THREE LECTURES

ON

THE PRINCIPLE OF LEAST ACTION IN NATURE,
ILLUSTRATED BY ANIMAL MECHANICS.*Delivered at the Royal Institution of Great Britain.*

BY THE

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LECTURE II.—Tuesday, May 30th, 1871.

Geometrical Classification of Muscles found in Animals.—Application of the principle of Least Action to several forms of Muscle, demonstrating the possibility of "predicting" Animal Structures by Mathematical Calculations similar to those used in Astronomy and the other exact Sciences.—Special Illustrations from the Limbs of the Tiger and Wings of the Albatross.

IN bringing to a conclusion my former lecture, I acted on the principle that I laid down of the "least action." Taking into consideration the feelings of the audience as well as of the lecturer, and judging by my own experience in hearing sermons and lectures, I thought that somewhat less than an hour's lecture would suit your tastes. I therefore threw overboard one interesting application of the principle of least action in order to lighten the ship, and bring her safely into harbour; but if it is your pleasure that I should now state the problem of the tendons of the fore and hind limbs of animals, which I omitted to state in my last lecture, I place myself in your hands; but you will have yourselves to blame if we do not carry out perfectly the principle of minimum trouble and least action by this rash proposal.

I hold in my hand the flexor tendon of the hind leg of the eland. You will observe that at one extremity it branches into three distinct tendons, and at the other extremity it divaricates into two. These three tendons are the connecting ropes that join the common tendon in the foot with the three great muscles of the leg that act upon it. Three streams of force enter the common tendon through these three different lines, and they are then distributed by the intervention of this divaricating tendon into two; these two applications of force are carried to the toes of the animal. Somewhat similar arrangements are found in the fore limb and hind limb of almost every animal. We have the muscles acting at one extremity of the tendons, which are the connecting ropes that join the muscular forces with their points of application; and we have these both in the fore and in the hind limb. Now, in the case of many animals the fore limb and the hind limb are always used for the same purpose. In the case of the llama, the horse, and the cow, the fore limb and the hind limb have scarcely any different functions: the animals are, in the strictest sense of the word, quadrupeds; their fore feet are used simply for the purposes of locomotion. But in the higher classes of animals, like tigers, cats, bears, dogs, monkeys, and ourselves, we have the fore limbs more or less differentiated in function from the hind limbs, and set apart for the use of the brain as grasping organs. In man himself, as you all know, this is carried on to its very highest limit. Except when we are little children we do not run upon our fore feet; we have lost the use of our fore limbs as feet, and we retain our hand as the highest characteristic man can possess of his great origin—the servant of his brain, a perfect instrument for carrying out the conceptions of the brain and of the intelligence with which he is endowed. We might therefore expect, and I did expect, to find, if I compared the hands and feet of higher groups of animals together, great differences in these tendons. A certain amount of friction must take place round the ankle-joint and round the wrist-joint; and, as friction helps the weaker force, I foresaw, if my principle of least action were correct, that I should find, in the case of a hand or fore limb of an animal, that the united strength of the tendons passing from the muscle to the common tendon would be greater than the united strength of the cross tendons applied to the toes or fingers. When I grasp an object in my hand the force comes from the muscles of the arm, passes through the tendons, and is then applied to the object grasped. If the principle of least action in nature be true, the united strength of the tendons above my wrist and below my wrist will not be the same; but advantage will be taken by nature of the necessary friction that takes place at the wrist to make the tendons in the fingers less than the tendons in the arm by exactly the extent to which they are

relieved by friction. On the other hand, in using my leg as an instrument of locomotion, the force comes by reaction from the ground upward: the ground by reaction presses upon my foot; the strength of the tendons between the foot and ankle is exactly what is necessary to prevent their rupture or injury; and, in passing beyond my ankle into the calf of the leg, I should expect, if the principle of least action be a true principle, able to unlock the secrets of animal construction, to find the reverse of what I found in the hand; I should expect to find the tendons which pass from the foot into the muscles having a less cross-section than those which pass from the toes into the common tendon. And this is actually the fact. I have examined upwards of eighty animals, and I find that animals might be very fairly classified, according to this peculiar arrangement of tendons in the hand or foot, as animals that possess a grasping power and use their hands as hands, and animals that are of a lower organisation, and use their fore feet not as hands but as organs of locomotion. In the hand of the tiger there is a friction of 22.7 per cent; in the foot of 46 per cent. But those frictions, you will observe, are reversed. The tendons of the fingers in the tiger's hand are less than the tendons in the forearm; and, *vice versa*, the tendons of the toes of the tiger are greater than those of the leg; so that, although this Table represents the friction in the hand and foot of various animals, you are to remember that the friction is *plus* in one case and *minus* in the other. The strength of the tendons in the forearm always exceeds the strength of the tendons of the fingers; while the strength of the tendons of the toes exceeds the strength of the tendons of the leg. In the wolf the corresponding figures are 31.4 and 34; in the bear, 35, and 25.9; in our cousin, the negro monkey, 27.4 and 8. This animal, you see, fully justifies the title which Cuvier applied to him of quadrumanous, for he has only a friction of 8 per cent. in his foot, because he uses it very much as a hand for the purposes of climbing; this is apparent in the low coefficient of friction shown in the hind foot.

The animals whose tendons suffers least from friction, at the wrist and ankle, are the goat and the kangaroo. The wrist of the goat is so admirably constructed that no force whatever is lost. The animal climbs a hill, runs up rocks, jumps from point to point, and he does so mainly by this admirable arrangement by which no force whatever is lost by friction in the wrist. The hind foot of the kangaroo, which is the great organ of locomotion in this animal, presents no friction at the heel. The most perfect organ of locomotion that we are acquainted with amongst quadrupeds (if we may call the kangaroo a quadruped, for he only uses two feet in locomotion) is the hind leg of the boomer kangaroo. The investigation which I have carried out in between seventy and eighty distinct animals shows in a most conclusive manner that the law of least action is attended to in every department of nature down to the most minute details. Even the expense of producing a few grains more or less of this glue (for a tendon is nothing but common glue) is carefully attended to; and in the laboratory of Nature the most rigorous and parsimonious economy is observed. Not even one grain of material is ever used when less would suffice for the purpose.

This may be carried out into very minute details which time will not allow me further to develop. I will merely call your attention to a rough sketch of the hind feet of monkeys of the old and the new world, which present many remarkable differences in construction from the feet of other animals. Their feet, as I said before, are fully entitled to the name of hands. We may classify the old and the new world monkeys by the peculiar arrangement of the tendons of their feet. In both, the tendons of the feet are supplied by two great muscles—the flexor hallucis longus and the flexor digitorum longus. (Fig 1.) You can see the distribution which I have endeavoured to show here. You see that the muscle of the great toe supplies half the first toe, the whole of the second, and the whole of the fifth; the other tendon supplies half the first toe, the whole of the third, and the whole of the fourth. Therefore the most natural action for the old world monkey would be to put the great toe opposite the third and fourth fingers, or opposite the second and fifth. The first, second, and fifth, would be a combination; the first, third, and fourth, would be a combination. In the monkeys of the new world there is a totally different arrangement. It is interesting to see how profoundly different these creatures are even in the structures connected with the hand and foot. You see here (Fig 2) one tendon supplying half the first toe and the whole of the second, third, and fourth; half the first and the whole of the fifth are supplied by the other muscle. Therefore in the South American monkeys, best known by those beautiful little Capuchin monkeys, so called from their monk-like appearance and the devout manner of crossing their hands over their breasts, the natural action is to place the first and fifth toes together, or the first, second, third, and fourth. In the occupation which is so common amongst them, and so useful to them, of gathering up small living creatures from their skins, you will find, if you watch

the habits of these monkeys in our gardens, that they fully bear out the anatomical theory I have explained. While the monkey of Africa prefers to grasp with the first, second, and fifth toes, the monkey of

Fig. 1.

Fig. 2.

South America will show equal dexterity in seizing an object with the first and fifth alone. Fig. 3 represents the tendons of the foot of the jaguar.

I now come to the proper subject of my present lecture, which is the classification of muscles. Muscles were originally classified by Alphonso

Fig. 3.

Fig. 4.

Borelli, who divided them into various groups; but, as this is not an historical or antiquarian sketch, I shall content myself with giving you my own classification, which is based upon his, and is a considerable improvement. I divide all muscles into the following; the prismatic muscle (fig. 4), where the fibres pass parallel to each other from bone to bone; the penniform muscle (fig. 5), where the fibres radiate at equal angles from a common tendinous line, and are inserted, of course, at each extremity into the bone; the triangular muscle, where the muscu-

lar fibres proceed from a fixed line, and are inserted not into a point, but into a line, so short that we may for practical purposes regard it as a point; and the fourth class I call quadrilateral muscles, where they are drawn in lines converging from one bone to another.

Fig. 5.

If A B represent one bone, and A' B' another bone (fig. 6), these bones may be curved in any way you please. In Nature, as you know, everything is curved in forms that mathematicians cannot imitate. We find the muscular fibres so arranged that, if A B and A' B' lie in the same plane, if I produced them all, they would pass through a common point of intersection. I ask you to take that for granted. I have proved it, but I will not trouble you with the proof. Therefore the quadrilateral muscle is really nothing but a triangular muscle with the top cut off. If I take the triangular muscle running from a bone to a point, and cut off the top of it and place the second bone along the section so cut off, I have a quadrilateral muscle. The quadrilateral muscle is easily dealt with as long as the two bones remain in the same plane. The contraction of the fibres causes these two bones to approach in the same plane. Often, however, A B and A' B' do not always remain in the same plane; they are not as accommodating as geometers and mathematicians would wish; they leave their plane and form what we call in geometry skew surfaces (fig. 6). This model intended to show the manner in which a plain quadrilateral muscle becomes what we call a skew surface. You are probably acquainted with the term from engineers using it in the construction of what are called skew bridges for railways. A skew surface is a very remarkable thing. It is made up of a number of straight lines, yet every portion of that surface, except along these particular lines, is a curve. Now I have succeeded in discovering that the particular skew surface, of which muscles are capable of assuming the shape, is the beautiful surface known to geometers by the name of the hyperboloid of one sheet. Here you see a number of straight lines, which I shall suppose to represent muscular fibres passing from the bone A B to another bone A' B'. I have made the bones of the same length,

but the results would be similar, if I made the bones of different lengths or of any curvature I pleased, and placed them in the same position. I now take this muscle and distort it out of its plane. You see I have now a curved surface in which every portion is made up of straight lines. I can curve the surface in the opposite direction, and so I make the hyperboloid of one sheet out of a plane

Fig. 6.

quadrilateral muscle. This is not a mere fiction of geometers. The adductor magnus muscle in the leg of man, and the great pectoral muscle in the wing of every bird, are living examples of the reality of this curious fact, that Nature constructs not merely plane muscular structures, but that she is capable of constructing muscular surfaces belonging to the most beautiful and elegant forms that have been studied and invented by abstract geometers. A friend of mine, one of the most distinguished of living geometers, when I informed him that Nature used familiarly the hyperboloid of one sheet in making her muscles, told me that his respect for her was considerably increased. The last forms of muscle to which I shall direct your attention are the sphincter muscle, which represents a number of circular fibres surrounding an orifice, and the ellipsoidal muscle, which represents muscles of greater or less thickness surrounding a cavity called ellipsoidal, because the cavity so formed is generally egg-shaped. In the next lecture I shall direct your attention to the most important of all these forms of muscles in the human heart and the hearts of animals. I shall confine our attention to-day to the more elementary muscles represented by the prismatic, penniform, triangular, quadrilateral, and the hyperboloid muscle of one sheet.

The prismatic muscle and the penniform muscle possess the remarkable property, which can be demonstrated mathematically, that in their contraction no loss whatever takes place. Nature, therefore, according to my principle, is entitled to employ these two forms of muscles whenever she pleases. She suffers no loss or injury by using these forms of muscles, and we find, therefore, that both these classes of muscles are constantly employed. When you come to the triangular, the quadrilateral, and skew muscles, we can demonstrate by mathematics that in the use of every such muscle there is a necessary loss of force. I may, therefore, be asked—How comes it, if the principle of least action be true, that Nature ever employs muscles involving a necessary loss of force? I answer, because Nature has other problems in view than mere economy of force in a single muscle. She has to consider if she economise force simply, without regard to other circumstances, such as beauty of form, and surface of least resistance, whether she might not lose rather than gain, taking into consideration all the conditions. I have always maintained that beauty of form, symmetry of outline, was one of the pre-existing conditions in the mind of the contriver of the universe, as well as economy of force. We find, therefore, that Nature

never uses a triangular or quadrilateral muscle except under great necessity, of which I shall now give you a remarkable example (fig. 7).

Fig. 7.

The most wonderful triangular muscle in the world is here shown in the biceps femoris muscle, or the flexor of the thigh in the tiger. The muscular fibres radiate from O; they are inserted from the middle of the thigh down to the heel. This enormous muscle forms one great sheet of muscle passing from the tuber ischii, and spread out over a space of three feet along the side of the leg. That muscle exists in me and in every other mammalian animal that lives. In most other animals it is arranged as a prismatic muscle. In my leg it is like a rope of parallel prismatic fibres. Now, I ask—"Why has Nature deliberately sacrificed a certain amount of force by putting a triangular muscle into the leg of the tiger to do the work which she does so effectually in my leg by a straight rope of muscle?" The answer is this, that I am a man and not a tiger; I am not intended as a tiger is, to hide in a jungle, to jump from the jungle at a troop of horsemen going by, to take one of them and carry him off in spite of the rest, and eat him. That is not the purpose for which the Creator brought me here; but if I were brought here for such a purpose I am sure I should have a triangular muscle in my leg. The weight of muscle to give the tiger the spring which enables him to do these feats is so enormous, that if it were placed as a single rope from point to point it would not only be a great deformity in his appearance, but would seriously impede him in his progress through the jungle. The clumsy nature of this enormous rope of muscle attached to him would injure him, therefore Nature has deliberately thrown overboard the first idea that might present itself, which was to put a great rope from point to point, and to make it strong enough. "No, I cannot do that," says Nature, "I must preserve beauty of form," making the tiger (what it is) the most beautiful creature

which God has created. Therefore, the tiger is given a triangular muscle with a certain amount of loss of force, but there is a gain by spreading the muscle over a great surface, a gain in the packing and shape of the leg—there is more gained than lost by the apparent sacrifice of force.

An interesting fact may here be stated, the extreme beauty of which every anatomist present will appreciate. We can demonstrate, and I ask you to take it for granted, that the resultant force of the fibres of quadrilateral and triangular muscles lies in the bisector of the vertical angle. When I take the triangular muscle in the leg of the tiger, and draw the bisector of that angle on a tiger's dead body, I find that the bisector of the angle passes rigorously through the top of the fibula, the peroneal or small bone of the tiger's leg, through the very spot in which the biceps muscle in my leg is inserted; so that, although the tiger's muscle is triangular, it really behaves like an imaginary muscle working along an imaginary line, passing from the same point in the tiger from which it passes in my pelvis to the very same point, the top of the fibula, to which it is attached in my leg also. Here Nature is not to be accused of departing from the principle of least work. In this case, the strict carrying out of that principle would injure her in other ways, as in the packing of the muscles; therefore she has deliberately abandoned it, making a small sacrifice in order to obtain a greater advantage. Nature always acts upon the French proverb, "*Reculer pour mieux sauter*." I have said before that she is at perfect liberty to use, as far as I am concerned, either the penniform or the prismatic muscle; and I cannot criticise her proceedings in that respect. Still her use of the penniform muscle is very sparing, as if she did not like to use her resources except when they were absolutely necessary. We find, although there is no loss of force in a penniform muscle, it is a rare form of muscle, and only resorted to when there is a worthy object. The most remarkable example I can give you of the penniform muscle in Nature is the muscle which lifts the wing of the bird. The bird's wing is depressed by great and powerful muscles, which I shall describe at the close of the lecture: it is lifted by a small compact muscle, which is placed upon the breast of the bird, in order to keep the centre of gravity of the bird as far back as possible. It is worthy of remark, that in the case of the ostrich, which does not fly, Nature places this muscle on the neck of the bird, because it is no injury to the ostrich to have the muscle on the neck; whereas it would be destruction to any other bird to have it so. This muscle placed upon the breast works by a tendon passing through a pulley, and changes through an angle of 180 degrees in its application, so as to lift the wing of the bird. The nature of a bird's flight is this: The depressor muscles of the wing must be made enormously great, to strike the air with the utmost force; the muscles which lift the wing must be made as light and small as possible, because their only object is to bring back the wing through the air after the stroke is made; this ought to be done in the shortest possible time, because, while the wing of the bird is rising through the air, the bird is falling: therefore we find that Nature, or rather the great Author of Nature, always employs the penniform muscle to lift a bird's wing; and for this reason, since the fibres converge at an angle towards each other, by compounding their forces the velocity along the diagonal is greater than it would be in a prismatic muscle. Thus no force is lost; and the bird is enabled to repeat the downward stroke much faster than if the prismatic form of muscle had been retained.

[To be continued.]

A CASE OF SMALL-POX USHERED IN WITH ROSEOLA VARIOLOSA.

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THERE are certain points of special interest in a case of small-pox formerly under my care in the Alice Hospital, Darmstadt, which render it somewhat worthy of notice at the present time. In reading the notes of the case, it will be observed that there was an almost total absence of premonitory symptoms at the commencement of the disease. The patient complained merely of slight headache and nausea, supposed to be due to the morphia given to relieve the sciatic pain. The invasion of the secondary fever was characterised by symptoms of unusual violence. Most commonly the secondary fever is noticed by an increase in the temperature. So it was in this case, but in addition there were repeated rigors of great severity. The first appearance of rash was in the right groin, where it was definitely localised. The eruption was from the first papular, but the papules were so closely aggregated together as to give a uniform aspect to the part, and this was more marked when the rash had spread to the left groin over the lower part of the abdomen. In his work on *Diseases of the Skin*, Hebra mentions some unusual

forms of rash noticed at an early stage of the disease, and "before the appearance of the true eruption." In one form—*roseola variolosa*—the duration of the efflorescence is very short, and it fades away as the characteristic papules become fully developed. In another form, he describes a rash which appears as a mere hyperæmia—or, in other instances, of an hæmorrhagic nature—at the lower part of the abdomen and upper parts of the thighs. The true small-pox eruption begins two or three days after its appearance. My case would seem more to resemble the *roseola variolosa*, differing from it, however, in the localisation of the rash, which rendered diagnosis extremely difficult, and caused no suspicion of small-pox. When the eruption had become more extended over the abdomen, it had some of the features of the second form described by Hebra.

The notes of the case are as follows. Carl Dietewig, aged 25, private in the 4th Hessian Infantry Regiment, was admitted into the Alice Hospital on December 11th, 1870. The patient stated that he had been ill for four weeks, during two of which he was in a lazareth near Orleans, with diarrhoea, but he had had no fever. On admission, he complained of pain in the course of the right sciatic nerve. This pain had continued for some days, and it had prevented him from walking. There was no tenderness on pressure, and no wasting of the limb. With this exception, he expressed himself, and to all appearances was, perfectly well.

Dec. 15th.—The patient could not sleep, owing to severe pain in the right sciatic region. In the evening he had a subcutaneous injection of a quarter of a grain of morphia.

Dec. 16th.—He slept well and had less pain. He complained of headache and a constant feeling of sickness.

Dec. 17th.—He was much the same as yesterday. A copious closely aggregated papular eruption appeared on the right groin. It was of a deep red hue. There was no irritation.

Dec. 18th.—The rash had spread over the lower part of the abdomen to the left groin, and as high as the umbilicus. The eruption was symmetrical. His appetite was good, and he felt well. The temperature at midday and in the evening was 104 deg. Fahr.

Dec. 19th.—Morning temperature 104 deg. Fahr.; pulse 120. Some fresh papules had appeared higher up on the abdomen, chest, forehead, and wrists. The evening temperature was 104.3 deg. Fahr.

Dec. 20th.—The morning temperature was 102.7 Fahr.; pulse 112. The patient had slept well. He had no pain. His appetite was good. The rash had spread copiously over the face, back, and arms. The papules were of a purple-red colour, and varied in size. On the abdomen where the spots were closely aggregated together, the appearance at a short distance was strikingly like that of erysipelas, though the colour was somewhat darker. On the back the papules were innumerable. On the original site of the rash—the right groin—the red blush was not so marked, and each isolated spot was not so red, nor so elevated. His face was uniformly swollen. There was some irritation about the eyes and nose. The evening temperature was 104 deg. Fahr.

Dec. 21st.—The morning temperature was 100.9 deg. Fahr.; pulse 104. On the right tonsil could be seen three or four white patches, each circumscribed, circular, and of the diameter of a small pea. On the right groin the eruption had almost disappeared. On the face it was in great part vesicular and pustular. The evening temperature was 103.1 deg. Fahr.; pulse 110.

Dec. 22nd.—The patient had slept well. With the exception of pain on swallowing, the patient said that he felt well. His face was very much swollen; eyes closed. On the arms each spot had a circumscribed red base; on this was an elevated flat disc of a pale yellow colour, and with a marked central depression. On the face many of the spots had run together. The tongue was thickly furred. He said that he was once vaccinated when a child, but no definite cicatrix was visible. The morning temperature was 99.5 deg. Fahr.; the evening temperature, 102.5 deg. Fahr.

Dec. 24th.—The morning temperature was 100.4 deg. Fahr. The patient slept well. He had no pain. This morning he had several "shivering" fits, during which his teeth chattered, and the bed was shaken violently. His legs were now covered with the eruption. The face was more swollen. Some of the spots on the face had burst. All were of a muddy yellow colour. He was said to have been breathing with difficulty, but at 6 P.M. there was no evident difficulty of respiration, and air entered his chest freely. His urine did not contain albumen. The evening temperature was 104.2 deg. Fahr.; pulse 120.

Dec. 25th.—In the morning the temperature was 104 deg. Fahr.; respiration 32. There was a great and apparent change for the worse. His breathing was anxious and laborious, and there was evidence of much obstruction. The face and hands were livid. He complained of "slime" in his throat. The patient died at 11.30 A.M. There was no necropsy.