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ACTION CURRENT STUDY IN MOVEMENT COORDINATION*[1]

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A. Introduction: Movement Analysis

The objective psychologist, hoping to get at the physiological side of behavior, is apt to plunge immediately into neurology trying to correlate brain activity with modes of experience. The result in many cases only accentuates the gap between the total experience as studied by the psychologist and neural activity as analyzed by the neurologist. But the experience of the organism is integrated, organized, and has its meaning in terms of coördinated movement. Knowledge of the muscle contraction patterns constituting our behavior is needed in psychology, and can be acquired only by detailed experimental analysis of movement coördination. Contraction of the musculature, unlike the spread of excitation through the central nervous system, can be analyzed in detail with techniques now available. Movement analysis, therefore, offers a definite experimental program for psychology. By starting with the analysis of simple movements and working on to the more complex overt coördinations, a systematized body of facts may be built up from which to approach the problems of the most complicated learned behavior including the more elusive implicit habits. Analysis of the coördination and association of overt movements is simpler and must come first.

This paper describes a method for recording muscle action potentials kymographically and summarizes the results of an experimental investigation of certain aspects of movement coördination: viz., the rapid contraction of the proximal supporting musculature, the muscular action involved in circular movement, the maximum rate of

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reciprocal movement, and the relaxation in antagonist muscles during slow movement.

B. Method and Apparatus

Kymograph records of the general type shown in Figure 2 were used throughout the study. The excursion of the moving member is recorded by attaching to the member a light silk thread on which is mounted a thin celluloid pointer. A section of rubber band at the end of the line allows the thread and pointer to follow the movements of the limb.

The time line, marking tenths of a second, is controlled by a synchronous motor driving a cogged wheel that revolves once per second to make and break the circuit ten times per revolution. The circuit runs through a magnetic marker which traces the time line on the drum. With a protractor one can divide the 100 sigma intervals into intervals of 10 sigma, making possible measurements with an average error of less than 5 sigma.

Two types of electrodes were used. Zinc plates about two square centimeters taped to the skin with a pad beneath moistened in electrode jelly were used for the grosser work. Electrodes of No. 28 insulated copper wire, inserted so as to lie beneath the skin just over the muscle, made it possible to tap a localized contraction. The wire was sharpened and the insulation scraped off for about 0.5 cm. at the point. After it was inserted a little over 1 cm. the wire was bent so as to lie flat on the skin where it was taped firmly in place for 2 cm. or so to prevent its moving. In work where the contraction is not vigorous the wire can be inserted directly into the muscle.

The amplifier consists of two resistance capacity coupled stages, one parallel-feed transformer coupled stage, and one transformer coupled push-pull output stage. The input circuit to the grid transformer is 10,000 ohms for surface electrodes and 2,500 ohms for inserted electrodes. The output circuit consists of type '89 tubes feeding the output push-pull transformer with 30 ohms impedence to the magnetic marker.

Special magnetic markers were built for recording action currents on the kymograph (Figure 1). These markers are sensitive to frequencies above 700 per second and prove very satisfactory for the purpose of the present study. They show presence of muscle action potentials and indicate their amplitude, but do not show the minute

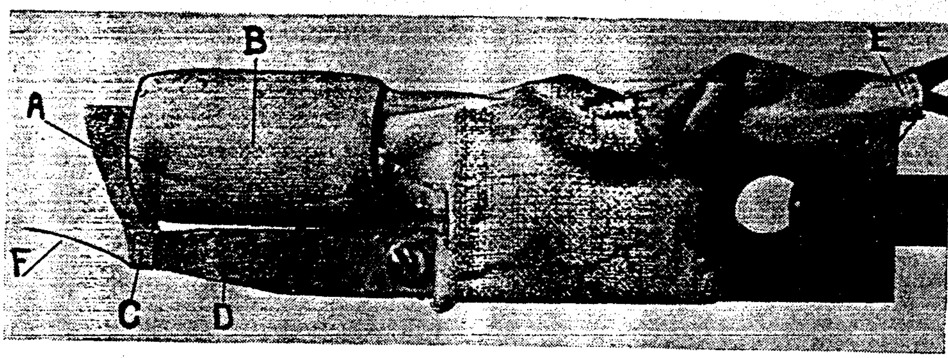

FIGURE 1

MAGNETIC MARKER USED FOR RECORDING ACTION POTENTIALS ON THE KYMOGRAPH

A—Pole-piece of soft iron.
B—Coil, about 500 turns of No. 40 insulated copper wire, covered with tape to protect from damage. Coil measures 2.5 cm. in length.
C—Movable armature, 3 by 4 mm. in area and 0.1 mm. in thickness, made of magnetic transformer iron. This joint is drawn toward the pole-piece (*A*) when current passed through the coil. It is held to (*D*) by two membranous strips of rubber which pull it sharply back into place when the magnetic attraction toward (*A*) ceases. The distance between (*A*) and (*C*) can be varied in the neighborhood of 1 mm.
D—Rigid part of armature, of soft iron same as (*A*).
E—Leads to amplifier.
F—Wire tip of spring steel, etched down to hair-like fineness, retraced in figure so as to be visible. The shorter the wire tip, the less the amplitude of excursion, but the more sensitive the marker and the more accurate the action-current record.

details of the pattern of action-current discharges shown by an oscillograph.

Figure 2 contains sample records showing how the marker works. They all show action currents accompanying extension of the wrist. The amplification has to be adjusted according to the amount of contraction one wishes to record. Record *B* shows the amplification quite low so that only the point of strongest contraction shows through. Compare this with Record *A* showing medium aplification. To record more accurately the onset of contraction or the presence of very slight tensions the amplification is increased as in Record *C*. Here the amplification is quite high so that the whole contraction is recorded. The regular spikes preceding the main contraction are due to the rhythmic firing of the motor units in a weak tension preparatory to making the actual movement of the hand. Where the action current is very strong the swinging armature is

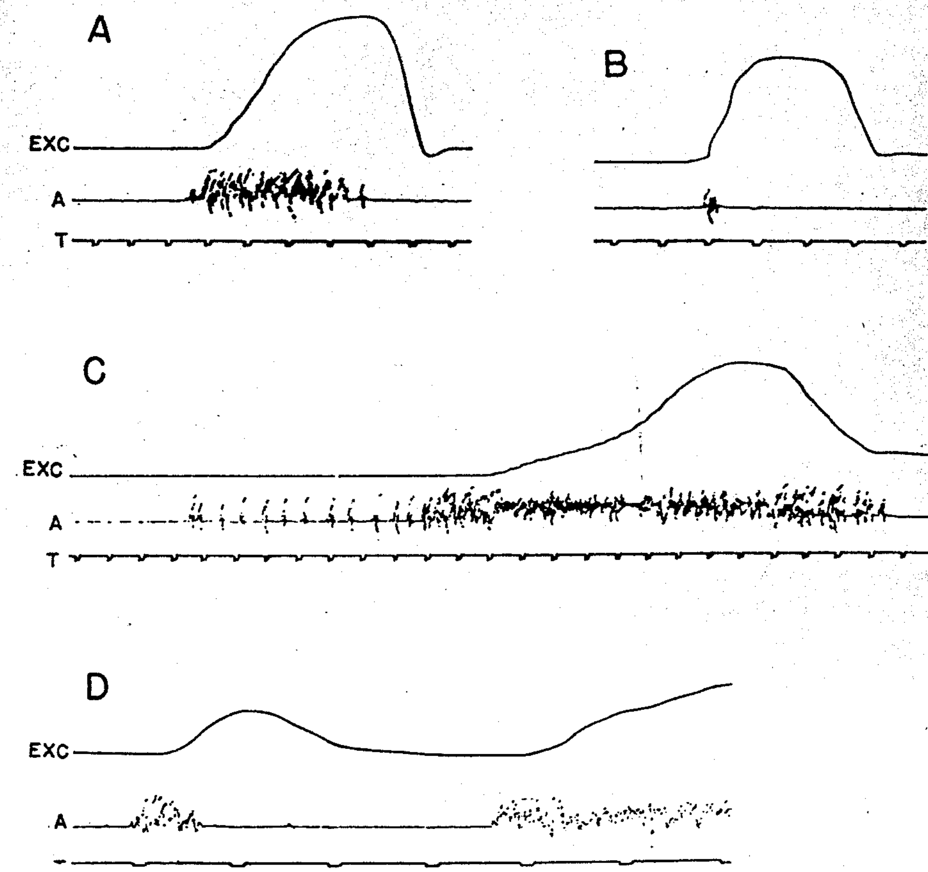

FIGURE 2

Sample Kymographic Action-Current Records, Demonstrating the Action of the Magnetic Marker

A—Medium amplification.
B—Low amplification.
C—High amplification.
D—Fast drum with medium amplification.
Exc—Excursion of the wrist, extension against gravity.
A—Action-current from extensor digitorum communis muscle of forearm.
T—Time, 0.1 sec.

held almost steadily against the pole piece and does not swing back to the base line. If desirable, the amplification can be changed gradually or suddenly within a single record. Speeding up the drum as in Record *D* makes it possible to read the time relations between excursion and action current more accurately, and shows more clearly the high sensitivity and lack of inertia of the magnetic marker.

Four subjects were used in the work on postural contraction, five in the study of circular movement, four in the work on maximal rates, and three in the work on slow, loose movement.

C. Rapid Contraction of the Proximal Supporting Musculature

Reciprocal tapping movements of the hand involve, in simple form, the action of antagonistic muscles, and illustrate many of the elementary principles of movement coördination. The action of the driving muscles in this type of movement has been worked out (5). However, the action of the larger supporting muscles of the upper arm and shoulder is not clear. These proximal muscles contract to hold the arm in position while the hand is being thrown back and forth by the flexors and extensors of the forearm. There is a question as to whether the supporting muscles fixate in a simple, steady contraction, or whether they make adjustments for the mechanical effect of each separate, distal movement.

Work on speech movements has shown that the supporting abdominal muscles no longer follow the separate rapid pulses of the intercostal muscles in the production of syllables after the rate increases above 3.5 - 4 per sec., but fixate in a steady contraction (4). Also it is known that the maximal rate for reciprocal movements of the whole arm involving the large muscles of the shoulder is much slower than that for the hand and fingers. Such facts indicate the possibility that the large proximal muscles of the body used in supporting the fine distal movements are not able to contract as rapidly as the smaller muscles, and are actually slower and more gross in their adjustments. The evidence presented below, however, indicates that the larger postural muscles are capable of contracting just as rapidly as the muscles of the distal segments; indeed, the larger muscles appear to contract synchronously with the driving muscles of the moving limb.

Rapid pulses were recorded from various large muscles of the trunk and limbs during rapid reciprocal movements of distal segments. Record *A* in Figure 3 shows a series of rapid contractions of the deltoid muscle while the hand executes reciprocal movements at the rate of eight per second. The pulses occur just as rapidly as those from the extensors and flexors of the forearm. The arm was held out horizontally from the shoulder so that the deltoid formed

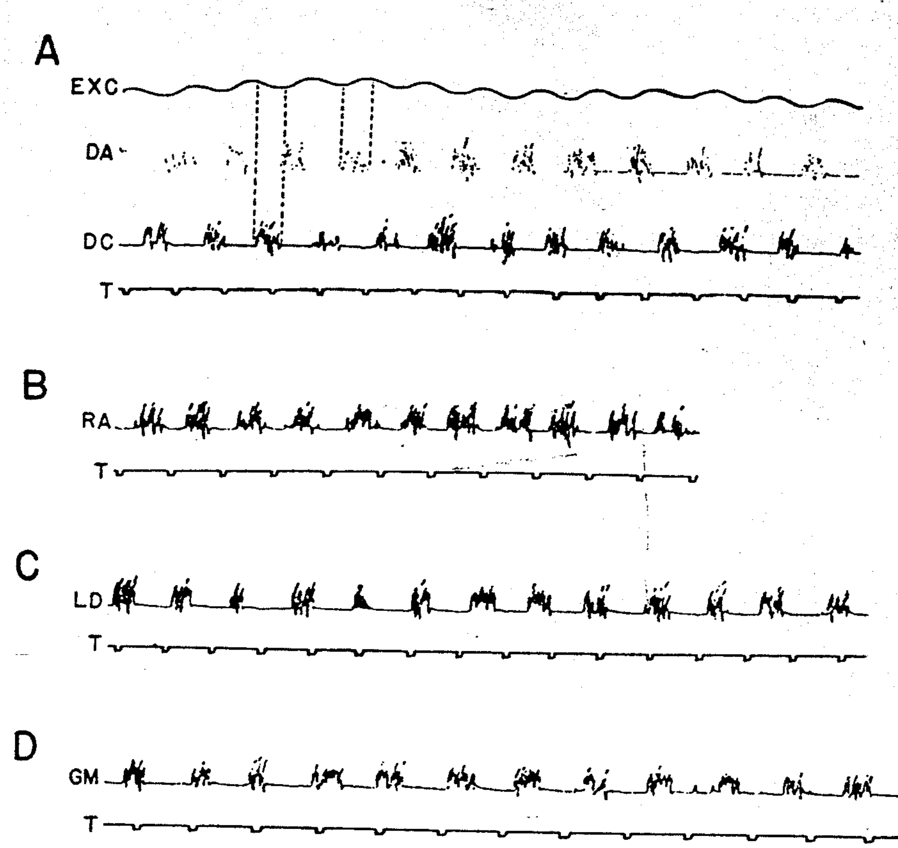

FIGURE 3

Contraction of Proximal Supporting Muscles During Rapid Reciprocal Movement of Distal Members

Exc—Excursion of upper arm. Reciprocal adduction and abduction caused by vibration from the wrist movement.
Da—Deltoid acromial.
Dc—Deltoid clavicular.
T—Time, 0.1 sec.
Ra—Rectus abdominis, epigastric region.
Ld—Lumbo-dorsalis.
Gm—Gluteus medius.

an essential part of the supporting posture. The contractions of both the acromial and clavicular portions of the deltoid muscle are shown pulling from opposite sides of the arm. These pulses may be superimposed on a continuous contraction, for the amplifier was adjusted to pick up only the change in tension. The whole arm vibrates to the movement of the hand, and the contractions of the deltoid seem to compensate for the mechanical rebound from the hand movement. The excursion shown is that of the upper arm near the elbow.

Record *B* in Figure 3 shows action currents taken from the epigastric region of the rectus abdominis occurring at the rate of 10 per second during reciprocal movement of the forearm. The subject, standing on his feet, leaned backward so that the abdominal muscles were stretched slightly. In this position they respond readily to the mechanical tugs of the shoulder girdle and rib cage caused by the rapid arm movement. Similar contractions from the lumbodorsalis are shown in Record *C*. In this case the subject stood on one foot and made rapid forced tremors in the other leg stretched out behind him. Record *D* shows contractions of the gluteus medius in the hip during reciprocal movements of the ankle.

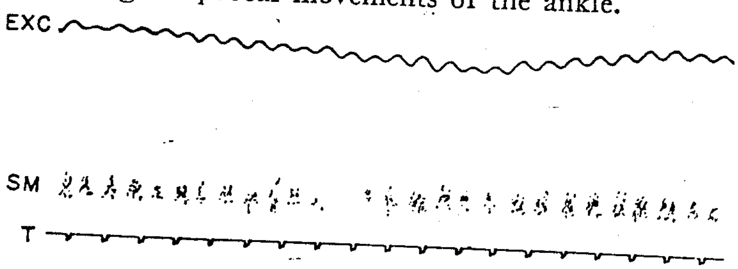

FIGURE 4

Forced Tremor Movements of the Head at the Rate of 15 per Second

Exc—Excursion of the head, taken from small block of wood held firmly between the teeth.

Sm—Scalenus medius.

T—Time, 0.1 sec.

The question is still open as to whether these rapid proximal pulses are set off by the mechanical stretching of the muscle, i.e., stretch reflex; or by some independent mechanism and so timed that the discharges anticipate the mechanical impact.

That the large muscles of the shoulder are quite capable of rapid contraction is further confirmed by the fact that although the maximal rate for reciprocal movements of the whole arm in one subject was about 5.5 per sec., the rate for the same movement with the same muscles, but with the arm flexed at the elbow to reduce the inertia, was about 8.5 per sec. When a 2-kilogram weight was attached to the flexed arm, the rate was slowed down again to about 5.5 per sec. The comparative slowness of the overt reciprocal movements driven by large muscles seems to depend upon factors of inertia, as the mass of the load to be moved rather than upon physiological differences.

D. Circular Movement

After analysis of the straight back and forth reciprocal movement revealing the antagonistic action of muscle groups in its most direct form, the next step is to determine how the muscles act to throw a limb about in a curved or circular movement. At slow speeds the contractions involved in pulling the arm through a curve can be easily anticipated and understood in terms of the contractions used in making the slow straight movement. But at high speeds where the contractions are occurring at a rapid rate and in short pulses, the question arises as to how the muscles, arranged in opposing groups about the limb, contract in order to pull the member smoothly through its circular course.

The movement used for study was a circular movement of the

FIGURE 5
Subject in Position to Make Circular Movement with Outstretched Arm

whole arm performed mainly by the muscles about the shoulder joint. The arm was kept straight at the elbow and rotated from the position shown in Figure 5. This position is unstrained, allows the arm to hang at a fairly open angle at the shoulder, and simplifies the gravity factor. The arm was rotated in a counter-clockwise direction. A hoop on the floor 40 cm. in diameter served as a guide for the movement which was made as circular as the practised subject could make it.

The incidence of contraction of the muscles in the circular movement was found to vary with the speed of the movement much the same as for the reciprocal movement, shown by previous studies (5). The deltoid clavicular muscle may be cited as a typical example to illustrate the shift in incidence with change in momentum. At very slow speed, the deltoid clavicular contracts to hold the arm up against gravity along the front arc of the circle. As the speed is increased, the contraction appears earlier and earlier until it has shifted completely around to the opposite side of the circle. At top speed the muscle acts largely to stop the momentum of the limb as well as to drive it forward and thus comes in along the back arc of the circle. At intermediate speeds the momentum of the limb neutralizes the pull of gravity so that the muscle contracts more on a tangent to the circle. Figure 6, Records *A, B, C* and *D,* show respectively the shift in incidence of contraction along the circle with increase in speed. In Record *A* at very slow speed the contraction comes in at the end of the first and the beginning of the second quadrants of the circle. In *B* at medium slow speed the contraction occurs through the fourth and first quadrants, in *C* at medium fast speed in the third and fourth quadrants, and in *D* at top speed the contraction has moved around to the third quadrant. In the rapid movement, then, any given muscle acts as it would in the reciprocal movement to check the momentum of the limb along the particular component in which it pulls and to start it back again in the opposite direction. In high speed coördinated movements muscles do much of their active contracting while the muscle is actually being stretched.

The results indicate that the simplest way to understand the circular movement is to think of it in terms of the straight reciprocal movement. Consider a reciprocal movement that is gradually shifted into a narrow elliptical movement, into a full elipse, and finally into a circle. As the movement is widened into a circle, other muscles

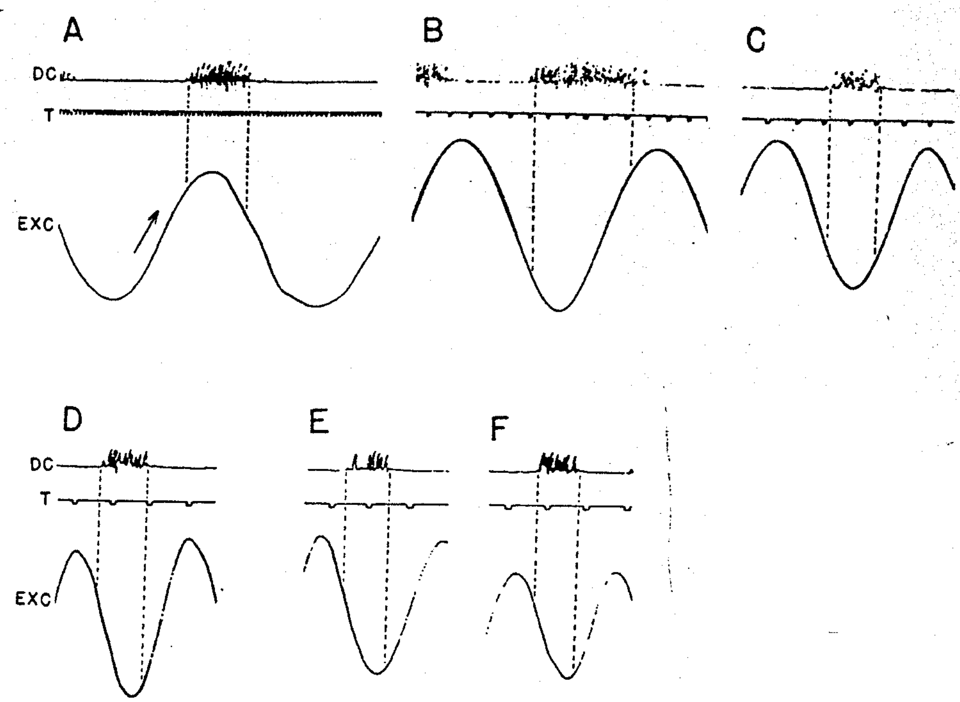

FIGURE 6

Records Illustrating Shift in Incidence of Contraction of the Deltoid Clavicular Muscle with Increase in Speed in Circular Movement, and Comparison of Circular Movement at Top Speed with Elliptical and Reciprocal Movements at Top Speed

A, B, C, D—circular movement at slow, medium slow, medium fast, and top speed respectively.
E—elliptical movement at top speed.
F—reciprocal movement at top speed.
Dc—Deltoid clavicular. Pulls in the direction indicated by the arrow to flex the arm.
T—Time, 0.1 sec.
Exc—The "*y*" or front-back component of the circular and elliptical movement, taken from the upper arm and reduced about one-sixth. The arm rotates in a counter-clockwise direction. The reciprocal movement is made along the *y*-axis of the circle.

come into play pulling the limb out of its straight course, but the action of the original driving muscles of the reciprocal movement is little changed. Comparison of Records *D, E,* and *F* of Figure 6 shows the similarity in incidence and duration of contraction of the deltoid clavicular in the circular, elliptical, and reciprocal movements made at maximum speed. It is the *Y*-axis component of the excursion of the elliptical and circular movements that is shown. The reciprocal movement is made along the Y-axis of the circle. If the main driving muscles of the reciprocal movement are not single but consist of a group of muscles or muscles with several separate heads such as the deltoid of the shoulder, then where the whole group contracts as one in the reciprocal movement, the different muscles and different heads of the same muscle contract separately in serial fashion in the circular movement, insofar as the different muscles or heads of muscles are capable of pulling at different angles.

A comparison of the maximum rates for reciprocal and circular movements in two practised subjects showed no difference between the two. The circular movement was made as rapidly as the reciprocal movement. The rates of both vary considerably, however, according to the length of the excursion, from about 3 per sec. for large reciprocal and circular movements two feet in diameter, up to 5.5—6 per sec. for small movements of 10 cm. in diameter. Contrary to records of similar movements of the finger and hand, the records of whole-arm movement show a decrease in the duration of the separate contractions accompanying the increase in rate.

There are a great many muscles involved in making this circular movement of the whole arm. Besides the main driving muscles around the shoulder, there are the muscles of the upper arm and forearm that must adjust to the changing strains on the elbow and wrist for every revolution; and the supporting muscles of the trunk, neck, and legs that must shift quickly to furnish a steady supporting posture for the movement. Some of the muscles more directly involved in the movement are listed in Figure 7 with a diagram to indicate the arc in which they contract as the arm swings at high speed along the circle. There was very little variation in the five subjects used. It is important that the subjects assume the same position from trial to trial in making the circular movement, because shifts in the posture make a change in the timing relations according to the angle at which the muscles pull on the arm.

It is difficult to generalize concerning circular movements because the patterns of contraction vary greatly for different limbs. Such factors as the distribution and size of muscles about the joint, the weight of the limb, and the specific posture of the limb at the moment of rotation all tend to modify the circular movement. It would seem, from the work to date, that the strongest contractions at any point in a fast curved movement will be made by those

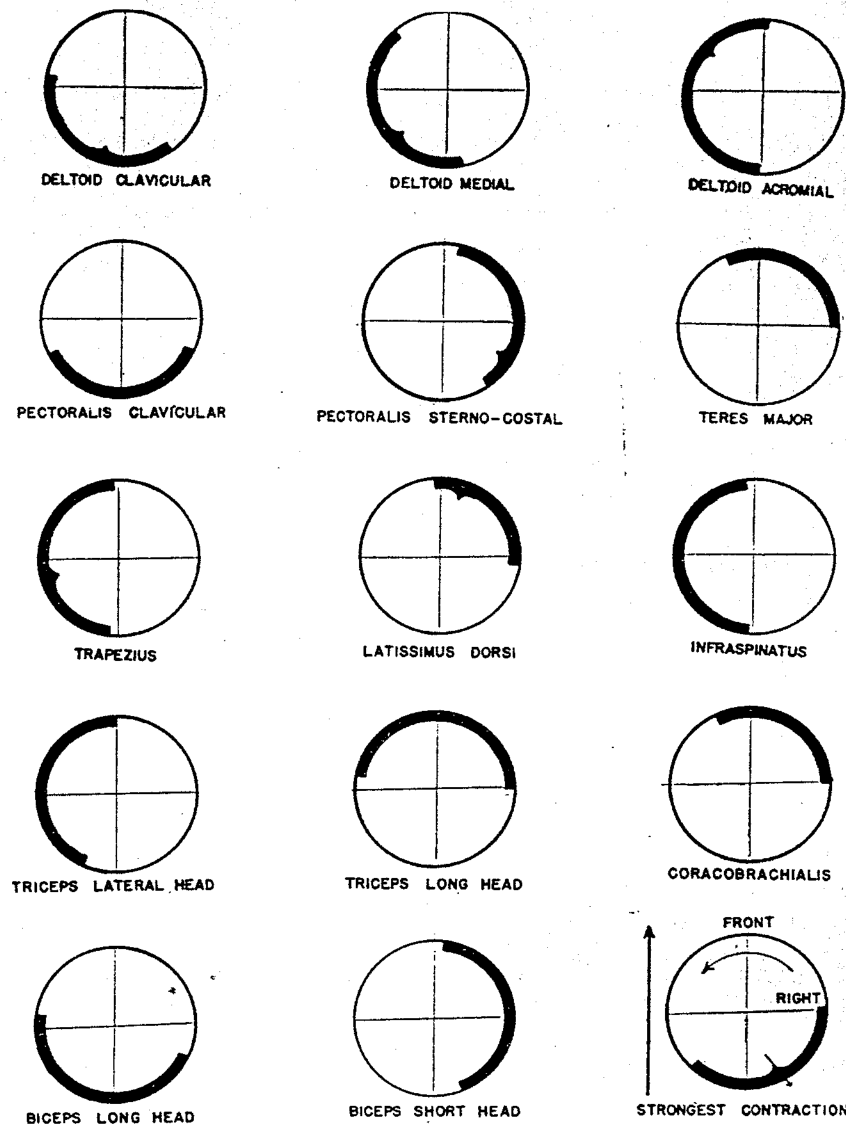

FIGURE 7

Diagrams Showing the Incidence of Contraction of the Various Muscles in Making the Circular Movement at High Speed

The diagrams are all marked alike as in the example at lower right. The subject is facing toward the top of the page. The circle is made at high speed in the counter-clockwise direction with the right arm. The heavy line marks the arc of the circle through which the particular muscle pulls, and the peak, where indicated, marks the point of strongest contraction.

muscles that would be involved most directly in making a reciprocal movement along the diameter of the curve at that point, and the antagonists of those muscles will be the only muscles that may be relaxed. Other muscles acting on the member will be in various stages of contraction, increasing or decreasing in tension, as may be seen from the diagrams, Figure 7. With each muscle contracting in turn and each contraction lasting as long as in the reciprocal movement there is considerable overlapping of contractions in the several muscles. In circular movements the contraction of any muscle is never directly opposed by its antagonist, but the limb is constantly being acted upon by one or more of the several muscles distributed about the joint.

From a practical point of view for the training and learning of skilled movement, it is interesting to notice the elaborate modifications in the neuro-muscular coördination of a given movement when the rate of the movement is varied and when the supporting postures are modified. Changes in speed, changes in the angle of the arm with respect to gravity, changes in the weight of an object held in the hand, changes of the angle between arm and shoulder and other shifts in general posture, all cause extreme variations in the physiological patterns underlying what, from an unanalytical observation, might appear to be a fairly constant simple response. These observations demonstrate very well the importance of peripheral conditions in the control of behavior.

Diversity in the constituent coördinations used in accomplishing the same functional end-result is characteristic of most human behavior. The neuro-muscular coördinations involved in even so simple a response as the spoken vowel vary according to the sounds that precede and follow. Gestalt psychologists have pointed out the wide variation possible in the sensory processes with a constant perception. On the motor side also the physiological processes are probably quite unlike in perceiving the same object on two different occasions, depending on the postural adjustments and other reactions going on in the subject at the time. Likewise the same images may be recalled, the same idea reviewed with neuro-muscular coördinations that are quite different according to the contextual reactions into which they fit and have their meaning. All of which suggests to those interested in the physiology of learning or in the formulation of a trace theory of memory the impracticability of trying to correlate the engrams with the customary unanalytical conceptions of behavior rather than with a detailed analysis of the neuromuscular coördinations comprising it.

E. Maximum Rate of Reciprocal Movement

Investigations of speech and tapping movements has shown that the maximum rate for serial movements of this type is about 8 - 10 per sec. In very exceptional cases the rate for forced tremors and for repeated syllables goes as high as 12 - 13 per sec. The short contractions operating these movements last about 45 - 50 sigma (5). This minimum duration for muscle contraction appears rather consistently throughout analysis of rapid tapping movements, articulatory speech movements, and forced tremor movements. The maximum rate and minimum contraction pulse of coördinated movement and factors that determine these limits are important to the problems of movement analysis.

The slowness of reciprocal movements of the whole arm, leg, and trunk as compared with those of the lips, tongue, hand, and finger seems to be due, as demonstrated above, to the weight of the load which the muscles have to move and not to the inability of the large muscles to contract in rapid pulses. The large muscles of the proximal segments of the limbs and of the trunk are able to contract rapidly under certain conditions where they do not have to pull the heavy member to which they are attached, to and fro. It is possible that the maximum rate for the finer, more rapid movements is also determined by the mechanical relations between muscle and mass of load.

Other factors, however, such as latent time of reflex arc, spread of impulses in the nervous system, continuance of tetanus in muscle after innervation stops, may enter in at rates up to 10 - 13 per second. Sherrington (3) finds that tetanus continues in a muscle preparation 30 sigma after the neural impulses stop. If volleys of impulses are fired into the muscle without allowing 30 sigma between the separate volleys, there must result an overlapping of tension in the muscle and blockage of the reciprocal movement. The minimum duration of the action potential itself seems to be at least 35 sigma. One can sometimes cause a single spike to come through the amplifiers, apparently the discharge of a single motor unit or the synchronous discharge of a few motor units in the muscle, but this is done only by very careful increase of excitation elsewhere in the system until a single discharge spills over into the relaxed muscle with no actual contraction pulse, in the usual sense, involved. As far as we know, one cannot reduce the duration of a muscle contraction below 35 - 40 sigma in any kind of overt movement.

The above facts suggest that the maximum rate of high speed movements may be limited by some intrinsic physiological property of the reflex circuit, rather than by the simple relation between muscle and load which limits the rate of gross movements. Favoring this notion is the fact that many different movements involving varied musculatures all seem to have their maximum limits at about the same rate. Hand, finger, ankle, and articulatory speech movements, all run up to a maximum of about 10 per second. Forced tremors of forearm and lower leg also run up between 8.5 and 10 per second. On the other hand, the organism is capable of making reciprocal movements far above this 10 per sec. rate. Figure 4 shows a record of forced tremor movements of the head with the contraction of the scalenus medius muscle of the neck occurring at a rate of 15 per second. This rate was fairly consistent for the subject. Another subject did the same movement consistently at about 17 per second. The minimum duration of the individual pulses is close to 35 sigma. The movement is a very short horizontal oscillation of the head as in shaking "no," made as a rapid shiver with the neck muscles very tense. Possibly it is the peculiar mechanical conditions about the neck and shoulder girdle that make the reciprocal contractions possible at so fast a rate.

It might be mentioned that in trying to determine the limiting factors in the maximum rate for reciprocal contraction, a device was set up that would vibrate the arm mechanically at speeds above the normal 10 per sec. rate. It consisted of a heavy rubber strap attached to an eccentric on the shaft of a motor. The strap was held in the hand and pulled tight against the rapid alternating pull of the eccentric. When the arm was thus vibrated with electrodes inserted on those muscles of the forearm, upper arm, and shoulder which were pulling against the strap, contractions were recorded from the tense muscles synchronous with the pull of the eccentric at rates from 13 to 40 per second. Tests made on other muscles showed that similar contractions did not occur in those muscles that were not tensed in pulling against the strap. Further investigation of these rapid rates of contraction is now in progress. One hesitates to say at present whether they are due to actual contraction of the muscle or whether they are artifacts.

F. Relaxation in Antagonist Muscles During Slow Movement

There is some question concerning the action of antagonist muscles in voluntary movement. Some investigators have held that there is some contraction of the antagonists in all movement (2, 6). Others have recognized a movement driven by the agonists alone with no contraction of the antagonists (1, 5). This has been called a ballistic movement.

Evidence from the present study indicates that also in many movements at moderate and slow speeds and in some cases where the limb is held still, as in holding a member up against gravity or in pushing against an obstacle, the antagonist muscles may remain relaxed. These relaxed parts of the musculature are quite as important as the contracting parts in determining the total operation of the organism from movement to movement.

With surface electrodes or with inserted electrodes placed some distance apart, it is difficult to be sure of relaxed conditions in the antagonists because of leakage from the contracting agonists. With localized concentric electrodes, however, or with wires inserted directly into the muscle a centimeter or less apart, it is possible to record very slight contractions of the muscle without leakage from opposing muscles. Leakage of potential tends to be strong between flexors and extensors of the forearm. It is somewhat less between biceps and triceps of the upper arm. At the shoulder the muscles come in at a wide angle from the trunk so that leakage between the abductor deltoid acromial and the adductor pectoralis major is very slight. Record *A,* Figure 8, shows a record of slow adduction and abduction of the whole arm from a position similar to that used for the circular movement shown above, and shows the relaxed state of the muscles through that part of the excursion where the opposing group acts against gravity. The amplification is very high in the record so that the slightest contractions will register as shown at the point half way across the record where rhythmic motor units come through from the deltoid acromial, characteristic, with these electrodes, of very weak contraction. Record *B* shows similarly

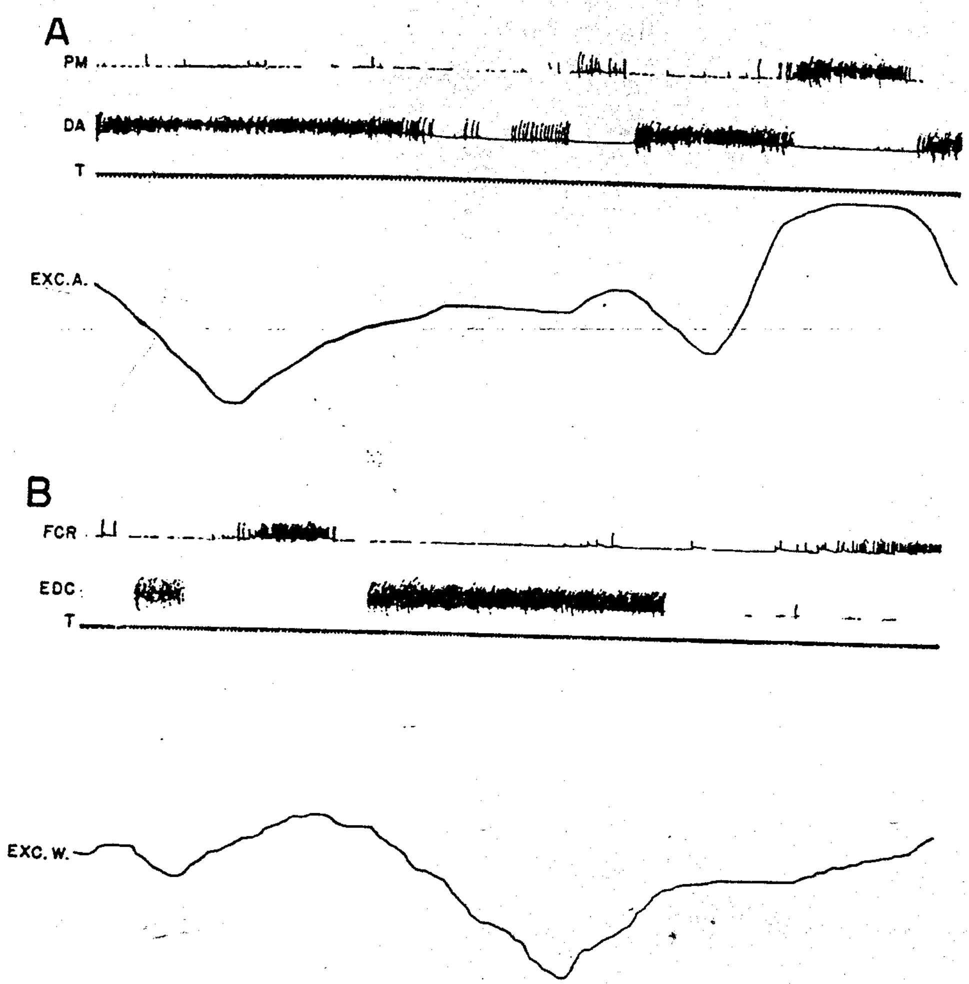

FIGURE 8

Records Showing Relaxation in the Antagonist Muscles During Slow Movement (*A*) of the Arm, and (*B*) of the Wrist Against Gravity

Pm—Pectoralis major.
Da—Deltoid acromial.
T—Time, 0.1 sec.
Exc. A.—Excursion of the arm, recorded from just above the elbow. Adduction is toward the top and abduction toward the bottom of the record.
Fcr—Flexor carpi radialis.
Edc—Extensor digitorum communis.
T—Time, 0.1 sec.
Exc. W.—Excursion of the wrist. The wrist is hung vertically from the forearm, then flexed and extended against gravity in an arc passing through the starting vertical position. Flexion is toward the top, extension toward the bottom of the record.

the relaxation of the antagonists in slow movements of the wrist moved pendulum-wise against gravity. Where the agonist contraction is strong, there is a little leakage through the electrodes on the antagonist. When the whole arm is held out forcibly against an obstacle with the deltoid, no action currents appear in the pectoral muscles, and vice versa, when the arm is held in forcibly against the body the deltoid acromial muscle shows no contraction. In the same way one can push hard against an obstacle with the triceps and leave the biceps relaxed, or pull and leave the triceps relaxed. The arm can be raised through the air with the palm down and biceps up leaving the forearm flexors and triceps relaxed. When the knee is raised by the extensors, the flexors may remain quite relaxed. These slow, loose movements are typical of many that occur against gravity or other opposing forces where the set of muscles acting in the direction of the opposing force stays relaxed.

G. Summary

1. A magnetic marker is described for recording action potentials kymographically.

2. In rapid distal movement—of the hand or foot, for example—there are sharp contractions of the supporting muscles of the trunk and upper limbs which keep pace with the distal movement.

3. The contractions of any single set of agonist-antagonist muscles involved in making a circular movement of the out-stretched arm are similar in function and in timing to those involved in making the straight reciprocal movement with those muscles—the difference between circular and reciprocal movement being mainly in the additional action of more driving muscles and in the breaking up of the general abduction-adduction groups into divisional, serial contractions.

4. There is little or no difference in the maximum rate for reciprocal and circular movements of the whole arm in two practised subjects.

5. The rate of the movements and the duration of the contraction in reciprocal movement of the whole arm varies with the length of excursion, contrary to findings for the wrist movement.

6. Folding the arm at the elbow to reduce the inertia of the member increases the maximum rate of reciprocal movement of the shoulder muscles from about 5.5 per sec. to about 8.5 per second.

7. The maximum rate found for reciprocal movement is 17.5 per second. It occurs in forced tremor movements of the head.

8. In many fixations and slow movements made against gravity or other opposing forces the antagonist muscles remain relaxed.

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