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 III.—Tuesday, June 6th, 1871.

Application of the principle of Least Action to the Heart and other involuntary Muscles.—The Mechanism of the Heart explained, and the amount of work done by it.—“Experimentum crucis” of the entire Theory, derived from the measurements of the Fibres of the Heart of Man and the Ox.—General conclusions as to the future progress of Animal Mechanics and Comparative Anatomy, when subject to the Rule of Geometry, the Queen and Mistress of all the Sciences.

I HAVE reserved for my closing lecture to day the most wonderful and remarkable of all the examples I am able to give you of the application of the principle of least action to animal mechanics. It relates to a question which deeply interests every person in this room; it relates to the action of our hearts. It is my intention to endeavour to lay before you the work which is done by our hearts, and the manner in which those hearts do their work. The story of the heart is a most wonderful and mysterious story, and you must make allowance for the difficulty of the subject, and the defects of the lecturer, if I fail to convey perfectly to your minds all that is in my own mind respecting it. It is not easy to condense into one short hour the results of a labour of ten years. The progress of discovery is slow, and it is difficult to explain to those who have not been travelling in the same paths of research as myself, all the meaning and the bearings of the facts which I have to state; you will therefore, I hope, excuse me if occasionally you fail to see the connecting link that joins one part of my reasoning with another, and take for granted that if I had a longer time at my disposal, or more art in the mode of laying my materials before you, I could make you perfectly understand all that I know with regard to this subject.

We have first to consider the question of the amount of work which is done by our hearts. The heart is a small muscle weighing only a few ounces, and it beats perpetually day and night, summer and winter. Frequently an old man's heart approaching a hundred years of age will be found on examination as perfect a mechanism and as complete as it was when he was a young man of twenty. In order to measure the force and power of the human heart, the most obvious method that would suggest itself is one that is impossible to adopt, because it would require the death of the person on whom the experiment was made. We have experimented on the hearts of horses, oxen, sheep, dogs, and other animals. The first of these series of experiments were made by the celebrated Dr. Hales at the close of the last century: they consisted in measuring, by direct experiment with tubes, the amount of the hydrostatical pressure inside the cavities of the hearts of these animals. These experiments showed that the hydrostatical pressure inside the hearts of animals varies; in the horse and ox and larger animals amounting to a pressure of nine feet perpendicular of fluid blood, and in the smaller animals to somewhat less. From these experiments we can calculate without much difficulty the total amount of work which is done by the heart of a horse, the heart of an ox, the heart of a sheep, or the heart of a dog; but you will see it would be impossible to perform such an experiment upon our own hearts, because the experiment is necessarily accompanied with the death of the animal that is operated upon. We can calculate from these experiments also what I call the coefficient of capillary resistance. The heart pumps the blood through the large arteries of the body into the capillary vessels which permeate every tissue in our frames, and the great resistance to the action of the heart occurs in forcing the blood through these capillary vessels. I have placed before you here, as the result of direct experiment, the coefficient of capillary resistance of the sheep, $\frac{1}{18.6}$; the dog, $\frac{1}{16.6}$; the horse, $\frac{1}{39.3}$; the ox, $\frac{1}{39.8}$. You observe in the sheep and dog the coefficients are double what they are in the horse and ox. These

animals group themselves naturally together into the smaller animals with a double coefficient of resistance, and the larger animals with a single coefficient. Now with which of these groups of animals are we to associate ourselves in making a calculation as to the amount of work which is performed daily by our hearts? As I explained before, we cannot perform direct experiments upon the human subject; but an accident placed in my power the means of making a very close approximation to this remarkable result. When the artery of a horse or of a cow is cut, we can measure with ease the height to which the blood will spout into the air; and when the experiment is made, we are surprised at first to find that the artery does not spout to the height of nine feet. We can prove that there is an hydrostatical pressure inside the heart of the horse amounting to a nine feet column of blood, but when the artery is cut the blood will only spout to a height of two and a half feet, Nature making instinctively a spontaneous effort to shut off the pressure to save the animal from death by bleeding. If, therefore, we could by any process arrive at the precise height to which the blood would spout from our arteries if wounded, and compare them with the corresponding experiment in the sheep, the horse, and the ox, we should find which of these groups of animals man is most closely allied to with regard to the circulation of his blood.

On the 18th of March, in the year 1863, I witnessed an operation in the theatre of the Meath Hospital in Dublin, performed upon a poor man, in whom, from various circumstances, I felt an interest. I was merely a spectator at the operation, therefore I had leisure to witness a remarkable phenomenon, and to draw inferences from it, which I could not have done if I had been actively engaged. In the course of the operation, a large artery was cut in a very unusual place, and, therefore, some delay occurred in tying it. The blood spouted in jets from the wounded artery for a minute, or two minutes, before it could be tied. When the operation was over, I examined with care the height of the table on which the man lay. The floor, which had been recently cleaned, was covered with spurts of blood which had fallen from the wounded man, and, by the application of a little geometry to the problem, I was easily able to ascertain, by taking the height of the table and the farthest positions of the spots of blood on the floor, the velocity with which the blood issued from the wounded artery. The curve described by the blood is a parabola, and, given two points on the parabola, every geometer knows that we can construct the parabola and calculate the angle of elevation and the velocity with which the fluid is projected. As soon as I had made this calculation, I found that if I had cut the artery of a man, and allowed the blood to spout directly into the air, it would spout to the height of 2.58 feet. Taking the mean of all Dr. Hales's experiments upon horses, I find that 2.53 feet is the height to which the heart of a horse will spout. We now have a most important and valuable result. We cannot compare directly the hydrostatical pressure inside the human heart with the hydrostatical pressure inside the heart of an ox, or of a cow, or of a horse: but we can, by this determination of the velocity of spouting blood, show a close relationship between the circulation in our own frames and the circulation in these animals, and, therefore, we may apply with confidence the coefficient of resistance which we find in the horse and the ox to our own cases. When this coefficient of resistance is used in the case of man, and the calculation is completed, we find the hydrostatical pressure inside the human heart to amount to 9.923 feet of blood; and, by using the number of times the heart beats—seventy times each minute—and the quantity of blood projected from the heart at each contraction, we can calculate, by very simple and elementary processes, the work done in a given time by the human heart. Now this work I shall represent for you in a form extremely easy to remember—a form which will show you the extraordinary amount of work that is done. I shall suppose that I cut out an ounce of muscle from the heart, and that I ask myself this question, What number of pounds can that contracting muscle lift in the course of a minute? I find that the contracting muscle, a single ounce in weight, of the human heart, will lift 20,576 pounds through the height of one foot in a minute. This I believe to be a very close approximation to the power of the heart; but, inasmuch as it was not obtained by direct, but by indirect reasoning, I thought it desirable to proceed to verify it by another process; and, in the verification of this coefficient of muscular force of the heart by a second process, I made use of a very interesting phenomenon. This phenomenon was observed by the celebrated Dr. Wollaston, who wrote a paper upon it, which is published in the *Philosophical Transactions* for 1809. Dr. Wollaston was the first person who noticed that, when our muscles are contracted, they give out a deep musical note. If any of you wish to repeat the experiment for yourselves, and satisfy yourselves about it, I will inform you of the simplest modes of doing so. If you go into a room by yourself in perfect silence, place your elbows firmly on the table, and close your ears

lightly with the forefingers, clenching the muscles of the forearm, you will hear immediately a deep musical hum, which never can be confounded with any other sound you heard before. Dr. Wollaston compares it most accurately to the rumbling sound produced by the noise of cabs driving over the pavement in the silence of the night. Or if you awaken at night and clench your teeth so as to call the masseter muscles into action, you will hear with the ear that lies next the pillow, which acts as a sounding board, this deep hum, which you can destroy by ceasing to clench your teeth, and renew at pleasure. You can, therefore, very soon satisfy yourself that the act of contracting the muscles is accompanied by some phenomenon that takes place in rapid succession, comparable with the motions that produce a musical note. My attention was first directed to this curious subject in a remarkable way; and it so happened that a young physician of Marseilles in a similar way was attracted to the study of this curious phenomenon. Dr. Collongues of Marseilles had charge of the cholera hospital in that town; and he observed, in studying some of the cases which had died, a remarkable fact. Dr. Collongues in Marseilles, and myself in Dublin, pursued our studies each without knowing that the other was engaged in them. A patient in cholera has his temperature much lower than the natural heat of the blood, which is 98 deg.; and it is well known to physicians that in diseases like fever, if the blood-heat rise some seven or eight degrees above that, the patient will die. It is equally well known that in diseases like cholera, if the blood-heat fall more than seven or eight degrees below 98, the patient will die. Therefore it is a strange fact that, when you examine the body of a person who has died of cholera, when you put your hand upon the body, it is warm; the temperature, which was 90 deg. before death, rises after death to 103 or 104 deg., just as if the person were still living and in the height of a violent fever. This is accompanied also with spontaneous movements occasionally of the limbs, which cause great alarm to persons who are not acquainted with this curious fact. Happening accidentally to place my ear against the arm of a patient who had died of cholera, to my astonishment I heard the well known musical hum. I sprang to my feet, and at once placed my ear to the man's heart, thinking that he was alive, and that I might be able to save him; but he was dead. The heart had ceased to beat, but the muscles still continued to live. The heart has been called by ancient physiologists the first to live and the last to die—*primum vivens, ultimum moriens*; but that is not true in cases of cholera. After the heart has ceased to live, after the brain has ceased to act, when the man is dead, his muscles live; their temperature rises, and the last traces of life remain in the body like the lingering music of the chords of a harp which the master's hand has ceased to play. I resolved to try and ascertain the precise note of this musical hum. I constructed a number of organ-pipes, and succeeded, by processes that would be too long to describe to you here, in imprisoning the musical hum in one of these pipes, where I could afterwards measure it at my leisure and determine its character. I had an organ-pipe made accurately to vibrate the note two octaves below C in the bass, which corresponds with thirty-two double vibrations in a second. The note two octaves below D in the bass corresponds with thirty-six double vibrations in the second. Now a very little trial showed me that the musical note of a muscle lay between these two notes. By fixing a second organ-pipe as exactly as I could to the musical hum of my own muscles, and then comparing the notes of the two organ-pipes by their beats, I was enabled to ascertain with, I believe, a considerable degree of precision, the exact note of the musical tone produced by the contraction of the muscles. This I made to be thirty-five and one-third vibrations per second. Shortly after I published this result, Dr. Collongues, who had moved from Marseilles to Paris, sent me a book which he had published a short time before my own, in which he had succeeded in proving, by measurements made with tuning-forks, that the vibration corresponding to the hum of the muscular contraction is thirty-six. This very remarkable result, obtained by two totally different methods of experimenting—by myself in Dublin with organ-pipes, and by Dr. Collongues in Marseilles with tuning-forks—immediately attracted attention. Dr. Collongues naturally was very uneasy about the question of priority; and I took the opportunity of calling upon him in Paris to explain to him that I admitted his priority, and that I was more pleased to find that we had succeeded independently of each other in obtaining the same note, than if I had myself established a claim to have made the first discovery. At the close of our interview, which was very friendly, he embraced me. He had a long black beard, and I have a distinct recollection that it smelt very strongly of tobacco.

My object in determining the musical note of a muscular contraction was to calculate by a second process a coefficient which would represent the amount of work that an ounce weight of muscle would be able to perform. The manner in which I conducted the experiments

was as follows. I held my arms horizontally, asking a friend to see that they neither rose above nor fell below the horizontal line. I held them in that position until I was completely tired; then I placed different weights on my arm in the same position, and I tried the experiment with many others. You will be astonished, if you try the experiment, how short a time you can hold out your arms perfectly horizontally. In this way, if I knew the rate at which muscular contraction takes place in the arms so held out, it was easy for a mathematician to calculate the amount of work done by each ounce of muscle engaged in holding up those arms. I had found that the musical note of the muscle vibrated thirty-five or thirty-six times in the second; and, having first got that fact, from the experiments made with holding weights in my extended arms, I was able to determine a second coefficient to be compared with the other which I had previously deduced from the hydrostatical pressure; viz., 20.576 lbs. This second coefficient came out exactly 20 lbs.; that is, the weight that can be lifted by an ounce of muscle of the heart through one foot in a single minute. This result I believe any experimenter on such subjects will admit to come in a reasonable degree close to that which I obtained from the hydrostatical pressure of the heart. I am, therefore, entitled to consider that somewhere about 20 lbs. can be lifted by every ounce of my heart in a single minute. But this conveys to your minds no adequate conception of the enormous amount of work which that represents. If I said 40 lbs. or 50 lbs. it would convey no impression to your minds; I therefore devised a plan for the purpose of showing you in this lecture how much you ought to wonder at the great work performed by the heart. I obtained from Mr. Robert Main in Oxford, and Mr. Maclaren, the celebrated trainer, the length of the Oxford and Cambridge boat-race course, and the cross-sections and plans of the Oxford eight-oared boat. The average time in which the race is rowed (it has been rowed twenty-one times in twenty-one years over the same course) is 23 minutes 3½ seconds, and the length of the course is 4.31 miles. From these data, and from the plans and sections of the boats kindly supplied by Mr. Maclaren, I was enabled, by using Professor Rankine's well-known formulæ for the resistance of ships, to determine the amount of work done by the muscles of the young men who pull in this hardly contested race. I find that during the twenty-three minutes the race lasts, every ounce of muscle in the arms and legs of the rowers works at the rate of 20.124 lbs. lifted through one foot each minute. This comes out to be very much like the amount of the work that my heart is doing at this moment; indeed, I am not sure that it is not doing more work than that now while I am lecturing. In the case of the young men who pull in this race for twenty-three minutes, every ounce of muscle in their arms and legs gives out a force that in a minute would lift 20 lbs. through a foot. If any of you have seen the exhausted condition of those young men when taken out of their boats after twenty-three minutes, you will, I think, agree with me that human nature could not endure such labour for forty minutes; yet the heart of an old man close upon a hundred years of age has worked for that hundred years of his life as hard as the muscles of the young men that pull in the Oxford and Cambridge eight-oared races.

[To be continued.]

A CHILD SERIOUSLY MUTILATED BY A YOUNG DOG.

On the 22nd May, a fine healthy child, aged twelve months, was left in a cradle by his mother while she went out for an errand. On her return, she found the child being sadly worried by a young terrier dog, six months old, that had been left with him in the house. Upon examination, I found the genital organs much mutilated. The poor little fellow was pale, fretful, and exhausted from loss of blood. Fully one-third of the scrotum was bitten off; no trace of a testicle was left; the prepuce was stripped off, and the glans all but separated from the body of the penis; the urethra was also pierced in two or three places. The treatment consisted simply in the application of a piece of lint soaked in a compound of lead-solution with sweet oil, frequently renewed; under this, the wounds soon healed nicely. For the first few days, he experienced considerable difficulty in micturition, but at present the urine is passed easily and freely through the natural passage. He now begins to crawl about, and is as lively as ever. Should my unlucky little patient ever attain the age of puberty, it will be interesting then to watch the progress of the case.

It may be asked what became of the brutish whelp. Strange to relate, the father of the child felt most unwilling to do away with his favourite young dog; however, one day I pretended to be anxious to examine the dog's teeth, and upon his jaws being separated, I at once gave him the benefit of a few drops of Scheele's acid, which instantly had a very desirable and most soothing effect.

JOHN WILLIAM.

Pen-y-groes, Carnarvon, 8th June, 1871.