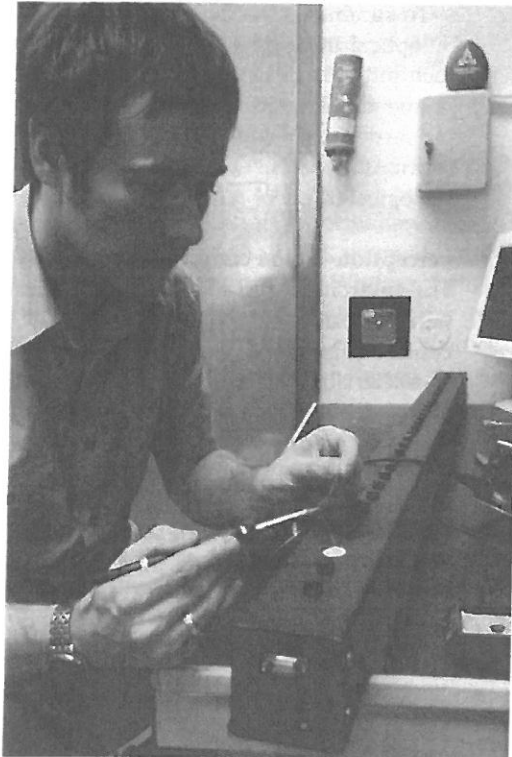


Fig. 9. Performing manual tasks requires control of the hands, a high level of coordination between other limbs and postural control. Different tools and shapes afford a different grasp and the grasp employed depends upon the task.

Gibson's theory of affordances therefore puts great importance on the link between perception and action. It is based on the premise that perceptual information is primarily constrained by the meaning of action (Rochat, 1995). If an animal guides its movement by affordances, it must be capable of perceiving the relationship between environmental properties and the properties of its own action system. One of the implications of this assumption is that actions are 'body-scaled' and perceptions are driven by intrinsic body measures as opposed to extrinsic or absolute measures. For example, Warren (1984) found that when a person was confronted with the problem of climbing the stairs, the 'climbability' was specified by a critical or boundary ratio between the person's leg length and the tread height. Ratios smaller than the critical ratio specify climbability, ratios larger than the critical height specify non-climbability. Hence body-scaled ratios can be used as a critical determinant of action choice, a change beyond the critical ratio determining a new class of action. Critical body-scaled ratios have been found for a variety of action patterns such as gait (Alexander, 1994), sitting height (Mark, 1987), walking through apertures (Warren and Whang, 1987) and reaching (Carello *et al.*, 1989). Thus, critical ratios can describe when a shift in behavior occurs (Van der Kamp *et al.*, 1998). In contrast, the switching between movement patterns may also emerge from the changes in the constraints imposed upon the action.

To summarize so far, affordances for action in an environment are specified by optical invariants and are contained within a unique frame of reference for each individual. Descriptions of the state of the environment can only ever be 'frame dependent' because affordances are perceived in relation to relevant properties of an individual (Turvey, 1986). Therefore, a mutually constraining relationship exists between intentionality, perception and action within an ecological frame of reference for each other.

Perception-action coupling

The environment provides opportunities and resources for action, and information to guide subsequent action. The natural physical approach to motor control suggests that perceptual information coordinates the spatio-temporal characteristics of the athlete's behavior in achieving an environmental goal. The specific movement of the performer creates perceptual information that is used to 'guide' the evolving dynamics of the neuromuscular system to the most adaptable pattern required for successful task execution. Gibson has considered the role of information in the control of movements to objects of varying location and orientation. Visual information is gained from the optic array, which has varying intensities dependent upon orientation and direction and the object from which it emits. This provides visual information, which assists control. Lee *et al.* (1982) used an ecological framework for under-



Fig. 10. In long jumping an accurate take-off is vital.

standing timing behavior in elite long jumpers. They argued that elite jumpers subconsciously used light energy from the take-off board (flow field) to modulate their stride pattern (force field) for take-off (Fig. 10). Large irregularities of the stride pattern in the last few strides are seen as evidence of using visual regulation.

An ecological perspective on the control of catching assigns primary importance to the fact that, for successful catching of a ball traveling on a relatively unpredictable trajectory, all the necessary information on which the spatial positioning and timing of the grasp of the hand are made must, by definition, be available in the optic array (Savelsbergh and Whiting, 1996). Indeed the narrow time window in which the performer has to initiate the grasp for a successful catch dictates that the performer must have access to predictive temporal information. Therefore there is a tight coupling between the action and invariant parameters of the environment.

Coordinative structure hypothesis

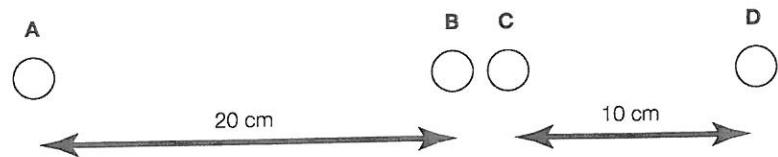
The natural physical approach to perception and action views the human biokinematic system as 'self-reading' and 'self-writing' (Kugler, 1986). There is no need for instructional devices for prescribing the pattern of contractions to specific muscles due to feedback and feedforward loops. Alternatively what is suggested is that coordinative structures are formed representing attractor states which are changing task solutions and do not need to be represented within the system.

Coordinative structures allow the performer to take advantage of the intrinsic design principle of the biomechanical system by temporarily assembling 'task-specific' devices in goal-directed behavior. These task-specific devices can be viewed as connections between component parts of the motor system. However, as a human performer acts in a dynamic environment, the energy that enters the system is ever-changing, and the temporal symmetry to which the system has been attracted becomes unstable. A modified version of the original action is therefore assembled. Information from the environment allows the system to move onto an appropriate attractor in order for a successful action to the problem or task to be found. In human performance, the information that is used to switch between attractor points surrounds the athlete.

In an attempt to assess the strength of upper-limb synchronization, researchers have explored the capability of human subjects to make different but simultaneous movements in limbs. Kelso *et al.* (1983) examined what would happen when an individual was asked to move each hand to a target that had a different index of difficulty. The tendency was for the two hands to come together regardless of the fact that they were moving to different-sized targets or targets that were differing distances away. In an earlier study, Kelso *et al.* (1979) found that limbs interacted by rescaling the temporal structure to obtain a common timing basis. Kelso *et al.* (1979) investigated bimanual aiming movements over different distances (6 cm and 24 cm). In the first of three experiments reported, subjects were required to move their index fingers from a centrally located position so the lateral targets could be touched as quickly and as accurately as possible. Subjects initiated two-handed movements almost simultaneously, the largest interlimb difference in reaction time (RT) being just 8 ms. Within-subject correlations for RTs between right and left hands in the two-handed conditions ranged from 0.95 to 0.97. Moreover, movement time (MT) data also showed that the subject's hands moved at different speeds to different target endpoints.

Activity

Draw the diagram below on a piece of paper



Start with a finger in circles B and C.

- 1 Move your left hand only from circle B to circle A on the left.
- 2 Move your right hand only from circle C to circle D on the right.
- 3 Now start with your fingers in B and C and move your left hand to circle A and back and your right hand to circle D and back.

You should find that when moving both hands together you start and finish at the same time as in the Kelso *et al.* (1983) experiment.

Thus one of the main findings of the study was that even when each limb was required to move different distances to the targets, time to peak velocity (TPV) and time to peak acceleration (TPA) for each limb showed a synchronous pattern, despite the fact that both limbs traveled at entirely different speeds. These findings led Kelso *et al.* (1979) to conclude that the brain sends signals to muscle groupings superimposed across the two limbs. Timing was seen as an essential variable (i.e. a variable that reflects the overall behavioral organization during action) in the control of bimanual coordination.

In particular the work of Kelso *et al.* (1979) has been interpreted as support for the theoretical notion that actions are controlled via coordinative structures (Turvey, 1977). Thus, during bimanual movements, rather than being controlled separately, the limbs are controlled via across-limb functional groups of muscles that form significant units of action thus reducing the cognitive load placed upon the executive system (Kelso *et al.*, 1979). Nevertheless, some studies have shown a partial distribution of this common temporal structure with increasing spatio-temporal divergence of bimanual movements, and thus other explanations have been investigated.

Conclusion

Theories of motor control provide the foundation on which practice should be based. These theories are not abstract ideas that have no relevance to the applied context. As we have seen in this section there are large differences between reflex, hierarchical, dynamical, and ecological theories. There are still conflicting opinions as to how relevant the general motor program is, and as to how appropriate dynamical and ecological theories of control are. Further research will no doubt continue to explore the pro and cons of each in a variety of movement contexts.

Further reading

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