ELECTROMYOGRAPHIC AND JOINT-MECHANICAL STUDIES IN QUADRUPEDAL LOCOMOTION

I. WALK

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Why can man walk bipedally? This problem has been interesting man from the ancient times. Prior to it, however, there is a preconditional thesis that an animal walks quadrupedally. If this thesis is not studied sufficiently, no human locomotion will be explained completely. In veterinary science, the fundamental study of locomotion is also very essential for establishing a method for the treatment of disorder in the motor apparatus which has been increasing in recent years. The quadrupedal locomotion is an integrated expression of co-ordination of the bone and muscle system with the control of the nervous system. The methodology of the study on this important theme is roughly classified into two types. One type is to study the locomotor apparatus by analyzing the movement of the bone and muscle system. The other is to study the nervous system which controls these effectors. Of course, locomotion will ultimately be made clear by integrating the results obtained by the two types of methodology, but little progress has been made so far in studies of either type.

The author has studied quadrupedal locomotion from the view point of the former type of methodology; namely, kinesiology. Since MUYBRIDGE²³⁾ studied the animal locomotion scientifically, papers have been presented on this subject. They are roughly classified methodologically into the following five groups: (1) Analyses of photographic records represented by MUYBRIDGE²³⁾ and others^{4,5,12~17,20,33,34,36~38,40}. (2) Analyses by comparative and functional anatomy represented by SMITH et al.³⁵⁾ and others^{11,17)}. (3) Theoretical analyses represented by GRAY^{8~10)} on the assumption that the animal body is a mechanical system. (4) Analyses in indirect measurement of muscle activity, such as an external force exerted on the ground, or electro-goniometry, represented by MANTER²¹⁾ and others^{2,7,18)}. (5) Analyses represented by NOMURA et al.^{27~30)} and others^{6,39)} on the basis of direct information on the muscle activity of the living animal.

Quadrupedal locomotion, which is a complicated problem, has been studied mainly under no dynamic conditions, such as items (2) and (3), and by analyses of indirect information, such as items (1) to (4). NOMURA who had carried out excellent studies on the joint mechanics of the horse also studied the posture and locomotion of the dog electromyographically and joint-mechanically^{24~31)}. He put emphasis, however, on the muscular action in postural adjustment and did not explain gallop, the most characteristic gait of cursorial mammals. At all events, it is the state of things that no marked progress has been made in the scientific analysis of this important problem. So the author made an attempt to study the quadrupedal locomotion by analyzing direct information on walk, trot, and gallop obtained from a dog on the treadmill. The dog was used as the representative of the quadrupeds, because it had a medium body conformation among

the mammals and could be trained easily.

Walk is a symmetrical gait. All authors admitted that walk almost perfectly met the ideal of the most effective locomotion with support and propulsion. MUYBRIDGE²³⁾ noted about walk that the supports were furnished alternately by two and by three feet in the normal walk and by alternations of three and of four feet in the slow walk, and limb sequences were LH (left hind foot) LF (left fore foot) RH (right hind foot) RF (right fore foot). NOMURA et al.³⁰⁾ recorded electromyograms of fifty kinds of the skeletal muscles in walking dog and discussed the co-operated muscular action. TOMITA³⁹⁾ also recorded the electromyograms of eight muscles of the four limbs while the dog was walking, by using the surface electrode technique, and compared the locomotion type of the dog with that of man. He explained that time sequence of the activities of protractors in four limbs was consistent with the backward cross type in dog, and with the forward cross type in man. ENGBERG et al.⁶⁾ recorded electromyographic activity in the cat walking.

MATERIALS AND METHODS

A three-year-old male Airedale terrier which seemed to have no locomotor deficiency and which had been trained for the locomotion on a treadmill was used for recording the electromyographic (EMG) activity of fifty skeletal muscles and taking 16-mm motion pictures. A four-year-old female mongrel dog was used for recording a cyclogram, which was taken on the level ground while the dog was walking side-on to the camera.

The records of motion pictures and the action potential of muscles were not synchronized. The speed of treadmill walking was 60 meters per minute. It was higher than that of walking performed by the subject in everyday life, but that speed was imposed because the rhythm of steps would not have been regular if walking had been slower on the treadmill. Bipolar fine wire electrodes were put into the middle of each of the fifty muscles by means of a 1/4 hypodermic needle. They had been made a enamel-covered copper wire 100 μ or sometimes 120 μ in diameter. An insulating enamel portion 0.5 cm in length at its distal tip was bared with concentrated sulfuric acid and bent back sharply against the needle shaft 0.5 cm long. The interval between electrodes was 2 cm. These electrodes seemed to cause little pain.

The electromyogram (EMG) of the caput longum of the *M. triceps brachii* was always recorded simultaneously with that of muscles in the neck and fore quarters, and the EMG of the *M. biceps femoris* with that of muscles of the hind quarters. A criterion was established to compare EMG activity among the 50 muscles. A switch, or a pedal, was made of two metal pieces 5 cm by 4 cm in size facing each other and banded under a sole with adhesive plaster. The circuit was closed when the sole got in contact with the ground. In each experiment, the action potential was compared between the muscles without banding the switch under the sole and those with the switch to investigate the effect of the switch. It was quite seldom for such comparison to reveal any difference. Only sometimes the shifting of the phase was noticed.

The oscillograph employed for amplifying and recording the electrical activity of the muscles was a nine-channel electroencephalograph of San-ei Sokki model EG-900 type which was equipped with an ink-writing recording system. The time constant in recording was 0.001 second. The action potential of seven muscles and turning on and off of the two switches set on both left and right feet were recorded simultaneously. Chart 1 shows the original record of EMG of muscles and the switches which make the stance phase (lower line) and the swing one (upper line) clear. The speed of recording paper was 6 cm

Chart 1. Electromyographic Activity of Muscles and the Swing-stance Phase of the Thoracic Limb in Walking

per second. The action potential of muscles was recorded three times in each experiment. The experiment was repeated three to seven times. Data for analysis were obtained from the regular activity pattern of muscles. Moreover, 16-mm motion pictures of treadmill walking of the dog were taken at 32 films per second in the upper, front, back, and side direction, and sequential frames through one stride were printed. Plate 1 shows the prints of successive pictures taken from the lateral direction. Part of Chart 2 shows changes of joints and axes of the skeleton which were measured in the enlarged pictures taken from the lateral direction and expressed diagrammatically.

RESULTS

The duration of the swing phase was about 11/60 second and that of the stance phase about 32/60 second in both fore and hind limb, while supports were furnished

Chart 2. Schematically Summarized Figures of Activity Patterns of Skeletal Muscles in the Walking Dog

1. <i>M. semispinalis capitis</i>	27. <i>M. extensor carpi ulnaris</i>
2. <i>M. splenius</i>	28. <i>M. flexor carpi radialis</i>
3. <i>M. sternomastoideus</i>	29. <i>M. flexor digitorum profundus</i>
4. <i>M. brachiocephalicus cleido-cervicalis</i>	30. <i>M. flexor carpi ulnaris</i>
5. <i>M. trapezius cervicalis</i>	31. <i>M. sacrospinalis (T4) (M. longissimus cervicis)</i>
6. <i>M. trapezius thoracicus</i>	32. <i>M. sacrospinalis (T9) (M. longissimus dorsi)</i>
7. <i>M. rhomboideus cervicalis</i>	33. <i>M. sacrospinalis (L4) (M. longissimus dorsi)</i>
8. <i>M. rhomboideus thoracicus</i>	34. <i>M. obliquus externus abdominis</i>
9. <i>M. serratus cervicis</i>	35. <i>M. rectus abdominis</i>
10. <i>M. serratus thoracis</i>	36. <i>M. iliopsoas</i>
11. <i>M. brachiocephalicus clavo-deltoides</i>	37. <i>M. gluteus superficialis</i>
12. <i>M. latissimus dorsi</i>	38. <i>M. gluteus medius</i>
13. <i>M. pectoralis superficialis</i>	39. <i>M. tensor fasciae latae</i>
14. <i>M. pectoralis profundus</i>	40. <i>M. biceps femoris</i>
15. <i>M. supraspinatus</i>	41. <i>M. semitendinosus</i>
16. <i>M. infraspinatus</i>	42. <i>M. semimembranosus</i>
17. <i>M. teres major</i>	43. <i>M. sartorius</i>
18. <i>M. deltoideus pars scapularis</i>	44. <i>M. gracilis</i>
19. <i>M. deltoideus pars acromialis</i>	45. <i>Mm. adductores</i>
20. <i>M. triceps brachii caput longum</i>	46. <i>M. rectus femoris</i>
21. <i>M. triceps brachii caput laterale</i>	47. <i>M. vastus lateralis</i>
22. <i>M. triceps brachii caput mediale</i>	48. <i>M. vastus medialis</i>
23. <i>M. biceps brachii</i>	49. <i>M. tibialis anterior</i>
24. <i>M. brachialis</i>	50. <i>M. extensor digitorum longus</i>
25. <i>M. extensor carpi radialis</i>	51. <i>M. gastrocnemius</i>
26. <i>M. extensor digitorum communis</i>	52. <i>M. flexor digitorum profundus</i>

alternately by two and by three feet (Plate 1). Plate 2 presents a cyclogram of walk which shows the locus of thirteen points at the center of each joint and other important points. The locus of the cyclogram of walk was not so smooth as that of trot or gallop. The shoulder joint was shown to move horizontally to the largest extent with little oscillation among the joints of the fore limb. The carpal joint increased the moving speed after taking off. The fore part of the body exhibited less oscillation than the hind one. Motion pictures taken from the front and back direction showed the fore limbs to abduct in the fore-swing phase and land on the ground with adducting. Chart 2 is a schematic figure in which the original records are summarized. In Table 1, the EMG activity of each muscle is classified quantitatively as follows: *nil* (0), *negligible* ($\pm$), *slight* (+), *moderate* (++) , *marked* (###) , and *very marked* (####) . T4, T9, and L4 of the *M. sacrospinalis* indicate that electrodes were placed at the sites 2 cm lateral to the fourth thoracic, ninth thoracic, and fourth lumbar vertebra, respectively.

DISCUSSION

Movement of the head and neck

On the cyclogram, the up and down motion of the head and neck depicts the curves of two peaks in each stride (Plate 2). It is not clear, however, on the treadmill walking (Chart 2). The dog walked on the treadmill, watching down at the roller around which a belt moved, and so performed a movement different from the natural one. The EMG activity of *M. semispinalis capitis* and *M. splenius* increased when the fore limb of the same side was extending at the end of the swing phase. This implies that these muscles work for the stabilization of the neck and the prevention of the head and neck from

Table 1. Electromyographic Activity of 50 Muscles Classified Quantitatively: Nil (0), Negligible ($\pm$), Slight (+), Moderate ($\pm\pm$), Marked ($\pm\pm\pm$), and Very Marked ($\pm\pm\pm\pm$)

Numbers 1~50 are correspondent to the respective numbers shown in Chart 2.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Swing phase	fore-swing	$\pm$	$\pm$	0	$\pm$	$\pm$	0	$\pm$	—	0	+	0	+	0	$\pm$	0	+	$\pm$	+	0	$\pm$	0	+	$\pm$	+	0	0	0	0	0	0	
	mid-swing	$\pm$	$\pm$	0	$\pm$	$\pm$	0	+	+	0	$\pm$	0	0	0	0	0	0	0	+	+	0	0	0	$\pm$	$\pm$	+	$\pm$	+	0	0	0	
	aft-swing	+	+	0	$\pm$	$\pm$	$\pm$	+	$\pm$	0	0	0	0	$\pm$	$\pm$	0	+	+	$\pm$	$\pm$	$\pm$	0	0	+	0	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	
Stance phase	fore-stance	$\pm$	+	0	0	$\pm$	$\pm$	$\pm$	$\pm$	+	0	+	0	0	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	+	$\pm$	+	0	0	0	0	$\pm$	$\pm$	+	+	0	$\pm$
	mid-stance	$\pm$	$\pm$	0	0	+	$\pm$	$\pm$	+	$\pm$	0	+	0	0	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	+	$\pm$	$\pm$	+	0	0	0	$\pm$	0	+	+	0	0
	aft-stance	+	+	0	$\pm$	+	$\pm$	$\pm$	$\pm$	+	+	$\pm$	+	0	$\pm$	$\pm$	+	$\pm$	$\pm$	0	$\pm$	$\pm$	$\pm$	$\pm$	+	$\pm$	0	$\pm$	$\pm$	+	0	0

Fore quarter

	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Swing phase	fore-swing	$\pm$	0	$\pm$	$\pm$	0	0	$\pm$	$\pm$	0	+	0	0	0	$\pm$	0	$\pm$	$\pm$	0	0
	mid-swing	0	0	$\pm$	+	0	0	0	0	0	$\pm$	0	0	$\pm$	0	0	+	$\pm$	+	0
	aft-swing	$\pm$	0	$\pm$	+	+	0	0	$\pm$	0	0	+	$\pm$	$\pm$	+	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
Stance phase	fore-stance	$\pm$	0	+	+	+	0	0	$\pm$	0	0	$\pm$	0	0	$\pm$	$\pm$	$\pm$	0	$\pm$	+
	mid-stance	0	0	$\pm$	$\pm$	$\pm$	0	$\pm$	0	0	0	0	0	0	$\pm$	$\pm$	0	0	0	$\pm$
	aft-stance	+	0	$\pm$	+	+	0	$\pm$	0	0	0	0	0	$\pm$	$\pm$	$\pm$	0	0	0	0

Hind quarter

descending against the reaction of the fore leg striking the ground.

Movement of the shoulder girdle

In locomotion, the activity of muscles is not so simple as used to be written in anatomical textbooks. For example, it has been explained that the *M. trapezius cervicalis* elevates the limb and draws it forward²²⁾ or draws the scapula forward during the swing phase³⁵⁾. In reality, however, this muscle becomes active chiefly to stabilize the shoulder joint when the scapula is drawn backward during the stance phase. The bursts of the *M. rhomboideus cervicalis et thoracicus* in the swing phase suggest that these muscles may keep the scapula upward so that the toe may not sweep the ground. These become the fulcrum of the fore limb during the swing phase. Although the activity pattern of EMG of muscles during the stance phase were changeable, many examples provided two peaks of activity. One peak suggests the support of the weight of the body in the mid-stance phase and the other the stabilization of the extended fore limb in the aft-stance phase. The *M. serratus cervicis* has its origo at the neck and its insertio at the scapula where complicated movements occur. Its increasing activity from the mid-swing phase suggests that it may stabilize the scapula in the aft-swing phase and also make the structure of the fore limb firm against the reaction from the ground. The *M. serratus cervicis* supports the weight of the body decreasingly and the *M. serratus thoracis* becomes to take its place during the stance phase. Most of the muscles connecting the scapula with the trunk is active in the stance phase, serving as antigravity muscles. The activity of the muscles stabilizing the shoulder girdle is particularly demanded, because the connection between trunk and fore limb depends on muscle, aponeurosis, and ligament.

Movement of the shoulder joint

Above mentioned, the shoulder joint was shown to move horizontally with little oscillation among the joint of the fore limb, whereas cattle and horses present the same phenomenon at the elbow joint³²⁾. This may result from the difference between digitigrade and unguligrade. The activity of the *M. brachiocephalicus clavo-deltoides*, which occurred just before and after leaving the ground, suggested that this muscle might be a spurt muscle. The phase of activity pattern of the *M. pectoralis superficialis* was changeable, because it was difficult to take an equilibrium in the treadmill walking. It is also considered that in the case of landing in a more abducted position, the activity of this muscle may appear in the aft-stance phase and in a more adducted position, it may do just before leaving the ground. The function of this muscle is considered primarily to prevent the abduction from occurring in the aft-stance phase and secondarily to extend the shoulder joint. The action of the *M. supraspinatus* is explained to consist in the extension of the shoulder joint and the forward advancement of the limb²²⁾. In locomotion, however, it was *moderate* activity during the stance phase in which the shoulder joint was flexing, and *negligible* activity in the swing phase.

That the burst of the *M. infraspinatus* disappeared in the aft-stance phase seemed to suggest that the range of the abduction or adduction of the shoulder joint might decrease in that phase and the activity of the muscle might not be necessary, or some other muscles, such as the *M. deltoideus*, might become active instead. SMITH et al.³⁵⁾ claimed that the main muscles flexing the fore arm were *M. latissimus dorsi* and *M. teres major* with, amongst others, the pectorales and deltoid assisting. In a dog, the *M. teres major* is a prime mover only in the aft-stance phase and does not act strongly in the fore- or mid-stance phase.

The shoulder joint of a dog is a triaxial ball-and-socket joint, but its chief movements are flexion and extension because of a restriction set by the lateral thoracic wall^{22,31)}.

Except the close-packed position in which the articular surface is fully congruent, all the positions of a joint are called loose-packed ones and the shoulder joint has three degrees of freedom. In that case, the surfaces of caput humeri and fossa articularis contact at one point at which the curvature of each surface is congruent and many muscles around the joint become active to stabilize the unstable contact. Namely, *M. brachiocephalicus clavo-deltoides* and *M. pectoralis superficialis* are active at first as brakers and then as triggers for the flexion in the swing phase. Then *M. latissimus dorsi*, *Mm. pectorales*, *M. supraspinatus*, and *pars acromialis* of the *M. deltoideus* co-ordinate actively in lifting a limb to prevent it from getting into contact with the ground in the mid-swing phase.

Movement of the elbow joint

The caput longum of the *M. triceps brachii* is a two joint muscle and is considered to flex the shoulder joint and extend the elbow joint. In walking, it shows an activity pattern different from that of the caput mediale et laterale of the *M. triceps brachii*. It acts as a stabilizer, rather than a flexor, for the shoulder joint and as a powerful extensor for the elbow joint in the swing phase.

The *M. biceps brachii*, two joint muscle, was claimed to act as a flexor for the elbow joint. NOMURA et al.³⁰⁾ explained that the elbow joint was stabilized unilaterally by the *M. triceps brachii* in the stance phase. This muscle, however, is active in the stance phase and may serve as a stabilizer for the shoulder joint. It seems, however, to serve for the bilateral stabilization of the monoaxial elbow joint, co-ordinating with the *M. triceps brachii*. So it is understood that the *M. biceps brachii* acts as a synergist for, rather than an antagonist against, the *M. triceps brachii*. The *M. brachialis* is a spurt muscle and antagonistic against the *M. triceps brachii*. The activity pattern of muscles around the elbow joint is difficult to understand only by the explanation from a functional anatomical point of view. It is seemingly a curious fact that the *M. triceps brachii*, an extensor of the elbow joint, is inactive in the aft-stance phase in which the elbow joint is extending. On the other hand, the *M. biceps brachii*, a flexor of this joint, increases its activity. INMAN et al.¹⁹⁾ found that a lag of approximately 0.08 ± 0.02 sec. existed between peak electrical activity and peak tension. Intervals from the *M. triceps brachii* becoming inactive to a fore limb leaving the ground was about 0.05 to 0.15 second. So it may be possible to explain it from this tension lag. It may be considered, however, that any mechanical force extend the elbow joint.

Movement of the carpal and metacarpo-phalangeal joints

The carpal joint is a diaxial and composite joints, including four joint surfaces, but it acts as a ginglymus, as a whole, permitting flexion and extension with some lateral movement²²⁾. The carpal joint is adducted over a period from the mid-swing to the aft-swing phase probably for the sake of the activity of the *M. extensor carpi radialis*. All the muscles moving the carpal and the metacarpo-phalangeal joints are active in decelerating the toe and stabilizing the joints bilaterally to support the body weight against the impact of striking the ground. *M. extensor carpi ulnaris* and *flexor carpi ulnaris* have almost the same activity pattern. As already mentioned, a fore limb landed in a slightly adducted position. So it is appropriate to consider that those muscles which stabilize the lateral side of the carpal joint are more active than those which are present inside, on the assumption that the weight may be put on the lateral side of the pad.

A short, sharp burst of activity occurs to the extensor muscles at the end of a whip-like motion of the carpal joint in the fore-swing phase to prevent this joint from being disturbed³⁾. The extension of the carpal and metacarpo-phalangeal joints is well performed by the activity of muscles than that of any other joint throughout the swing

phase. This suggests that these joints have to change the angle of joint more considerably than any other joints throughout the swing phase (Chart 2). This change is necessary for pointing (preparation for landing) just before landing on the ground.

Gravity attempts to flex the carpal and metacarpo-phalangeal joints in the fore-stance phase, because the fore limb inclines forward. The vertical line drawn through the center of gravity of the body falls behind these points. So the extensors have seemingly to be active to extend the joints in opposition to gravity. The fact is, however, that the active muscles are all the flexors, except the *M. extensor carpi ulnaris*. Then, what forces produce the extension of the carpal and metacarpo-phalangeal joints in the stance phase? The moment around the limb, and propelling force by the other limbs are regarded as such forces. Besides, the flexors act as synergists for these forces.

The movement in the fore limb as a whole should be investigated. Just after taking off, some muscles had strong activity for stabilization, deceleration, and flexion, and then only a few extensor muscles were active in the latter half of the fore-swing phase (Chart 2). Probably gravity may also have worked as an extensor. Some muscles were active for the clearance of the toes in the mid swing phase. Many muscles had activity for deceleration and stabilization for pointing in the aft-swing phase.

The activity pattern of each muscle was complicated throughout the stance phase, because the fore limb had to support the body more than the hind limb and assist the forward motion to a minor extent^{2,18,21}). The muscles are roughly classified into three groups on the basis of the EMG activity pattern. The first group consists of *M. latissimus dorsi*, *M. infraspinatus*, *caput laterale et mediale* of the *M. triceps brachii*, *M. extensor carpi ulnaris* and *M. flexor carpi ulnaris*. These muscles are active over a period from striking the ground to the mid-stance phase, but inactive in the aft-stance phase, in which the fore limb becomes inclined backward. The second group is composed of *M. pectoralis superficialis*, *M. teres major*, *pars scapularis* of the *M. deltoideus*, and *M. flexor carpi radialis*. These muscles have activity in the aft-stance phase. The third group consists of *M. supraspinatus*, *pars acromialis* of the *M. deltoideus*, *M. biceps brachii*, and *M. flexor digitorum profundus*. These muscles are considered to possess the activity characteristic of both the first and second group.

The muscles of the first group are antigavity muscles, perform the bilateral stabilization of each joint, and support the body weight. In this period, the fore limb is considered to be stabilized from the scapula to the toe like a solid stick, though the shoulder, elbow and carpal joint have a role to exercise a buffer action (Chart 2, Plate 2). Then the extrinsic muscles become active and may propel the body by a moment which occurs between the shoulder girdle and the toe. GRAY⁸) named it the method of rowing a canoe by the paddle. The muscles of the second group become active in the aft-stance phase. As a fore limb goes nearer a vertical line drawn through the center of gravity of the body in the aft-stance phase, it has to support and propel the body, and exert a strong force when leaving the ground. When the fore limb leaves the ground, the EMG of its muscles indicates that not only the carpal joint but also other joints are flexed by these muscles. These results imply that the action of pulling up the fore limb is performed.

That the EMG activity pattern of the fore limb muscles which are situated nearer the center of the weight is very complicated unlike that of the hind limb muscles suggests that the role of a balancer is very important for a fore limb than that of a propeller. The slower the speed of locomotion, the stronger the activity of a fore limb as a balancer rather than a propeller. This can be admitted by the fact that the EMG activity of muscles in walking is not so regular as that of those in trotting or galloping. In walking, every time the number of limbs upon the ground changes, the center of gravity of the

body is displaced a little. So the muscles of the limbs must work for adjustment and control.

Movement of the trunk

The M. sacrospinalis is a long epaxial muscle and shows some difference in activity according to the site of it. The T9 of the M. sacrospinalis is active for the stabilization of the axial skeleton before and after landing of a fore limb. The L4 of this muscle is active in flexing the lumbar region laterally. This region assists the hind limb to step forward. The M. rectus abdominis is always active for the conformation of the abdominal region.

Movement of the hip joint

The hip joint is a triaxial ball-and-socket joint like the shoulder joint and is known as enarthrosis. Its range from flexion to extension, or from 80 to 120 degrees, however, is wider than the shoulder joint, so the name enarthrosis is not appropriate for the dog³¹⁾ (Chart 2). Even if the hip joint performs such seemingly simple movement as flexion and extension, the activity of many muscles will be necessary for such movement. The activity of M. iliopsoas, M. tensor fasciae latae, M. semitendinosus, and M. sartorius which occurs just before the hind limb leaves the ground suggests the deceleration and flexion of the hip joint. In the mid-swing phase M. iliopsoas and M. sartorius also become active for the clearance of the toe. The M. biceps femoris is a two joint muscle and induces deceleration and extension of the hip joint as a prime mover. In the aft-swing phase, M. iliopsoas, M. gluteus medius, M. biceps femoris, M. semimembranosus, and M. gracilis are already active for the stabilization of the hip joint against the reaction from the ground. If the EMG activity of the thigh muscles is compared with that of the muscles of the thoracic limb, it will be recognized that the former is simpler and weaker in the EMG activity pattern (Chart 2, Table 1).

Movement of the stifle joint

The stifle joint is a typical ginglymus to allow only extension and flexion in spite of composite joints³¹⁾. The M. rectus femoris has a particular activity phase, as compared with any other quadriceps muscles. This is probably because the M. rectus femoris is a two joint muscle. The M. vastus medialis et lateralis are active till the midst of the aft-stance phase, because strong activity of muscles is required for the stabilization of the stifle joint in the stance phase. The M. rectus femoris shows *slight* activity to propel the body by pressing the ground when a hind limb becomes inclined backward.

Movement of tarsal and metatarso-phalangeal joints

The tarsal joint performs its function as a typical ginglymus in the dog, although it is composite joints³¹⁾. So the two flexor muscles of the tarsal joint, M. tibialis anterior and M. extensor digitorum longus, perform the clearance of the toe and act only during the swing phase. The M. gastrocnemius is a two joint muscle which flexes the stifle joint and extends the tarsal one. Many anatomists have recognized that this muscle has an activity as an extensor of the tarsal joint when a hind limb leaves the ground, but its EMG activity has *moderate* activity just before and after the hind limb strikes the ground. This suggests that the M. gastrocnemius mainly performs an action to stabilize the stifle and the tarsal joints against the reaction of the ground.

The M. extensor digitorum longus has no activity throughout the stance phase while the metatarso-phalangeal joint is extending gradually. The vertical line drawn through the center of gravity of the body always passes in front of this joint. So, gravity, moment around the hind limb, the floor reaction, and propelling force by the other limbs extend this joint. Those forces and the contraction force of the flexors flex the metatarso-phalangeal joint synergically.

The movement in the hind limb as a whole should be investigated. Throughout the swing phase the movement of the hind limb is very simple, as compared with that of the fore limb. The tarsal joint, after taking off of a hind limb, depicts a rising curve on the cyclogram which attained the maximum at a near point toward the site of taking off and fell gradually toward the site of striking the ground (Plate 2). This situation is different from the locus of the carpal joint. It is considered that the structure of the tarsal joint is different from that of the carpal joint. It is, however, also considered that the pointing of a hind limb starts already from the highest point. Why does a hind limb start pointing so early? This phenomenon can be understood by explaining why so many muscles of the hind limb produce activity just before and after striking the ground.

A marked difference in movement between the fore and the hind limb is that the former lands on the ground at the site which is most apart from the vertical line drawn from the center of gravity of the body, and the latter at the site which is the nearest to this line. Hence, the fore limb need not take such a structure as a weight-bearing bracer in the fore-stance phase, while the hind limb must do so as soon as it strikes against the ground, for it has to support the weight of the body at once. This may be the reason why the hind limb must make the structure of a brace in the aft-swing phase. Such muscles as *M. gluteus*, *M. biceps femoris*, *M. quadriceps femoris*, *M. gastrocnemius*, and *M. flexor digitorum profundus* have *slight* to *marked* activity in and after the aft-swing phase, which stabilize every joint to support the weight against the reaction of the ground and then propel the body. It is easy to understand that the hind limb produces a propelling force earlier in the stance phase than the fore limb. The greater the friction, the larger the propelling force which has been produced by the limb operated as a lever. In the aft-stance phase, the *M. quadriceps femoris* presses the ground and also propels the trunk. That only a few muscles act in the aft-stance phase when a hind limb is extending may be characteristic of walking on the treadmill in which it is not necessary to kick the ground, or of walking in an Airedale terrier which loads more of the body weight on the fore quarters than any other species. It may be also considered, however, that a hind limb leaves the ground at the time when a toe is far apart from the center of gravity of the body and that the weight loaded on the hind limb decreases greatly. So the hind limbs need not support the body weight, unlike the fore limbs. They may be able to flex every joint by the weak activity of muscles in addition to utilizing a mechanical reaction which is obtained from the propelling force, and to leave the ground.

SUMMARY

A dog was used to record the electromyographic activity of fifty skeletal muscles, 16-mm motion pictures and a cyclogram. From these data, activity of each muscle, muscle coordination, movement of joints, and differences between the fore and hind limb were discussed. The results obtained are summarized as follows.

- (1) Many muscles of the shoulder girdle and shoulder joint were active in the stance phase, as antigravity muscles.
- (2) The *M. triceps brachii* was inactive in the aft-stance phase in which the elbow joint was extending, whereas the *M. biceps brachii* increased its activity.
- (3) All the muscles moving the carpal and metacarpo-phalangeal joint were active in decelerating the toe and stabilizing the joint bilaterally to support the weight against the impact of striking the ground.
- (4) The flexors of the foot muscles were active mainly in the stance phase.

(5) Many muscles of the fore limb were especially active in the mid- and aft-stance phase, whereas those of the hind limb produced activity just before and after striking the ground. There was a marked difference in movement between the fore and the hind limb. The fore limb landed on the ground which was most apart from the vertical line drawn from the center of gravity of the body. On the other hand, the hind limb landed at a site of the ground which was nearest to this vertical line. Hence, the fore limb had not to make a structure as a weight-bearing bracer in the fore-stance phase, whereas the hind limb had to make this structure as soon as it struck the ground. This is because the hind limb had to support the weight of the body at once and its muscles showed strong activity just before and after the stance phase.

(6) The electromyographic activity pattern of the fore-limb muscles, which are situated nearer the center of gravity of the body, was very much complicated, unlike that of the hind-limb muscles. This finding suggested that the fore limb might play a more important role as a balancer than as a propeller.

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四足獣の歩行運動の筋電図学的・関節機構学的研究

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四足獣の歩行運動の研究は、19世紀以来科学的に研究されてきているが、ほとんど解明されていないというのが現状である。今回著者は、キネジオロジーの立場から、この問題の解明を試みた。

1. 完全に訓練したエアデル犬に、トレッドミルにより、60 m/min. の常歩運動 walk を賦課し、(1) 50種類の骨格筋の筋電図、(2) 16mm シネカメラによる1完歩の連続引伸ばし印画、(3) 引伸ばしフィルム上で計測した13カ所の傾斜角および関節角のダイアグラム、および(4) サイクログラムの4種類の方法を用いて、常歩運動における個々の筋の働き方、四肢関節周囲筋の協同運

動および前後肢の働き方の相違などについて論議した。

2. 躯幹と肩帯を結ぶ筋の多くは、スタンス期に抗重力的に活動する。

3. 上腕三頭筋 (*M. triceps brachii*) の長頭 (*caput longum*) が、外側頭 (*caput laterale*) および内側頭 (*caput mediale*) と筋の活動位相を異にするのは、それが2関節性筋のためである。長頭はスイング期に肘関節の伸筋として、外側頭および内側頭はスタンス期に肘関節の固定筋として活動する。膝関節における2関節性筋である大腿直筋 (*M. rectus femoris*) と外側広筋 (*M.*

vastus lateralis) および内側広筋 (M. vastus medialis) のあいだにも同様の現象がみられる。

なお、上腕二頭筋 (M. biceps brachii) は、スタンス期に活動を持続するので、スタンス期における肘関節は、両側性に固定されることになる。

4. 前肢の筋の活動様式は、後肢のそれに比べるとはるかに複雑である。これは、前肢がpropeller としての働きよりも、balancer としての働きがより強いことを示している。

5. 後肢には、スイング期後期からスタンス期

前期にかけて活動する筋が多い。前肢では、重心線からもっとも離れた位置に肢端が着地するので、着地から負重までに免重期間が存在し、その間に、賦課に対応する支柱としての構築を組み上げればよい。これに対して、後肢では、重心線にもっとも近い位置に肢端が着地するので、着地と同時に負重に対処しなければならぬから、すでにスイング期後期に、賦課に対応する構築を作っているためである。

EXPLANATION OF PLATES

PLATE I

Fig. 1. Successive photographs of one stride of a walking dog.

PLATE II

Fig. 2. Illustration of 13 points at the center of joints and important sites which are attached to a dog. (1) Nose. (2) Head. (3) Withers. (4) Shoulder joint. (5) Elbow joint. (6) Carpal joint. (7) Metacarpo-phalangeal joint. (8) Center of the back. (9) Root of the tail. (10) Hip joint. (11) Knee joint. (12) Tarsal joint. (13) Metatarso-phalangeal joint.

Fig. 3. Cyclogram of cranial half, at points 1 to 7, of a walking dog.

Fig. 4. Cyclogram of caudal half, at points 8 to 13, of a walking dog.

←proceeding