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"Some Types of Movements"

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Some Types of Movements

Automatic vehicles on four wheels are lifelike in their front-to-back polarization (sensors in front, motors in the back), in their up-down polarization reflecting their contact with the ground (or water surface), and in the bilateral symmetry of their body with paired sensors and motors. There are animals so constituted mainly among the small aquatic species. Larger animals moving in the water, in the air or on the surface of the earth have articulated appendages which provide the motor system with an increased number of degrees of freedom. The nerve centers which govern their coordinated activity are large and poorly understood. They pose fascinating problems of interpretation, not so much, I suspect, because of their intrinsic complexity, but mainly because we do not know in what terms the states and changes of the motor system are represented in the brain. The cerebellum is probably the part of the vertebrate brain in which the "wiring" is best known, but the basic operation it performs is still obscure. Its action is undoubtedly important in motor coordination. When it is disturbed, the impression one gains is that of movements which reach their goals in a qualitative way, but with difficulty, as if the physics of the moving parts were disregarded. Possibly the intact cerebellum computes the equations of mechanics, adding "smoothness" to the movements dictated in a rough qualitative way by the cerebral cortex. But does the cerebellum "know" Newton's laws and Hamiltonian mechanics? I doubt it. Are there other ways of computing movements? Are there shortcuts which provide the desired effects without cumbersome calculations? These are questions relevant to future theories of the cerebellum, and already touched upon by some.[6] I want to contribute a few general considerations on movements which are perhaps preparatory to an understanding of the physics of movement as the cerebellum understands it. Some of these thoughts emerged from conversations I had with Dr. Gin McCollum during her stay in Tübingen in 1986. Sloppy physics, however, is not her responsibility.

MOVEMENT BY REDEFINITION OF THE SYSTEM

Linear and angular momentum are conserved. A rocket emitting a jet of gas, a gun recoiling, a man catching a heavy ball move only in so far as the thing moving is redefined with respect to the original condition: the rocket without the gas, the gun without the bullet (and the gunpowder), the man plus the ball. It must be remembered that living beings are essentially of one piece. They do incorporate and expel matter, but the dynamics of this is very rarely used for propulsion: the jet of larval libellulas, or that of the octopus escaping. Catching a heavy thing, resisting the jump of an aggressor are, however, of this kind: the body has to deal with a change in linear and/or angular momentum.

ROTATION VS. EXPANSION

Generally, skeletal muscles are attached to bones in such a way that the result of their contraction is rotation around a joint (visceral muscles are different). Thus torque, moment of inertia, and angular momentum are expressions which occur naturally in the descriptions of such movements, and terms akin to these physical definitions most likely are used in the neurological computation of movement. Not only do the various segments of a jointed arm rotate around the axes of the joints, but the arm itself, when lengthening or shortening, may impart angular momentum to the system body plus arm as a whole. The angular momenta, and the torques produced by the segments of a limb often cancel. Arms and legs are composed of two main segments each (upper arm and forearm, thigh and lower leg) which contribute to extension and flexion with opposite and roughly equal angular momenta. Extension of the two arms in opposite directions produces no net angular momentum in the body as a whole, nor does symmetrical extension or flexion of both legs. Such movements can be described in terms of contraction and expansion like some of the movements of mollusks.

Contraction and expansion change the moments of inertia around some of the axes of the body. Moments of inertia must be of prime importance in the control of movements if torques are what the muscles produce. The physics of jointed limbs is complicated because rotation in one joint generally changes the moment of inertia involved in the rotation of another joint. Think of an arm positioned with a right angle at the elbow. Pendular movements of the upper arm and forearm cannot be both harmonic when performed at the same time, since the change of the moment of inertia due to movement of the forearm interferes with the pendular movement of the arm around the shoulder (Figure 1).

MOVEMENTS WITHOUT SUPPORT

A space ship at rest in absolute space is condemned to stay put with its center of mass, although its shell may be seen to move for short distances when there are changes of its inner configuration: the crew rushing from one side of the cabin to the other. Can it suddenly start to rotate? It can, with the crew marching around in the opposite direction to preserve angular momentum. Can it rotate around a certain angle and then stop, with exactly the same inner configuration at the beginning and at the end of the movement? It can, if the dance of the crew stops after having gone around an integer number of times. Could an animal, suspended in free space, change its orientation by rotating around an axis? This would seem to be more complicated, since there are no wheels inside the animal which may rotate and then stop regaining the original configuration: everything is connected in the animal body; any rotation would necessarily result in a twist. Still, by combining contraction, expansion and bending an animal could move part of its mass around in a circle to produce a net rotation of its body with exactly the same configuration as before. Think of a weightless man in space holding a heavy mass close to his body (Figure 2a).

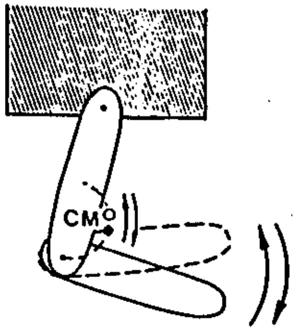


FIGURE 1 The center of mass of the arm (CM) shifts with changes of the elbow angle. Pendular motion of the forearm interferes with pendular motion in the shoulder joint.

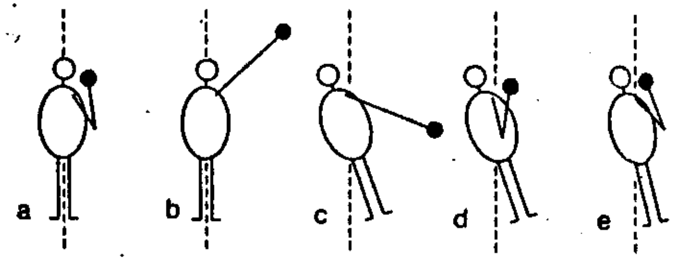


FIGURE 2 The sequence a to e shows how a man suspended in space can change his position.

He may extend the arm holding the mass (b), then swing the arm around (c), imparting equal and opposite torques to the arm and to the body, then bring the mass again close to his body (d) and finally rotate the arm back to its original position (e). The moment of inertia of the arm after the flexion is smaller than that of the extended arm, while the moment of inertia of the body stays the same. The torque which brings the arm back to its original position produces rotation of the body by an angle less than that of its (opposite) rotation during the swing of the extended arm. The net result is a rotation of the whole system with an unchanged internal configuration. It is said that cats land on their feet thanks to rotations of their tail by which they correct deviations from the vertical position. Extension, rotation and contraction are the only way a skater can put himself back in the upright position when he threatens to fall, since he cannot exert any torques against the practically frictionless contact of his legs with the ground. Most likely this kind of correction is also applied with normal upright posture even when friction against the ground is available. The complicated sequence of contractions in the muscles of the whole body which follows a jerk of the platform on which the subject is standing[2,5] may reflect (in part) such dynamic strategies.

NAHVI'S PRINCIPLE

Mahmood Nahvi learned this observing crane operators on construction sites. A crane holding a load suspended from a long cable, if it were rotated in one swing to the position where the cargo is to be grounded would produce long-lasting pendular movements of the load, making it impossible for the workers to get at it. The strategy used by the crane operators is the following (Figure 3): They rotate the crane quickly to a position half way between the starting position and the target position and stop it there. The load swings to where it is going to end up and loses

its kinetic energy at the end of the pendular movement. At that time the crane is quickly swung around the rest of the way, the load is thereby lowered, losing its gravitational energy as well, and can be safely delivered.

It was Nahvi's contention[4] that with all the elastic energy stored in tendons and in the muscles themselves between the contracting elements and the load, every contraction would be followed by oscillations, unless the temporal pattern of the contraction were preprogrammed to compensate for the stored energy, quite analogously to the strategy of the crane operators. Nahvi thought that the generality of this principle in motor control, and the large amount of stored information and/or computation which it involves, well deserves a computer of the size and complexity of the cerebellum.

The strategy used by the crane operator may be a clue to the understanding of the triphasic, sometimes quadriphasic pattern of muscular contractions observed in many rapid movements of the limb,[6] of the head[3] and of the whole body.[2] A contraction of the agonist muscle is followed by a contraction of the antagonist, stopping the movement before it reaches the goal, which then again is followed by a contraction of the agonist, completing the movement. This is strongly reminiscent of Nahvi's principle.

CENTERS OF MASS

One piece of information which must at all times be present in the control apparatus governing a system of jointed masses is the position of the center of mass of the

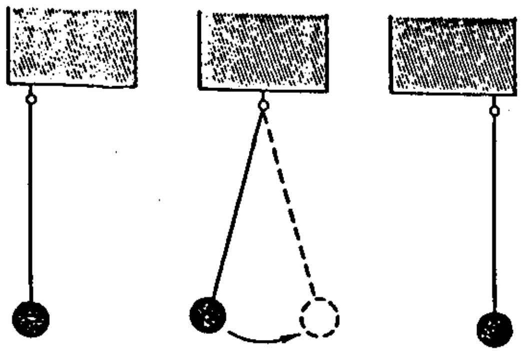


FIGURE 3 The strategy used by the crane operator.

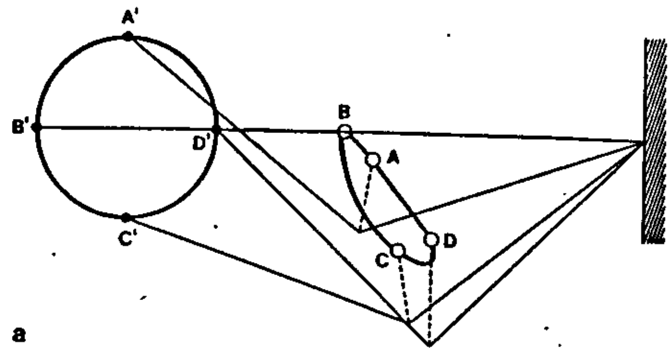
body. The center of mass shifts with changes of the configuration of the body, e.g., extension or flexion of limbs, when they are not balanced around it, as they sometimes are. It may be located outside of the body as defined by its outer surface, e.g., in a person bending over or sitting on a chair. The position of the center of mass is important because the geometrical relation between it and the vector of displacement of partial masses of the body decides whether the result is rotation one way or the opposite way or just linear displacement of the body, or no movement at all.

In cases where the movements of a (relatively light) arm can be regarded in isolation, being approximately independent from the concomitant movements of a (relatively massy) trunk, the center of mass of the arm itself becomes important. Except for the fully extended position, the center of mass is outside the arm, on the bisectrix of the elbow angle (assuming the upper arm and forearm as having the same shape and mass, Figure 1). The positions of the center of mass correspond one-to-one to those of the tip of the extremity.

It has been shown[7] that circles drawn repetitively in the frontal plane, like on a blackboard, with the extended arm, turn out quite satisfactory, whereas circles drawn on a sagittal plane (i.e., parallel to the plane of mirror symmetry of the body) are strongly distorted. In the latter case, flexion of the elbow is involved, the center of mass moving in and out along the bisectrix of the elbow. The distortion observed may be related to a tendency of the center of mass to move on a circle which would result in a distorted circle at the tip of the extremity holding the drawing implement (Figure 4). In the case of the circle drawn with the extended arm, the center of mass does move on a circle, a movement which may be simply compounded out of two pendular harmonic motions of the arm, at right angles to each other. This is apparently easy to perform.

THROWING AND JUMPING

Throwing an object implies imparting it acceleration toward the velocity with which it leaves the hand. The hand accompanies the object, exerting force on it for a certain time, during which it accelerates. In order to keep in contact, the hand has to accelerate too. In certain cases, e.g., when throwing with a flexion of the forearm (Figure 5a) starting with an extended arm, the accelerated motion is apparently accomplished entirely through an accelerated contraction of the muscle. In other cases (Figure 5b), the geometry of the joint and of the tendon help, as when throwing by an extension of the forearm starting from a bent elbow (which is in fact more efficient). There, in the course of the movement, the lever arm on the side of the muscle, although anatomically constant, becomes actually shorter because its projection on a line perpendicular to the direction of the muscle shortens. Thus the contraction of the muscle at a constant speed results in an accelerated rotation of the forearm in the elbow joint.



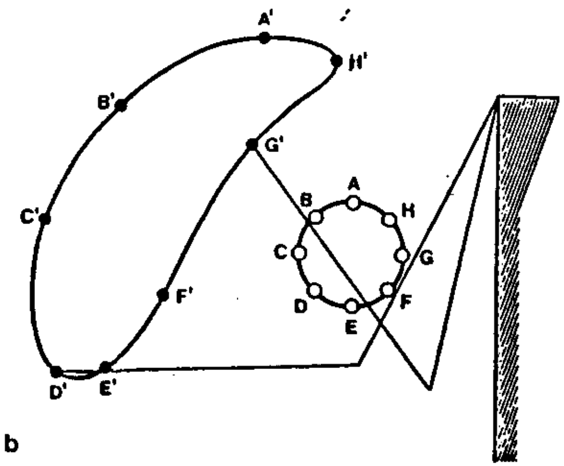


FIGURE 4 The tendency of the center of mass of the arm to move on a circle makes it difficult to draw a circle. a: If the hand is constrained to move on a circle, the center of mass describes the awkward figure A, B, C, D. b: Conversely, if the center of mass is allowed to move on a circle A to H, the figure described by the tip of the arm is A' to H'.

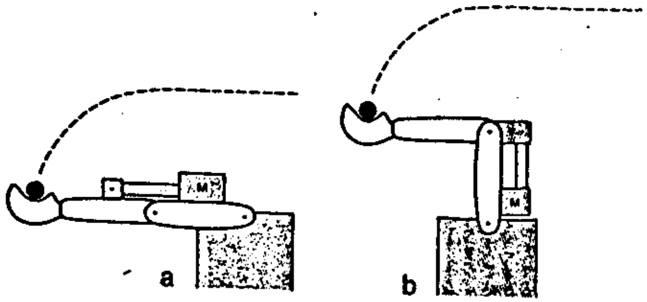


FIGURE 5 In throwing, i.e., imparting acceleration to a mass, the geometry of the joint s important. Going from flexion to extension (b) is more advantageous than going from extension to flexion (a).

The situation is even more dramatic in jumping, which is really "throwing" :he entire body. Here the geometry of the knee joint (Figure 6) is definitely advan- :ageous, with the femur rolling on the plane of the tibia, making the gain of the oint (degrees of rotation per unit of shortening of the muscle) progressively greater between flexion and extension.

HARMONIC OSCILLATIONS

'n very rapid oscillatory movements of the forearm, as occur sometimes in musical performance, e.g., in the bowing of string instruments, the movement becomes almost perfectly sinusoidal.[1] When the voluntary movement is stopped, the arm continues to oscillate for a few cycles at roughly the same frequency, implying that here is a spring- like operation involved in the movement. What the nervous system apparently does in this case, is to adjust the elasticity of the joint by setting the 'tonus" of the muscles to a certain value, appropriate for the desired frequency, and to feed the resulting spring-like oscillation with energy at the correct phase.

"GAITS" OF A JOINTED ARM

Limbs are composed of discrete masses connected by a number of joints, each having between 1 and 3 degrees of freedom. The movements of such a system thus

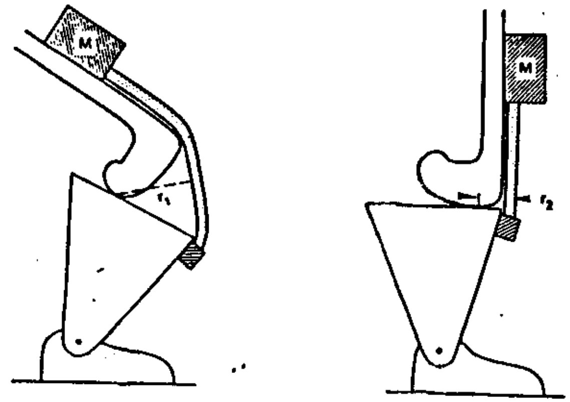


FIGURE 6 The knee joint: variable leverage.

can be classified in a natural way, by noting the qualitative relationships between the rotations in the various joints. The human arm can be schematized as three segments (upper arm, forearm and hand) moving in three joints (shoulder, elbow and wrist). When the movement is confined to one plane, as it is in the bowing arm of a violinist, each of the joints has one degree of freedom, the shoulder losing its second degree of freedom of rotation and the rotation of the forearm around its long axis being eliminated. Consider a periodic movement of the arm such as up and down bowing. Each joint may contribute to the movement, or oppose it by moving in the opposite direction, or not move at all. Thus the number of qualitatively different movements of the arm is $3^3 = 27$. If movement of the bow in one direction is to result, we must eliminate the 2^3 cases in which none of the joints moves in that direction, all of them either being at rest or moving in the opposite direction. Thus the useful patterns of movement for any one direction are $3^3 - 2^3 = 19$. In theory, any of these patterns for the up-bowing may be combined with any of the patterns for the down-bowing, bringing the number of "gaits" for the up-and-down movement to 361, although most of the time, but by no means always, symmetrical patterns are used for the up and down strokes. A number of these gaits are used, more or less consciously, by the violinist, in order to produce varying musical effects. The teacher may use such expressions such as "with a stiff wrist" or "movement from the shoulder" or "elastic operation of the wrist" to induce one or the other movement.

OTHER KINDS OF MOVEMENT

Besides throwing and catching, pushing and pulling are also interactions with foreign bodies, where the communal center of mass of the actor and the object acted upon certainly plays an important role in the control of the system. Here the internal representation of events in the outside world, which we usually do not associate with the motor system, obviously must become part of the motor control.

A very special kind of movement, reserved to primates and particularly prominent in humans, is the detailed operation of the fingers in performances such as peeling an orange, extracting a worm from a hole, drawing, handwriting, typing or playing the piano. Here the interest is more in the realm of information and control, rather than in the problems of biomechanics.

CONCLUSION

It was my intention to show that the movements in space of articulated bodies pose problems of a different kind from those treated in elementary or even not so elementary textbooks of mechanics. The account which I gave was naive on purpose. It is my contention that the brain deals with movements in a naive way. If we hope to understand the role of the cerebellum and of other centers concerned with movement, we must lower ourselves to that level.

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