Biomechanics of the hind limb of the horse and dog

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BIOMECHANICS of the hind limb of HORSE and DOG

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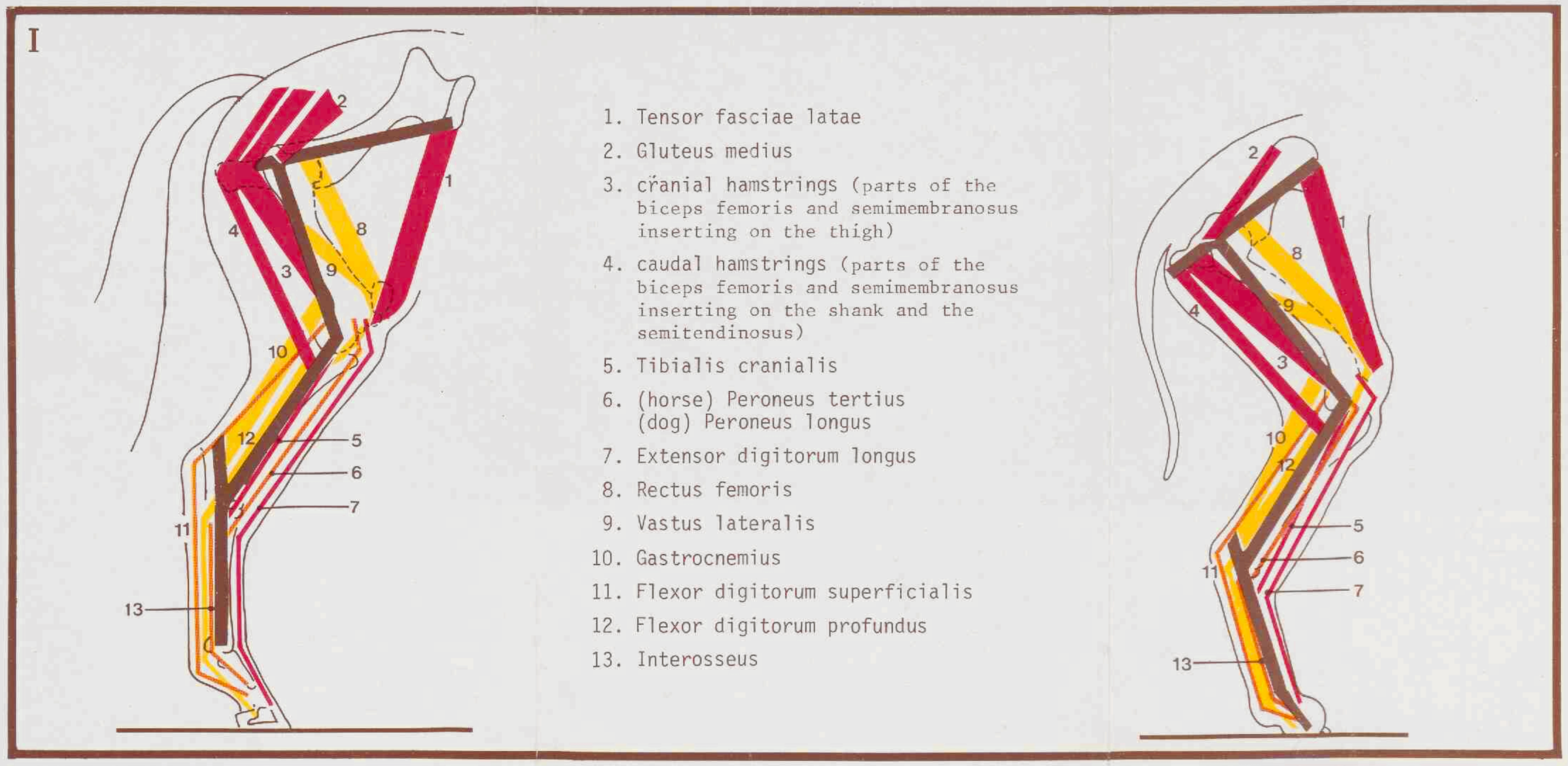
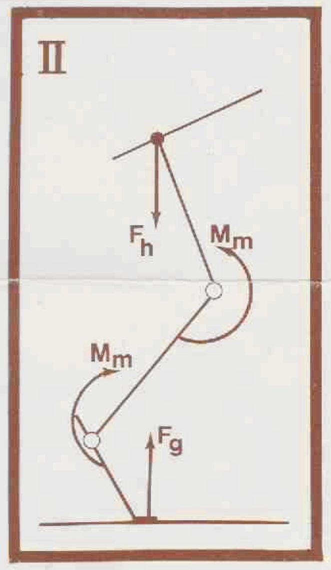
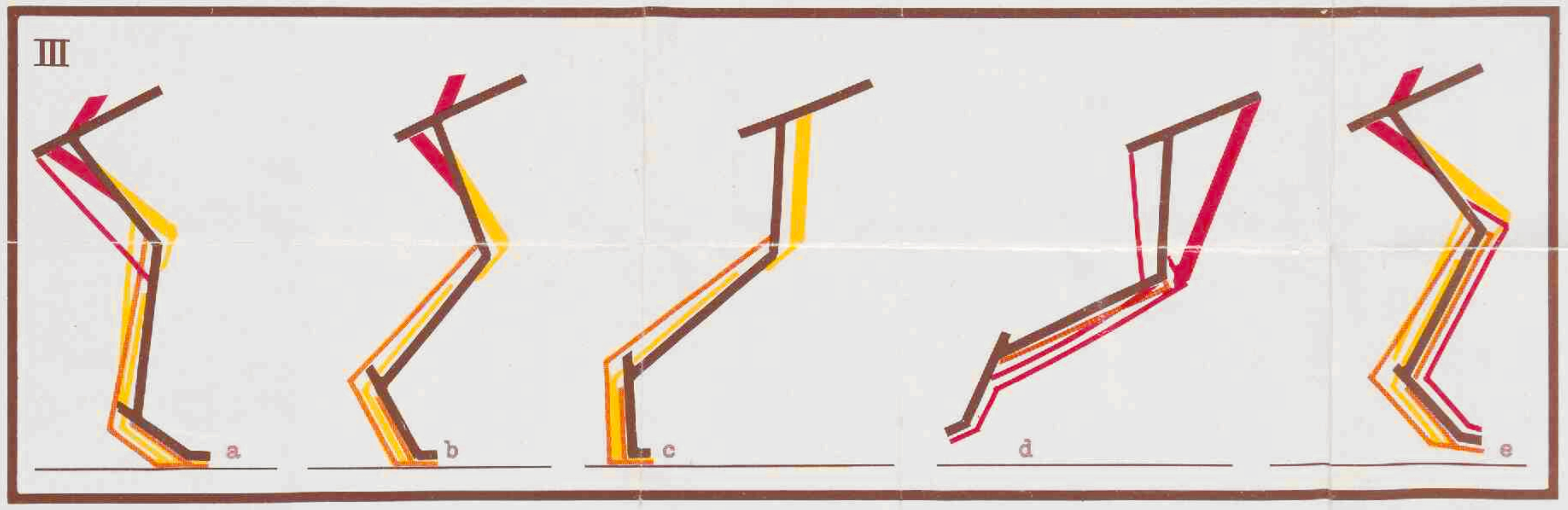
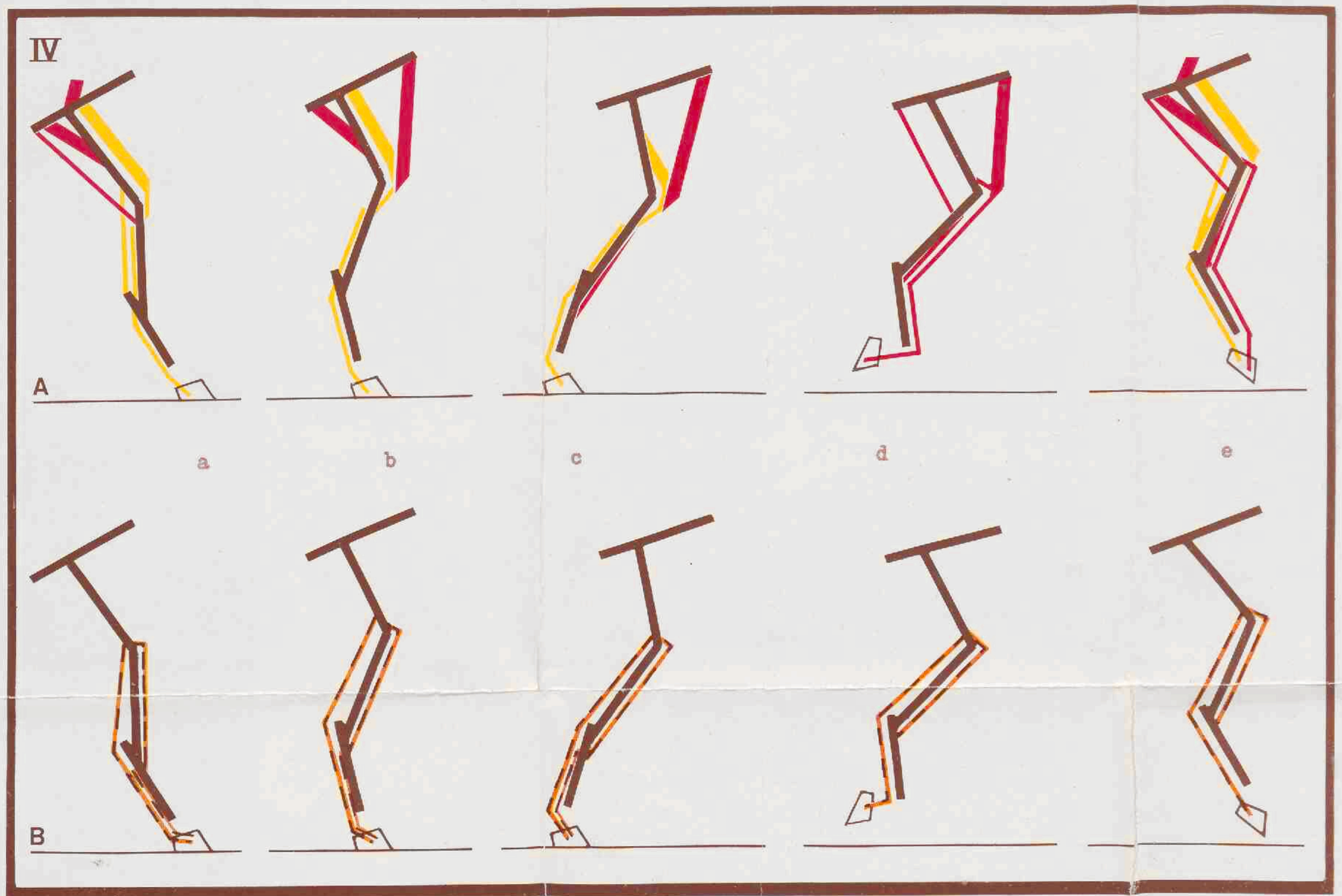
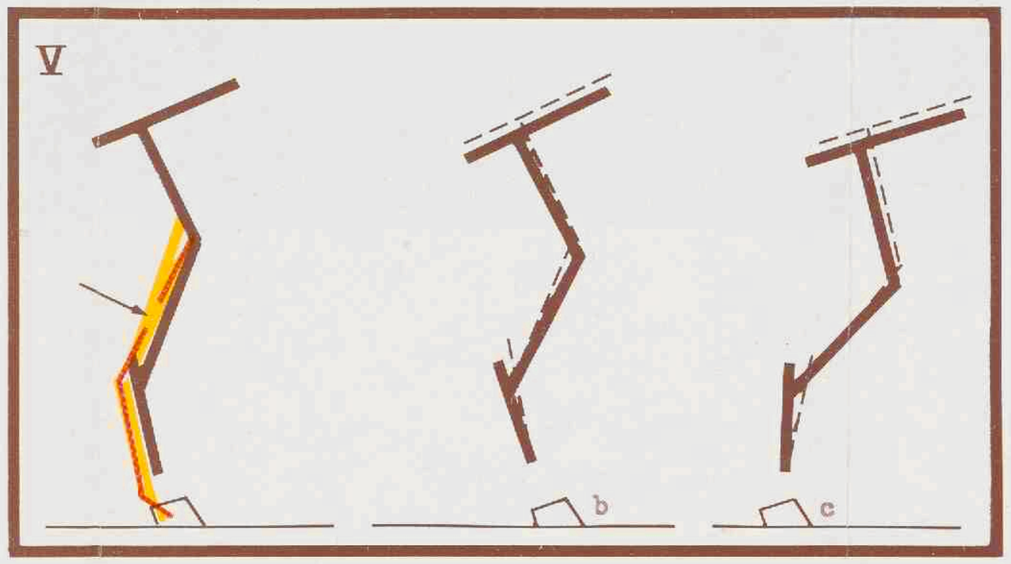


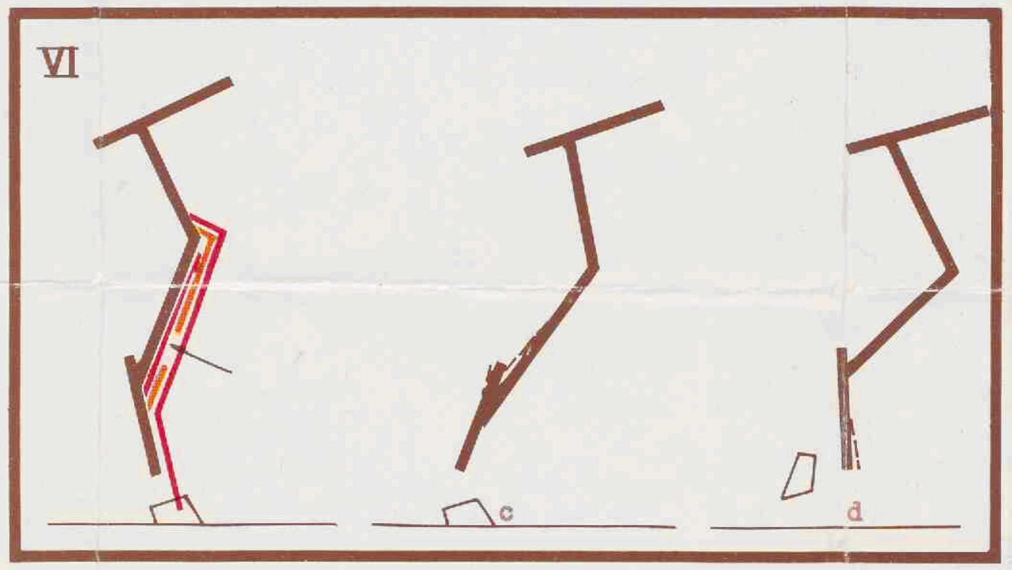
1. Tensor fasciae latae
2. Gluteus medius
3. cranial hamstrings (parts of the biceps femoris and semimembranosus inserting on the thigh)
4. caudal hamstrings (parts of the biceps femoris and semimembranosus inserting on the shank and the semitendinosus)
5. Tibialis cranialis
6. (horse) Peroneus tertius (dog) Peroneus longus
7. Extensor digitorum longus
8. Rectus femoris
9. Vastus lateralis
10. Gastrocnemius
11. Flexor digitorum superficialis
12. Flexor digitorum profundus
13. Interosseus

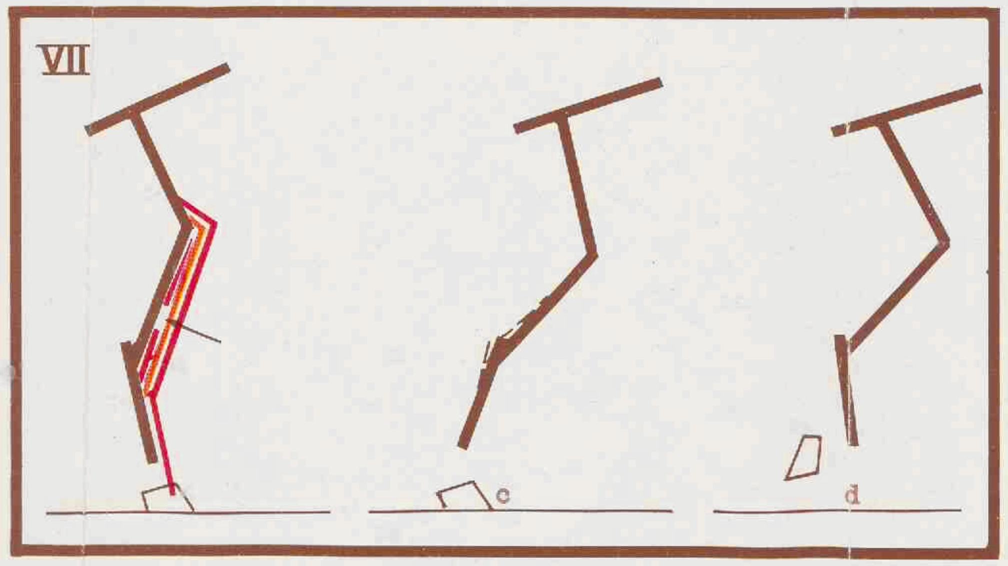


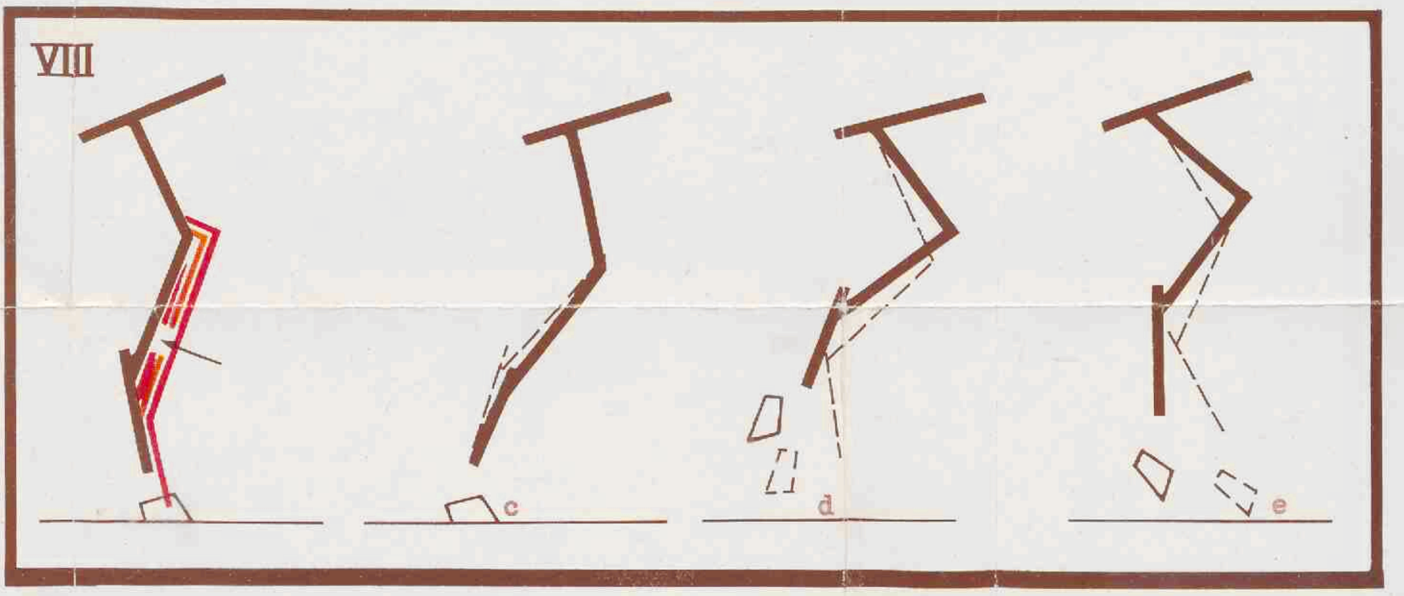


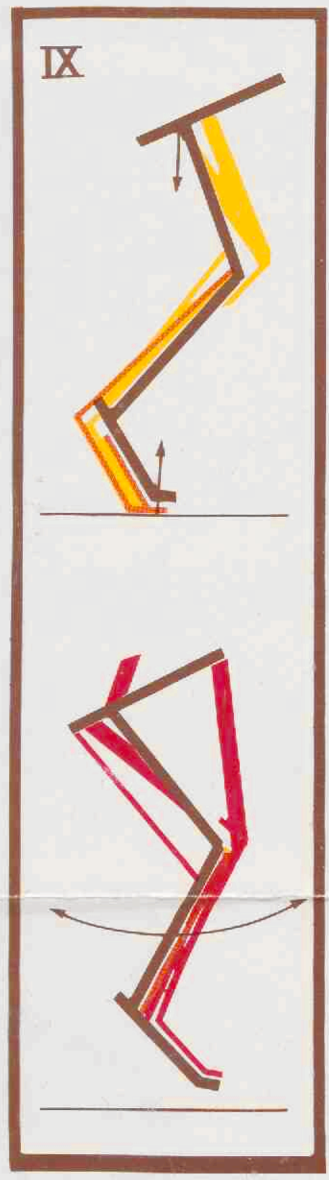


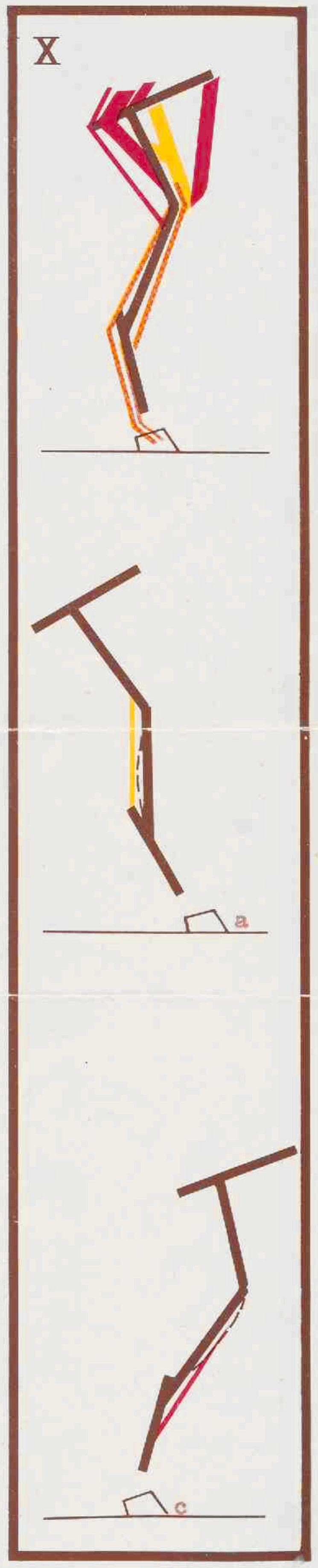












Biomechanics of the hind limb of the horse and dog

Proefschrift
ter verkrijging van de graad van doctor in de
diergeneeskunde aan de Rijksuniversiteit te Utrecht,
op gezag van de Rector Magnificus Prof. Dr. A. Verhoeff,
volgens besluit van het College van Decanen in het
openbaar te verdedigen op donderdag 8 juni 1978
des namiddags te 4.15 uur

door

Gerrit Hendrik Wentink
geboren op 6 januari 1945
te Zelhem

Promotoren: Dr. D.M. Badoux
Prof. Dr. A. Huson (Rijksuniversiteit Leiden)

Aan de nagedachtenis aan mijn vader

Aan mijn moeder

Aan Ineke, Esther en Robbert

CONTENTS

VOORWOORD

Aan dit onderzoek hebben vele mensen meegewerkt; ik denk aan de samenwerking met hen met genoegen terug en ik breng hierbij mijn oprechte dank uit voor hun inzet. Op deze pagina kan ik slechts enkelen vermelden.

In de eerste plaats wil ik Dr. D.M. Badoux en Prof. Dr. A. Huson noemen. Dr. Badoux heeft mijn belangstelling voor mechanische aspekten van de voortbeweging gewekt; deze belangstelling heeft geresulteerd in dit proefschrift dat hoofdzakelijk onder zijn leiding tot stand kwam. Bij de interpretatie zijn de suggesties en opbouwende kritiek van Prof. Huson van even grote betekenis geweest.

Dank ben ik ook verschuldigd aan Professor Dr.K.M. Dyce die een belangrijk aandeel heeft gehad bij de voorbereiding van de definitieve versie van de manuskripten.

Met grote waardering denk ik terug aan de vruchtbare diskussies die ik tijdens de uitvoering van dit onderzoek heb gevoerd met Ir. C.W. Spoor, Dr. P.L. Lijnse en Dr. W. Hartman.

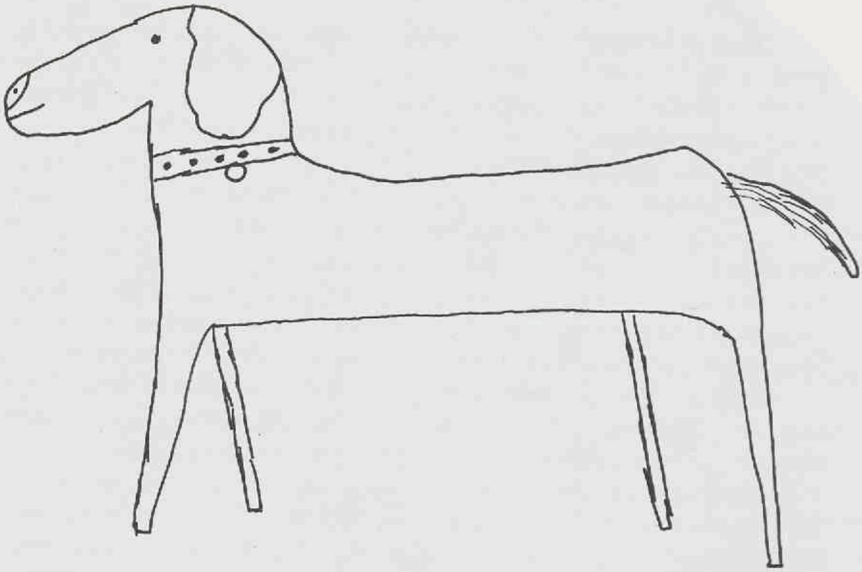
Zonder de technische assistentie van de heren C.J. Slieker (electromyografie), M. Klein en Chr. van Nieuwenhuisen (film), en van Drs. J.S.M.M. van Dieten (experimentele chirurgie) was dit onderzoek onmogelijk geweest. De inbreng van de heren J.G. Nokkert, P.W. Hoogeveen en G.W. Hol, en van mej. A.C. Rosweide heb ik hogelijk op prijs gesteld. De technische faciliteiten die ter beschikking werden gesteld door Prof. Dr. G.H. Huisman en Dr. J. Kroneman hebben belangrijk bijgedragen tot een vlot verloop van dit onderzoek.

De vormgeving van dit proefschrift is tot stand gekomen onder leiding van de heren H.H. Otter en H. Schifferstein: een woord van dank alleen is eigenlijk onvoldoende voor hun bijdrage.

De manuskripten zijn drukklaar gemaakt door mevrouw L.J.M. Michielsen-Pelders.

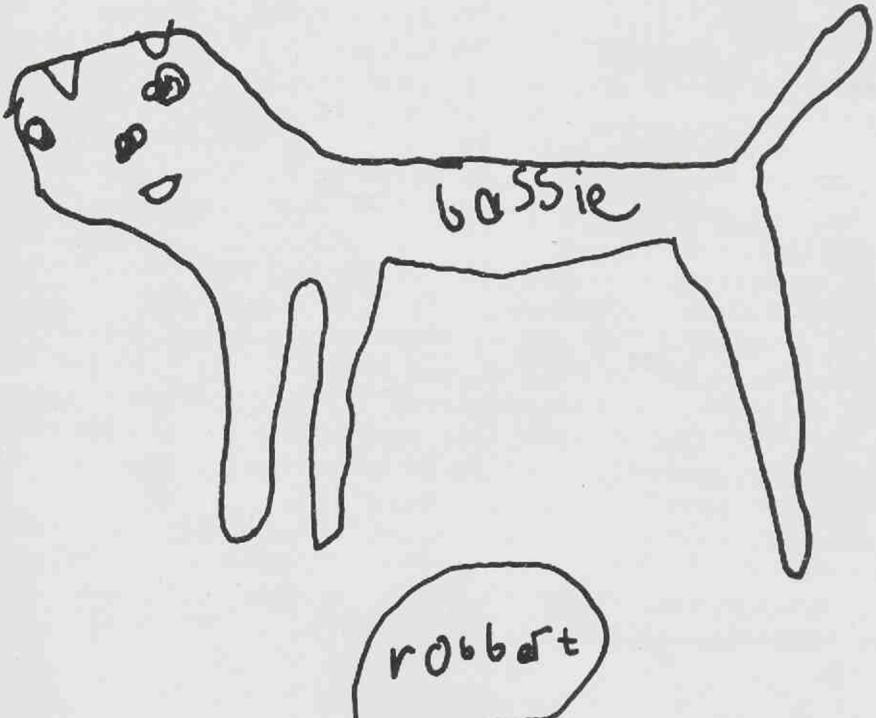
Bij deze gevoelens van dankbaarheid komt ook verwarring: enerzijds is er de opluchting over de voltooing - om tot slot van het werk het begin te schrijven lijkt het éinde - anderzijds komt er een verlangen naar meer. Immers, dit onderzoek biedt mij een geweldig zicht op de biomechanica en betekent daardoor in zekere zin pas een begin.

Op deze pagina hoort ook een verontschuldiging: Ineke, Esther en Robbert, veel tijd waarop jullie recht hadden, zit in de pagina's van dit proefschrift, en dat tekort kan ik met de opdracht alleen niet rechttrekken.



voer

Esther



INTRODUCTION

An Arabian proverb says that paradise on earth is to be found on the back of a horse, in the pages of a book and in the arms of a woman.
Hence, writing a booklet on horses would be a pleasant task, were it not that the publication of a monograph intended to explain some mechanical aspects of the horse's locomotion is in fact an hazardous undertaking. This is the more so since many scientists have dealt with the subject to which the present study is only a modest contribution.

The more general literature of animal locomotion is exhaustive but often rather superficial and attention will be focused on the records of equine locomotion. One may appropriately begin with the work of Hayes, which was published in 1893. Hayes considered the relation between the conformation of a horse and its physical capabilities. He analyzed the aptness of horses for draught, speed and endurance by comparison of their external conformation with that of other animal species with pronounced locomotor abilities. In his evaluation of the external features of the limbs with respect to their task, he left out of consideration the function of the intrinsic muscles and tendons. About 70 years later, Adams (1966) also contents himself with a purely verbal record of the movements of the limbs; he derived the function of the muscles and tendons, as well as the sequence of their activities in the moving limb, from their points of origin and insertion.

The impetus for a pictorial survey of animal locomotion was given by Muybridge, who in 1878 (see Pearson, 1976) and in 1892 published photographic records of moving horses. From this time, cinematography has proven itself to be indispensable for the study of all aspects of animal locomotion and in a sense it has provided the basis of modern kinesiology. Footfall patterns, angular changes in joints during locomotion, the duration of the periods of ground contact and toe-off as well as movements of parts of the body other than limbs have been studied by cinerecords of moving animals (Alexander, 1974, 1977; Fredericson, 1972; Gambaryan, 1974; Hildebrand, 1965, 1968; Manter, 1938; Muybridge, 1892).

It goes without saying that either a verbal or a pictorial record, nor even a combination of both, is sufficient to give a proper insight into the intricate relation between external conformation and intrinsic structure. Apart from the oldest practice of macroscopical dissection a welter of newer techniques has become available to the anatomist which enable him to apply methods of modern technical and mechanical analysis to living structures. These can conveniently be lumped under the head "biomechanics" and they include: polariscopic methods for the determination of the qualitative and quantitative stress in homogeneous models of bones (Badoux, 1977); in vivo measurement of strain in bones during successive stages of the locomotor cycle (Lanyon and Smith, 1970; Rybicki et al., 1977; Turner et al., 1975); force plate and "measuring shoes" studies of forces exerted on the ground by the limbs (Barclay, 1953; Björk, 1958; Kimura and Endo, 1972; Pratt and O'Connor, 1976); changes in the angles of the limb joints as registered by electrogoniometry (Adrian et al., 1966; Taylor et al., 1966); thermography to provide information on the load on phalangeal bones (Dalin et al., 1973); and electromyography to establish the periods and duration of activity in various muscles (Engberg and Lundberg, 1969; Tokuriki, 1973; Gambaryan, 1974). Each of these methods gives information on different aspects of locomotion.

The clinical aspects of normal and aberrant patterns of equine locomotion have long engaged the attention of many authors; Rooney (1969, 1975), however, was the first to synthesize equine locomotion from a mechanical point of view and he attempted to explain aspects of wear and tear by estimating the effect of asynchronous and jerky movements in limbs after prolonged and forced locomotion of horses on the track. However, the lack of objective measurements of locomotory parameters and of a reliable evaluation of the forces renders Rooney's interesting books quite speculative.

The facilities provided by the Institute of Veterinary Anatomy, supplemented by those offered by other departments*) enabled the analysis of locomotion by a coordinated application of cinematography, electromyography, dissection and experimental surgery. The technical facilities did not afford the incorporation of force plate studies or bone strain measurements.

The departments of Veterinary Physiology, Veterinary Surgery and Internal Medicine.

The aim of this study was primarily to describe the movements of the hind limb at walk in relation with the periods of muscular activity with emphasis upon the role of the muscles located parallel with the tendons of the crural reciprocal apparatus. The latter aspect was a follow-up of a study by Badoux (1970), who postulated that the crural muscles of the horse centre the line of action of the load through the long axis of the tibia. Badoux based his theory on the calculation of the effect of the force developed by the gastrocnemius muscle, counteracted by the peroneus tertius tendon in a statical situation. During the progress of the present study it became clear that the angular changes in stifle and hock joints in the horse were less strictly coupled by the tendons of the reciprocal apparatus than could be expected from the proper meaning of the term "reciprocal", so that the study of the role of these tendons as well as that of the muscles became of equal importance. Although this study provides additional evidence which supports the alledged role of the crural muscles of the horse, it must be emphasized that the question whether these muscles centre the load on the tibia can only be answered by in vivo bone strain measurements.

The study includes comparison of certain aspects of the kinematics of the hind limb of the horse with that of the dog, a species which lacks the reciprocal tendinous apparatus; it also includes a comparison of the kinematics of the hind limb of horses before and after transection of the tendons of the reciprocal apparatus.

II. METHODS

a) Introduction

Living and inanimate bodies are subject to the same physical rules and therefore they obey the three fundamental Newtonian laws of motion. The first law states that a body continues its state of rest or uniform rectilinear motion unless it is compelled to change that state by applied forces. The second law says that the change of movement per unit of time is proportional to the applied force and takes place in the direction of that force. The third law states that forces always occur in pairs, consisting of two equal opposites; in other words: for every action there must be a reaction. When a land dwelling animal retracts its limb to push its body forward, the ground reaction exerts an equal but opposite background force against the foot (fig. 1).

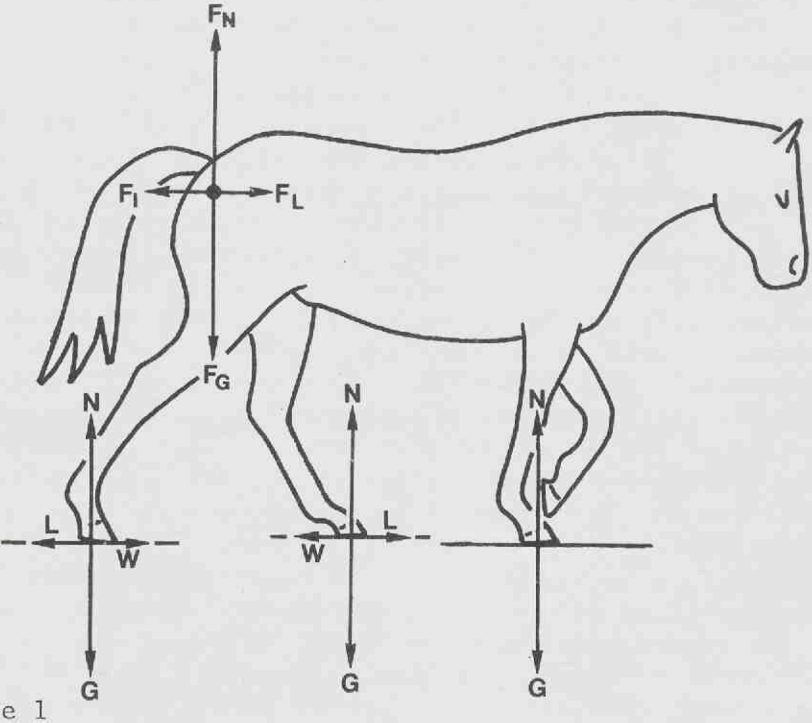


Figure 1
A schematic representation of the forces exerted at the right hip joint and at the feet.
F_N and F_L: the direction of the vertical and horizontal components of the force exerted by the femoral head against the acetabular wall.
F_G and F_I: the direction of the vertical and horizontal components of the force exerted by the acetabular wall against the femoral head.
G and L: the direction of the vertical and horizontal components of the force exerted by the feet against the ground.
N and W: the direction of the vertical and horizontal components of the force exerted by the ground against the feet, normal reaction and friction respectively.
All forces occur in pairs of equal magnitude, but opposite direction (sense).

The complicated structure of the animal locomotory organs renders the evaluation of the direct and indirect effects of intrinsic and extrinsic forces very difficult, the more so since it is technically very difficult to measure in vivo forces within the locomotor system. It is common practice therefore to approach locomotor problems by reducing the living structure to an appropriate model which is more easily accessible to a mechanical analysis.

b) Model of the hind limb

In this study a three-bar two-hinge mechanism represents the basic structure of the hind limb (fig. 2); the three bars are the thigh, shank and cannon (in the dog metatarsus and digit) respectively, the hinge points

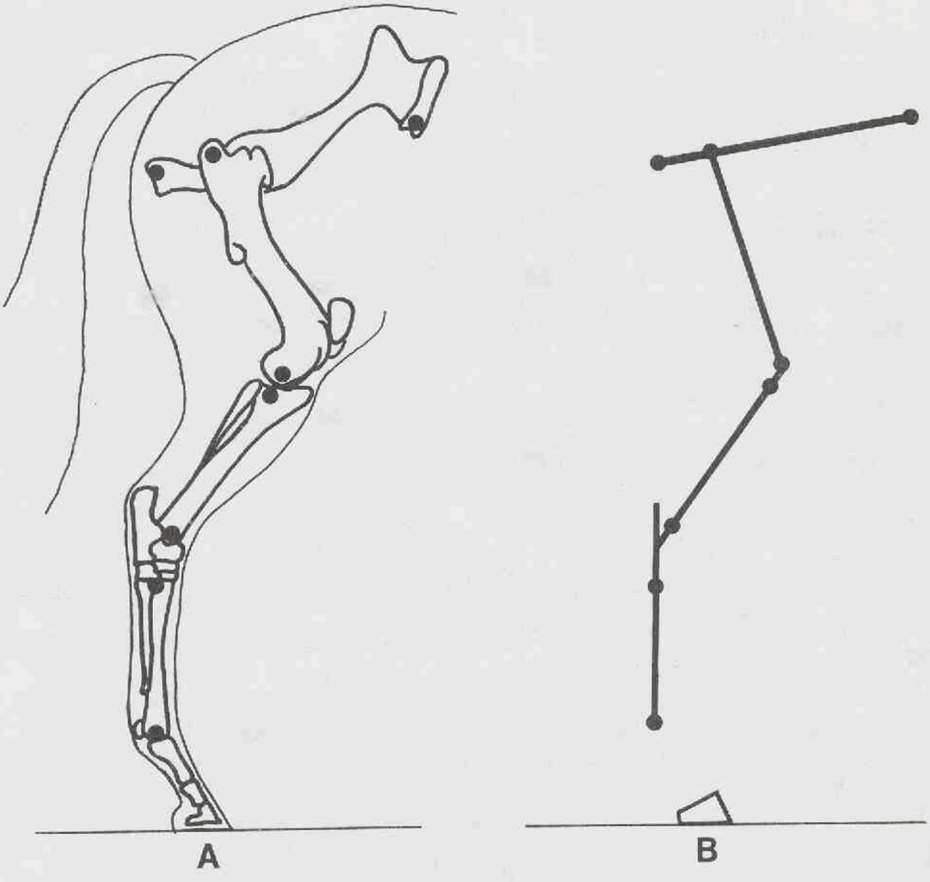


Figure 2
The position of the markers on the skin over the skeletal points indicated (A), and the model of the hind limb based on these markers (B).

the stifle and hock joints. In this model the hinges and the centres of gravity (centroids) of the bars are well-defined points within geometrical bodies in which the mass is evenly distributed. In the actual limb however, the centroids of the segments shift due to muscular contractions and the pivot points (hypomochlions) of the joints alter their position in flexion and extension. Hence, the animal body constitutes a more complex structure with a continuous change of its mechanical state.

The biomechanical analysis of the model gives information on the relative magnitude and sense of the forces applied to the limb segments and the joints and may therefore contribute to understanding of the mechanical background of the processes of wear and tear in the locomotory apparatus.

c) The moving animal

There is a wide variety in the patterns of locomotion in animals. This study was focused primarily on the walk, since a good part of it was carried out with horses and dogs walking on a moving belt which hampers studies of fast gaits.

Walk is a slow gait in which alternately two or three feet are in contact with the ground; a limb is lifted after replacement of its contralateral fellow. The cycle of a stride commences when the limb is placed. The support phase (i.e. the period in which the foot is in contact with the ground) covers about 60 % of the cycle of a stride, the remaining 40 % being consumed by the

Figure 3
Schematic representation of the horse at walk.
A. The positions of the limbs in eight successive stages of the walk.
B. The footfall pattern of the corresponding stages.
C. The periods of ground contact of the limbs are given in horizontal black bars. The bars represent from top to bottom the right hind limb, the right front limb, the left hind limb and the left front limb. The period of the support phases is about 60 % of the cycle of a stride.


A
B
C

swing phase. The cycle is completed with replacement of the limb. The sequence of the footfall pattern for the normal walk may be presented 1. right hind limb, 2. right fore limb, 3. left hind limb, 4. left fore limb, 5. right hind limb again. This pattern is found in most quadrupedal animals (Hildebrand, 1963, 1968; Pearson, 1976), although some prefer an ipsilateral (laterally coupled) gait to the above described contralateral (diagonally coupled) pattern. A schematic representation of the walk is given in fig. 3.

c1) The support phase

During the support phase the (hind) limb has a twofold task: a. it supports the body, i.e. it prevents sagging by the action of its intrinsic muscles which by fixing the hinges convert the mechanism into a strut suited to oppose the forces applied at the proximal (hip) and distal (foot) ends; b. it propels the body, i.e. it acts as a lever and rotates hip and foot. From Newton's third law it follows that the total action at the distal end of the limb (i.e. the foot) against the ground (which is the vectorial sum of the vertical weight and the horizontal force due to muscular action) is counteracted by the total ground reaction (which in turn is the vectorial sum of the vertical normal reaction and the horizontal frictional force) (fig. 1). The magnitude of the ground reactions has been measured in the dog (Barclay, 1953; Kimura and Endo, 1972) and horse (Pratt and O'Connor, 1976). In the first part of the support phase, the sense of friction is opposite to the direction of progression and has a retarding (negative) effect. In the last part of the support phase friction and progression have the same (positive) sense (fig. 1). The net effect of friction during the total support phase of the hind limb is positive.

At the proximal end of the limb - the hip joint - the partial body weight is vertically transferred from the acetabular roof to the femoral head and the forces exerted by the other limbs in contact with the ground are horizontally transferred from the acetabular wall to the corresponding aspect of the femoral head. At placing, this horizontal force has a sense in the direction of progression; it is composed of the propulsive force of the contralateral hind limb at the proper hip joint and of inertia (see section d.), as follows from

Newton's first law (fig. 1). In the middle of the support phase the limb has to deal preponderantly with the forces in the vertical direction acting at foot and hip; friction is insignificant in this part of the cycle. At the end of the support phase, the sense of friction is positive and pushes the body forward; this forward impulse, however, is counteracted at the hip by the combined friction of the other hind limb in contact with the ground and by the effect of inertia (see section d.).

c2) The swing phase

During the swing phase the limb swings forward, its joints are flexed, and its centre of gravity is brought closer to the pivot point at the hip. This flexion diminishes the distance r between pivot point and centre of gravity of the whole limb and hence decreases the moment of inertia ($I = mr^2$).
At the end of the swing phase, the hind limb regains its favourable position for the following support phase.

The biomechanical analysis of the hind limb describes the action of the muscles which oppose the effects of the above mentioned external forces.

d) Methods of calculation

The method by which the hind limb is divided into segments, the determination of their mass and the position of the centre of gravity (centroid), the pictorial reconstruction of a complete cycle of a stride from the cinematographical record and the determination of the periods of muscular activity by electromyography are amply described in the separate papers (1, 2, 3).

In the pictorial reconstructions, the travel of the centroids was measured in three strides of every animal (fig. 4). The stride pictured in an optimal cinematographical recording was chosen to approach speed and acceleration.

The displacement (s) was measured in the horizontal (X) and vertical (Y) directions. The speed (velocity) $\bar{v}$ of the centroid of the limb segments in the middle of the time interval initially chosen is the rate of displacement in both directions (X and Y), hence

$$\vec{v} = \frac{\Delta \vec{s}}{\Delta t} \qquad (1)$$

SI units $m.s^{-1}$

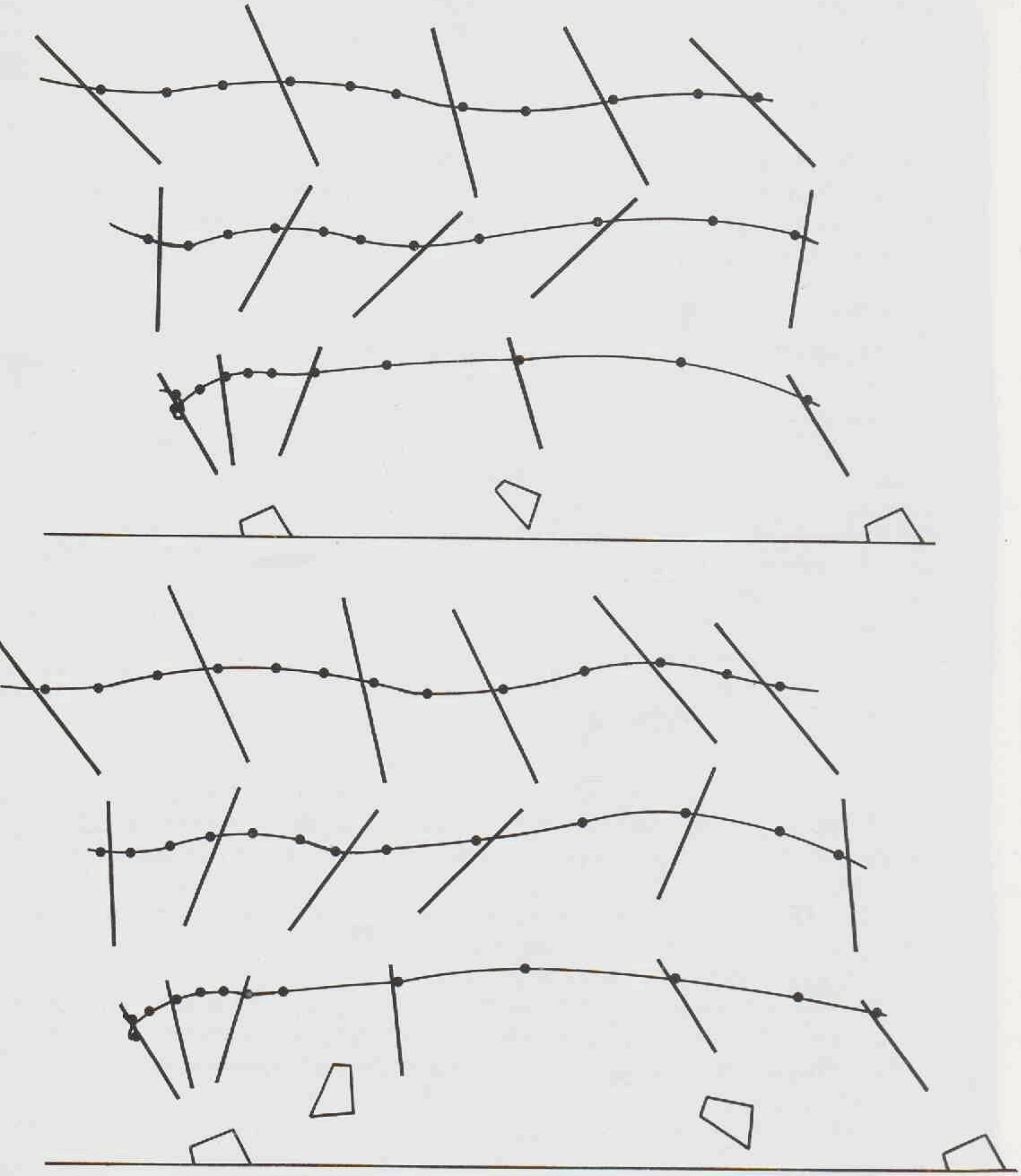


Figure 4
The reconstruction of the cycle of a stride of two different horses taken from the film. The black dots represent the positions of the centres of gravity of the limb segments at regular intervals during the cycle of a stride.

The acceleration $(\bar{a})$ is expressed as the rate of change of velocity, hence

$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} \qquad (2)$$

SI units $\quad m.s^{-2}$

The analysis of the cinematographical record clearly demonstrates that the change of speed per unit of time of the centroid of a limb segment is unequal in magnitude and direction, hence the acceleration is variable.

The force (F) required to obtain the observed acceleration follows from the product of the mass of the segment and the acceleration:

$$\vec{F} = m.\vec{a} \qquad (3)$$

SI units Newton (N)

The force was calculated for the accelerations in both directions (X and Y). The resultant force F_r is the vectorial sum of F_X and F_Y, and this is the force which is required at the centre of gravity of the segment in order to produce the rate of acceleration.
It must be kept in mind, however, that F_r is not identical with the resultant F_R of all forces acting upon the segment under consideration. This latter force F_R is parallel with and equals F_r, but its point of application lies at some distance from the centroid: its moment induces a rotation of the segment around its centre of gravity. The movement of two segments relative to each other is expressed by the angular changes of the joints. For every individual, these changes have been measured in three strides; their average was taken as the starting point for further calculations.

The average angular velocity $(\overline{\omega})$ in the middle of the time interval initially chosen is defined as the rate of change of the joint angle $(\Delta \theta)$ between two segments in the time interval (Δt), and is an approximation of the actual angular velocity:

$$\vec{\omega} = \frac{\Delta \theta}{\Delta t} \qquad (4)$$

SI units $\quad rad.s^{-1}$

The angular acceleration ($\bar{\beta}$) is the rate of change in the angular velocity of two segments with respect to each other about their joint axis:

$$\vec{\beta} = \frac{\Delta \vec{\omega}}{\Delta t} \qquad (5)$$

SI units $\quad$ $\mathrm{rad.s}^{-2}$

The parameters referred to above enable to approach the linear and angular acceleration and the required forces at the centres of gravity. For descriptive reasons, however, some remarks should be made about moments, although these are not available. Generally speaking, a moment which produces a given angular acceleration (α) is the product of α and the moment of inertia. It must be kept in mind, that α applies to the angular acceleration of the axis of a segment with respect to the one axis of an established coordinate system, whereas β (5) refers to the angular acceleration between two linked segments. Hence cannot be used for calculations of a moment referred to above.

The movements of a segment are governed by F_R, which is the resultant of gravitational force (applied at the centre of gravity) and forces applied at the proximal and distal ends of the segment. The position of the segment in the kinematic chain determines the character of the latter forces. In the case of an end link (foot), the reactional force is the vectorial sum of the normal reaction and friction at the distal end; the other force at the proximal end incorporates the effect of muscular forces. In any other link, the forces at the ends comprise the effect of the muscular forces at both ends.

In order to be able to calculate the forces at both ends one has to know the numerical value of the reactional forces, but for technical reasons set forth above measurements of the ground reaction were impossible.

Therefore, the contribution of the muscles to the movements of the limb was only estimated from the vectorial direction of F_r, from the angular acceleration β at the joints, and from the potential function (based on origin and insertion) of the muscles which display activity.

In the fourth paper the forces and moments which eventually cause the movements of a segment are for pure descriptive reasons lumped in two formulas:

$$F = F_g + F_{n+w} + F_m \qquad (6)$$

$$M + M_g + M_{n+w} + M_m + M_i \qquad (7)$$

It must be kept in mind, that the effect of the reactional F_{n+w} and M_{n+w} eventually depends for each segment on its position in the kinematic chain.
In the latter formula M_i denotes the moment of the inertial force about the axis of the joint; its acceleration is equal in magnitude but opposite in direction to the acceleration applied at the joint axis.

In the second, third and fourth paper, the force of inertia has been interpreted as being substantially equal but oppositely directed to the sum of the external forces operant at the segments to allow a statical approach (see fig. 5 in paper 4). From the standpoint of theoretical physics, this procedure can be criticized.

The d'Alembert conception of Newtonian mechanics essentially consists of regarding the mass-acceleration product of Newton's second law (for an invariant mass) as a "stop the motion" force, which permits a dynamics problem to appear like a statics problem (Fanger, 1970). This "stop the motion" force (or series of component forces in the case of separate limb segments) is often termed the reverse effective force or the inertia force on the mass. It is exactly equal to, but oppositely directed from the body m.a product. Were such a force to be represented on the free body diagram by a vector $F_I = -ma$, it would create an impression of static equilibrium. It has been common to speak of the d'Alembert principle as a means of creating dynamic equilibrium. Indeed this is a confusing and paradoxical terminology. If F_I were added to both members of the second law equation, we would obtain:

$$F + F_I = ma + F_I = ma + (-ma) = 0 \qquad (8)$$

In the presence of such a force, the body motion would be stopped and the problem would be amenable to statical analysis. However, the factor of body acceleration cannot be so easily evaded, as will be seen when one replaces the F_I of the left member of the equation by its equivalent

$$F - ma = 0 \qquad (9)$$

which appears as a pure manipulation of mathematics: the inertia force is purely fictitious.

In spite of the above conclusions, however, the d'Alembert principle not only played a significant role in the historical development of dynamics but also carries a considerable significance in the current context of moving animals; it allows one to consider the effects of forces on the limb and its segments in a state of dynamic equilibrium.

e) Possible errors

The skeletal points which were indicated for the cinerecords have been amply explained in the papers (1, 2, 3). The skin over these parts was marked while the animals were standing square and the animals were then filmed in this position. From these pictures a model of the skeletal parts of the limb was constructed; this model was then carefully redrawn in the outline of the hind limb of the walking animal on the successive filmframes.

Since the determination of velocities and accelerations was based upon an analysis of cinerecords, possible sources of errors can be found in:

1) a discrepancy between the position of the markers on the skin with respect to the underlying bony structures. This may lead to misinterpretation in the reconstruction of the model of the hind limb.

2) inaccuracies in the measurements at the pictorial reconstruction of the cycle of a stride, which may lead to errors in the calculations of the linear and angular accelerations.

The attention was primarily focused upon the relation between the displacements of the centres of gravity of the three segments and the relation between the changes in the angles of the joints during a stride. In normal animals, these relations were fairly constant (fig. 4), although differences between consecutive strides of a single animal and between various individuals occurred.

ad 1) The greatest variation of the markers on the skin was observed on the thigh: the caudal part of the greater trochanter measures about 6 cm; hence the absolute error is 3 cm. At the distal end of the femur the absolute error is 2 cm. In the reconstruction of the model thus a possible relative error of 12 percent in the length of the femur, and of 6 percent in the position of the centre of gravity of the thigh may exist. The deviation of the markers indicating the skeletal parts of the tibia and the metatarsus was less due to the smaller dimensions of these skeletal points (3 percent for both tibia and metatarsus). This inaccuracy in the positions of the markers leads to a relative error in the determination of the actual angle of the stifle of about 10 percent, and of the hock of about 6 percent. However, in the reconstruction of a complete cycle of a stride this error remains constant.

ad 2) The relative error in the measurements in the reconstruction of the model is independent of the errors mentioned under 1). For the displacements of the centres of gravity this error is 5 percent, and for the angles of the joints 7 percent.

f) Papers

The first paper describes the periods of activity of the muscles of the hind limb of the dog.

The second paper gives kinematical and kinetical characteristics of the hind limb of the dog.

The study was continued to determine the periods of muscular activity of the muscles of the hind limb of the horse, its kinematics and some aspects of its kinetics; the results are described in the third paper.

In the fourth paper the kinematics of the hind limb of the dog (digitigrade) and of the horse (unguligrade) have been compared, and the consequences for the locomotory abilities of both species are discussed.

The last paper describes the effect of experimental surgery of the tendons of the reciprocal tendinous apparatus and of the cranial tibial muscle on the locomotor performance of the hind limb in horses

REFERENCES

Adams, O.R. : Lameness in horses. Philadelphia : Lea and Febiger (2nd ed.) (1966).

Adrian, M.J.; Roy, W.E.; Karpovich, P.V. : Normal gait of the dog : an electrogoniometric study. Amer. J. Vet. Res. 27, 90-95 (1966).

Alexander, R. McN. : The mechanics of jumping by a dog, Canis familiaris. J. Zool., London 173, 549-573 (1974).

Alexander, R. McN. : Allometry of the limbs of antelopes (bovidae). J. Zool., London 183, 125-146 (1977).

Badoux, D.M. : The statical function of some crural muscles in the horse. Acta Anat. 75, 396-407 (1970).

Barclay, O.R. : Some aspects of the mechanics of mammalian locomotion. J. Exp. Biol. 30, 116-120 (1953).

Björk, G. : Studies on the draught force of horses. Acta Agric. Scand., suppl. 4 (1958).

Dalin, G.; Drevemo, S.; Fredericson, I.; Jonsson, K.: Ergonometric aspects of locomotor asymmetry in Standard bred horses trotting through turns. Acta Vet. Scand., suppl. 44 (1973).

Engberg, J.; Lundberg, A. : An electromyographic analysis of muscular activity in the hind limb of the cat during unrestrained locomotion. Acta Physiol. Scand. 75, 614-630 (1969).

Fanger, C.G. : Engineering mechanics : statics and dynamics. Columbus, Ohio : C.E. Merill Publishing Company (1970).

Fredericson, I.; Drevemo, S. : A photogrammetric method of two-dimensional fast moving horses. Acta Vet. Scand. suppl. 37 (1972).

Gambaryan, P.P. : How mammals run. New York, Toronto: John Wiley and Sons (1974).

Hayes, M.H. : Points of the horse. London: Stanley Paul & Co. Ltd., (7th reversed ed. 1969; first published 1893).

Hildebrand, M. : Symmetrical gaits of horses. Science 150, 701-708 (1965).

Hildebrand, M. : Symmetrical gaits of dogs in relation to body build. J. Morphol. 124, 353-360 (1968).

Kimura, T.; Endo, B. : Comparison of force of foot between quadrupedal walking of dog and bipedal walking of man. J. Fac. Sci. Tokyo 5, 119-130 (1972).

Lanyon, L.E.; Smith, R.N. : Bone strain in the tibia during normal quadrupedal locomotion. Acta Orthop. Scand. 41, 238-248 (1970).

Manter, J.T. : The dynamics of quadrupedal locomotion. J. Exp. Biol. 15, 522-540 (1938).

Muybridge, E. : Animals in motion. ed. L.S. Brown, New York : Dover Publications (renewed ed. 1957, first edition 1892).

Pearson, K. : The control of walking. Sci. Amer. 235, 72-87 (1976).

Pratt, G.W.; O'Connor, J.T. : Force plate studies of equine biomechanics. Amer. J. Vet. Res. 37, 1251-1255 (1976).

Rooney, J.R. : Biomechanics of lameness in horses. Baltimore: Williams and Wilkins (1969).

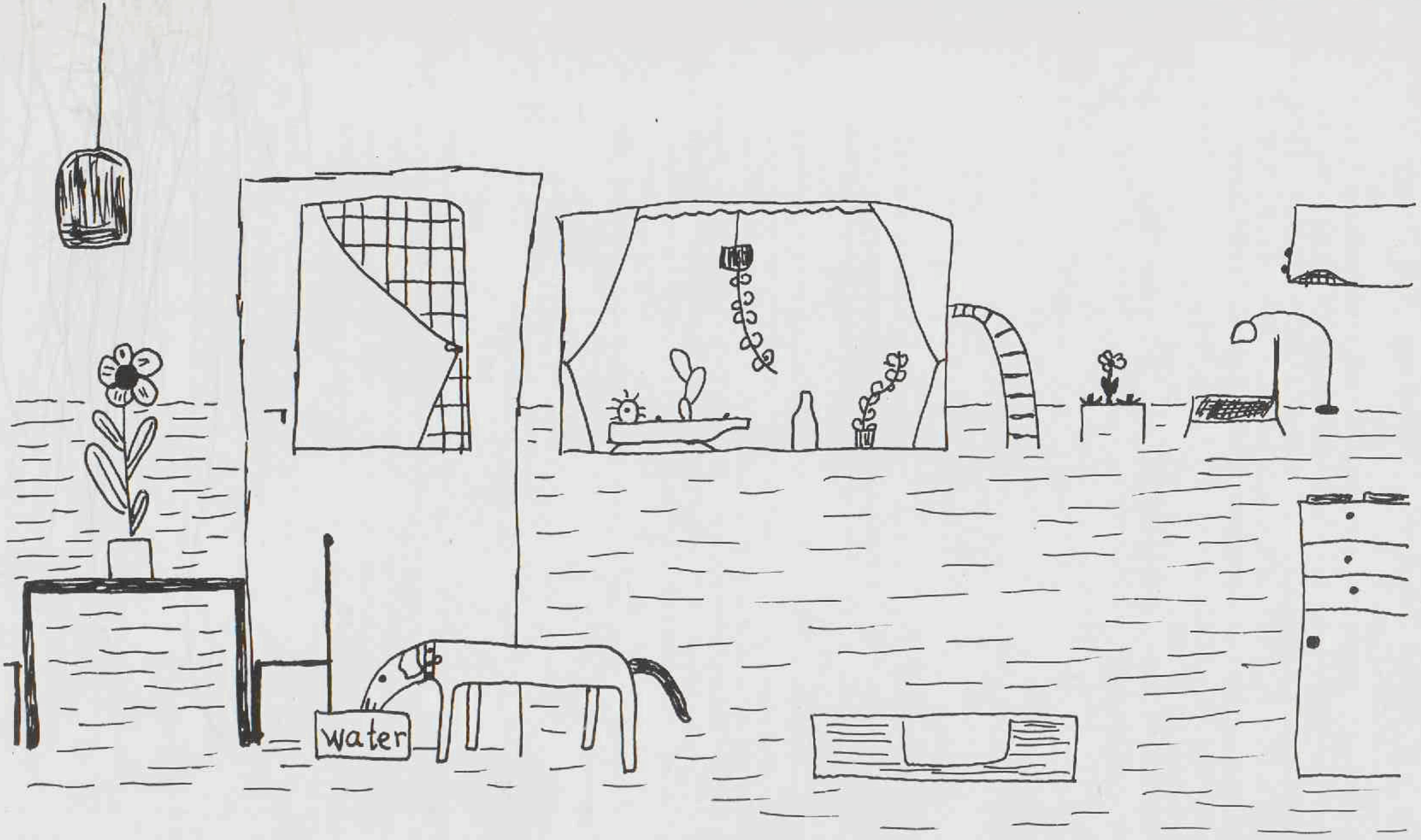
Rooney, J.R. : The lame horse. Cranbury, New Jersey : Barnes & Co. (1975).

Rybicki, E.F.; Mills, E.J.; Turner, A.S.; Simonen, F.A. : In vivo and analytical studies of forces and moments in equine long bones. J. Biomech. 10, 701-705 (1977).

Taylor, B.M.; Tipton, C.M.; Adrian, M.; Karpovich, P.V. : Action of certain joints in the legs of the horse recorded electrogoniometrically. Amer. J. Vet. Res. 116, 85-89 (1966).

Tokuriki, M. : Electromyographic and joint-mechanical studies in quadrupedal locomotion. I. Walk. Jap. J. Vet. Sci. 5, 433-446 (1973).

Turner, A.S.; Mills, E.J.; Gabel, A.A. : In vivo measurement of bone strain in the horse. Amer. J. Vet. Res. 36, 1573-1579 (1975).



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Acta anat. *96:* 70–80 (1976)

The action of the hind limb musculature of the dog in walking

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Key words. Locomotion · Muscles of hindlimb · Dog

Abstract. This study was performed by means of cinephotography and electromyography. The results were correlated with earlier investigations concerning the forces exerted by the pads of walking dogs. A concept about the action of individual muscles of the hind limb during a stride was formed.

The principal conclusions are: (1) The hamstrings are divisible into a cranial and a caudal group, the first consisting of the cranial parts of the M. biceps femoris and M. semimembranosus, the second of the caudal parts of these muscles, together with the M. semitendinosus. The chief function of both groups is to extend the hip; the caudal group also flexes the stifle. (2) Activity is present in the greatest number of muscles during the change in the sense of movement of the limb. (3) During the last stages of the stance phase the number of muscles showing electrical activity diminishes, while the force exerted by the pads in a horizontal direction increases. Non-muscular forces, e.g. inertia, play an important role during movement.

Introduction

While there has been much research on the fundamental physiology of muscle, remarkably little attention has been paid to the actions and uses of individual muscles in natural circumstances. The actions conventionally ascribed to them are largely common-sense deductions from their attachments, for which there is an almost total lack of experimental evidence. Moreover, the authors of most standard texts have been content to ascribe all movement to muscular activity, to the neglect of other factors.

The purpose of the present paper is to confirm and extend the knowledge of the actions of individual hind limb muscles of the dog during walking. Walk is defined as the slow gait

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in which two or three feet are alternately in contact with the ground and each foot is lifted only after its contralateral fellow is replaced. It is recognized that there are variations in the walk and individuals display a preference for a diagonal or lateral support, expressed by differences in the relative durations of the periods when only two feet are in ground contact. These differences proved to be irrelevant. In this study electromyography was combined with cine-photography, a combination which reveals which muscles are active during particular movements.

Several methods have been applied in earlier studies of canine locomotion. Hildebrand [1968] recorded the walk on motion pictures and expressed it by means of a gait formula. Adrian *et al.* [1966] measured the angular changes of the joints with electrogoniometers. Barclay [1953] and Hutton *et al.* [1969] registered the forces exerted by the pads during a normal stride. The electromyographic investigations of certain Japanese workers [Nomura *et al.*, 1966, Tokuriki, 1973] provide detailed information upon the sequence and duration of activity of individual muscles in different gaits.

Material and methods

Five greyhounds with normal gaits were required to walk in an encaged 'trottoir roulant', while being filmed from the right side at an exposure rate of 64 frames/sec. A switch attached below the right metatarsal pad closed a circuit when compressed by a force exceeding 7 N (this relatively small force is exceeded during almost the whole stance phase) [Barclay, 1953; Hutton *et al.*, 1969]. Closure of the circuit was registered on the EMG trace and also illuminated a lamp within the picture field. The speed at which the trottoir was operated determined the pattern of the walk and was adjusted to produce open and closed circuits of equal duration. The average speed at which the dogs walked was 1,25 m·sec^1 (4.5 km·h^1). The moment when the circuit was opened as the foot was about to be lifted from the ground was chosen as the starting point of the step cycle. The cycle was divided into 22 stages, corresponding to alternate frames of the film records. The interval between stages was thus 0.031 (2/64) sec.

The joint angles were measured for each stage of the cycle. They were determined by measuring the angles enclosed by strips of adhesive tape extended between trochanter major and lateral epicondyle of the femur, the lateral condyle and lateral malleolus of the tibia, and the proximal and distal ends of the lateral metatarsal bone, all of which are easily palpated. The ischial and coxal tuber were also marked. Since the skin is only slightly movable over these skeletal parts, the angles measured give an acceptable indication of the changes at the joints. The joint angles were measured over the flexor aspects.

For the electromyographic investigation two platinum wire electrodes, from which the insulation of the terminal 1–2 mm had been removed, were inserted in the middle of the muscle belly. Electrical activity was assessed from the loudspeaker and monitor of a DISA electromyograph type 14 A 30, and the signals registered on a Schwarzer carbon writer (frequency response 75–350 Hz). No attempt was made to quantify the response: the presence or absence of muscular activity alone was noted.

Results and interpretation

The principal results are given in tabular form (fig. 1). The perpendicular distance between trochanter major – and thus the acetabulum – and the ground is least duting stages 0 and 11, when both hind pads have contact with the ground; it is greatest in the middle of both stance and swing phases. The acetabulum thus follows and undulating course in which the difference between the highest and lowest points is 1,3 cm (in those dogs standing about 60 cm at the tuber coxae). There was no measurable horizontal displacement of the trochanter major in relation to the cage, indicating a constant velocity of the trunk. The distance between trochanter major and the distal end of Mt 5 was taken as a measure of the functional length of the limb. This length shortens from stages 0–6, increases thereafter to reach its maximum in stage 9 just before the paw makes contact with the ground. It shortens again in the beginning of the stance phase when a lead of 7 N is accepted by the foot, and remains almost constant during the whole stance phase (to 22). From the film, conclusions can be made of movements in the sagittal plane alone and the interpretation of muscle action is correspondingly restricted.

The changes in the joint angles scarcely need explanation. The changes at the hip are out of phase with those at the stifle and hock during most of the cycle. Stifle and hock follow approximately the same course; a difference exists only in stages 1 and 2 and again in stages 10 and 11 when the foot is lifted and replaced.

The deviation from the vertical of the axis of the femur varies between 0 and 40°. These extremes are attained in stage 1 when the leg is lifted and in stage 8 shortly before the foot makes contact with the ground. The angle of the tibial axis with the vertical varies between 70 and 0°. The extremes are

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Fig. 1. The arrows indicate lifting (↑) and replacing (↓) of the foot at stages 1 and 10, respectively. The angular changes are given in the upper part; in the lower part the average periods of muscular activity are represented by the black blocks, individual variations by the hatched extensions. 1 = M. interosseus; 2 = m. gastrocnemius medialis; 3 = m. gastrocnemius lateralis; 4 = m. flexor digitorum superficialis; 5 = m. hallucis longus; 6 = m. popliteus; 7 = m. peroneus longus; 8 = m. extensor digitorum longus; 9 = m. tibialis cranialis; 10 = m. gracilis; 11 = m. adductor; 12 = m. pectineus; 13 = m. semimembranosus pars cranialis; 14 = m. semimembranosus pars caudalis; 15 = m. semitendinosus; 16 = m. biceps femoris pars caudalis; 17 = m. biceps femoris pars cranialis; 18 = m. vastus lateralis (in one dog, activity in the m. vastus medialis was simultaneously with that in the m. vastus lateralis, as was described by TOKURIKI [1973]; so the period of activity of the m. vastus lateralis is accepted to represent the activity of the whole vastus group); 19 = m. rectus femoris; 20 = m. tensor fasciae latae; 21 = m. sartorius; 22 = m. gluteus medius.

The action of the hind limb musculature of the dog in walking

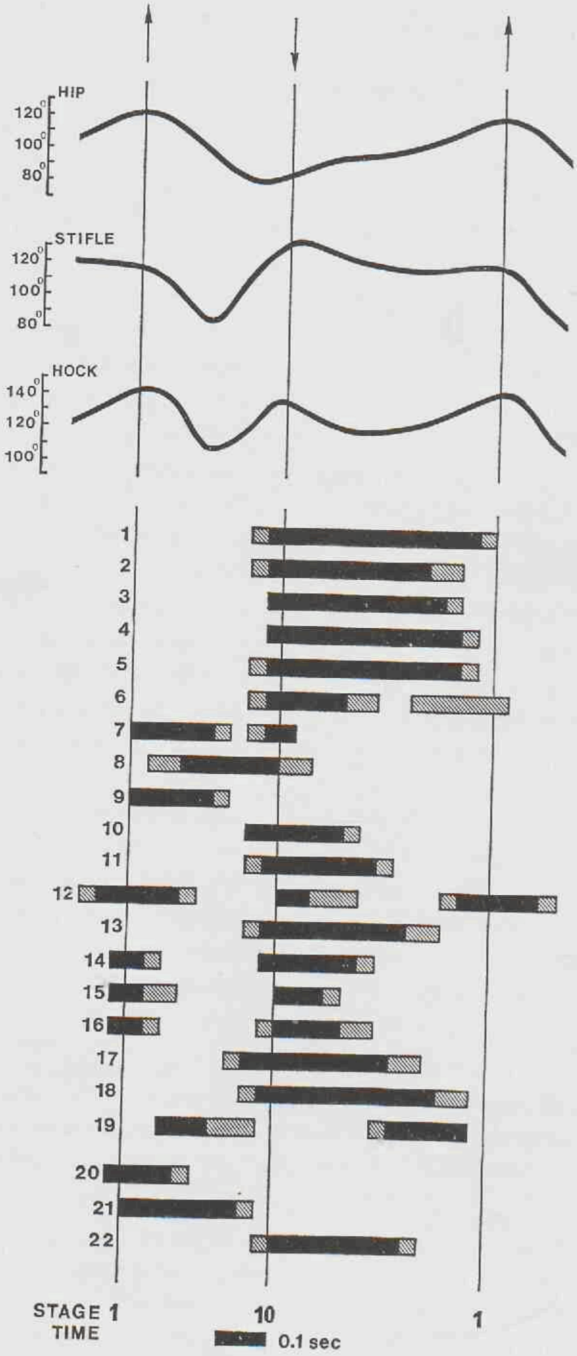

Table I. Body weight, gait formula [HILDEBRAND, 1968], and speed on the trottoir roulant

Dog	Body weight	Gait formula	Speed	
	kg		$m \cdot sec^{-1}$	$km \cdot h^{-1}$
I	23	62/6	1,27	4,6
II	24	63/23	1.19	4.3
III	22	65/22	1.27	4.6
IV	22	63/21	1.25	4.5
V	21	64/20	1.22	4.4

reached in stages 3 and 4 early in the swing phase and in stage 10 at replacement. The angle between the vertical and the axis of the pes varies between 20 and 45°. The extremes are reached in stages 2 and 3 and 10 and 11, respectively. The gait types of the dogs are expressed according to the formula of HILDEBRAND [1968] (table I).

The results of the electromyographic investigations are given in figure 1. It must be born in mind that registrable electrical activity precedes contraction by some 20 $m \cdot sec^{-1}$ and ceases an equal period after this [GRILLNER, 1972]. The greatest number of muscles is active in stages 9–14 (about the time of replacement of the foot) and in stages 21–2 (when it is again lifted). During the stance phase the number of muscles in action diminishes, although the force in the horizontal direction – push off – reaches its greatest value at the end of this phase (stages 20 and 21) [BARCLAY, 1953]. Muscular activity is thus largely concentrated in those periods in which there occurs a change in the sense of the movement of the limb.

The step cycle commences when the foot is lifted. Immediately before ground contact is lost, the limb is stretched behind the animal and, were it unopposed, would retain this position and drag behind. In fact, the thigh is rotated forward as the foot is raised. The stifle is flexed and the hock follows suit after a short period of continuing extension. Flexion of the stifle and hock shortens the functional length of the limb, bringing the centre of gravity closer to the centre of rotation at the hip and thus reducing the relative rotational moment of inertia. This economizes the muscular effort required to advance the foot which, after initially lagging behind, is accelerated to achieve a forward speed exceeding that of the proximal segments of the limb. The muscles engaged in these early stages of the swing phase include cranial and caudal extrinsic muscles of the thigh. The former (tensor and sartorius) prevail at the hip to overcome the combined inertial and gravitational forces and the braking effect of the caudal hamstrings. The situation is reversed at

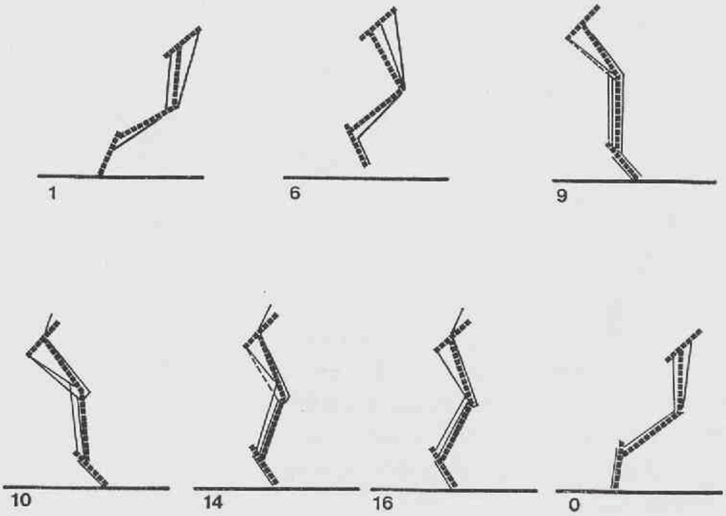

Fig. 2. The schematic drawings represent successive stages of the step cycle. The active muscles or groups of muscles are indicated by the smaller lines. In stage 1 the backward movement of the limb is reversed by the action of the tensor and sartorius. Meanwhile the stifle is flexed by the action of the caudal hamstrings. The pes is protracted as the tarsus is flexed by the tibialis cranialis and the peroneus longus. In midswing (stage 6) the limb continues to be protracted by the sartorius, rectus and extensor digitorum. Just before the foot is replaced (stage 9), the limb is converted to a strut by the action of the intrisic muscles; the vastus group, the calf muscles, the interossei, and the extensor digitorum. The forward swing of the thigh is checked by the cranial hamstring. The strut is maintained by the action of the intrinsic muscles during the whole stance phase. The caudal hamstrings come into action at stage 10 to check the forward velocity of crus and pes; they remain active until the foot passes below the stifle in stage 14. The gluteus and the cranial hamstrings advance the body over the limb. The retractors cease their activity when the hip has passed over the foot in stages 16–18. Before the limb is lifted in stage 0, activity ceases in a number of the muscles which transform the limb into a strut. Contraction of the vasti is replaced by contraction of the rectus femoris.

the stifle, where flexion develops against gravity but assisted by inertia. Since flexion continues after the caudal hamstrings become inactive it must then be due either to their passive insufficiency (as they are tensed by the continuing flexion of the hip) or to the activity of the caudal belly of the sartorius. The dorsal crural muscles flex the hock and impart a forward momentum to the foot. By the middle of the swing phase the limb has attained its greatest forward speed and its least functional length. Subsequently it lengthens and since extension of the hock precedes activity in the relevant musculature this must be due to gravity and centrifugal force. Inertia maintains the forward movement but the expected acceleration of the foot as the limb lengthens does not occur: it must be checked by the passive resistance of the caudal muscles and periarticular structure since it precedes activity on the relevant musculature. Immediately prior to the foot re-establishing ground contact, the cranial hamstrings and probably also the gracilis and adductor will check the forward velocity of the limb.

The simultaneous activity in the flexors and extensors of the stifle, hock and toes appears wasteful but presumably braces the limb against the forthcoming shock of landing and prepares it for its supporting role. Several forces act on the joints on the moment of foot replacement. At the hip, muscular activity (middle gluteus and all hamstrings) and the horizontal component of the ground reaction promote extension: inertia and the normal force promote flexion. The former prevail. The extensor forces acting on the stifle are inertia, the normal force and the force exerted by the vasti: the flexor forces are those generated by the caudal hamstrings, gastrocnemii and superficial flexor, and the frictional force. Similarly at the hock, intertia, the normal force and the digital extensor act to flex the joint, whilst the calf muscles and friction tend to extend it. Both joints are flexed.

At the present time the values of most of these forces are unknown; BARCLAY [1953] and HUTTON *et al.* [1969] have measured the components of the ground reaction and have shown that the horizontal component, friction, is relatively minor in comparison with the normal force and perhaps can be neglected. This allows certain provisional deductions concerning the relative importance of the muscular activities. For example, since the tarsal joint is flexed in spite of the action of the powerful calf muscles, it is clear that the forces represented by inertia and the normal reaction are dominant.

The stifle first flexes but is soon stabilized. The values of the various forces acting on the joint have not been determined, but here also the horizontal component of the ground reaction can perhaps be neglected. The period of activity of the caudal hamstrings corresponds to that when flexion is observed, and terminates when the stifle reaches a position directly above the foot support (stage 14). Applying the results of BARCLAY [1953], it may be assumed that between stages 10 and 14 the hind limb has a retarding influence on the movement of the body and thereafter accelerates it. The potential effects of contraction of the caudal hamstrings are to retract the limb and to flex the stifle. Since the vasti are also active and will antagonize any action of the caudal hamstrings on the stifle it seems probable that their effect is limited to retraction of the limb. The simultaneous activity in flexors and extensors of the sifle probably stabilizes this notoriously unstable joint, a role shared by the popliteus, which is now also engaged. Stifle flexion brings the centre of gravity closer to the centre of rotation at the foot. The curve followed by the centre of gravity is thus flattened, reducing the force required to carry the centre of gravity over and beyond the foot. The retractor activity of the cranial hamstrings and the middle gluteal muscle continue until stage 18. No muslces are active to extend the hip during the last stages of the stance phase and the final extension of this joint as the body continues forward must be due to inertia.

The influence of the normal force changes at stage 14; during the remainder of the stance phase it supplements the flexor activity of the calf muscles in balancing the vasti and inertia. The quadriceps group (initially the vasti, later the rectus), both heads of the gastrocnemius, the flexor superficialis and the hallucis longus approximate the limb to a strut over which the body moves. The long digital flexors and the interossei press the toes against the ground, providing a strong grip for support and propulsion. With the onset of activity in the tensor fasciae latae in stage zero, the cycle recommences.

Discussion

The results of this electromyographic investigation generally confirm those obtained by NOMURA *et al.* [1966] and TOKURIKI [1973] in dogs, and by ENGBERG and LUNDBERG [1969] in cats, but amplify them on a number of points. The changes of the joint angles are also in general agreement with those obtained in previous investigations in dogs [ADRIAN *et al.,* 1966]. Electromyography reveals which muscles are active when particular movements are performed; it does not reveal whether the muscle contributes to the movement, opposes it or is merely adjusting its length to the altered positions of its attachments. The direction of the forces developed by the individual muscles is determined by their attachments. Although the magnitude of these forces cannot at present be determined, an indication of their relative values can be deduced from analysis of the forces operating in each phase of the cycle. By studying the sequences and durations of activity of the muscles, a concept was formed of the contribution of each muscle to the movements.

The interpretation offered of the activity of the hamstring group is the most critical point to emerge. The analysis of the function of these muscles has long presented difficulties as comparison of a number of anatomical texts will reveal [GRAU, 1943; BRADLEY and GRAHAME, 1948; SISSON and

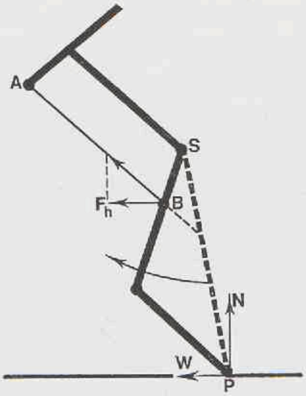

Fig. 3. AB = Line between origin and insertion of the caudal hamstrings; F_h = horizontal component of the force of the caudal hamstrings; S = stifle; P = pads; N = normal force; W = friction. For explanation, see text.

GROSSMAN, 1955; NICKEL *et al.*, 1968]. The results clearly show that the cranial and caudal parts of this muscle mass do not act synchronously but in quite different functional contexts. Their prime action as extensors of the thigh is not in doubt, but their effects upon the stifle require more attention.

Many textbooks describe their actions with reference to the horse and leave it to be inferred that they are the same in other species; they assert that the cranial parts are extensors of the stifle whilst the caudal parts (i.e. semitendinosus and caudal biceps femoris) are flexors when the kinetic chain is open, extensors when it is closed (i.e. when the foot is on the ground). MILLER *et al.* [1964] and EVANS and DELA HUNTA [1971], writing specifically of the dog, ascribe these alternative actions to the caudal parts of the semimembranosus and the biceps femoris. ALEXANDER [1974], in a discussion of the mechanics of jumping in the dog, minimizes the influence of the hamstring muscles at the stifle. He ignores any extensor action but ascribes a flexor function to the caudal parts. The interpretation concerning the function of the caudal hamstrings given here follows from the analysis shown in figure 3: AB indicates the line between origin and insertion of the caudal hamstrings and is the vectorial representation of the muscular force. Its horizontal component is F_h. If extension of the stifle may be produced by the moment of F_h about S, there must be present in point P a force in the opposite sense, with a moment about S of at least equal magnitude to oppose the movement of the limb segment SP in the sense indicated by the arrow. Since the force W (friction) acting at point P was shown by BARCLAY [1953] and HUTTON *et al.*

[1969] to have the same sense as F_h it follows that the caudal hamstrings cannot extend the stifle in these circumstances. The possibility that in other circumstances they act as conventionally described is not excluded.

The periods of activity in the extrinsic limb musculature agree with the predictions of BARCLEY [1953]. This author found differences between the horizontal forces actually exerted by the pads and those he expected on theoretical grounds. He explained these differences by assuming activity in the cranial extrinsic limb musculature when the limb is retracted and in the caudal muscles when the limb is protracted, as proved to be the case.

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References

ADRIAN, M.J.; ROY, W.E., and KARPOVICH, P.V.: Normal gait of the dog: an electrogoniometric study. Am. J. vet. Res. *27:* 90–95 (1966).

ALEXANDER, R.MCN.: The mechanics of jumping by a dog (Canis familiaris). J. Zool., Lond. *173:* 549–573 (1974).

BARCLAY, O.R.: Some aspects of the mechanics of mammalian locomotion. J. exp. Biol. *30:* 116–120 (1953).

BRADLEY, O.C. and GRAHAME, T.: Topographical anatomy of the dog; 5th ed. (Oliver & Boyd, Edinburgh 1948).

EVANS, H.E. and DELAHUNTA, A.: Miller's guide to the dissection of the dog (Saunders, Philadelphia 1971).

ENGBERG, J. and LUNDBERG, A.: An electromyographic analysis of muscular activity in the hindlimb of the cat during unrestrained locomotion. Acta physiol. scand. *75:* 614–630 (1969).

GRAU, H.: Das Muskelsystem. Der aktive Bewegungsapparat; in ELLENBERGER und BAUM Handb. d. vergl. Anat. d. Haustiere; 18. Aufl. (Springer, Berlin 1943).

GRILLNER, S.: The role of muscle stifness in meeting the changing postural and locomotor requirements for the force development by the ankle extensors. Acta physiol. scand. *86:* 92–108 (1972).

HILDEBRAND, M.: Symmetrical gaits of dogs in relation to body build. J. Morph. *124:* 353–360 (1968).

HUTTON, W.C.; FREEMAN, M.A.R., and SWANSON, S.A.V.: The forces exerted by the pads of the walking dog. J. small Anim. Pract. *10:* 71–77 (1969).

MILLER, M.E.; CHRISTENSEN, G.C., and EVANS, H.E.: Anatomy of the dog. (Saunders, Philadelphia 1964).

NICKEL, R.; SCHUMMER, A. und SEIFERLE, E.: Lehrbuch der Anatomie der Haustiere; 3. Aufl. vol. 1 (Parey, Berlin 1968).

NOMURA, S.; SAWAZAKI. H., and IBARAKI, T.: Co-operated muscular action in postural adjustment and motion in dog, from the view point of electromyographic kinesiology and joint mechanics. IV. About muscular activity in walk and trot. Jap. J. zoot. Sci. *37:* 221–229 (1966).

SISSON, S. and GROSSMAN, J.D.: The anatomy of the domestic animals; 4th ed. (Saunders, Philadelphia 1955).

TOKURIKI, M.: Electromyographic and joint-mechanical studies in quadrupedal locomotion. I. Walk. Jap. J. vet. Sci. *5:* 443–446 (1973).

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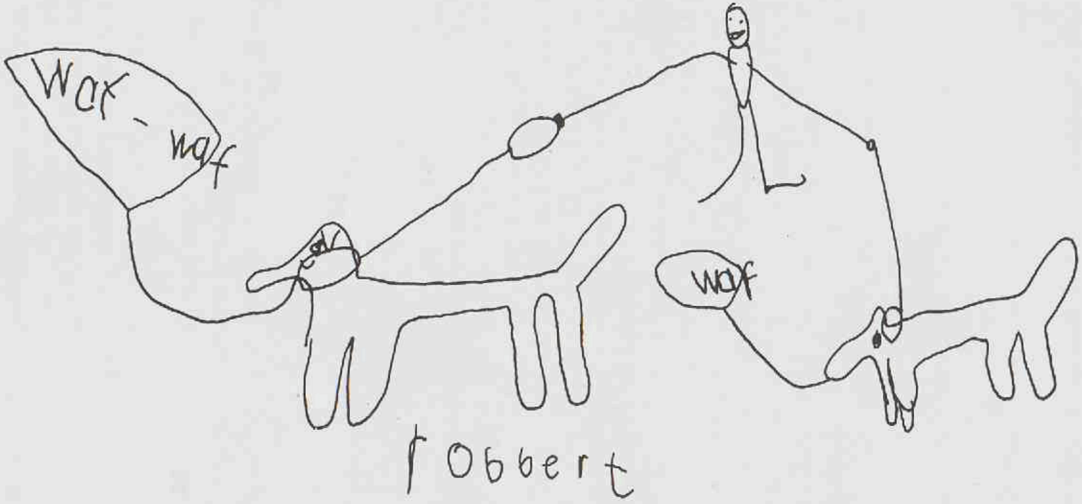
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Anat. Embryol. 151, 171–181 (1977)

Anatomy
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Biokinetical Analysis of Hind Limb Movements of the Dog

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Summary: This study of movements of the hind limb of the dog was performed with the aid of cinephotography and electromyography. The weights of the limb segments and their centers of gravity were determined. From these data the forces operating at the centers of the limb segments during a cycle of a stride have been calculated and their influence on the joints have been analysed.

From this study is concluded: 1) muscular activity is present when the effect of external forces must be overcome and subsides when these external forces act "positively" in the direction of the progression; 2) gravity and ground-reaction play an important role in the propulsion of the body, especially when there is no activity in the important retractors of the limb at the end of the support phase; 3) moments about the stifle and tarsal joints are opposite at the end of support phase and swing phase; 4) activity of the flexor digitorum superficialis (and also of the gastrocnemius muscles) during the support phase and of the peroneus longus muscle during the swing phase contribute to the coordination of the movements and to the stabilization of these joints.

Key words: Biomechanics – Hind limb – Dog – Muscles

Introduction

Animal locomotion involves a close functional interaction between external and internal forces. External forces comprise gravitation, ground reaction and inertia. The effect of air resistance may be neglected since the speed at which animals move is only moderate.

The skeletal muscles provide the most important source of internal force. During progression the muscles produce a series of coordinated movements of the body and appendages either to counteract or to strengthen the effect of external forces.

Many studies have been made of mammalian locomotion. The anatomical and mechanical aspects of locomotion were postulated by Gray (1944). Then cinephotography (Hildebrand, 1960, 1968; Gambaryan, 1974), electrogoniometry (Adrian *et al.*, 1966), force platforms (Manter, 1938; Barclay, 1953; Kimura, 1972; Alexander 1974), and electromyography (Nomura, 1966; Engberg *et al.*, 1969; Gambaryan, 1974; Tokuriki, 1974 and 1975; Wentink, 1976) have been employed individually or in combination to analyze locomotion.

However, little information is available on the interplay of internal and external forces during quadrupedal locomotion. Only Barclay (1946, 1953) points to differences between recorded and calculated external forces. He predicted activity in the extrinsic retractors of the limb during protracted limb position and in the extrinsic protractors during retracted limb position. Both statements were later proved to be correct (Wentink, 1976).

The purpose of the present study is to investigate the relationship between external and muscular forces operating at the hind limb of the dog.

Material and Methods

Six purebred greyhounds and one mongrel greyhound were trained to walk on an encaged treadmill and filmed from the right lateral side with an exposure rate of 64, 127 or 251 frames per second. The periods of activity of two muscles at a time were simultaneously amplified with a DISA electromyograph type 14 A 30 and displayed on a Schwarzer recorder (frequency limits 75–350 Hz). No attempt was made to quantify the response: the presence or absence of muscular activity alone was noted (Wentink, 1976).

Periods of muscular activity of the biceps femoris, rectus femoris, sartorius and semitendinosus muscles were measured in two dogs while walking normally on the ground. The muscular activity proved to be restricted to the same parts of the normal cycle of a stride as in dogs that walked on the moving belt (Figs. 5 and 6).

The surface of the moving belt was marked every 10 cm. The sciatic tuber, the coxal tuber, the major trochanter, the lateral epicondyl of the femur, the proximal and distal ends of the fibula and of the fifth metatarsal bone were marked with adhesive tape on the skin surface. A switch attached to the right metatarsal pad indicated the periods at which the foot made contact with the ground.

After termination of the experiments, four dogs (among which was the mongrel greyhound) were killed by exsanguination, and frozen in toto. The hind limbs were removed and transsected at the pivot points of stifle and tarsus following the cutting lines indicated in Fig. 1. The limb segments were then weighed and equilibrated on a sharp metal wedge parallel with and perpendicular to the long axis of the

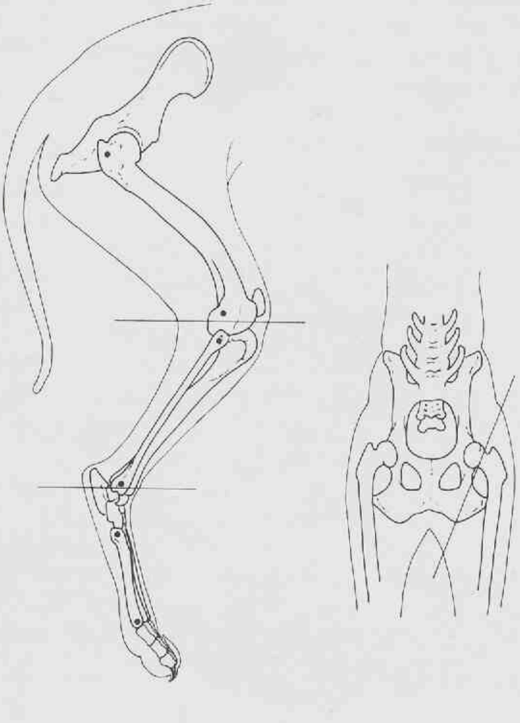

Fig. 1. Transsection of the limb in the segments of thigh, leg and foot is indicated by the solid horizontal lines; the plane of separation of the limb from the body is demonstrated in the inset. Dots indicate the positions of the adhesive tape on the skin of the animal

bones. The points of intersection of these two lines approximated the center of gravity of the limb segments in a paramedian plane.

In each walking dog, the records of three strides were selected for force calculations. Every second, fifth or tenth frame (depending on the speed of exposure rate during filming) was analyzed by an analyzing projector. The transpositions of the marked skeletal points within the cage and the speed of the moving belt enabled the reconstruction of a normal cycle of a stride in which the positions of the centers of gravity of the limb segments were plotted. One dog was selected on the basis of its kinematical performance, the cycle of which is given in Fig. 2.

From this figure the movement of the centers were expressed per unit of time in horizontal (X) and vertical (Y) directions.

The velocity of the centers of gravity in both directions can be calculated from:

$$\frac{ds}{dt} = v_t \qquad (\mathrm{m.\ sec^{-1}}).$$

The velocity v_t was supposed to occur in the middle of the selected time intervals.
The acceleration of the centers of gravity follows from:

$$\frac{dv}{dt} = a_t \qquad (\mathrm{m.\ sec^{-2}}).$$

Multiplication of the mass of the limb segments and the accelerations in the X- and the Y-directions gives the forces F_x and F_y applied at the center of gravity.

Vectorial summation of F_x and F_y gives the resultant F_r of all forces applied at the centers of gravity, a force which equalizes the sum of gravitational, reactive, and muscular forces and of inertia.

The values of F_r have been plotted in the schematical representation of the step cycle. The perpendicular distance from the momentary pivot of the joints (the point of intersection of the lines connecting the marked skeletal points on one limb segment) to the line of action of F_r is the arm (d) of the moment, hence the moment is:

$M = F_r \quad x \quad d$ (in Newtonmeters).

For the support phase, this moment was calculated by multiplying the F_r acting at the center of gravity of the limb segment proximal to the joint under consideration by its proper distance (d) to the pivot point. For the swing phase the F_r acting at the center of gravity of the limb segment distal to the joint was multiplied by its distance (d) to determine its moment (Figs. 5, 6 and 7).

The Fig. 4–7 represent the calculations of the specimen of Fig. 2. These calculations were similar to the calculations of the four dogs, in which the centers of gravity were determined.

Results and Interpretation

The principal results of this study are presented in the Figures (2–7). A complete biokinematical description of the cycle of a stride was presented in a previous paper (Wentink, 1976), hence only a short description will be presented here.

During placing, the forward foot movement is abruptly stopped resulting in friction (W) at the point of contact between foot and ground, a force acting opposite to the forward movement of the body (Fig. 3) (Barclay, 1953; Kimura, 1972). Following foot placing, the inertia of the thigh and the vertical ground reaction act together to produce an extensor moment about the stifle joint; friction (W) and gravity tend to flex this joint. In this period activity is present in the vastus muscles, which extend the stifle and also in the gastrocnemius and superficial flexor muscles (the caudal calf muscles) which flex the stifle joint. The combined action of external and muscular forces work to provide stability of the stifle joint.

Retraction of the limb occurs chiefly by the action of the powerful cranial parts of the biceps femoris and the semimembranosus muscles (the cranial hamstrings) assisted by the gluteus, adductor and gracilis muscles; the latter two muscles also adduct the limb. Shortly thereafter, activity begins in the caudal parts of the biceps femoris and of the semimembranosus muscles and in the semitendinosus (the caudal hamstrings). The antagonism between inertia, the ground reaction and the force

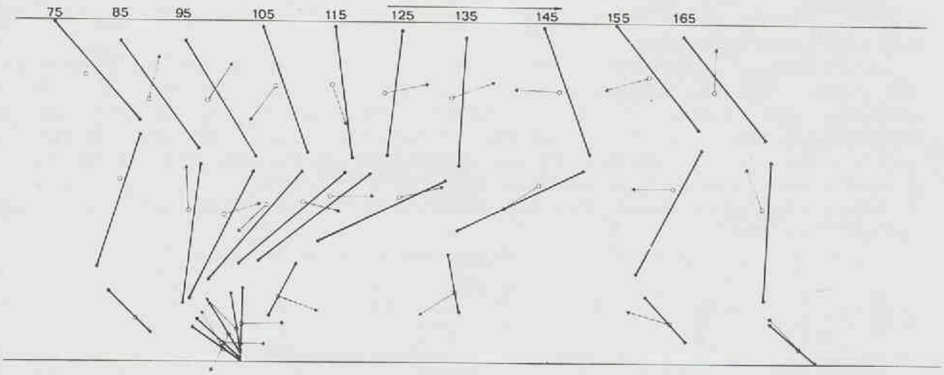

Fig. 2. Positions of the limb segments at intervals of 0.08 sec. Solid dots represent the positions of the skeletal points marked by adhesive tape on the animal. Open circles indicate the averaged positions of the centres of gravity for the segments (average of four dogs). Arrows indicate the forces (F_r) applied to the centers of gravity in each stage for this specimen. The frame numbers of the film are given for each limb position

exerted by the vastus muscles on one side, and friction, gravity, and the force exerted by the caudal calf muscles on the other (which together stabilize the stifle joint), enable the caudal hamstrings to assist in the retraction of leg and foot. Thus, during the support phase the caudal hamstrings retract the limb. Their activity ceases almost at the moment when the foot passes the vertical through the stifle, which is at the very moment at which the vertical ground reaction exerts a flexor moment about the stifle joint. A continued activity of this muscle group beyond this point in the cycle would otherwise result in a lifting of the foot from the ground by flexion of the stifle.

The activity in the other part of the hamstrings and of the vastus group stops nearly at the moment at which the ground reaction exerts a flexor moment about the stifle joint and an extensor moment about the hip joint, at the same time, activity begins in the rectus femoris muscle, which antagonizes stifle flexion and hip extension so that the foot is pressed against the ground.

During the support phase the tarsal joint is held in extension, by the combined action of the gastrocnemius and by that of the superficial flexor and of the hallucis longus muscles (Fig. 5). The action of the latter two muscles and the interosseus muscle presses the toes against the ground and gives the body a mainly upward and forward impulse.

As soon as the activities in the vastus and gastrocnemius muscles subside, a marked increase in what were initially small moments about stifle and tarsal joints occurs.

In the first stages of the swing phase the upward and forward directed impulses on the limb segments diminish quickly under the effect of gravity and inertia. The effect of the gravity on leg and foot is opposed by the action of the caudal hamstrings which lifts both limb segments. Thus, during the swing phase this muscle group acts as a flexor of the stifle joint.

The actions of the sartorius and the tensor fasciae latae muscles in the swing phase antagonize the effect of inertia on the mass of thigh and leg. These muscles are only incidentally assisted by the rectus femoris muscle in the middle of the swing

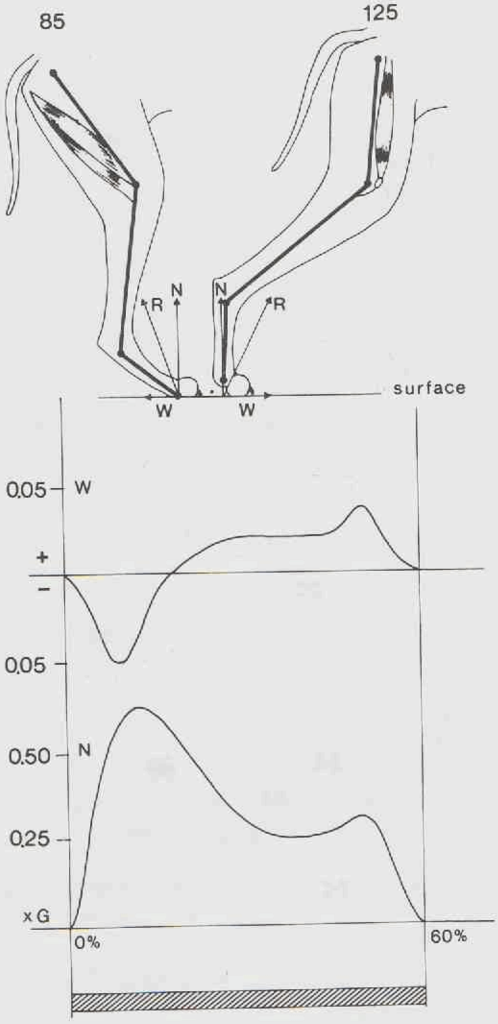

Fig. 3. Forces exerted by the ground on the foot during the support phase. Curves representing the values of these forces are redrawn after Kimura (1972). W = friction, N = normal reaction, R = the resultant of W and N. Extrinsic muscles which display activity are indicated by the lines connecting their origin from the pelvis and their insertion around the stifle; the caudal group represents the adductor, gracilis and the hamstring muscles and the cranial muscle is the rectus femoris. Positive values of W represent the horizontal ground reaction in the direction of the progression of the animal, negative values opposite to the animals movement

phase (Fig. 6). The activity of the cranial tibial and the peroneus longus muscles opposes the effect of inertia on the mass of the foot.

The activities of the peroneus longus and the extensor digitorum longus muscles in the second half of the swing phase prevent extension of the tarsal joint and flexion of the digital joints, the latter being caused by gravity and centrifugal forces.

At the end of the swing phase the forward movement of the limb is mastered as follows: firstly the forward swing of the thigh is counteracted by the action of the cranial hamstrings, the gracilis and the adductor muscles; secondly the forward swing of the leg is balanced by the action of the caudal hamstrings. The interval of time, which the breaking of leg lags behind the breaking of the thigh increases the length of the stride.

The action of the calf muscles controls the forward movement of the foot; the swing phase ends by placing the foot (replacing the foot) which initiates the frictional force, and the next cycle commences.

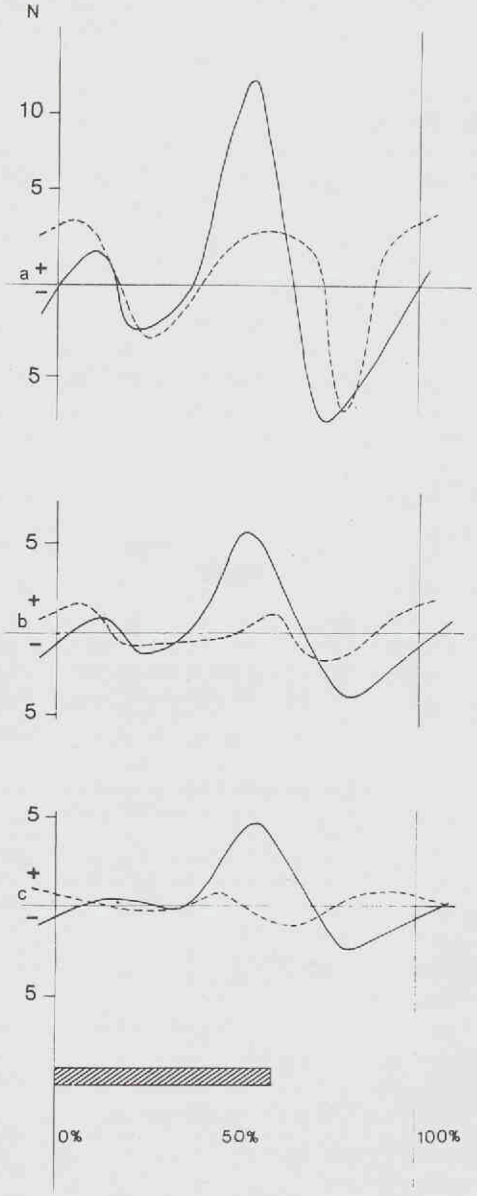

Fig. 4. Forces F_r applied to the centers of gravity of the limb segments thigh (a), leg (b), and foot (c) during a complete cycle of a stride (0–100%) in Newton (*N*). Forces in the horizontal direction (*X*) are given by the solid lines. Positive values represent forces in the directions of the progression of the animal. Negative values represent forces with a direction contrary to that of the movement of the animal. Forces in the vertical direction (*Y*) are given by the interrupted lines. Positive values represent forces with an upward direction. Negative values represent forces with a downward direction

Discussion

Apparently, there is no activity in the most powerful retractors of the limb when, at the end of the stance phase, maximum friction occurs in the direction of progression of the animal (Barclay, 1953; Kimura, 1972). In contrast with this, activity is present in the rectus femoris muscle at the end of the stance phase, an activity which antagonizes propulsion.

The timing of muscular activity recorded in the experimental but unnatural conditions did not differ from the results obtained from dogs walking on the ground (Figs. 5 and 6).

Barclay (1946 and 1953) observed differences between the measured and the calculated magnitude of the horizontal component of the ground reaction (friction). The calculated magnitude of friction when the body weight was partially supported by the limb in its oblique, retracted position was greater than the measured value. The recorded activity in the rectus femoris muscle in the present study is in accordance with this observation, since there would be activity in the protractors of the limb when it is in a retracted position. This activity makes smooth flowing the otherwise jerky propulsion of the body.

The propulsive effect on the body is ultimately brought about by gravity which, at the end of the support phase, provokes a ground reaction, the horizontal component of which acts in the direction of the movement of the body. Therefore, it is the ground reaction (normal and frictional) which is responsible for the propulsion of the body during slow progression (Fig. 3). This supposition is in accordance with Barclay's views (1946, 1953).

The same principles are valid for the progression of the cat in which approximately the same sequence in the periods of muscular activity of the hind limb muscles has been recorded (Engberg *et al.*, 1969; Gambaryan, 1974). The conclusion seems justified, that this principle may be valid for slow quadrupedal locomotion in general.

During the beginning of the support phase, the animal avails itself of muscle activity to counteract the effect of the external forces; in fact, the external forces oppose progression at this period. At the end of this phase the external forces contribute to progression so that the animal profits from these forces and makes a minimum use of its muscles.

During the swing phase, the combined effects of gravity and inertia must be overcome. As soon as the inertia initially operating opposite to the sense of movement has been overcome (*i.e.* when the limb moves in the direction of progression), the activity in the protractors, except the iliopsoas muscle (Tokuriki, 1974) ceases. Then the profitable effect of inertia must be mastered by the activity of the retractors near the end of the swing phase before the foot is replaced. According to Hildebrand (1960), in quadrupedal locomotion a large amount of energy is used to accelerate and to decelerate the limbs during the swing phase.

In the support phase as well as in the swing phase, the animal avails itself of the external forces, as soon as these contribute to forward movement. The muscles are called upon during these periods only when the effect of the external forces must be overcome to make them profitable for the forward impulse of the animal.

Moments about the stifle and tarsal joints have an opposite sense during nearly the entire step cycle. At the end of the support phase there is a strong increment of the moments about these joints (Fig. 7); the stifle experiences an extensor moment and, following the cessation of the activity of the gastrocnemius muscle, the tarsal joint undergoes a flexor moment. The stabilizing influence of this muscle on both joints is a natural consequence. When the activity of the gastrocnemius muscle ceases, the superficial flexor coordinates the movements of stifle and tarsus.

At the end of the swing phase the moments about stifle and tarsal joints increase but in an opposite sense; the stifle experiences a flexor moment and the tarsus an extensor moment. The peroneus longus muscle antagonizes the opposite moments about the stifle and tarsal joints in this period of the step cycle.

Thus, the coordination between the movements of stifle and tarsus is largely

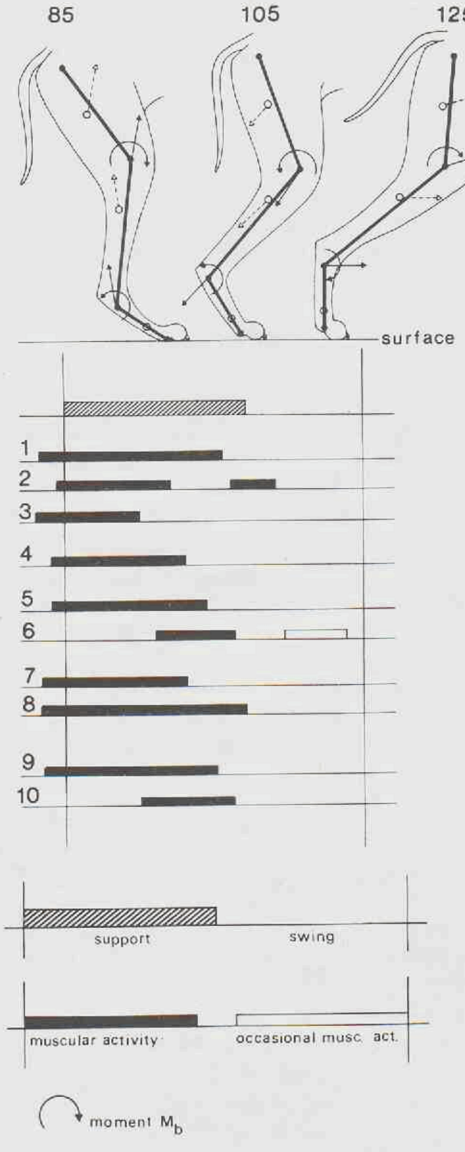

Fig. 5. Forces applied to the centers of gravity of the limb segments during the support phase are indicated by interrupted arrows. Their moments about the pivot points of the stifle and tarsal joints are represented by M_b. Muscles which display activity are listed in the lower part of the figure: numbers 1–8 represent recordings when the dogs walked on the moving belt, numbers 9 and 10 when the dogs walked on the ground. *1*, Cranial hamstrings; *2*, Caudal hamstrings; *3*, M. adductor and M. gracilis; *4*, M. gluteus medius and M. gluteus superficialis; *5*, M. vastus lateralis; *6*, M. rectus femoris; *7*, M. gastrocnemius medialis and lateralis; *8*, M. flexor superficialis, M. hallucis longus, and M. interosseus; *9*, Cranial part of M. biceps femoris; *10*, M. rectus femoris

brought about by the superficial flexor and the peroneus longus muscles. (In the horse there is a strong tendinous component in the analogous muscles, a subject which will be considered in a future report.)

On a strictly anatomical basis the muscles of the hind limb can be divided as follows: 1) origins and insertions, distinguishing between extrinsic muscles which originate from the skeleton of the trunk, and intrinsic muscles which take their origin from the limb bones (Gray, 1944). 2) The internal organization of the muscles; either parallel-fibered or pennate.

The extrinsic muscles are a functional entity; they form a loop which begins at the ilium, cranially to the hip joint, and passes to the distal part of the femur and the

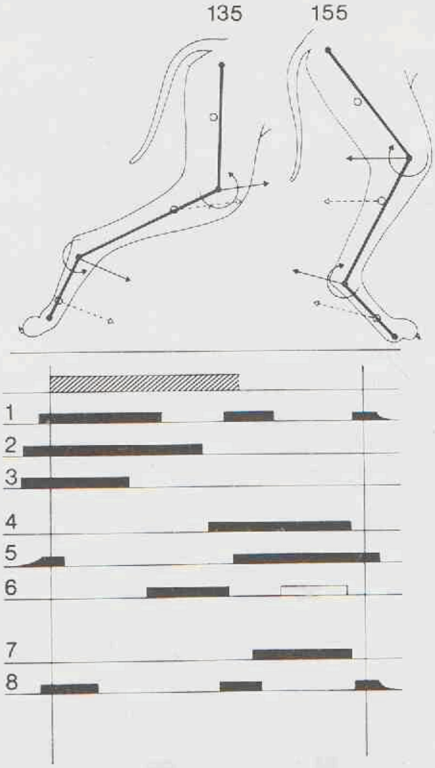

Fig. 6. Forces operant during the swing phase in the centers of gravity of the limb segments and their moments (M_b) about the pivot points of stifle and tarsal joints. Muscles which display activity are given in the lower part of the figure. Numbers 1–6 represent recordings when the dogs walked on the moving belt, numbers 7 and 8 when the dogs walked on the ground. *1*, caudal hamstrings; *2*, cranial hamstrings; *3*, M. adductor and M. gracilis; *4*, M. sartorius and M. tensor fasciae latae; *5*, M. tibialis cranialis, M. extensor digitorum longus and M. peroneus longus; *6*, M. rectus femoris; *7*, M. sartorius; *8*, M. semitendinosus

proximal end of the tibia. The caudal part of the loop extends from these bones to the sciatic tuber of the pelvis caudal to the hip joint. An exception is made for the rectus femoris muscle, which is included in the group of intrinsic muscles (see below).

The limb is in fact suspended in this loop, the cranial part of which (tensor fasciae latae, sartorius, iliopsoas muscles) displays its activity mainly in the beginning of the swing phase and counteracts the effect of inertia. The caudal part of the loop (the semitendinosus and cranial and caudal parts of the biceps femoris, and the semimembranosus muscles in which the gluteal muscles may also be included) exerts its activity at the end of the swing phase in order to stop the forward movement of the limb, first that of the thigh and then that of the leg. The latter group remains active in the first half of the support phase and counteracts the initial negative effect of the friction by retraction of the limb. A comparable interpretation has been given of the action of the extrinsic muscles in man (Groh, 1974).

One group of intrinsic muscles displays activity in the beginning of the swing phase: the intrinsic muscles on the dorsal side of the tibia (cranial tibial, extensor digitorum longus, peroneus longus muscles). Their action is also to counteract the effect of inertia in the beginning of the swing phase. The muscles of both groups are parallel-fibered; their prime action is to overcome the negative effect of the external forces and to bring about the movements of the limb.

Of the remaining intrinsic muscles some display activity during the entire support phase, others during only definite periods of the support phase. The activity of the rectus femoris muscle occurs mainly during this phase. Although this muscle is extrinsic in nature, it is included in this group. The function of this group of intrinsic

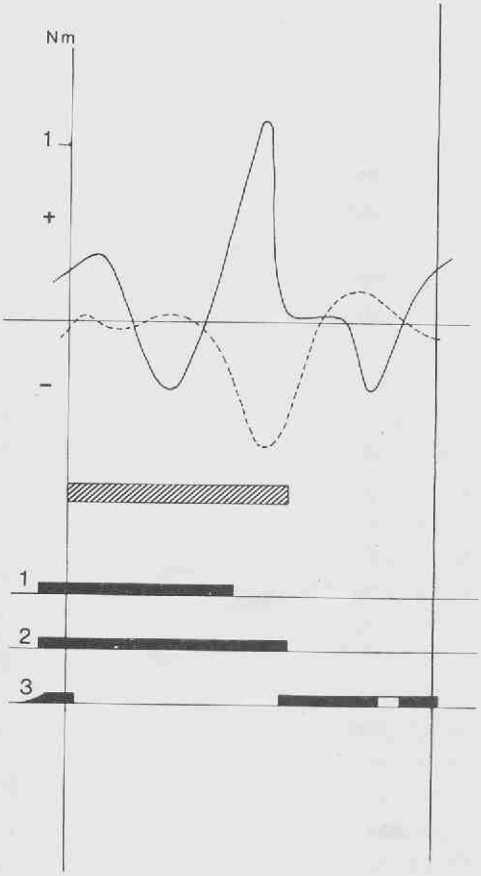

Fig. 7. Moments (of the forces applied to the centers of gravity cf the limb segments) about the stifle joint (solid line) and about the tarsal joint (interrupted line) in Newtonmeters (Nm). Activities of gastrocnemius (1), superficial flexor (2) and peroneus longus (3) muscles are given in the lower part of the figure

muscles is to transform the limb into a "strut" over which the body moves forward. These muscles are pennate.

The parallel-fibered muscles move the intrinsic joints of the limb while the pennate muscles provide the stability of the limb during the support phase.

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References

Adrian, M.J., Roy, W.E., Karpovich, P.V.: Normal gait of the dog: an electrogoniometric study. Am. J. Vet. Res. **27**, 90–95 (1966)

Alexander, R.McN.: The mechanics of jumping by a dog (Canis familiaris). J. Zool. Lond. **173**, 549–573 (1974)

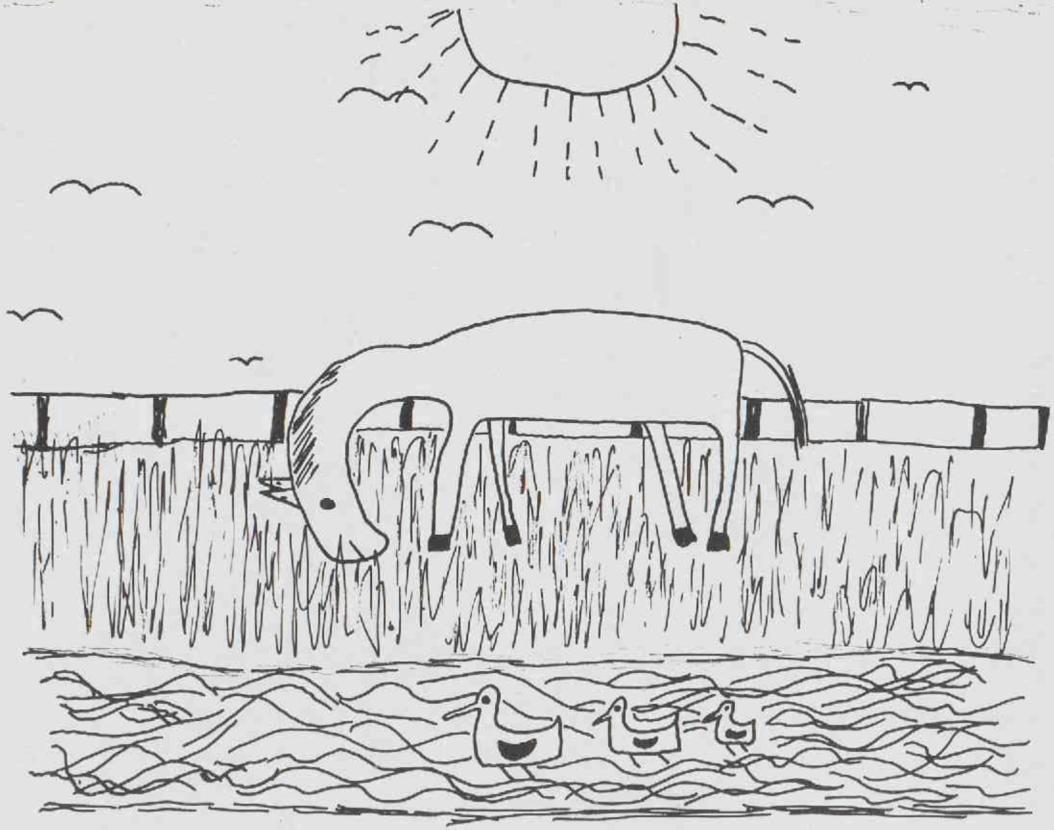
Barclay, O.R.: The mechanics of amphibian locomotion. J. Exp. Biol. **23**, 177–203 (1946)

Barclay, O.R.: Some aspects of the mechanics of mammalian locomotion. J. Exp. Biol. **30**, 116–120 (1953)

Engberg, J., Lundberg, A.: An electromyographic analysis of muscular activity in the hind limb of the cat during unrestrained locomotion. Acta physiol. Scan. **75**, 614–630 (1969)

Gambaryan, P.P.: How animals run. New York-Toronto: John Wiiey & Sons (1974)
Gray, J.: Studies in the mechanics of the tetrapod skeleton. J. Exp. Biol. **20**, 88–116 (1944)
Groh, H.: Die Kräfte bei menschlicher Körperbewegung. In: Biopolymere und Biomechanik von Bindegewebesystemen (F. Hartmann, ed.) Berlin-Heidelberg-New York: Springer Verlag, 1974
Hildebrand, M.: How animals run. Sci. Am. **5**, 148–157 (1960)
Hildebrand, M.: Symmetrical gaits of dogs in relation to body build. J. Morphol. **124**, 353–360 (1968)
Kimura, T., Endo, B.: Comparison of force of foot between quadrupedal walking of dog and bipedal walking of man. J. Fac. Sci. Uni. Tokyo **5**, 119–130 (1972)
Manter, J.T.: The dynamics of quadrupedal walking. J. Exp. Biol. **15**, 522–540 (1938)
Tokuriki, M.: Electromyographic and joint-mechanical studies in quadrupedal locomotion. I. Walk. Jap. J. Vet. Sci. **5**, 433–446 (1973)

Received December 9, 1976



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Anat. Embryol. 152, 261–272 (1978)

Anatomy
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Biokinetical Analysis of the Movements of the Pelvic Limb of the Horse and the Role of the Muscles in the Walk and the Trot

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Summary. The movements of the right hind limb of horses with normal locomotion were studied using cinephotography and electromyography. A model of the cycle of a stride in the walk and the trot was constructed and the kinetic parameters of the segments of the limb were calculated. A good correlation was obtained between the kinetics and the periods of the cycle of a stride during which individual muscles display activity. The results of this study demonstrate that:

a) The number of muscles displaying activity is greatest at placing and lifting, i.e., when a change occurs in the direction of the movement of the limb;

b) At the walk, the greatest forces operant at the centres of gravity of the limb segments in the direction of the progression are present in the beginning and the end of the support phase. The first top in the acceleration curve is produced by activity in the retractors of the limb (hamstrings, gluteus medius muscles). At the end of the support phase, when activity in the retractors of the limb no longer exists, the dynamic effect of the moment of the weight about the point of support of the stabilized inclined limb, as well as the elastic resilience of the muscular tissue are responsible for the push-off. At the trot, the greatest forces in the direction of progression are exerted in the middle of the support phase and are largely due to muscular action;

c) In the second part of the support phase in the walk, the stifle flexes and the hock extends, which results in stretching the tendinous peroneus tertius and subsequently in flexion of the hock as soon as the hoof starts rolling over;

d) The gastrocnemius and cranial tibial muscles in the reciprocal tendinous apparatus centre the line of action of the resultant load on the tibia during the locomotion and reduce the strain due to bending;

e) At the end of the support phase, the action of the rectus femoris muscle is replaced by that of the vastus lateralis, which prevents hooking of the patella on the medial ridge of the femoral trochlea by rotating it laterally around a longitudinal axis.

Key words: Biomechanics – Hind limb – Horse – Locomotion – Muscles

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I. Introduction

Many investigators have studied the locomotion of horses, using cinephotography (Hildebrand, 1960, 1965; Fredricson and Drevemo, 1972; Rooney, 1969, 1975), electrogoniometry (Taylor et al., 1966)), thermography (Dalin et al., 1973), force plates (Björk, 1958; Pratt and O'Connor, 1976), or a theoretical approach based upon anatomical and physical data (Badoux, 1973; Bradley and Grahame, 1946; Grau, 1943; Gray, 1944, 1956; Seiferle, 1968; Sisson, 1975).

The results of these studies are either restricted to the statical situation or to tne kinematics of the limbs. Whenever muscular functions are described, any experimental verification concerning the actions of the muscles during natural progression is lacking, hence the conclusions about the function of the muscles are based on 'common sense' deductions from the loci of origin and insertion of the muscles or on direct visual observation of moving horses.

In this context, the role of the crural reciprocal apparatus, consisting of the superficial flexor and peroneus tertius muscles, has been explained within the function of the stay apparatus (Badoux, 1970; Bradley and Grahame, 1946; Grau, 1943; Seiferle, 1968; Sisson, 1975).

In veterinary anatomical text books, only scanty information is found about the role of these muscles during progression.

The purposes of the present report are: (a) to give information on the periods of the step cycle during which some muscles of the hind limb of the horse display activity; (b) to describe the interplay of muscular and external forces (inertia, gravity, ground reaction); and (c) to give an explanation of the role of the muscles during progression. In this study cinephotography and electromyography were used.

Walk is defined as the regular, slow and stable mode of progression, during which two or three feet are alternately in contact with the ground; each foot is lifted only after replacement of its contra-lateral fellow. The support phase is about 60% of a complete step cycle.

Trot is defined as a rather speedy gait, during whioh the limbs are moved and placed in a regular diagonal pattern; during the suspension phase no feet are in contact with the ground. The support phase is about 40% of a complete step cycle.

II. Materials and Methods

Eight ponies and horses with normal locomotion were used for the experiments. The characteristics of the individual animals are given in Table 1.

The animals were filmed (exposure rate: 110 to 125 frames per second) from the right lateral side in the walk and the trot, while their reins were kept loose. The skin over the sciatic tuber, coxal tuber, major trochanter and lateral epicondyle of the femur, the lateral condyle and lateral malleolus of the tibia, and the lateral proximal and distal ends of the metatarsus was marked with pieces of adhesive tape measuring one square centimeter. The animals were also filmed while standing square. The outlines of the femur, tibia and metatarsus were reconstructed and then traced onto every eighth frame of the film. Since the skin over the coxal and sciatic tuber is only slightly movable, these skeletal landmarks were redrawn directly from the film frames. The lines connecting the landmarks on the pelvis, femur, tibia and metatarus, respectively give information on the geometrical changes occurring at the joints during progression. The angles at the intersection of these lines were measured over the flexor aspect of the joints, and by this procedure normal cycles of a stride in the walk and the trot were reconstructed (Fig. 2).

Five animals were trained to walk and trot on a moving belt for electromyographic studies. Two platinum wire electrodes from which the insulation of the terminal 1–2 mm had been removed were inserted into the muscle bellies of the right hind limb (Wentink, 1976).

Table 1. Characteristics of the individual horses

Horse	Breed	Sex	Age	Body weight (kg)	Height at the withers (m)
I	Gelder	male	9 months	274	1.46
II	Gelder	male	8 months	263	1.41
III	Welsh	male castrated	3 years	246	1.30
IV	Welsh	male castrated	3 years	332	1.45
V	Fjord	female	7 years	520	1.54
VI	Welsh	male castrated	6 years	362	1.44
VII	Fjord	female	6 years	490	1.51
VIII	Welsh	male castrated	5 years	288	1.30

The periods of activity of three muscles (always including the tensor fasciae latae) were simultaneously assessed from the loudspeaker and monitor of a DISA Electromyograph type 14 A 30 (frequency limits: 75–1000 Hz) and registered on a magnetic tape recorder (Bell & Howell, type VR 3200). No attempt was made to quantify the response: only the presence or absence of muscular activity was noted. During the experiments a switch, attached under the right hind hoof, closed a circuit when touching the ground; this contact was registered on the tape simultaneously with the EMG signals. During one session, when the horses were filmed from an oblique frontal position, closure of the circuit was arranged to illuminate a lamp in the picture field. The simultaneous registration of the circuit signals on the tape recorder and the film establishes a good correlation.

After the experiments, four horses were killed by exsanguination and fixed with a 10% formalin solution. Their hind limbs were removed and divided into thigh, shank and metatarsus (Fig. 1).

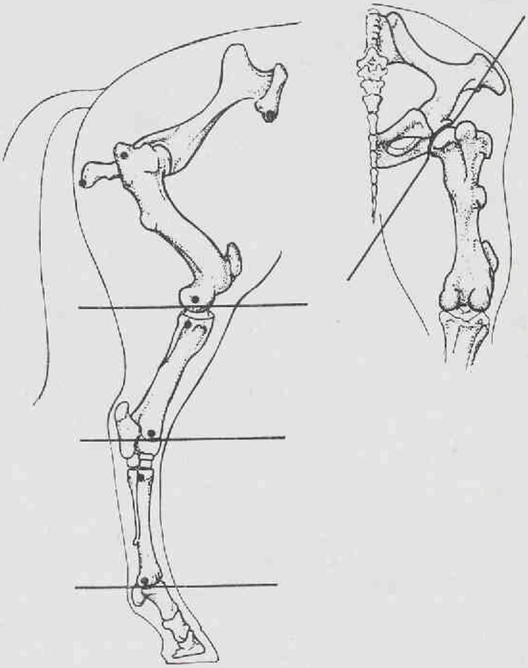

Fig. 1. Transsection of the limb in the segments thigh, shank, metatarsus and digit is indicated by solid horizontal lines. The place of separation of the limb from the body is given by the solid line in the inset. The black dots indicate the positions of the markings on the animal

The weights of the segments were determined. They were then photographed, while suspended by a rope attached to the segments in a paramedian plane at two different points in successive photographs. The point of intersection of the vertical lines in the two positions was taken as the centre of gravity of the segments, and this was plotted into the reconstructed cycle of a stride. From these figures, the displacements of the centres of gravity were derived per unit of time in horizontal (X) and vertical (Y) directions. Velocity (v), acceleration (a) and force (F) in both directions applied to the centres of gravity follow from:

$$v = \frac{ds}{dt} \tag{1}$$

$$a = \frac{dv}{dt} \tag{2}$$

$$F = m.a \tag{3}$$

The magnitude of the velocity, acceleration and force were calculated for the middle of the time intervals initially chosen.

III. Results

The results are given in Tables 2 and 3 and in Figures 2, 3, 4, 5 and 6. The gait is characterized by the gait formula of Hildebrand (1965), the first number giving the percentage of the step cycle during which the hind limb is in contact with the ground, and the second number the percentage of the step cycle by which the footfall of the right fore limb lags behind that of the right hind limb.

At the walk, the (caudal part of) the greater trochanter—and the acetabulum—follow an undulating path. The difference between the highest and lowest points of this course is about 5% of the height at the withers. The perpendicular distance from the greater trochanter to the ground is greatest in the middle of the support and swing phases, and is least at lifting and replacing the limb when both hind limbs are in contact with the ground. The perpendicular distance is somewhat greater in the support phase than in the swing phase, which means that the pelvis drops around a longitudinal axis to the unsupported side.

Table 2. The extreme positions of the individual limb segments

	Maximal protraction	Percent of the cycle	Maximal retraction	Percent of the cycle
Walk				
Thigh	+38°	95%	+6°	55%
Crus	+4°	100%	−55°	60%
Metatarsus	+40°	90%	−21°	55%
Trot				
Thigh	+35°	85%	+8°	40%
Crus	0°	100%	−55°	60%
Metatarsus	+45°	80%	−21°	40%

+: cranial in front of a perpendicular line.
−: caudal of a perpendicular line.
The angle is formed between the perpendicular line from the proximal point of the limb segment indicated and the line connecting the proximal and distal point of the segments of the limb.

Table 3. Characteristics of the gait of the individual horses

Horse	Velocity (km/hr)	Step formula	Time swing (seconds)	Time support (seconds)
Walk				
I	5.8	62/26	0.39	0.63
II	5.7	62/27	0.38	0.62
III	5.8	63/23	0.34	0.58
IV	6.2	64/24	0.36	0.63
V	5.5	66/26	0.38	0.75
VI	6.5	61/31	0.33	0.52
VII	6.5	63/24	0.36	0.61
VIII	5.1	63/23	0.32	0.54
Trot				
I	10.8	39/51	0.41	0.26
II	10.5	42/52	0.37	0.27
III	12.3	41/52	0.31	0.21
IV	16.5	40/53	0.32	0.22
V	16.6	48/51	0.33	0.30
VI	14.7	45/50	0.28	0.23
VII	16.1	40/49	0.32	0.22
VIII	12.4	40/49	0.31	0.21

The swing of the hind limb measured by the angle formed between the lines connecting the caudal part of the greater trochanter and the distal part of the metatarsus in the retracted and protracted position is 43°: the retraction caudal to the perpendicular is 19°, the protraction cranial to that line is 24°. For further details of the kinematics of the cycle of a stride see Tables 2 and 3, and Figures 2, 3 and 5.

There is flexion of the stifle in the second part of the support phase and extension of the hock in the same period, hence a considerable stretch must develop in the peroneus tertius. This results in flexion of the hock at the end of the support phase, when the hoof starts turning over. During the swing phase and the first part of the support phase the changes at stifle and hock have the same sense.

At the trot, the highest points on the undulating course of the acetabulum are reached in the beginning and end of the swing phase. The lowest points are reached in the middle of the support and swing phase: in the middle of the swing phase the perpendicular distance between the greater trochanter and the ground is somewhat greater than in the support phase, which means that the pelvis is lifted around a longitudinal axis to the unsupported side. The difference between the highest and lowest points of the path of the acetabulum is about 4.5% of the height at the withers.

The hind limb makes a swing from maximal retraction to maximal protraction of 37°: the retraction is 16° and the protraction is 21°. For further details see Tables 2 and 3, and Figures 2, 3 and 5. The changes in the stifle and hock joints in the second part of the support phase do not diverge as much in the trot as in the walk: the angle at the stifle is almost constant after the initial flexion in the first part of the support phase.

At placing in the walk and the trot, the hoof of the hind limb still has some forward velocity; the velocity of the front hoof, however, is zero at placement, as already described by Rooney (1969).

The periods in which the muscles display activity are grossly the same in the walk and the trot (Fig. 4). The parts of the biceps femoris, semitendinosus and

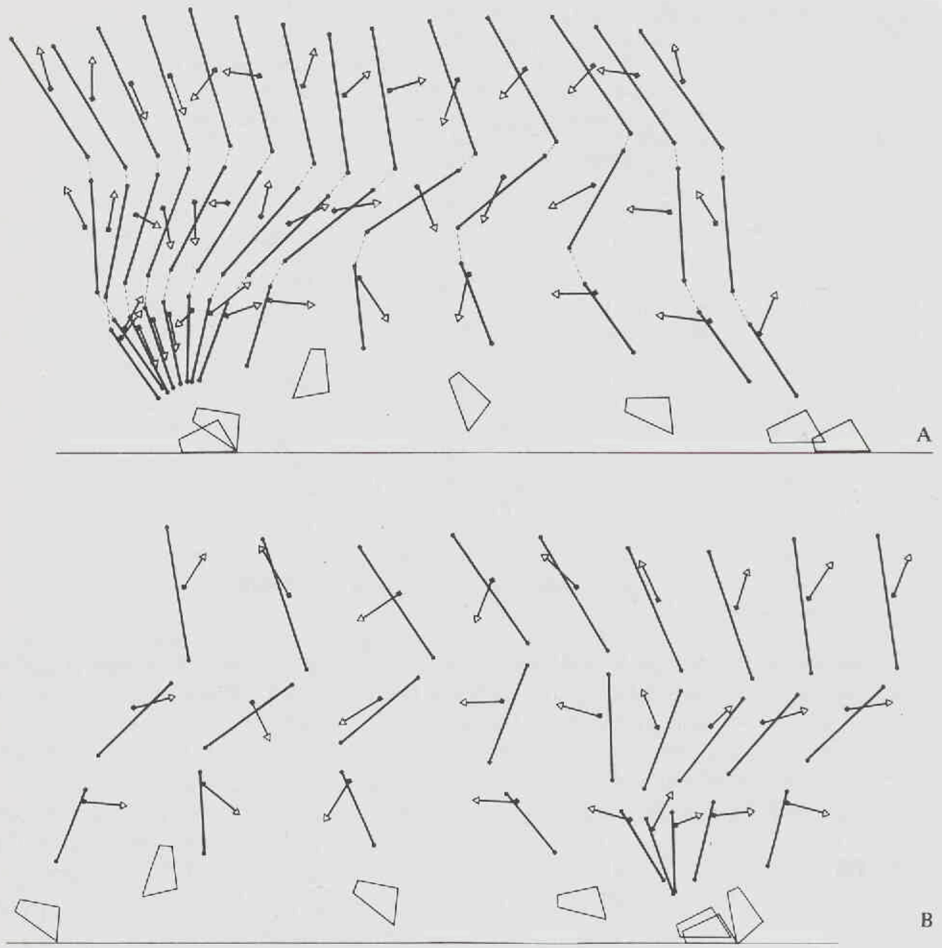

Fig. 2A and B. Position of the limb segments in the walk (**A**) and the trot (**B**) at intervals of 0.08 s. The dots give the positions of the marked skeletal points, the squares the positions of the centres of gravity. The arrowheads indicate the sense of the forces applied to the centres of gravity in each stage

semimembranosus originating from the sacral vertebrae and sacro-sciatic ligaments displayed activity in incidental strides of a single horse. In the trot, however, these muscular heads are active in every stride. Activity is present in the greatest number of muscles at placing and lifting of the leg; the number of muscles displaying activity diminishes during the support phase and also during the swing phase. Thus, muscular activity is largely concentrated in those periods, in which there is a change in the sense of the movement of the limb.

When maximal friction in the direction of the movement of the animal is present at the end of the support phase (Pratt and O'Connor, 1976) there is activity in a protractor of the limb (tensor fasciae latae muscle) which antagonizes propulsion—hence other factors must contribute to the push-off at the walk.

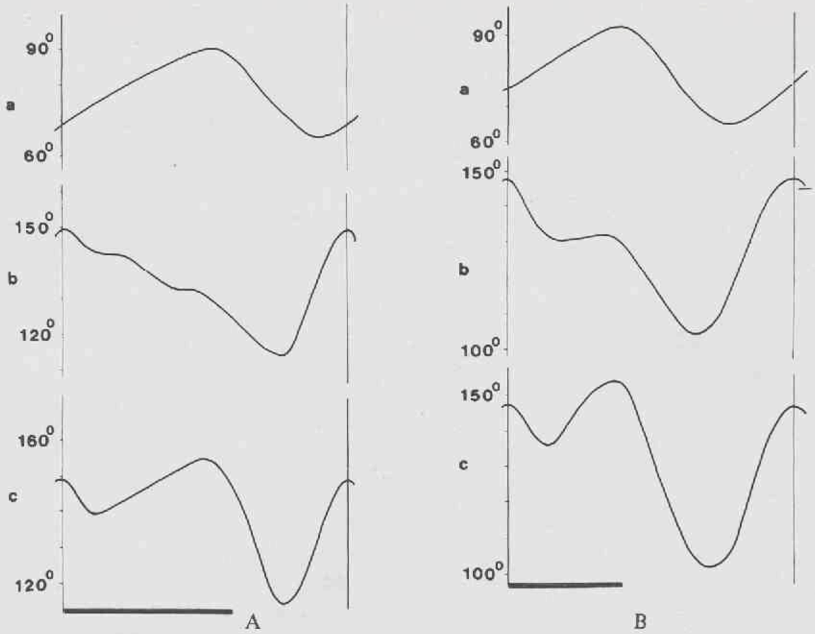

Fig. 3A and B. The angular changes of the hip (a), stifle (b) and hock (c) in the walk (**A**) and the trot (**B**). The support phase is indicated by the solid horizontal line at the bottom of the figure

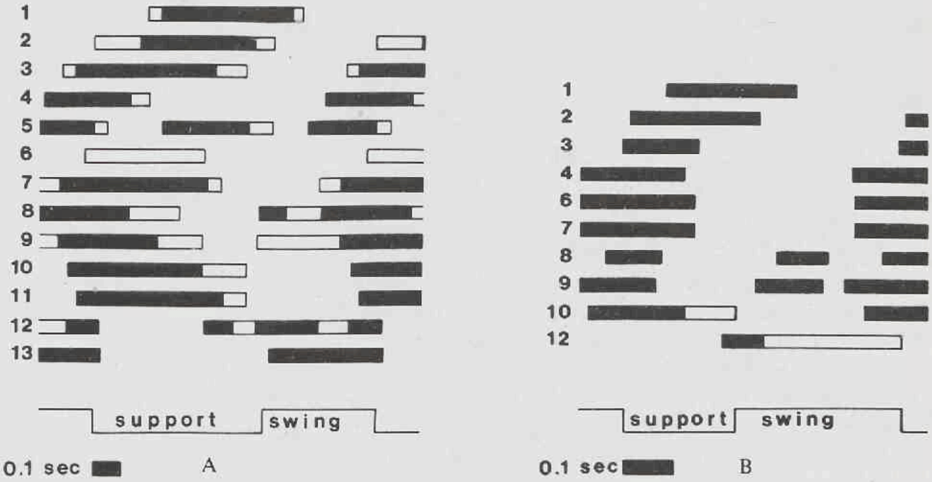

Fig. 4A and B. The average periods of activity of the muscles during the walk (**A**) is given by the black blocks, the extremes of incidental periodical activity are represented by the white extensions. For the trot (**B**) incidental periodical muscular activity is only given for the cranial tibial and gastrocnemius muscles. Further, all muscular activity has been listed by black blocks. 1. M. tensor fasciae latae; 2. M. vastus lateralis; 3. M. rectus femoris; 4. M. gluteus medius; 5. M. gluteus superficialis; 6. sacral heads of M. biceps femoris, M. semitendinosus and M. semimembranosus; 7. cranial part of M. biceps femoris; 8. M. caudal part of M. biceps femoris; 9. M. semitendinosus; 10. M. gastrocnemius; 11. M. hallucis longus; 12. M. tibialis cranialis; 13. M. extensor pedis longus

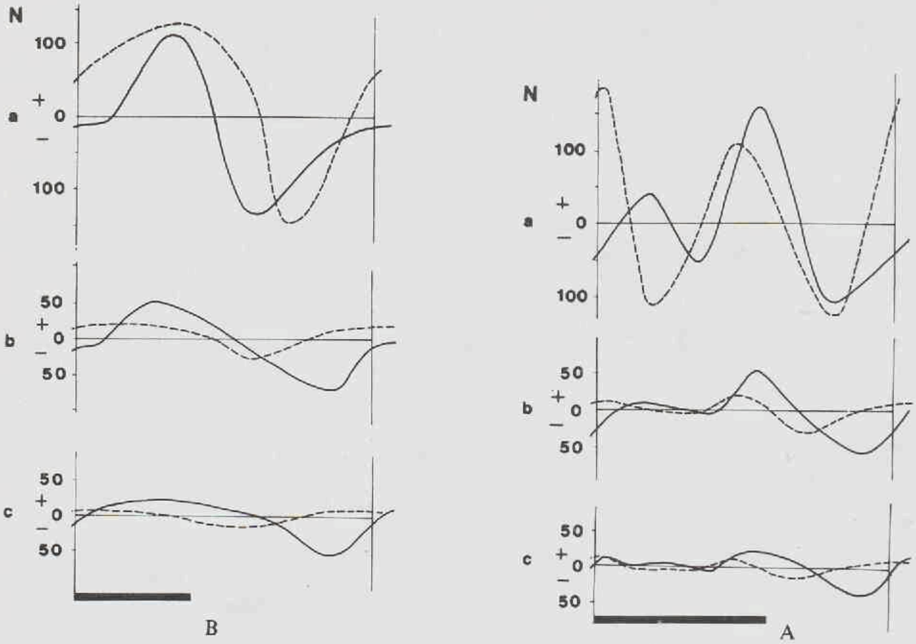

Fig. 5A and B. The forces applied to the centres of gravity of the thigh (a), shank (b), and metatarsus (c) in the walk (**A**) and the trot (**B**). Forces in the X-direction are given by solid lines, forces in the Y-direction by interrupted lines. Positive values represent forces with a forward (X) or upward (Y) direction, negative values indicate forces in a backward (X) or downward (Y) direction

At placing, the resultant of the external forces at the hoof (friction, inertia, normal reaction) and at the hip (inertia, body weight) flex stifle and hock (Fig. 6). This is counteracted by the action of the rectus femoris, gastrocnemius and deep digital flexor muscles. These muscles transform the limb into a strut over which the body moves as over a spoke. The action of the deep digital flexor antagonizes overextension of the digit.

In the first part of the support phase the friction is opposite to the movement of the body. The couple formed by the forces in the vertical direction operating at hoof and hip is of a greater magnitude than that formed by the horizontal forces, so that the former tends to turn the right limb in an anticlockwise direction (Fig. 6).

Friction and the couple in the vertical direction counteract progression and they are antagonized by the forces exerted by the retractors of the limb, i.e., the three parts of the biceps femoris, the semitendinosus, the medial gluteal muscles, and probably also the gracilis, adductor and semimembranosus muscles, which retract the stabilized limb. Extension of the stifle by the action of the caudal and middle parts of the biceps femoris and the semitendinosus muscles is not possible; the horizontal component of the force exerted by these muscles has a flexor moment about the stifle joint (cf. the situation in the dog, Wentink, 1976; Gray, 1956). Extension of the stifle by these muscles could be established by a force distal to the stifle exerting an extensor moment about this joint. However, in the first part of the support phase, the friction and the horizontal component of the muscular force are colinear; the stifle is kept extended throughout the support phase by subsequent

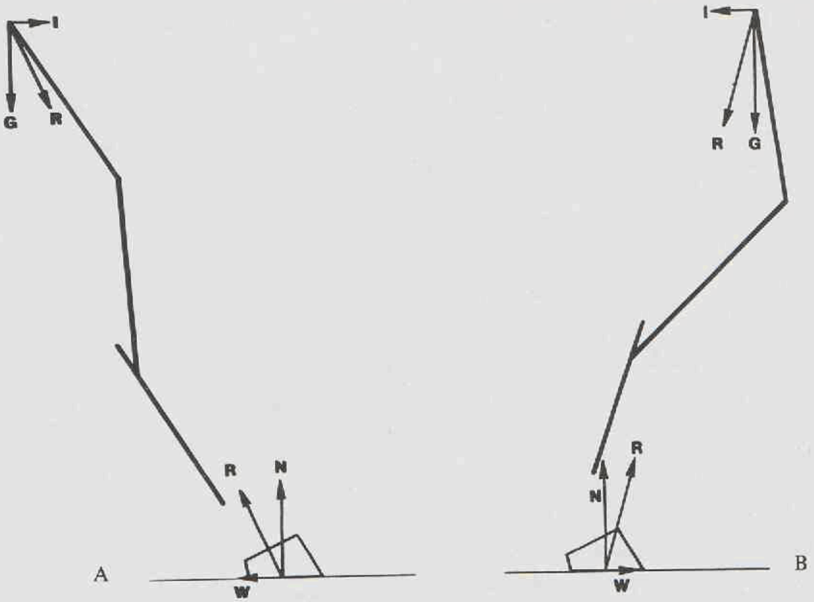

Fig. 6A and B. Position of the limb segments at placing (**A**) and lifting (**B**). G = weight; I = inertia; R = resultant; W = friction; N = normal reaction. In the force G the effect of the inertia due to the undulating course of the pelvis is included

action of the quadriceps components, the rectus femoris and then the lateral vastus. The retractors of the limb cease their activity when the acetabulum has moved over the supporting hoof. The push-off in the final part of the support phase cannot therefore be provoked by the action of the retractors of the limb.

In the last stages of the support phase, the hock extends against muscular action, since its extension is antagonized by the tendinosus peroneus tertius and the cranial tibial muscle, which now displays activity. The force of inertia, which has a sense opposite to the force operating at the centre of gravity (Fig. 5), the action of the deep digital flexor and the normal reaction extend this joint. Though the magnitude of these forces cannot be calculated exactly, extension of the hock stresses the relative importance of the effect of inertia and the normal reaction. The digital flexors contribute to the push-off by flexion of the digit, pressing the hoof against the ground.

The swing is initiated by the action of the tensor fasciae latae muscle at the end of the support phase, probably supported by the actions of the iliopsoas and sartorius muscles. As soon as the limb moves in a forward direction, the activity in the former muscles subsides. The limb is shortened by flexion of the stifle, which is brought about the action of the caudal part of the biceps, frequently assisted by the middle part of this muscle and by the action of the semitendinosus. In the swing phase the caudal and middle parts of the biceps femoris and the semitendinosus muscles act as flexors of the stifle.

The hock is flexed by the cranial tibial muscle and by the elastic energy of the peroneus tertius tendon, stored during the stretching of this elastic band in the second part of the support phase by opposite movements of stifle and hock. The digital extensor opposes the effect of inertia of the digit. Shortening of the limb brings the centre of gravity of the limb closer to the pivot point at the hip and thus reduces the moment of inertia about the hip joint.

In the second part of the swing phase activity begins in all retractors of the limb, bracing the effect of inertia which tends to continue the forward movement of the limb. Activity starts also in those muscles which transform the limb into a strut and prepare it for placing.

IV. Discussion

The changes in the joint angles found in this study are in general agreement with those described by Taylor et al. (1966), Gambaryan (1974) for the tarsal joint and by Rooney (1969, 1975) for tarsal and stifle joints (namely flexion of the stifle and extension of the hock in the second part of the support phase). The difference in the numerical values are probably due to the different breeds investigated.

Electromyography only reveals which muscles are actively involved in the specific movements. The line of action of the force developed by an individual muscle follows from its loci of origin and insertion. Although the exact magnitudes of the forces are unknown, their action can be appreciated by analysing their overall effect during a stride, and the specific contribution of various groups of muscles to the movement can be deduced.

In the walk, the highest point of the undulating course of the acetabulum is reached in the middle of the support phase (Fig. 2). It is brought into that position by the action of the retractors of the limb, pushing the body forward over the stabilized limb and opposing the couple of vertical forces, operating at hip and hoof, and the friction, both of which counteract progression (Fig. 6).

The activity of the retractors ceases shortly after the middle of the support phase. At that moment, the couple of vertical forces favours progression. The second top of the acceleration at the end of the support phase is evoked without activity in the retractors of the limb. The push-off at the walk must be largely attributed to the dynamical effect of the weight, supported by the inclined limb, which provokes a friction in the direction of the movement (Fig. 6). Further, the remaining elastic tension in the muscles is involved in the push-off. Thus, at the walk, the muscles antagonize the external forces which oppose the forward movement of the animal and they cease their activity when the external forces contribute effectively to the progression. During the first part of the support phase at the trot the dynamical effect of the body weight is flattened out; in the middle of the support phase the maximal forces in X and Y directions (Fig. 5) are exerted by the action of the gluteus medius muscle and by the hamstrings, whose sacral heads are now also actively involved. The acetabulum reaches its highest point immediately after the support phase. The push-off in the trot is largely achieved by the action of muscles. The trot requires more muscular energy than the walk, because of the faster movements of the limbs in the swing phases, but the forces operating at the centres of gravity of the limb segments are smaller than in the walk (Fig. 5).

Badoux (1970), dealing with the function of the gastrocnemius muscle in the reciprocal tendinous apparatus, demonstrated a reduction of the compressive and tensile strain in the tibia in a statical situation.

At placing, in the walk and the trot, the effect of inertia tends to continue the movement of the body. This causes bending and a corresponding tensile strain over the plantar and a compressive strain over the dorsal aspect of the tibia (Lanyon and

Smith, 1970). The tensile strain may be reduced by contraction of the gastrocnemius muscle, which is actually active in this period of the cycle of the stride, and which produces a counteracting moment of the tibia. These observations support Badoux's calculations.

At the end of the support phase there is no activity in this muscle. In the walk, the greatest force in the direction of the movement of the animal is achieved at the end of the support phase, and thus the effect of inertia which counteracts the forward force is maximal. Therefore, a tensile strain over the dorsal and a compressive strain over the plantar aspect of the tibia may be expected (Badoux, 1973). The tensile strain can be reduced by the contraction of the cranial tibial muscle, which also prevents over-extension of the hock. Activity in the cranial tibial muscle in the end of the support phase supports the 'cunian' tendon operation in spavin (Adams, 1966).

In the trot, the maximal force in the horizontal direction is exerted in the middle of the support phase. At the end of this phase, this force and inertia are both so small that no activity is required in the cranial tibial muscle. In our opinion the muscles in the reciprocal tendinous apparatus centre the line of action of the resultant load on the tibia during locomotion and consequently reduce the stress due to bending.

A large amount of energy required for quadrupedal locomotion is spent when accelerating and decelerating the limbs in the swing phase (Hildebrand, 1960). In the swing, the centre of gravity of the limb should be brought as closely as possible to the pivot point at the hip which reduces the accelerating moments. Replacing muscular tissue by tendons, which display a potential to flex and to extend the hock, brings the centre of gravity closer to the hip and therefore reduces the energy necessary during the swing phase.

The unlocking of the patellar mechanism of the stifle joint is ascribed to the biceps femoris muscle or to the lateral vastus muscle (Grau, 1943; Seiferle, 1968; Sisson, 1975). In the support phase activity is first present in the rectus femoris and subsequently in the lateral vastus. Continuing activity in the rectus throughout the support phase would interfere with the tilting of the patella over the femoral trochlea. The lateral vastus extends the stifle and turns the patella around a longitudinal axis running from the middle of its base towards its apex, and pulls it in a lateral direction. This muscle prevents hooking of the patella on the medial ridge of the femoral trochlea, assisted by the middle part of the biceps femoris muscle.

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References

Adams, O.R.: Lameness in horses. Philadelphia: Lea & Febiger (2nd ed.) 1966

Badoux, D.M.: The statical function of some crural muscles in the horse. Act. Anat. **75**, 396–407 (1970)

Badoux, D.M.: Biomechanics of the third metatarsal bone in the horse. Proc. Kon. Ned. Akad. v. Wetensch., **C78**, 257–269 (1973)

Björk, G.: Studies on the draught force of horses. Acta Agric. Scand., suppl. 4 (1958)

Bradley, O.C., Grahame, T.: The topographical anatomy of the limbs of the horse, 2nd ed. Edinburgh: Green & Son (1946)

Dalin, G., Drevemo, S., Fredricson, J., Jonsson, K.: Ergonomic aspects of locomotor asymmetry in Standard bred horses trotting through turns. Acta Vet. Scand. suppl. 44 (1973)

Fredricson, I., Drevemo, S.: A photogrammetric method of two-dimensional fast moving horses. Acta Vet. Scand. suppl. 37 (1972)

Gambaryan, P.P.: How mammals run. New York, Toronto: John Wiley & Sons 1974

Grau, H.: Das Muskelsystem. Der aktive Bewegungsapparat. In: Elleberger und Baum, Handbuch der vergleichende Anatomie der Haustiere (18e ed.) Berlin-Heidelberg-New York: Springer Verlag 1943 (reprint 1974)

Gray, J.: Studies in the mechanics of the tetrapod skeleton. J. Exp. Biol. **20**, 88–116 (1944)

Gray, J.: Muscular activity during locomotion. Brit. Med. Bull. **12**, 203–209 (1956)

Hildebrand, M.: How animals run. Sci. Amer. **5**, 148–157 (1960)

Hildebrand, M.: Symmetrical gaits of horses. Science **150**, 701–708 (1965)

Lanyon, L.E., Smith, R.N.: Bone strain in the tibia during normal quadrupedal locomotion. Acta Orthop. Scand. **41**, 238–248 (1970)

Pratt, G.W., O'Connor, J.T.: Force plate studies of equine biomechanics. Am. J. Vet. Res. **37**, 1251–1255 (1976)

Rooney, J.R.: Biomechanics of lameness in horses. Baltimore: Williams and Wilkins 1969

Rooney, J.R.: The lame horse. Cranbury, New Jersey: Barnes and Co. 1975

Seiferle, E.: Aktiver Bewegungsapparat, Muskelsystem. In: Lehrbuch der Anatomie der Haustiere, Band I (ed. R. Nickel, A. Schummer, E. Seiferle) Berlin/Hamburg: Paul Parey, dritte Auflage, 1968

Sisson, S.: Myologie (Equine). In: Sisson and Grossman's The anatomy of the domestic animals (ed. R. Getty) 5th ed. Philadelphia-London-Toronto: Saunders 1975

Taylor, B.M., Tipton, C.M., Adrian, M., Karpovich, P.V.: Action of certain joints in the legs of the horse recorded electrogoniometrically. Am. J. Vet. Res. **116**, 85–89 (1966)

Wentink, G.H.: The action of the hind limb musculature of the dog in walking. Acta Anat. **96**, 70–80 (1976)

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DYNAMICS OF THE HIND LIMB AT WALK IN HORSE AND DOG.

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SUMMARY

The dynamics of the hind limbs of the horse and the dog at the walk are compared. The kinematics were studied by electromyography in animals walking on a moving belt, and by cinephotography in horses walking on the ground and in dogs walking on a moving belt and on the ground.

This study reveals that: 1) the retraction of the hoof (foot) relative to the hip at the end of the support phase is less in the horse than in the dog; 2) the change in the sense of the movements of the hind limb segments at the end of the support phase and in the begin of the swing phase occurs earlier in the horse (55-60 % of the cycle of a stride) than in the dog (70 %); 3) there is in both species no activity in the retractor muscles of the hind limb at the end of the support phase, so that the push-off is effectuated by the dynamic effect of the load (gravity), and the elastic resilience in the retractor muscles; 4) in the horse, the cannon passes beyond the vertical and makes it necessary to bring the cranial tibial muscle into action to prevent overextension of the hock joint; in the dog, the metatarsus remains in an approximately vertical position and the superficial digital flexor muscle remains active throughout the support phase; 5) at placing, the moment of F_I (fig. 1) about the foot provokes a tensile strain on the plantar aspect of the tibia and a compressive strain on its dorsal aspect: the action of the gastrocnemius muscle centres the line of action of the load on the tibia in this phase; 6) at the end of the support phase the relatively greater moment of F_I about the hoof in the horse makes it necessary to bring the cranial tibial muscle into action to centre the line of action of the load on the tibia; 7) the tendinous interosseus and superficial digital flexor muscle of the horse store elastic energy at impact and use this energy to stretch the peroneus tertius tendon, which energy is ultimately used to flex the hock at lifting; the superficial digital flexor and the peroneus tertius tendons coordinate the movements of stifle and hock during the swing phases; all the components mentioned save energy: the horse is an animal build for great stamina; 8) in the dog the analoga of the aforementioned tendons are muscular and, in consequence, the dog is able to dig the digits and claws into the ground for a strong grip and great friction: the digitigrade dog is adapted for high jumping and for great speed.

Key words:

Biomechanics - hind limb - dog - horse - muscles - digitigrade - unguligrade

I. INTRODUCTION

During locomotion the limbs are used for support and also as levers for propulsion: the feet exert forces upon the ground and reactional forces push the body forward.

The intrinsic forces are produced by muscles which stabilize the limbs during the support phase and move the joints during the swing phase. Articular friction is negligible, but some energy is spent in overcoming the specific stiffness of the materials of the locomotory apparatus. The external forces acting upon animal during progression are gravity, normal reaction and friction between feet and ground, and inertia. Since the speed is low, air resistance may be neglected. Several authors have studied the structure and action of the limbs by various methods (Badoux, 1964, 1970, 1972; Barclay, 1953; Gambaryan, 1974; Gray, 1944, 1956; Hildebrand, 1960, 1965, 1968; Howell, 1965; Kimura et al., 1972; Manter, 1938; Pratt et al., 1976; Rooney, 1969; Tokuriki, 1973; Wentink, 1976, 1977, 1978). From their work emanates the following picture of the action of the hind limb.

During the first part of the support phase, the principal external forces to be counteracted by muscular action are gravity and ground reaction; they tend to flex the joints of the hind limb and this is opposed by the action of the extensor muscles: these muscles transform the limb into a springy strut, which is shortened by flexion of the joints towards the middle of the support phase. As a consequence, the path followed by the centre of gravity of the hind-quarters flattens, which prevents waste of energy in vertical movements. Moreover, the strut provokes a ground reaction: the sense of its horizontal component (friction) is opposite to that of progression in the first part of the support phase; this braking effect is antagonized by the retractor muscles of the limb. In the second part of the support phase, progression and friction have the same sense; in this period there is - during walk - no activity in the retractor muscles. So the push-off at walk must be partly due to the propulsive effect of the moment of the load applied proximally to the inclined strut and to stored tensile energy in the retractor muscles. The pitching effect of the load is opposed by activity of the protractor muscles which smoothes the jerky effect of the external forces.

In the last part of the support phase, the projection of the centre of gravity moves further away from the point of support at the foot, which causes a decrease of the relative magnitude of the vertical component of the ground reaction; the horizontal component gains in relative magnitude. After push-off, the limb swings forward relative to the trunk and obtains a position suitable for the following support phase. In the swing phase the limb is shortened by flexion of the joints: this brings the centre of gravity of the limb closer to the pivot point at the hip. The initial acceleration and subsequent deceleration of the limb during the swing phase absorb the greater part of the energy spent at locomotion. The closer the centre of gravity of the limb is to the hip, the less will be the energy required to swing the limb forward.

The aim of the present paper is to describe the role of the muscles of the unguligrade (horse) and the digitigrade (dog) hind limb and to interprete the differences in anatomy with respect to the locomotory abilities of the two types.

II. MATERIALS AND METHODS

Nine horses and ponies and seven Greyhounds with a normal locomotion pattern were studied; specific methods have been described in more detail in previous papers (Wentink, 1976, 1977, 1978).

The horses walked (6 $km.hr^{-1}$) on the ground and were filmed from the right side (exposure rate 125 frames per second). The dogs walked (4.5 $km.hr^{-1}$) on a moving belt (exposure rate 125-250 frames per second): two of them have also been filmed while walking on the ground (exposure rate 64 frames per second): no essential differences were observed in the movements of the hind limb segments in the two circumstances. Observations on the kinematics are restricted to movement in a sagittal plane.

The periods of muscular activity in the horses and in the dogs walking on the moving belts were registered using platinum wire electrodes. The activity was assessed from the monitor screen and loudspeaker of a DISA Electromyograph type 14 A 30, and embodied on a tape recorder (Bell and Howell type VR 3200). Electromyographic studies were also made of two dogs walking on the ground: no essential differences were observed in the periods of muscular activity in animals walking on the ground and on the moving belt.

After termination of the experiments the animals were killed and embalmed with formalin. The limbs were removed and divided into the segments thigh, shank and cannon (table I). In the horses the centres of gravity of the limb segments were determined by suspending the segments at two different points in their paramedian plane, in the dogs by twice balancing the segments on a sharp rim, first perpendicular to and then parallel with the long axes of the bones. The intersection of the two lines determines the centre of gravity with sufficient accuracy.

The resultant of all forces applied at the centre of gravity of each limb segment is F_r; it is composed of gravity (F_g), ground reaction (F_{n+w}), and muscular forces (F_m):

$$F = F_g + F_{n+w} + F_m \qquad (1)$$

The force F_r follows from

$$\vec{F}_r = m.\vec{a} \qquad (2)$$

The acceleration (a) of the centres of gravity in the horizontal (X) and vertical (Y) directions can be derived from:

$$\vec{v} = \frac{d\vec{s}}{dt} \qquad (3), \text{ and}$$

$$\vec{a} = \frac{d\vec{v}}{dt} \qquad (4)$$

The acceleration is given for the middle of each of the time intervals initially chosen.

The limb segments rotate relative to each other, whilst the centres of rotation (pivot points at the joints) move with respect to the earth. The resulting rotational moment (M_r) is the sum of the moments of the forces about the pivot points at the joints, i.e. gravity (M_g), ground reaction (M_{n+w}), inertia (M_i) and muscular moment (M_m):

$$M_r = M_g + M_{n+w} + M_i + M_m = I.\beta \qquad (5),$$

in which I is the moment of inertia and ß the angular acceleration in radians.sec^{-2}, which is derived from the changes of the joint angles per unit of time:

$$\vec{\omega} = \frac{d\theta}{dt} \qquad (6),$$

$$\vec{\beta} = \frac{d\vec{\omega}}{dt} \qquad (7)$$

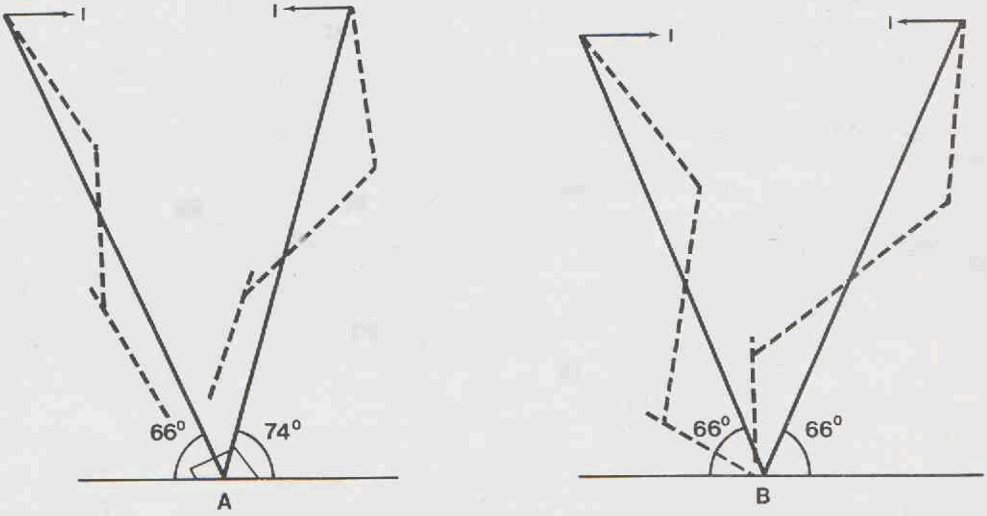


Fig. 1
The inclination (α) of the mechanical axis (solid lines; length l) of the limb shortly after placing and shortly before lifting in the horse (A) and the dog (B). I represents the sense of the horizontal inertia (in fact the force of the acetabulum on the femoral head, called in the text the force F_I).

The angular accelerations are given for the middle of the time intervals initially chosen.

III.RESULTS

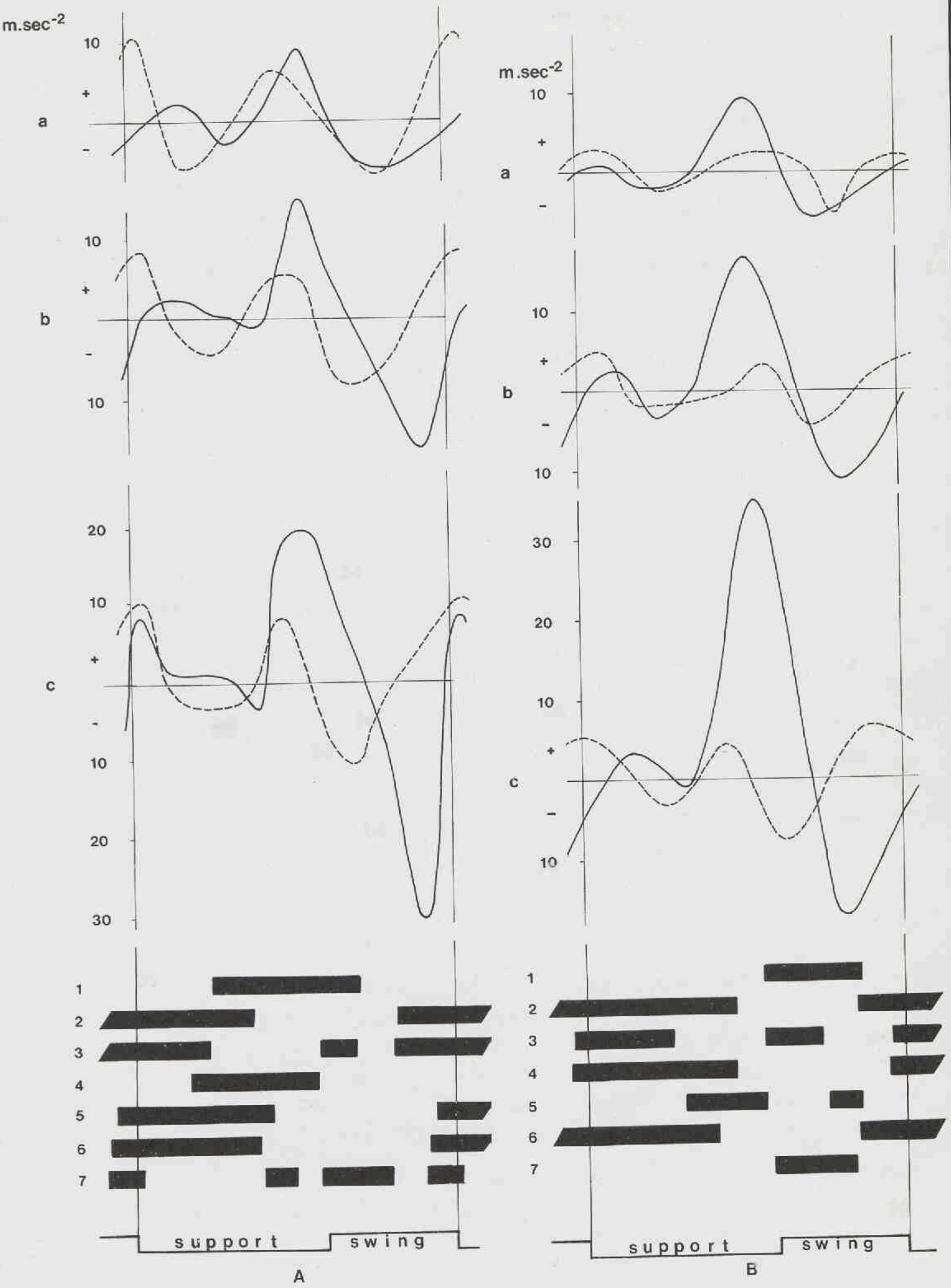
The results are given in the tables and in figures 1 to 5 inclusive. Complete descriptions of the cycles of a stride of both horse and dog have been published previously (Wentink, 1976, 1977, 1978); in the present report attention is focused on the similarities and differences in the kinematics and muscular actions between the two types.
In the horse the fetlock hyperextends at placing and the metatarsus initially moves backwards. Stretching of the interosseus and the digital flexor tendons stores elastic energy. In the dog the toes are placed flat on the ground.

In the first part of the support phase the resultant of friction and normal reaction at the hoof (foot), and the resultant of F_I (fig.1) and gravity at the hip exert flexing moments about stifle and hock joints. These joints are stabilized by the action of the quadriceps muscle (fig. 4) (rectus femoris in the horse, the vastus group in the dog), and by the action of the gastrocnemius, the superficial and deep digital flexor muscles: the limb

Fig.2
Accelerations of thigh (a), shank (b) and cannon (c) in the horse (A) and the dog (B)at walk in the horizontal (X; solid lines) and vertical (Y; broken lines) directions
Positive values represent accelerations with a forward (X) or upward (Y) sense, negative values represent accelerations with a backward (X) or downward (Y) sense.
The periods of muscular activity are given below.

1. protractor muscles (horse: M. tensor fasciae latae; dog: M. tensor fasciae latae and M. sartorius).
2. cranial hamstrings (inserting on the thigh and at the stifle) and M. gluteus medius.
3. caudal hamstrings (inserting on the shank).
4. M. vastus lateralis.
5. M. rectus femoris.
6. M. gastrocnemius.
7. M. tibialis cranialis.

The support phase is indicated by the solid line at the bottom.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is transformed into a springy strut which supports the body and acts as a lever (fig. 5).

In the first part of the support phase stifle and hock flex in both horse and dog. However, in the horse the stifle continues to flex throughout the support phase; in the dog it is kept at an almost constant angle after some initial flexion. In both types, but especially in the horse, the hock extends in the second part of the support phase. Flexion of stifle and hock in the first part of the support phase and extension of the hock in the last part flatten the path followed by the centre of gravity of the hind quarters, so that no energy is wasted in vertical movements. Propulsion of the body by the retraction of the hind limb in the first part of the support phase is opposed by the forces in the vertical direction (normal force and gravity), forming a couple which tends to turn the right hind limb anticlockwise when viewed from the right side; moreover,

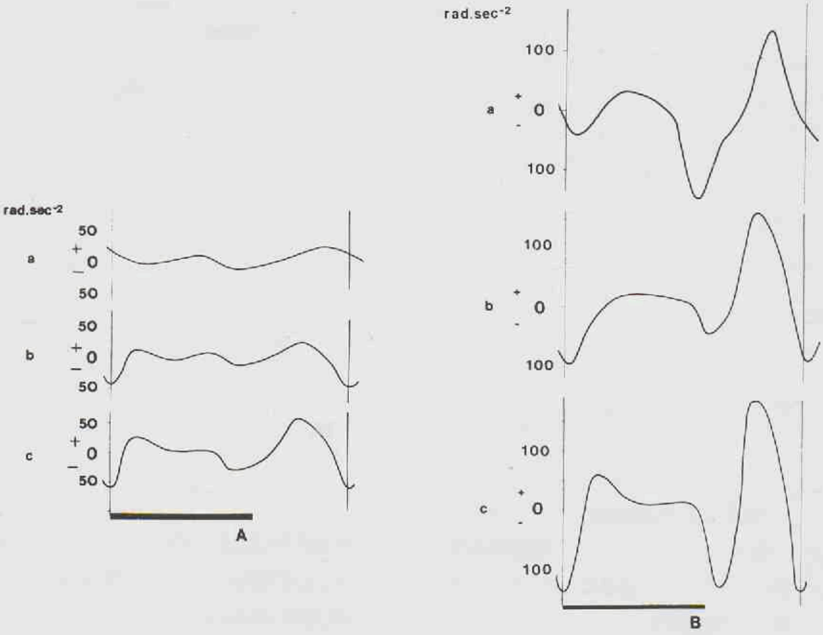


Fig. 3
Angular accelerations at the hip (a), stifle (b) and hock (c) in the horse (A) and the dog (B). Positive values represent angular accelerations with an extending effect, negative values represent angular accelerations with a flexing effect. The support phase is indicated by the solid line.

the sense of progression and friction are opposite. The retractors of the limb (medial gluteal and hamstring muscles) antagonize the retarding forces, extend the hip and produce the first top in the graph of the horizontal acceleration (fig. 3).

After the middle of the support phase the couple of vertical forces turns the right hind limb clockwise and promotes extension of the hip. Activity ceases in the retractor muscles and begins in the protractor muscles (tensor fasciae latae muscle in the horse, rectus femoris muscle in the dog). In this period, the friction in the sense of progression of the animal reaches its maximal value (Kimura et al., 1972; Pratt et al., 1976). Hence the friction in this period of the cycle must be due to the pitching effect of the load (supported by the hind limb acting as an inclined strut), which produces the second top in the graph of the horizontal acceleration. In man, a similar progressive effect of the load (gravity) is described by Elftman (1966). The antagonizing effect of the activity in the protractor muscles smoothes the otherwise jerky propulsion.

At placing, flexion of the joints by the action of the external forces is opposed by muscular activity. The moments of the muscles about the joints cause an increase in the initially negative angular accelerations (fig. 4).

At the end of the support phase - when the forces in the horizontal direction have grown in relative importance, and hoof and toes still are flat on the ground - there are evident differences in the positions of the hind limb segments of the two types. The femur never passes the vertical in the horse, but does so in the dog; the tibia of the horse remains in a more vertical position when compared with that in the dog; the cannon in the horse passes beyond the vertical, while in the dog it remains almost vertical (fig. 1).
Further, the active muscles are different: the tensor fasciae latae and cranial tibial muscles in the horse, the rectus femoris and superficial flexor muscles in the dog (fig. 2).

To achieve stability at the end of the support phase, the resultant of all forces acting upon the limb segments must pass through the pivot points at the joints (fig.5).

In the dog (fig. 5B), the resultant (R_1) of the ground reaction and the force exerted by the digital flexor muscles passes through the pivot point of the metatarsophalangeal joint (considering the digits as a single unit). The resultant (R_2) of the force (F_c) between the distal ends of the metatarsal and sesamoid bones, provoked by the action of the interosseus muscle, and R_1 passes through the pivot point at the hock. The resultant (R_3) of the reactional force (F_a) between talus and tibia, provoked by the action of the crural part of the superficial digital flexor muscle using the metatarsus as a lever, and R_2 passes through the pivot point at the stifle.

In the horse, there is a comparable situation in the distal phalangeal and fetlock joints (Badoux, 1972): the resultant (R_1) of the ground reaction (F_b) and the force of the digital flexor muscles (F_f) passes through the pivot point of the fetlock, and the resultant (R_2) of the elastic force in the interosseus tendon (F_c) and R_1 passes through the pivot point of the hock (fig. 5). The position of the crural part of the superficial digital flexor tendon relative to the position of the cannon makes it almost impossible for this muscle - provided this muscle could contract - to use the cannon as a lever; hence in the horse, R_3 is the resultant of the force (F_a) in the cranial tibial muscle and the peroneus tertius tendon, and of R_2 which passes through the pivot point at the stifle.

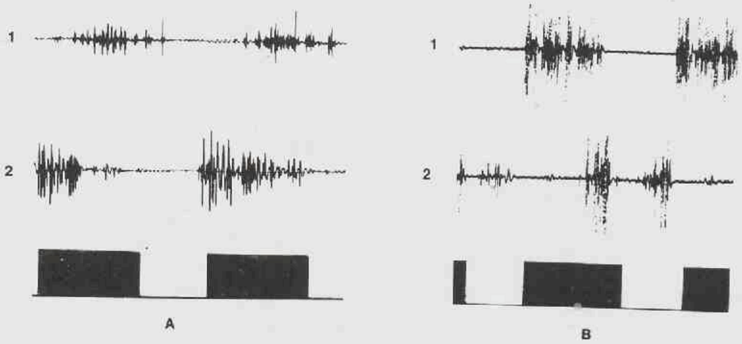


Fig. 4
Electromyograms of the quadriceps muscle of the horse (A) and the dog (B) at walk.
1. M. vastus lateralis.
2. M. rectus femoris.

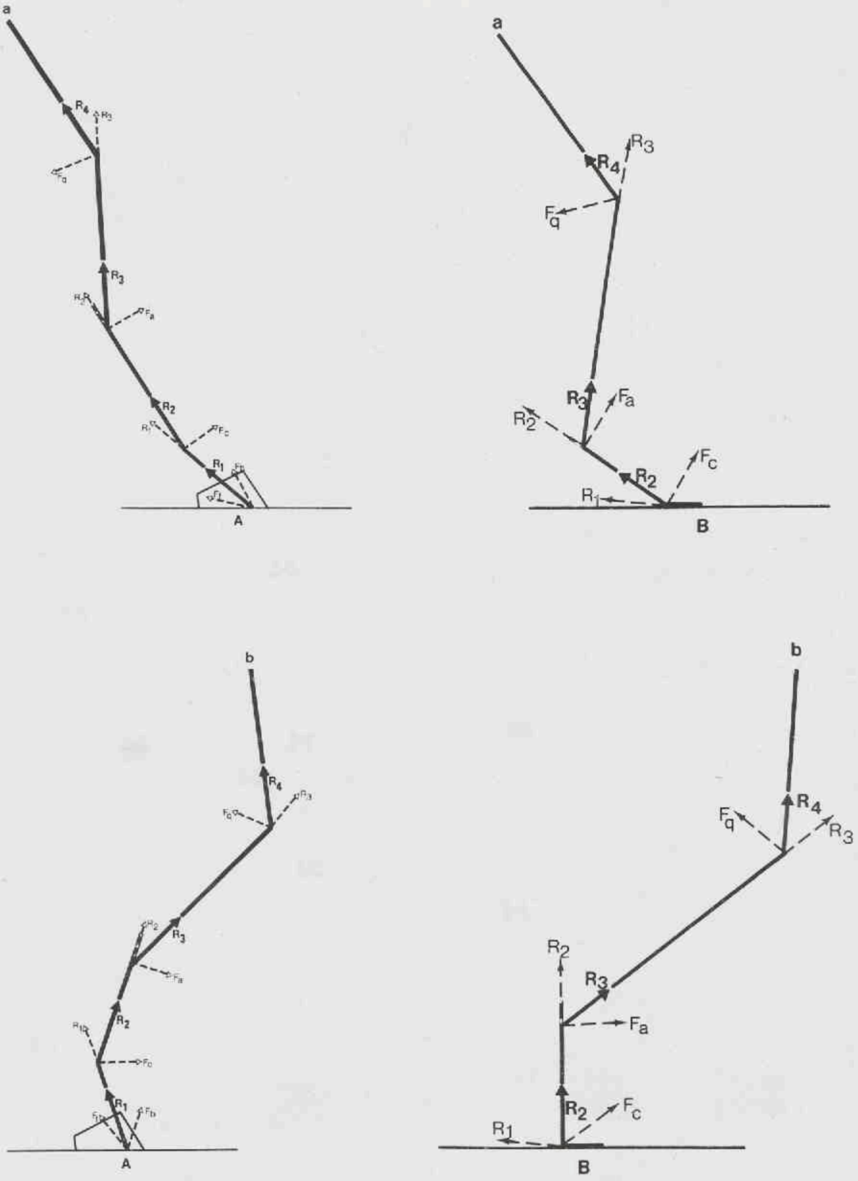


Fig. 5
Schematic representation of the sense of the forces applied at the joints of the horse (A) and the dog (B) at placing (a) and at the end of the support phase (b). (For explanation see text).

Table I

Relative lengths and weights of the hind limb segments in 4 horses and 4 Greyhounds. The relative weights are expressed in percentages of the total weight (100 %) of the hind limb. The relative lengths of the segments are expressed in percentages of the sum (100 %) of the lengths (1) between the caudal part of the greater trochanter and the lateral epicondyl of the femur, (2) the lateral tibial condyle and lateral styloid process, and (3) the proximal and distal ends of the cannon.

	Horse	Dog
weight		
thigh	71 ± 4.6 %	74 ± 0.8 %
shank	19 ± 3.4 %	18 ± 1 %
cannon	6 ± 1.3 %	
digit	4 ± 0.5 %	
cannon + digit	10 ± 1.3 %	8 ± 0.6 %
length		
thigh	41 ± 2.5 %	41 ± 1.5 %
shank	32 ± 1.4 %	42 ± 1 %
cannon	27 ± 1.7 %	17 ± 1.4 %

R_4 is the resultant of the force (F_q) by which the patella is pressed against the femoral trochlea - a force exerted by the action of the lateral vastus muscle in the horse, by the rectus femoris muscle in the dog - and of R_3, which passes through the pivot point at the hip.

At the end of the support phase, the sense of the angular accelerations becomes negative (fig. 3); at hip and hock this is promoted by muscular actions, at the stifle however, muscular activity has an opposite effect. This difference in the effect of the muscular moments about hip and hock on the one hand, and about the stifle on the other, is easily explained by the fact that the flexor aspect of hip and hock is on the cranial side of the limb whilst the flexor aspect of the stifle is on the caudal side.

In the swing phase the limb is shortened by flexion of stifle and hock. This brings the centre of gravity of the limb closer to the pivot point at the hip and

Table II

Percentage of the cycle of a walking stride at which the long axes of the limb segments are in the extreme retracted or protracted position.

	horse		dog	
	maximal retraction	maximal protraction	maximal retraction	maximal protraction
thigh	55 %	95 %	60 %	95 %
shank	60	100	75	100
cannon	55	90	70	5

thus reduces the moment of inertia about this joint. Protraction is initiated by the action of the tensor fasciae latae muscle; in the dog, and probably also in the horse, by the action of the sartorius and iliopsoas muscles. Flexion of the stifle at lifting is the result of the combined effect of inertia and muscular actions. The caudal hamstrings (which insert on the tibia) lift shank and foot, hence they counteract the action of gravity and centrifugal force. The more vertical position of the tibia at the end of the support phase in the horse increases the relative contribution of inertia to the total moment about the stifle in comparison with the situation in the dog. Activity was consistently registered only in the caudal part of the biceps femoris muscle in the horse, but in all muscles of the caudal hamstring group in the dog in almost every stride.

The hock is flexed by release of elastic strain energy stored in the peroneus tertius tendon and by the action of the cranial tibial muscle both of which oppose the effect of inertia about the hock joint. In the first part of the swing phase, the angular accelerations of the limb segments increase in spite of the activity in the flexor muscles. This phenomenon may be explained by the effect of inertia and by the moment of gravity of shank and foot about the stifle. At the end of the swing phase the length of the limb increases. At hip and hock, the effect of inertia is opposed by the action of the extensor muscles, and at the stifle by the action of the flexor muscles. In the last part of the swing phase the limb is prepared for the impact at landing by simultaneous activity in flexors and extensors of stifle and hock, and retraction begins as a result of the action of the middle gluteal and hamstring muscles. In spite of the activity in the extensor muscles, the angular accelerations at hip and hock become negative (fig. 3) due to the effect of inertia. The angular acceleration at the stifle becomes negative by the action of the caudal hamstrings which oppose the inertia of shank and foot about the stifle joint. The difference in the effect of the muscular moments about hip and hock on the one hand and about the stifle on the other may be explained by the different positions of the flexor aspects of the joints with respect to the sense of the effect of inertia.

IV. DISCUSSION

In walk, muscular activity primarily opposes the effect of external forces : it stops when the effect of the external forces contributes to progression. At the end of the support and swing phases muscles control pitch and swing: they smooth both push-off and placing of the limb. The effect of muscular actions on the sense of the angular accelerations may depend on the effect of the external forces.

The muscles of the hind limb can be divided into extrinsic muscles (which originate from the skeleton of the trunk) and intrinsic muscles (which have both origin and insertion on the skeleton of the limb). The intrinsic muscles can be subdivided in parallel-fibered (on the cranial aspect of the tibia) and pennate muscles (extensors of stifle and hock, flexors of the digits). The latter group, and the rectus femoris muscle which also has a pennate structure, display activity during part or all the support phase and stabilize the limb; the former group is active during portions of the swing phase.

The extrinsic muscles form a loop in which the limb is suspended. The caudal part of this loop displays activity at the end of the swing phase and during the first part of the support phase; it decelerates the swing and propels the body in the support phase. The cranial part of the loop is active in the first part of the swing phase and protracts the limb; the caudal hamstrings are also active in this period and - in unison with the muscles on the cranial aspect of the tibia - they bring the centre of gravity of the limb closer to the pivot point at the hip. The extrinsic muscles (parallel-fibered) and the muscles on the cranial aspect of the tibia are prime movers, while the pennate muscles are stabilizers, i.e.they transform the limb into a springy strut during the support phase.

In the first part of the support phase, the moment of the force F_I (i.e. the horizontal inertia acting at the hip) about the foot provokes in both types a tensile stress at the plantar aspect of the tibia and a compressive stress at its cranial side (fig. 1). In this period the activity in the gastrocnemius muscle may centre the line of action of the load on the tibia. This is in accordance with the calculations of Badoux (1970) for a statical situation.

The most crucial phenomenon to be explained is the difference in dynamics between horse and dog at the end of the support phase. In this period of the cycle the relative magnitude of the moment of F_I about the foot increases; this moment follows from (fig. 2):

$$M_I = F_I \cdot l \cdot \sin\alpha \qquad (7)$$

Since l and α , as well as the mass are grater in the horse than in the dog, the effect of inertia is greater in the former. In the horse, the muscles active at the end of the support phase are located on the cranial aspect of the limb and therefore are able to oppose the effect of inertia. The moment of F_I about the foot induces at this time a tensile stress on the cranial aspect of the tibia and a compressive stress on its caudal aspect: this effect is more pronounced in the horse than in the Greyhound. In the horse, the activity of the cranial tibial muscle centres the line of action of the load on the tibia in the last part of the support phase. When considering the anatomical differences between horse (unguligrade) and dog (digitigrade), the substitution of muscles by tendinous structures in the horse is remarkable: the interosseus, the superficial digital flexor, and the analogon of the peroneus longus (peroneus tertius) are all tendinous in the horse but muscular in the dog.

When comparing the locomotory abilities of horse and dog, it must be kept in mind, however, that the muscular strength in the horse is relatively less, due to the less favourable ratio between body mass and muscular cross section.

In the horse, the superficial digital flexor and interosseus tendons are stretched at placing and consequently they store elastic strain energy. After the middle of the support phase, this stored energy contributes to the lift of the fetlock and the cannon: the hock extends and the stifle flexes. The inverse angular movements of hock and stifle passively extend the peroneus tertius tendon; this also leads to storage of elastic energy, which is used to flex the hock when lifting the limb (table II),

During the swing phase, stifle and hock are initially flexed and then extended in unison: substitution of muscular tissue by tendons with the same potential function, i.e. to flex and to extend the hock, saves energy. Further, both angular acceleration and swing of the hind limb are smaller in the horse than in the dog, which also saves energy (Hildebrand, 1960): the horse is an animal built for great stamina and is a stayer (Gambaryan, 1974).

In the digitigrade animal (dog) the interosseus and superficial digital flexor muscles dig the toes and claws in the ground and this provides a strong grip. The coefficient of friction between the pads of a dog and the ground is greater than that between the hoof of a horse and the ground (Badoux, 1964), so that in digitigrade animals the forward impulse can be relatively greater than in unguligrades. Dogs may clear obstacles of two metres or more; horses are able to jump less high in comparison with the dog. The greater friction promotes a more vigorous push-off and a potentially greater speed: the fastest land going animal is the digitigrade cheetah, a well-known sprinter.

REFERENCES

Badoux, D.M. : Friction between feet and ground. Nature 202, 266-267 (1964).

Badoux, D.M. : The statical function of some crural muscles in the horse. Acta Anat. 75, 396-407 (1970).

Badoux, D.M. : Biomechanics of the autopodium of the equine hind leg. Koninkl. Nederl. Akademie van Wetensch. 75C, 224-242 (1972).

Barclay, O. : Some aspects of the mechanics of mammalian locomotion. J. Exp. Biol. 30, 116-120 (1953).

Elftman, H. : Biomechanics of muscle. J. Bone and Joint Surg. 48A, 363-377 (1966).

Gambaryan, P.P. : How mammals run. New York - Toronto: John Wiley and Sons (1974).

Gray, J. : Studies in the mechanics of the tetrapod skeleton. J. Exp. Biol. 20, 88-116 (1944).

Gray, J. : Muscular activity during locomotion. Brit. Med. Bull. 12, 203-209 (1956).

Hildebrand, M. : How animals run. Sci. Amer. 5, 148-157 (1960).

Hildebrand, M. : Symmetrical gaits of horses. Science 150, 701-708 (1965).

Hildebrand, M. : Symmetrical gaits of dogs in relation to body build. J. Morphol. 124, 353-360 (1968).

Howell, A.B. : Speed in animals. New York : Hafner (1965).

Kimura, T., Endo, B. : Comparison of force of foot between quadrupedal walking of dog and bipedal walking of man. J. Fac. Sci. Uni. Tokyo 5, 119-130 (1972).

Manter, J.T. : The dynamics of quadrupedal walking. J. Exp. Biol. 15, 522-540 (1938).

Pratt, G.W., O'Connor, T. : Force plate studies of equine biomechanics. Amer. J. Vet. Res. 37, 1251-1255 (1976).

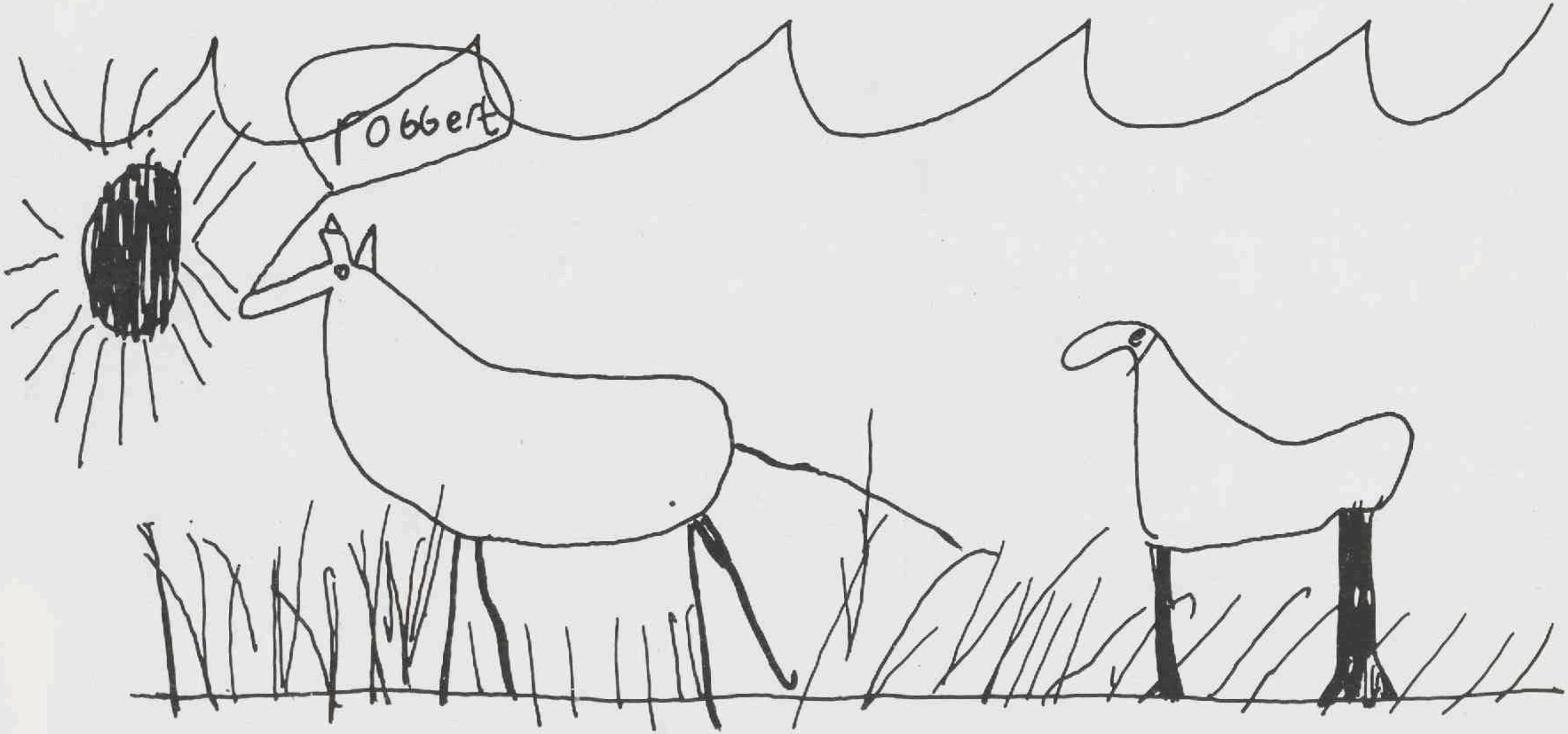
Rooney, J.R. : Biomechanics of lameness in horses. Baltimore : The Williams and Wilkins Company (1969).

Tokuriki, M. : Electromyographic and joint mechanical studies in quadrupedal locomotion. I. Walk. Jap. J. Vet. Sci. 35, 433-446 (1973).

Wentink, G.H. : The action of the hind limb musculature of the dog in walking. Acta Anat. 96, 70-80 (1976).

Wentink, G.H. : Biokinetical analysis of hind limb movements of the dog. Anat. Embryol. 151, 171-181 (1977).

Wentink, G.H. : Biokinetical analysis of the movements of the pelvic limb of the horse and the role of the muscles in walk and trot. Anat. Embryol. 152, 261-272 (1978).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AN EXPERIMENTAL STUDY ON THE ROLE OF THE RECIPROCAL TENDINOUS APPARATUS OF THE HORSE AT WALK.

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SUMMARY

The locomotor pattern of the hind limb of seven horses has been studied in intact animals and after transection of the following structures: the peroneus tertius tendon, the cranial tibial muscle, both cranial tibial muscle and peroneus tertius tendon, and the superficial digital flexor tendon. The investigation was carried out by high speed cinematography and electromyography. It is concluded that (1) the muscles and tendons over the cranial aspect of the tibia play an important role during the support phase; (2) the movements of the hind limb can be performed without the action of the cranial tibial and gastrocnemius muscles; (3) the tendons in the shank store elastic energy during the support phase; (4) the gastrocnemius and cranial tibial muscles may centre the force of the load through the long axis of the tibia.

Key words:

Biomechanics - hind limb - reciprocal tendinous apparatus - locomotion - horse.

I. INTRODUCTION

The function of the superficial digital flexor and the peroneus tertius tendons - denoted as the reciprocal tendinous apparatus - has been explained by several authors (Bradley and Grahame, 1946; Grau, 1943; Seiferle, 1968; Sisson, 1975) as a part of the mechanism that enables the horse to remain standing with a minimum of muscular effort.

Badoux (1970) calculated the effect of a force developed by the gastrocnemius muscle, counteracted by the peroneus tertius tendon. The action of this muscle centres the line of action of the load through the long axis of the tibia in a statical situation.

In a previous paper the action of the tendons of the reciprocal tendinous apparatus were described as elastic strands (Wentink, 1978a). So far as the elastic properties of these tendons are concerned, it may be noted that Alexander (1977a;1977b) calculated the elastic strain energy for tendons (2,000 - 9,000 J.kg^{-1}) and pointed to the importance of storage of elastic strain energy in tendons during locomotion. In this respect, Hildebrand's (1960) statements are of value; he pointed to the amount of energy that is spent in accelerating and decelerating the limbs during the swing phase. The synchronisation of the movements of stifle and hock during the swing phase is a consequence of the action of the reciprocal tendinous apparatus. Strubelt (1928), however, does not mention any consequences on the locomotor pattern of the hind limb after transection of either the peroneus tertius or the superficial digital flexor tendon.

Previous papers (Wentink, 1978a; 1978b) dealt with the role of the muscles of the hind limb. In this paper the locomotor pattern of the hind limb at walk is described for horses with intact and with transected tendons.

II. MATERIALS AND METHODS

The experiments were performed with seven horses and ponies, three of which were included in a previous study (Wentink, 1978a, horses I, II and III). In four horses the peroneus tertius tendon was transected about 10 cm above the hock joint; in a fifth horse the cranial tibial muscle was transected at the same level. After filming the locomotion of these operated animals, the peroneus tertius in the latter horse, and the cranial tibial muscle in one horse of the former group were also cut. In two additional horses the superficial digital flexor tendon was transected about 10 cm above the level of the calcaneus. The operations were performed under general anaesthesia.

The animals were filmed from the right lateral side after marking of the skin over the skeletal points (exposure rate 110 to 150 frames per second). The analysis of the movements is restricted to the sagittal plane. The attention was focused primarily upon the relation between the accelerations of the centres of gravity of the three segments and upon the relation between the changes of stifle and hock during a stride. In unoperated animals these relations were fairly constant although differences occurred between consecutive strides of a single horse and between various horses.

In order to exclude effects of individual variation, the kinematic patterns of the hind limb have been compared in the same animals before and after operation.

The periods of activity of the gastrocnemius and cranial tibial muscles have been assessed as previously described (Wentink, 1978a).

Information about the calculation of the accelerations of the centres of gravity and of the angular accelerations can be found in previous papers (Wentink, 1977; 1978a; 1978b). Since the calculation was based upon analysis of cinerecords, a possible source of errors is a discrepancy between the position of the markers on the skin with respect to the underlying bony structures which may lead to misinterpretations in the outline of the model.

The relative error in the position of the centre of gravity of thigh, shank and cannon were 6, 3 and 3 percent respectively, that in the angle of stifle and hock 10 and 6 percent. During a complete cycle of a stride, however, the effect of this error remains constant.

Independent of the errors mentioned above, inaccuracies in the pictorial reconstruction of the cycle from the cinematographical record may lead to errors in the calculation of the linear and angular accelerations, which were 5 and 6 percent respectively.

III.RESULTS

The results obtained in three horses are given in the figures 1 to 3 and in table I; the data of the other horses are comparable.

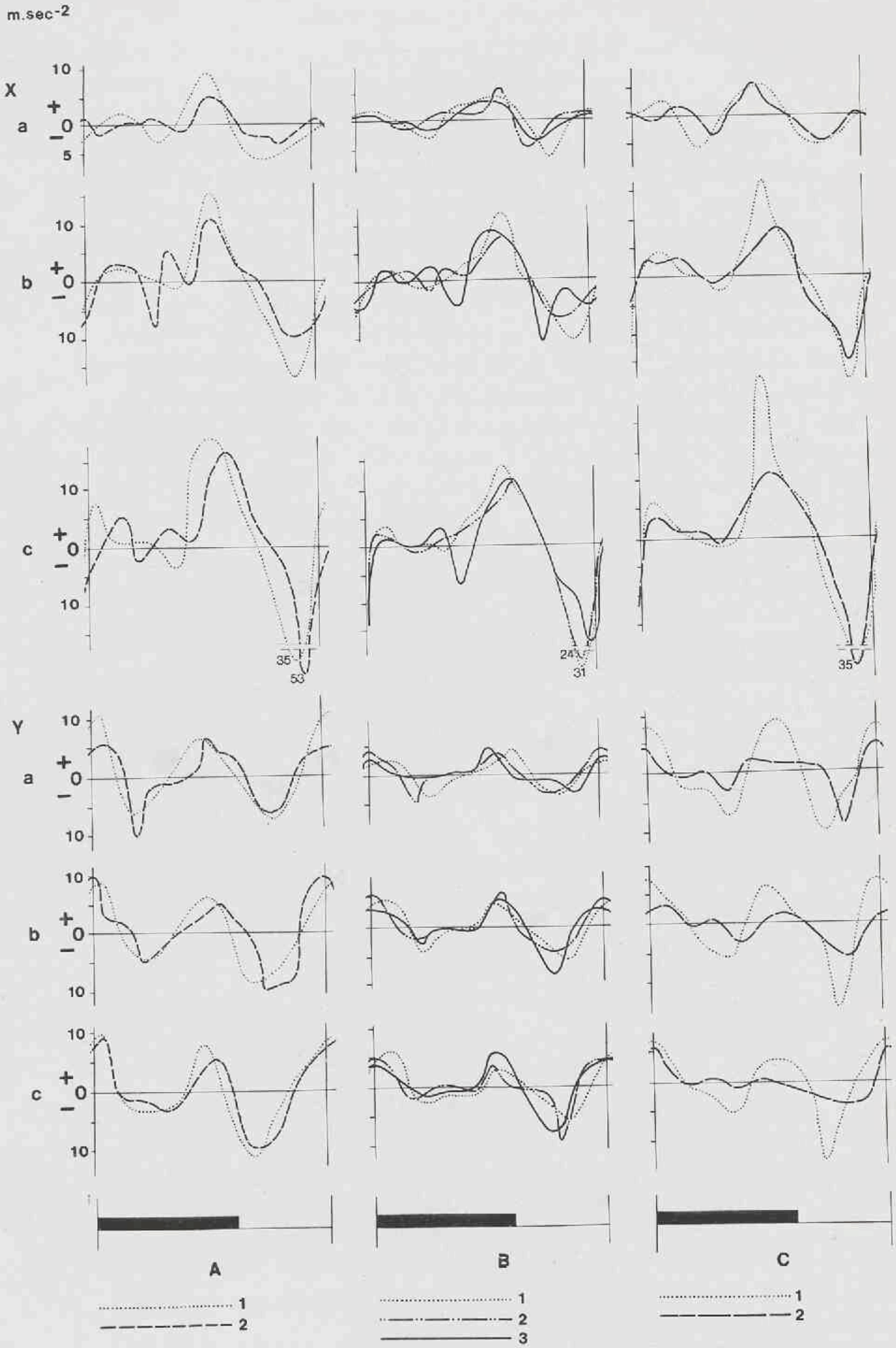
Extension of the fetlock and flexion of the hock is opposed by the superficial digital flexor and interosseus tendons; these tendons stretch during impact. The action of these tendons is complemented by the action of the deep digital flexor and the gastrocnemius muscles. The positive angular acceleration at the hock diminishes after transection of the superficial digital flexor tendon in all strides of both horses operated (fig. 2C); this demonstrates the important role of this tendon in absorbing the shock at landing. Apparently the gastrocnemius muscle alone is incapable of coping with the effect on the hock joint of the impact.

Extension of the hock in the last part of the support phase must be ascribed to the deep digital flexor, since activity in the gastrocnemius muscle is lacking in this part of the cycle, even after transection of the superficial digital flexor tendon. The superficial digital flexor and the interosseus tendons store elastic energy on impact and this is subsequently used to promote the simultaneous vertical acceleration of cannon and shank at the end of the support phase. The diminution of these accelerations after transection of the superficial digital flexor tendons stresses the role of this tendon in the upward accelerations of these segments and of the trunk (fig. 1C).

The distal pull of the superficial digital flexor tendon causes a negative angular acceleration at the stifle; the quadriceps muscle hardly opposes flexion of this joint. Transection of this tendon cancels the rotation of the femur and enables the quadriceps muscle to extend the stifle in the last part of the support phase, a phenomenon observed in all strides after operation (fig. 2C; Table I, C).

A compensatory decrease in the activity of the quadriceps muscle may be responsible for the reduction of the angular acceleration at the stifle during impact and for the decrease of the horizontal acceleration of the centre of gravity of the thigh in the first part of

Fig.1
Accelerations in the horizontal (X) and vertical (Y) directions of the centres of gravity of the thigh (a), the shank (b) and the metatarsus (c) before and after experimental surgery. The abnormal and normal situation for each individual have been compared. Each curve represents one stride selected on the cinematographical performance. Positive values represent accelerations with a forward (X) or upward (Y) direction, negative values a backward (X) or downward (Y) direction.
The solid horizontal bar indicates the support phase.
A : Before (5,8 $km.h^{-1}$; 1) and after transection of the peroneus tertius tendon (5,5 $km.h^{-1}$; 2).
B : Before (5 $km.h^{-1}$; 1), after transection of the cranial tibial muscle (4,5 $km.h^{-1}$; 2) and after transection of both cranial tibial muscle and the peroneus tertius tendon (4,2 $km.h^{-1}$; 3).
C : Before (6,9 $km.h^{-1}$; 1) and after transection of the superficial digital flexor tendon (5,1 $km.h^{-1}$; 2).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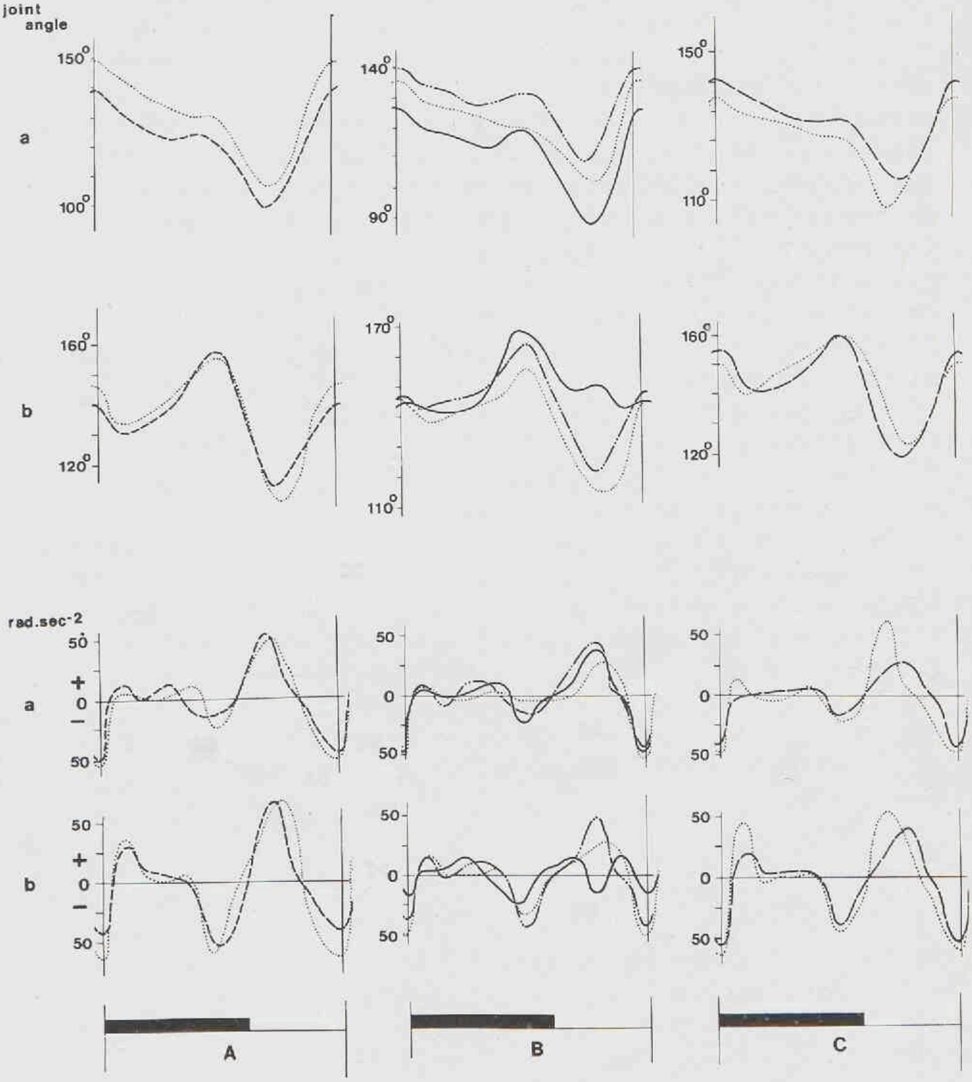
the support phase (fig. 1C); the latter phenomenon was observed in all strides after operation, but also in two strides of an unoperated horse.

The opposite angular changes at stifle and hock in the second half of the support phase stretch the peroneus tertius tendon. Transection of this tendon results in a decrease of the angular acceleration at the stifle in the first part of the support phase (fig. 2A), and in a change of the pattern of the forward acceleration of the centre of gravity of the thigh in all strides of the operated animals (fig. 1A).

This can be readily explained by the fact that now the caudal pull of the superficial digital flexor tendon is not counteracted by the peroneus tertius tendon. In the last part of the support phase the stifle is extended by the action of the quadriceps muscle.

The positive angular acceleration of the hock joint is prolonged, which causes an overextension of this joint, partly balanced by the cranial tibial muscle. Transection of this muscle alone hardly interferes with the angular changes of the hock joint; cutting the peroneus tertius tendon and the cranial tibial muscle enables the superficial flexor tendon to extend the hock maximally (table IB, fig. 1B, 2B). Extension of the hock, leads in the absence of a simultaneous forward movement of the thigh to an initial increase and subsequent decrease of the horizontal acceleration of the centres of gravity of cannon and shank (fig. 1B). Thus, transection of the cranial tibial muscle and the peroneus tertius tendon severely disturbs the pattern of the acceleration of the centres of gravity of the limb in the horizontal direction; the acceleration in

Fig.2
Changes in the angles of stifle and hock, and in the angular accelerations before and after experimental surgery. The average of three abnormal and three normal strides are compared for each animal; a denotes the stifle, b the hock joint. Positive values represent an extending, negative values a flexing angular acceleration.
The solid horizontal bar indicates the support phase.
Further legends see figure 1.


joint angle
150°
100°
a
140°
90°
150°
110°
160°
120°
b
170°
110°
160°
120°
rad.sec-2
50
+
0
−
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a
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−
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b
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50
0
50
A
B
C

the vertical direction does not deviate much from the normal situation (fig. 1B). This experiment confirms the important role of the peroneus tertius tendon and the cranial tibial muscle during the support phase.

Flexion of the stifle and hock occurs simultaneously at the end of the support phase. Transection of the cranial tibial muscle affects neither the moment of flexion of the hock (fig. 2B), nor the moment at which the cannon overtakes the shank (fig. 3B). Cutting the peroneus tertius tendon causes flexion of the hock to lag slightly behind that of the stifle (fig. 2A, table IA) and the moment at which the cannon overtakes the shank is also delayed (fig. 3A). In this situation flexion of the hock joint depends on muscular activity alone. Transection of both the cranial tibial muscle and the peroneus tertius tendon makes flexion of the hock almost impossible. The initial flexion in the first part of the swing phase is passively brought about by the weight of the cannon. The movements of the cannon are then determined by the acceleration of the shank and the increased flexion of the stifle. The shank is decelerated in the middle of the swing phase and the inertia of the cannon leads to a jerky flexion of the hock (fig. 1B, 2B, table IB). Transection of the superficial digital flexor tendon prolonges flexion of the stifle and hock in the swing phase and also reduces the downward accelerations of shank and cannon (fig. 1C; table IC).

Fig.3
Velocities of the centre of gravity of the thigh, the shank and the metatarsus in the horizontal (X) direction of a normal limb (AI) compared with those in the same limb after transection of the peroneus tertius (AII), in another normal horse (BI) compared with those of the same limb after transection of the cranial tibial muscle (BII) and after transection of both the peroneus tertius tendon and the cranial tibial muscle (BIII).
The solid bars indicate the support phase.
The extreme percentages of the cycle of a stride at which the cannon overtakes the shank are (all strides have been recalculated to a support phase of 60 %):
AI : 54-59 %; AII : 62-63 %; BI : 57-58 %; BII : 56-60 %; BIII : 61-72 %.

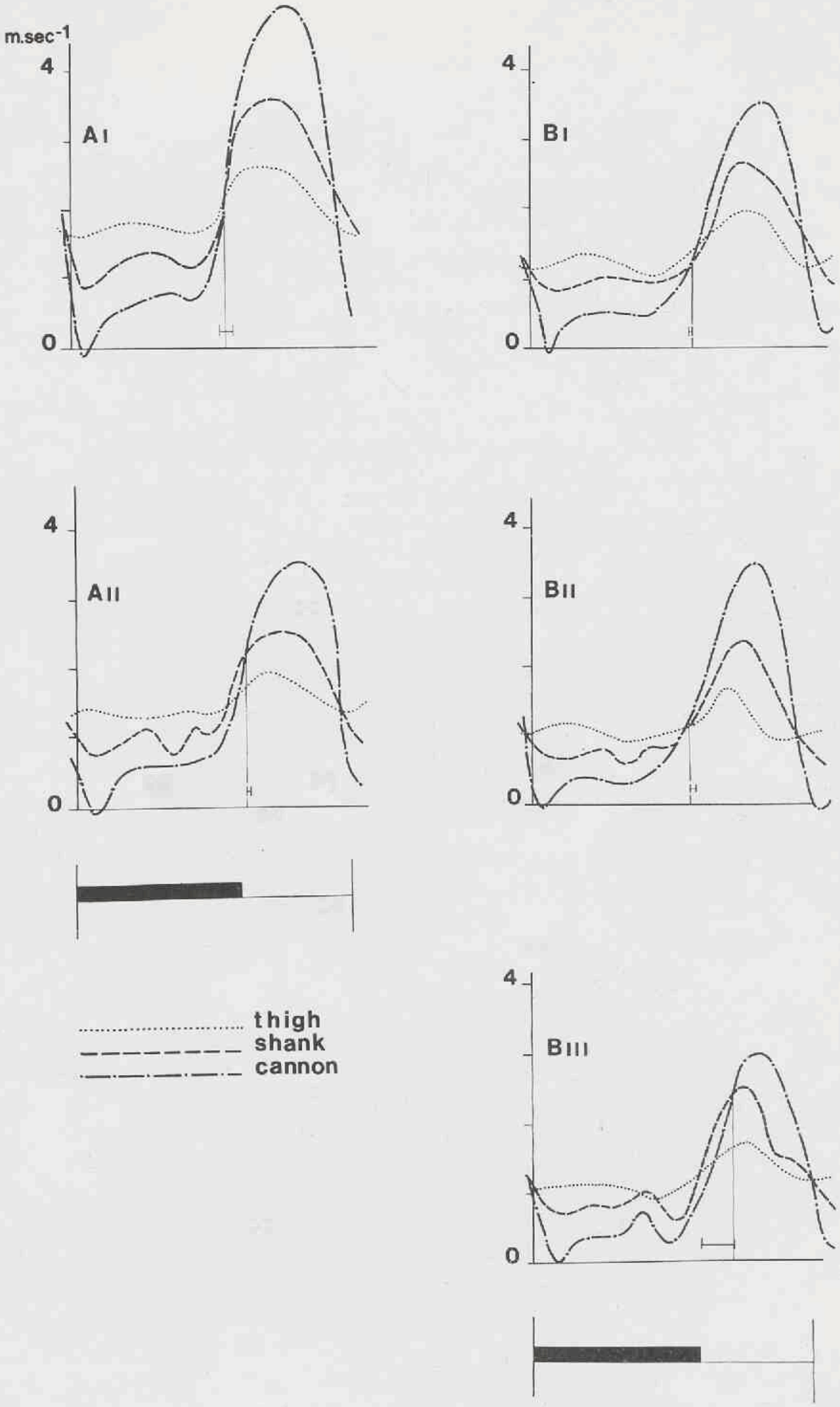

m.sec-1
4
0
AI
BI
AII
BII
BIII
thigh
shank
cannon

TABLE I

Extreme values of the changes of the angles of stifle and hock joints (fig. 2). The amount of changes is given for three horses before and after experimental surgery.

	Support phase				Swing phase			
	Flexion		Extension[1]		Flexion		Extension	
	degrees	period	degrees	period	degrees	period	degrees	period
A.								
Stifle joint before	14-23	0-42%	0	42-51%	22-28	51-75%	36-48	75-100%
after transection of the per. tert.	14-20	0-36%	0-1	36-48%	21-26	48-71%	35-44	71-100%
Hock joint before	9-16	0-11%	22-25	11-51%	44-48	51-77%	32-41	77-100%
after transection of the per. tert.	6-12	0-11%	28-30	11-51%	44-47	51-78%	22-29	78-100%
B.								
Stifle joint before	17-18	0-52%	0	0	16-17	52-82%	33-35	82-100%
after transection of the cran.tib.m.	9-18	0-36%	3-7	36-52%	20-25	52-78%	26-36	78-100%
after transection of the cran.tib.m. and per. tert.	9-17	0-34%	0-8	34-52%	25-36	52-76%	34-43	76-100%
Hock joint before	7-8	0-10%	17-19	10-53%	42-44	53-83%	30-35	83-100%
after transection of the cran.tib.m.	1-12	0-10%	17-27	10-52%	43-47	52-82%	27-31	82-100%
after transection of the cran.tib.m. and per. tert.	1-8	0-16%	25-28	16-47%	The cannon pendulates			
C.								
Stifle joint before	13-15	0-47%	0	47-55%	21-23	55-71%	35-39	71-100%
after transection of the sup.dig.fl.	13-19	0-43%	1-4	43-54%	18-23	54-76%	32-38	76-100%
Hock joint before	11-17	0-9%	23-29	9-52%	39-44	52-76%	30-32	76-100%
after transection of the sup.dig.fl.	13-16	0-21%	20-23	21-54%	38-43	54-80%	29-37	80-100%

1) In horses A and C the angle of the stifle joint is constant during a part of the support phase, whilst in horse B flexion is continued throughout the support phase.

IV. DISCUSSION

Both support and swing phase are affected by transection of either the peroneus tertius or the superficial digital flexor tendons. This is in contradiction with the results of Strubelt (1928) and may be explained by the fact that the used, rather aged horses were reluctant to move.
Transection of the cranial tibial muscle causes an initial increase and subsequent decrease of the acceleration of the centre of gravity of the shank at the end of the support phase.

At placing, the superficial digital flexor and interosseus tendons are stretched by the body weight and store elastic energy. When released, the elastic energy assists in lifting cannon and shank by flexion of the fetlock joint and extension of the hock joint. The distal pull of the superficial digital flexor tendon leads to flexion of the stifle joint, to stretching of the peroneus tertius tendon and thus to storage of elastic energy in preparation for flexion of the hock joint at the end of the support phase
The gastrocnemius and cranial tibial muscles assist the action of these tendons. In this context, mention may be made of the calculations of Alexander (1977b) who demonstrated that the elastic energy stored in the tendons of the antilope hind limb makes a considerable contribution to locomotor performance. Some authors (Chassin et al., 1976; Hildebrand, 1960) argue that most energy spent at locomotion is used to accelerate and decelerate the limbs during the swing phase. Alternate stretching of the tendons of the reciprocal tendinous apparatus during the support phase stores energy, which is made available in the subsequent swing phase. Such a mechanism economizes energy during locomotion. Equids are of course well known as "stayers".

In the dog, a digitigrade animal lacking the reciprocal tendinous apparatus, the activity of the muscles over the caudal aspect of the tibia is restricted to the support phase, and that of the muscles over the cranial aspect to the swing phase (Tokuriki, 1973; Wentink, 1976). Hence there is a clear difference between the unguligrade horse and the digitigrade dog with respect to the coordination and the use of the crural muscles, especially at the end of the support phase. Moreover, in the dog the movements of the distal segment are performed by energy-consuming muscular action, while in the horse the tendons of the reciprocal tendinous apparatus make an appreciable contribution to the movements.

From the foregoing analysis it appears that movements of the hind limb of the horse may be performed without participation of the gastrocnemius and cranial tibial muscles. The movements of the thigh are primarily induced by the extrinsic muscles originating from the pelvis and inserting on femur and tibia which form a muscular loop in which the limb is suspended (Wentink, 1977; 1978a). The movements of the stifle are transmitted to the hock joint by the tendons of the reciprocal tendinous apparatus. With a view to the limited contribution of the gastrocnemius and cranial tibial muscles to the limb dynamics on the one side and their impressive mass on the other, it is reasonable to assume that these muscles play a role in centering the line of action of the load on the tibia during the support phase (Badoux, 1970; Wentink, 1978a). In vivo bone strain measurements of the tibia which may support this assertion are in hand.

REFERENCES

Alexander, R. McN., Bennet-Clark, H.C. : Storage of elastic energy in muscle and other tissue. Nature 265, 114-117 (1977a).

Alexander, R. McN.: Allometry of the limbs of antilopes (Bovidae). J. Zool., Lond. 183, 125-146 (1977b).

Badoux, D.M. : The statical function of some crural muscles in the horse. Act. Anat. 76, 396-407 (1970).

Bradley, O.C., Grahame, T. : The topographical anatomy of the limbs of the horse, 2nd ed. Edinburgh: Green & Son (1946).

Chassin, P.S., Taylor, C.R., Heglund, N.C., Seeherman, H.J.: Locomotion in lions: energetic cost and maximum aerobic capacity. Zool. 49, 1-10 (1976).

Grau, H. : Das Muskelsystem. Der aktive Bewegungsapparat. In: Ellenberger und Baum, Handbuch der Vergleichende Anatomie der Haustiere (18th ed.) Berlin, Heidelberg, New York : Springer Verlag 1943 (reprint 1974).

Hildebrand, M. : How animals run. Sci. Amer. 5, 148-157 (1960).

Seiferle, E. : Aktiver Bewegungsapparat, Muskelsystem. In: Lehrbuch der Anatomie der Haustiere, Band I (ed. R. Nickel, A. Schummer, E. Seiferle) Berlin, Hamburg: Paul Parey, dritte Auflage (1968).

Sisson, S. : Myology (Equine). In: Sisson and Grossman's The anatomy of the domestic animals (ed. R. Getty), 5th ed. Philadelphia, London, Toronto: Saunders 1975.

Strubelt : Über die Bedeutung des Lacertus fibrosus und des Tendo femorotarseus für das Stehen und die Bewegung des Pferdes. Arch. Tierheilk. 57, 575-585 (1928).

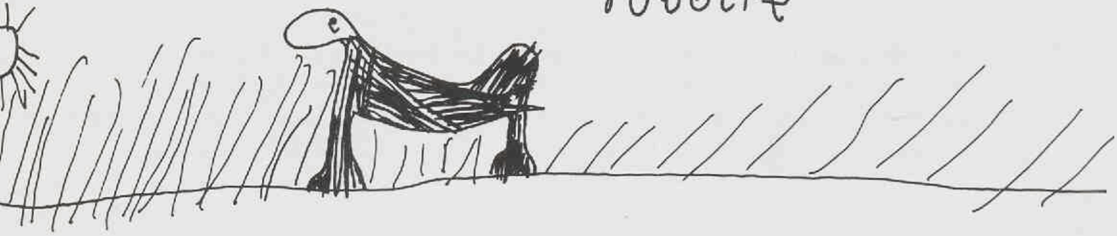
Tokuriki, M. : Electromyographic and joint-mechanical studies in quadrupedal locomotion. Jap. J. Vet. Sci. 35, 433-446 (1973).

Wentink, G.H. : The action of the hind limb musculature of the dog in walking. Acta Anat. 96, 70-80 (1976).

Wentink, G.H. : Biokinetical analysis of hind limb movements of the dog. Anat. Embryol. 151, 171-181 (1977).

Wentink, G.H. : Biokinetical analysis of the movements of the pelvic limb of the horse and the role of the muscles in the walk and the trot. Anat. Embryol. 152, 261-272 (1978a).

Wentink, G.H. : Dynamics of the hind limb at walk in horse and dog. Anat. Embryol. (submitted) (1978b).



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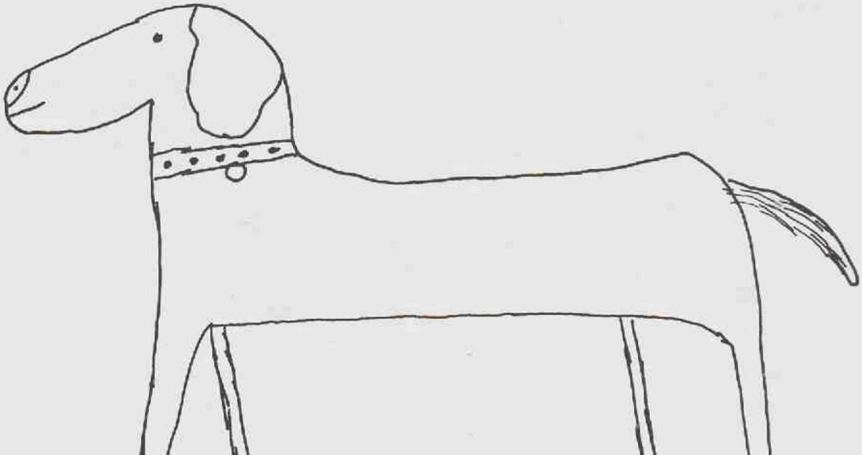

oer

Esther

BIOMECHANICS OF THE HIND LIMB OF HORSE AND DOG

SYNOPSIS

1. Introduction

In this synopsis a visualization of the results is presented in a pictorial survey. These results were based on electromyography and cinematography; the available technical facilities excluded the use of force plates, so that data from literature concerning the sense of the forces operating at the foot have been incorporated.

Electromyography reveals when muscles display activity during a stride. However, it does not give information whether a muscle contributes to a specific movement, opposes it or is active merely to adjust its length to the altered spatial position of its origin and insertion. In combination with the kinematical data from the cinerecord conclusions about the action of the muscles during the cycle of a stride can be drawn.

The plate pictures in figure I a model with the schematic representation of the bones and muscles; at left the hind limb of the horse, at right that of the dog.

In figure II the effect of the external forces applied at the femoral head (F_h) and at the foot (F_g) is visualized; these forces have flexing moments about stifle and hock joints and are opposed by intrinsic muscular moments (M_m). In figures III and IV the muscles which display activity are drawn in a model of the skeleton in the successive stages of the cycle of a stride, which commences at the moment of placing of the foot and ends at replacing for the following support phase (a, b and c denote the beginning, the middle and the end of the support phase, d and e the beginning and end of the swing phase). Figure III shows the active muscles in the dog, figure IVA those in the horse. In fig.IVB the stretching and shortening of the tendons of the reciprocal apparatus is separately given: stretching is given by the longer, shortening by the shorter broken lines.

In the lower figures V to VIII inclusive the effect of transection of the tendons and of the cranial tibial muscle is given: in the first pictures is indicated which structure is cut.

A concept of the anatomical arrangement of the muscles of th hind limb is given fig. IX.

Although the effects of the external forces acting on the limb take place simultaneously, the corresponding function of the muscles are dealt with separately.

2. Muscular actions

During the support phase flexion of stifle and hock (fig. II) is prevented by the actions of the extensor muscles of these joints. The limb is then transformed into a springy strut over which the body moves as over a spoke. Dynamically speaking, the limb is used as a lever to develop the push-off at the end of the support phase. In both species the stifle joint is kept extended by the action of the quadriceps muscle (fig. III and IV). In the dog this is brought about by the lateral vastus, and, in the second part of the support phase, by the action of the rectus femoris muscle; in the horse initially by the rectus femoris and in the second part by the action of the lateral vastus muscle. This difference in the periods of activity of the parts of the quadriceps muscle may be explained by the locking mechanism of the stifle of the horse: activity in the lateral vastus muscle at the end of the support phase prevents hooking of the patella on the medial ridge of the femoral trochlea by the lateral rotation of the patella around its longitudinal axis.

In the dog (fig. III) the hock joint is kept extended by the muscles over the caudal aspect of the tibia: initially by the combined action of the gastrocnemius and superficial digital flexor muscles, in the last part of the support phase by only activity of the latter muscle. The deep digital flexor muscle may assist in the stabilization of the hock, but its main action is in unison with the interosseus muscle to press the digits against the ground and to provide strong grip.

In the first part of the support phase in the horse (fig. IVA) activity is present in the muscles over the caudal aspect of the tibia (gastrocnemius and deep digital flexor muscles); in the last part of the support phase the cranial tibial muscle comes into action and the activity in the gastrocnemius ceases. The mechanical moments about the hock joint are now equilibrated by the deep digital flexor and cranial tibial muscles.

There exists a remarkable difference between the digitigrade dog and the unguligrade horse in the coordination of activities in the crural muscles. This may be explained by the positions of the shank and cannon in this particular part of the cycle: the inclination of the tibia with respect to the vertical is greater in the dog than in the horse. The metatarsus of the dog has an approximately vertical position in this stage of the cycle when all pads are in contact with the ground, while in the horse the cannon always passes the vertical while the hoof is still in contact with the ground. Data from force plate studies suggest that in the horse the vector of the resultant ground reaction passes through the hock joint, while in the dog it passes in front of the hock and thus has a flexor moment about this joint.

The limb is intrinsically stabilized and supports the (partial) weight of the body. In the first part of the support phase it acts as an inclined strut provoking a friction with a sense opposite to the animal's progression: the limb then opposes the forward movement of the animal. The limb is retracted by the hamstring and middle gluteal muscles (in the dog by the adductor and gracilis muscles also); the effect of the inertia of the body is complemented by the action of these muscles in bringing the proximal end of the limb into a position in which the dynamic effect of the weight provokes a friction in the sense of the animals progression, which is suitable for the push-off. At this moment, the activity in the retractor muscles stops. The effect of friction is smoothed by the protractor muscles (tensor fasciae latae muscle and - in the dog - the rectus femoris muscle) to prevent jerks in the progression.

In the swing phase the joints are flexed - the stifle by the action of the caudal hamstrings, the hock by the action of the cranial tibial muscle assisted by the long digital extensor muscle. The main action of the latter is to extend the digit(s). The limb is protracted by the tensor fasciae latae muscle, in the dog by the sartorius muscle also.

At the end of the swing phase the forward movement of the limb is checked by the action of the retractor muscles of the limb and by the action of the extensors of the hock joint.

From this survey of the actions of the muscles it emerges that the muscles of the hind limb can be divided into two functional groups (fig. IX).

1. The muscles which transform the limb into a springy strut during the support phase: these muscles are printed in yellow. Their activity is restricted to the end of the swing phase and to all or part of the support phase

These muscles comprise the quadriceps group, the gastrocnemius and the deep digital flexor muscles in both species and the superficial digital flexor and the interosseus muscles in the dog. These muscles have a pennate structure, with the exception of the interosseus muscle in the dog.

2. The extrinsic muscles of the limb and the muscles over the cranial aspect of the tibia, printed in red. These muscles are parallel-fibered. The extrinsic muscles form a loop in which the limb is suspended: the caudal part is active to check the forward swing of the limb in the last part of the swing phase; in the first part of the support phase it moves the body over the stabilized limb and complements the effect of inertia. The cranial part of this loop displays activity at the end of the support phase. It smoothes the otherwise jerky propulsion by the dynamic effect of the weight and gives the limb a forward acceleration in the first part of the swing phase. The stifle is then flexed by the caudal hamstrings and the hock by the muscles over the cranial aspect of the tibia; flexion of these joints brings the centre of gravity of the limb closer to the hip and diminishes the moment of rotational inertia about the pivot point. The muscles of this latter group are prime movers of the limb, those of the former group are stabilizers of the limb.

When considering the anatomical differences between horse and dog, there is a remarkable "substitution" of muscular tissue by tendinous analogues in the horse (superficial digital flexor, interosseus and peroneus tertius). In the dog the muscles help to dig the claws into the ground, which results in a strong grip and a forced push-off. Moreover, the coefficient of friction between the pads of a dog and the ground is greater than that between the hoof of a horse and the ground, so that in the digitigrade dog the forward impulse can be relatively greater than in the unguligrade horse. Dogs may clear obstacles of two metres or more and rely on sudden sprints to capture prey animals.

3. The role of the reciprocal tendinous apparatus in the horse

The effect of the load on these tendons is shown schematically in figure IVA.

At placing (a), the interosseus and superficial digital flexor tendons are stretched (long broken lines) by the impact and store elastic energy. This energy gives the limb and the trunk a (mainly upward) acceleration in the middle of the support phase. The pull of the superficial digital flexor tendon at the femur flexes the stifle during this phase. The opposite angular movements of stifle and hock stretch the peroneus tertius tendon which in turn stores elastic energy (c): thus in a sense, the elastic energy stored at impact is transfered from the tendons over the caudal aspect to those over the cranial aspect of the tibia. This energy is ultimately used to flex the hock in the last phase of the support phase when the hoof starts rolling over.

The effects of transection of the above mentioned tendons and of the cranial tibial muscle are given in figures V to VIII inclusive: the solid models give the abnormal, the interrupted models the normal situation.

3a) Transection of the superficial digital flexor tendon (fig. V) diminishes the upward force operating at the segments of the limb. The stifle extends at the end of the support phase when the femur is relieved from the distal pull of this tendon; flexion of the hock joint is prolonged during the support phase.

3b) Transection of the peroneus tertius tendon (fig. VI) enables the extensor forces to extend the hock at the end of the support phase. This results in an irregular pattern in the effect of the forces applied at the centres of gravity of shank and cannon, a phenomenon also observed after transection of the cranial tibial muscle (fig. VII) as well as after transection of both structures over the cranial aspect of the tibia (fig. VIII).

After eliminating the peroneus tertius tendon, flexion of the hock joint and the forward acceleration of the cannon depend on muscular activity alone.

In the intact animal the cannon overtakes the shank in the last part of the support phase; after transection of the peroneus tertius tendon this effect is only seen in the first part of the swing phase. This illustrates the role of the latter tendon in the flexion of the hock joint. In the normal dog, flexion of the hock merely depends upon muscular activity and takes also place in the first part of the swing phase.

3c) Transection of the cranial tibial muscle (fig. VII) does not influence the moment at which the cannon overtakes the shank, but transection of both the peroneus tertius tendon and the cranial tibial muscle (fig. VIII) severely disturbs the pattern of the movements of the cannon. The delayed flexion of the hock and the kink in the Achilles tendon, described in the clinical literature as occurring after peroneus tertius rupture, were seen only after the latter operation.

The reciprocal tendinous apparatus plays a role in the conservation of energy: the horse is a well-known stayer. The limb can theoretically be moved by the extrinsic muscles and then in the horse the angular changes of the stifle joint are transmitted by the reciprocal tendinous apparatus to the hock joint. Hence, theoretically the intrinsic movements of the hind limb of the horse might be performed without the action of the gastrocnemius and cranial tibial muscles (fig. X). These muscles however, are active during that part of the cycle in which the tendons over the same aspect of the tibia are stretched. With an eye to the impressive mass of these muscles, a complementory function is suggested, which is pictured in fig. X.

At placing the effect of inertia provokes a tensile stress over the caudal aspect of the tibia and a compressive stress over its cranial side pictured by the broken line: in this situation the line of action of the load may be centered through the long axis of the tibia by the action of the gastrocnemius muscle. At the end of the support phase the effect of inertia is reversed and so a tensile stress may be expected over the cranial aspect and a compressive stress over the caudal aspect of the tibia pictured by the broken line: in this situation the cranial tibial muscle may centre the line of action of the load through the long axis of the tibia.

SUMMARY

This study deals with the biomechanics of the hind limb of horse and dog, and is concentrated on the role of the crural muscles parallel to the tendons of the reciprocal apparatus. The limbs were divided into three segments: thigh, shank and cannon (in the dog metatarsus and digits); their weight and the position of the centres of gravity were determined. The kinematical data were obtained by cinephotography, the periods of muscular activity by electromyography.

From these data a concept was formed of the action of the individual muscles and the cooperation of various muscle groups at walk; this was correlated with data from literature concerning the forces exerted by the feet on the ground.

Differences in the movements of the hind limb of horses before and after transection of the tendons of the reciprocal apparatus contributed to the insight into the role of these tendons during the cycle of a stride. It has been concluded that: 1) the muscles of the hind limb can be divided into two groups: a) the prime movers (the extrinsic muscles and the muscles over the cranial aspect of the tibia) which display activity mainly during the swing phase, and b) the stabilizers (the extensor muscles of stifle and hock and the flexor muscles of the digits) which display activity mainly during the whole or part of the support phase; 2) the hamstring muscles can be divided into a cranial (inserting on the thigh) and a caudal group (inserting on the shank); both extend the hip joint during the support phase, the latter flexes the stifle during the swing phase; 3) activity is present in the greatest number of muscles when a change in the sense of the movement of the limb occurs, i.e. at placing and lifting; 4) at walk, muscular activity is developed to antagonize external forces, and ceases when the effect of the external forces contributes to progression. So, the push-off is largely due to the dynamic effect of the mass of the animal; 5) reversion of the movement of the limb takes place at the end of the support phase in the horse, in the first part of the swing phase in the dog; 6) the difference in the periods of activity in the parts of the quadriceps muscle (at the end of the support phase the lateral vastus in the horse, the rectus femoris muscle in the dog) is explained by the locking mechanism of the patella on the medial ridge of the femoral trochlea in the horse: in order to prevent locking the lateral vastus rotates the patella laterally;

7) in the horse flexion of the stifle is continued throughout the support phase, while in the second part of this phase extension of the hock takes place; 8) the subsequent stretching of the tendons of the reciprocal apparatus during the support phase stores elastic energy, which is ultimately used to flex the hock joint; 9) the muscular digital flexor muscles in the dog dig the claws in the ground for strong grip and forced push-off; 10) in the horse the metatarsus passes beyond the vertical so that the cranial tibial muscle comes into action to prevent overextension of the hock joint; in the dog the metatarsus remains in a vertical position at the end of the support phase and the cranial tibial muscle does not display activity; 11) in the horse the movements of the hind limb might theoretically be performed without activity in the gastrocnemius and cranial tibial muscles; these muscles may centre the line of action of the load through the long axis of the tibia. Bone strain analysis is necessary to proof this assumption.

SAMENVATTING

Dit proefschrift beschrijft het onderzoek van enige biomechanische aspekten van de bewegingen van het achterbeen van paard en hond, geconcentreerd op de rol van de spieren van het crus binnen het spanzaag mechanisme. Het achterbeen is verdeeld in de segmenten dij, schenkel en pijp (bij de hond middenvoet en tenen); het gewicht en het zwaartepunt van de segmenten zijn bepaald. De kinematische gegevens zijn in filmbeelden opgemeten; de periodes waarin de verschillende spieren aktiviteit ontplooien zijn met behulp van elektromyografie geregistreerd.

Uit deze gegevens is afgeleid welke bijdrage de verschillende spieren aan de bewegingen van het been tijdens de stap leveren, en welke koordinatie er bestaat tussen spiergroepen. De interpretatie is gekorreleerd met literatuurgegevens over de krachten die de voet op de grond uitoefent. Verschillen in het bewegingspatroon van het achterbeen van paarden voor en na doorsnijden van pezen van het spanzaagmechanisme hebben bijgedragen tot het verkrijgen van inzicht in de dynamische betekenis van deze pezen tijdens de stap.

Uit deze studie blijkt dat: 1) de spieren van het achterbeen verdeeld kunnen worden in twee groepen: a) <u>bewegers</u> (de extrinsieke spieren en de spieren gelegen aan de craniale zijde van de tibia), die hoofdzakelijk aktief zijn in de zweeffase; b) stabilisatoren (de strekkers van knie en sprong en de buigers van de tenen), die in hoofdzaak aktief zijn gedurende de hele steunfase of een deel ervan; 2) de broekspieren verdeeld kunnen worden in een craniale (die aan de dij insereert) en een caudale (die aan de schenkel insereert) groep; beide spiergroepen strekken de heup tijdens de steunfase, de laatstgenoemde buigt de knie in de zweeffase; 3) het aantal aktieve spieren het grootst is bij het neerzetten en bij het optillen van het been; 4) tijdens de stap de spieren aktief zijn om de (externe) krachten tegen te werken; zodra deze krachten bijdragen aan de voortbeweging houdt aktiviteit in de relevante spiergroepen op. De afzet wordt grotendeels teweeggebracht door het dynamisch effect van de massa van het dier; 5) bij het paard. de voorwaartse beweging van het achterbeen begint in het laatste deel van de steunfase, bij de hond in het begin van de zweeffase; 6) de verschillen in de periodes waarin aktiviteit in de delen van de quadriceps optreedt (aan het einde van de steunfase de M. vastus lateralis bij het paard, de M. rectus femoris bij de hond) verklaard kan worden door het slotmechanisme van de knie van het paard: om vasthaken van de knieschijf op de mediale rolkam van de trochlea femoris te voorkomen draait de M. vastus lateralis de knieschijf naar lateraal; 7) bij het paard gedurende de hele steunfase buiging optreedt van de knie, terwijl in het tweede deel van de steunfase de sprong wordt gestrekt; 8) de pezen van het spanzaagmechanisme gedurende de steunfase elastische energie opslaan; deze energie wordt gebruikt voor de buiging van de sprong; 9) de hond met zijn geheel uit spierweefsel bestaande teenbuigers de nagels in de grond kan drukken ten behoeve van een geforceerde afzet; 10) aan het einde van de steunfase bij het paard en niet bij de hond aktiviteit optreedt in de M. tibialis cranialis; dit verschil wordt verklaard doordat bij het paard de pijp aan het einde van de steunfase de vertikale lijn passeert, terwijl bij de hond de middenvoet ongeveer vertikaal blijft; 11) de bewegingen van het achterbeen van het paard theoretische uitgevoerd zouden kunnen worden zonder aanwezigheid van de M. gastrocnemius en de M. tibialis cranialis. Deze spieren centreren mogelijk de werklijn van de belasting op het been door de lengteas van de tibia. Deze veronderstelling kan alleen bewezen worden door in vivo onderzoek met rekstrookjes.

CURRICULUM VITAE

De schrijver van dit proefschrift werd geboren op 6 januari 1945 te Zelhem. Na het behalen van het diploma Gymnasium B aan het Gemeentelijk Lyceum te Enschede in 1963 werd een begin gemaakt met de studie Diergeneeskunde aan de Rijksuniversiteit te Utrecht. Hij beeindigde deze studie in 1969 en trad als wetenschappelijk medewerker in dienst van de Kliniek voor Kleine Huisdieren. Sinds 1973 is de schrijver van dit proefschrift verbonden aan het Instituut voor Veterinaire Anatomie (Vakgroep Funktionele Morfologie) van bovengenoemde Rijksuniversiteit.

STELLINGEN

I

De transektie van de mediale insertiepees van de M. tibialis cranialis (spatpees) als therapie tegen spat moet twijfelachtig genoemd worden: het resultaat van deze ingreep hangt af van de ernst van de veranderingen aan kraakbeen en spongiosa van os tarsi centrale en os tarsale tertium.

II

De diagnose "ruptuur van de peroneus tertius" dient te worden gewijzigd in "ruptuur van de peroneus tertius en M. tibialis cranialis".

III

Het feit dat bij het paard degeneratieve veranderingen het meest worden gezien in het spronggewricht en bij de hond in het kniegewricht wordt waarschijnlijk mede veroorzaakt door verschil in gebruik van de spieren van het achterbeen bij beide diersoorten.

IV

Bij het dubbeltreden van de tenen van het achterbeen van de hond dient te worden gedacht aan een beschadiging van zowel de N. tibialis als de N. peroneus en niet van de N. peroneus alleen.

V

De mate waarin bij het paard buiging van de knie optreedt in de steunfase wordt mede bepaald door leeftijd en ras.

VI

De gelijktijdige aktiviteit in de M. tibialis cranialis en de diepe buiger bij het paard rechtvaardigt de uitspraak, dat de M. tibialis cranialis niet alleen als flexor kan worden beschouwd.

VII

De opvatting als zouden unguligrade dieren met viertenige spreidvoeten minder ver in de grond zakken en dus beter zijn aangepast aan het lopen op drassige grond dan ééntenige unguligrade dieren, wordt door de feiten niet gesteund.

VIII

Het verschil in relief van de tibia bij Hipparion en Equus wettigt het vermoeden dat een spanzaagmechanisme niet bij het eerstgenoemde geslacht voorkwam.

IX

Het klinisch gerichte onderwijs van vakgroepen in de Faculteit der Diergeneeskunde dient zodanig van inhoud en opzet te zijn, dat het in principe door àlle ervaren dierenarts-docenten van die vakgroep kan worden gegeven.

X

Het ware wenselijk om voor een examen behalve een norm ook een maximum aantal jaren vast te stellen.

XI

De prikklok registreert slechts lijfelijke, geen geestelijke afwezigheid; voor velen onder de moderne vrijgestelden is er dus niets te duchten.

XII

Wanneer het Nederlands voetbalelftal uit politici zou worden geselekteerd, dan zou het Nederlandse volk uitsluitend taktische besprekingen te zien krijgen.

Biomechanics of the hind limb
of horse and dog

G.H. Wentink

8 juni 1978