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Origin of Muscular Power

by

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ON

THE ORIGIN OF MUSCULAR POWER.

BY

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UNDER this title there appeared in a recent Number of the Philosophical Magazine an able article by Professors Fick and Wislicenus*, in which these gentlemen describe the results of experiments made upon themselves before, during, and after an ascent of the Faulhorn in Switzerland. In these experiments the amount of measured work performed in the ascent of the mountain was shown to exceed, by more than three-fourths, the amount which it would be theoretically possible to realize from the maximum amount of muscle-oxidation indicated by the total quantity of nitrogen in the urine.

The data afforded by these experiments appear to me to render utterly untenable the theory that muscular power is derived from muscle-oxidation. Nevertheless, in the application of these data to the problem under consideration, one important link was found to be wanting, viz. the amount of actual energy generated by the oxidation of a given weight of muscle in the human body. Fick and Wislicenus refer to this missing link in the following words:—"The question now arises, what quantity of heat is generated when muscle is burnt to the products in which its constituent elements leave the human body through the lungs and kidneys? At present, unfortunately, there are not the experimental data required to give an accurate answer to this important question; for neither the heat of combustion of muscle, nor of the nitrogenous *residue* of muscle (urea), is known."

* Phil. Mag. vol. xxxi. p. 485.

Owing to the want of these data, the numerical results of the experiment of Fick and Wislicenus are rendered less conclusive against the hypothesis of muscle-oxidation than they otherwise would have been; whilst similar determinations which have been made by Edward Smith, Haughton, Playfair, and others are even liable to a total misinterpretation from the same cause.

I have endeavoured to supply this want by the calorimetrical determination of the actual energy evolved by the combustion of muscle and of urea in oxygen: but, inasmuch as uric and hippuric acids frequently appear in the urine as products of a less perfect muscle-oxidation, I have also determined the calorific value of these substances, and have added purified albumen and beef fat to the list. Creatin would also have been included; but, although I was furnished with an ample supply of this substance through the kindness of Dr. Dittmar, all attempts to burn it in the calorimeter were fruitless. In numerous trials under varied conditions it always exploded violently on ignition.

The determination of the actual energy developed by the combustion of the above-named substances is surrounded by formidable difficulties, which have probably prevented their previous execution. It is impossible to effect their complete combustion in oxygen gas, under conditions which permit of the accurate measurement of the heat evolved; but preliminary experiments showed that complete oxidation could be secured by deflagration with potassic chlorate; and, although this method is doubtless inferior in accuracy to the calorimetrical methods usually employed, it is hoped that, with the corrections described below, the results obtained merit sufficient confidence to render them useful in subsequent discussions of this and allied subjects. The determinations were made in a calorimeter devised some years ago by Lewis Thompson, and which I have repeatedly used with satisfaction in other determinations of a like kind. This instrument consists of a copper tube made to contain a mixture of potassic chlorate with the combustible substance, and which can be enclosed in a kind of diving-bell, also of copper, and so lowered to the bottom of a suitable vessel containing a known quantity (2 litres) of water. The experiments were conducted in the following manner:—19·5 grams* of chlorate of potash, to which about one-eighth of manganic oxide was added, were intimately mixed with a known weight (generally about 2 grams) of the substance whose thermal value was to be determined; and the mixture being then placed in the copper tube above mentioned, a small piece of cotton thread, previously

* I follow the example of the Registrar-General in abbreviating the French word *gramme* to gram.

steeped in potassic chlorate and dried, was inserted in the mixture. The temperature of the water in the calorimeter was now carefully ascertained by a delicate thermometer, and, the end of the cotton thread being ignited, the tube with its contents was placed in the copper bell and lowered to the bottom of the water. As soon as the combustion reached the mixture, a stream of gases issued from numerous small openings at the lower edge of the bell and rose to the surface of the water—a height of about 10 inches. At the termination of the deflagration, the water was allowed free access to the interior of the bell, by opening a stopcock connected with the bell by a small tube rising above the surface of the water in the calorimeter. The gases in the interior of the bell were thus displaced by the incumbent column of water; and by moving the bell up and down repeatedly, a perfect equilibrium of temperature throughout the entire mass of water was quickly established. The temperature of the water was again carefully observed; and the difference between this and the previous observation gives the calorific power, or the potential energy, of the substance consumed, expressed as heat.

The value thus obtained, however, is obviously subject to the following corrections:—

1. The amount of heat absorbed by the calorimeter and apparatus employed: *to be added.*

2. The amount of heat carried away by the escaping gases after issuing from the water: *to be added.*

3. The amount of heat due to the decomposition of the chlorate of potash employed: *to be deducted.*

4. The amount of heat equivalent to the work performed, by the gases generated, in overcoming the pressure of the atmosphere: *to be added.*

Although the errors due to these causes to some extent neutralize each other, there is still an outstanding balance of sufficient importance to require that the necessary corrections should be carefully attended to.

The amount of error from the first cause was once for all experimentally determined, and was added to the increase of temperature observed in each experiment.

The amount of heat carried away by the escaping gases after issuing from the water may be divided into two items, viz.:—

α. The amount of heat rendered latent by the water which is carried off by the gases in the form of vapour.

β. The amount of heat carried off by these gases by reason of their temperature being above that of the water from which they issue.

It was ascertained that a stream of dry air passed through the water of the calorimeter at about the same rate and for the same period of time as the gaseous products of combustion, depressed the temperature of the water by only 0°·02 C.

By placing a delicate thermometer in the escaping gases, and another in the water, no appreciable difference of temperature could be observed. Both these corrections may therefore be safely neglected.

The two remaining corrections can be best considered together, since a single careful determination eliminates both. When a combustible substance is burnt in gaseous oxygen, the conditions are essentially different from those which obtain when the same substance is consumed at the expense of the combined or solid oxygen of potassic chlorate. In the first case the products of combustion, when cooled to the temperature of the water in the calorimeter, occupy less space than the substances concerned in the combustion, and therefore no part of the energy developed is expended in external work—that is, in overcoming the pressure of the atmosphere. In the second case both the combustible and the supporter of combustion are in the solid condition, whilst a considerable proportion of the products of combustion are gases. The generation of the latter cannot take place without the performance of external work; for every cubic inch produced must obviously, in overcoming atmospheric pressure, perform an amount of work equivalent in round numbers to the lifting of a weight of 15 lbs. to the height of one inch. In performing this work the gases are cooled, and consequently less heat is communicated to the water of the calorimeter. Nevertheless the loss of heat due to this cause is but small. Under the actual conditions of the experiments detailed below, its amount would only have increased the temperature of the water in the calorimeter by 0°·07 C. Even this slight error is entirely eliminated by the final correction which we have now to consider.

It is well known that the decomposition of potassic chlorate into potassic chloride and free oxygen is attended with the evolution of heat: if a few grains of manganic oxide, or, better, of ferric oxide, be dropped into an ounce or two of fused potassic chlorate, which is slowly disengaging oxygen, the evolution of gas immediately proceeds with great violence, and the mixture becomes visibly red-hot, although the external application of heat be discontinued from the moment when the metallic oxide is added. The latter remains unaltered at the close of the operation. It is thus obvious that potassic chlorate, on being decomposed, furnishes considerably more heat than that which is necessary to gasify the oxygen which it evolves. It was therefore necessary to determine the amount of heat thus evolved by the quantity of potassic chlorate (9·75 grms.) mixed with one gram of the substance burnt in each of the following determinations. This was effected by the use of two copper tubes, the one placed within the other. The interior tube was charged with a known weight of the same mixture of potassic chlorate and manganic oxide as that used for the subsequent experiments, whilst the annular space between the two tubes was filled with a combustible mixture of chlorate and spermaceti, the calorific value of which had been previously ascertained. The latter mixture was ignited in the calorimeter as before; and the heat generated during its combustion effected the complete decomposition of the chlorate in the interior cylinder, as was proved by a subsequent examination of the liquid in the calorimeter, which contained no traces of undecomposed chlorate. The following are the results of five experiments thus made, expressed in units of heat, the unit being equal to 1 gram of water raised through 1° C. of temperature.

First experiment	340
Second experiment . . .	300
Third experiment . . .	375
Fourth experiment . . .	438
Fifth experiment . . .	438
	1891
Mean	378

This result was confirmed by the following experiments:—

(1) Starch was burnt, first, in a current of oxygen gas, and secondly by admixture with potassic chlorate and manganic oxide.

Heat-units furnished by 1 grm. of starch burnt with 9·75 grms. of potassic chlorate . .	4290
Heat-units furnished by the same weight of starch burnt in a stream of oxygen gas . . .	3964
Difference	326

(2) Phenylic alcohol was burnt with potassic chlorate, and the result compared with the calorific value of this substance as determined by Favre and Silbermann.

Heat-units furnished by 1 grm. of phenylic alcohol burnt with 9·75 grms. potassic chlorate.	8183
Heat-units furnished by 1 grm. of phenylic alcohol when burnt with gaseous oxygen (Favre and Silbermann)	7842
Difference	341

These three determinations of the heat evolved by the decomposition of 9·75 grms. of potassic chlorate, furnishing the numbers 378, 326, and 341, agree as closely as could be expected when it is considered that all experimental errors are necessarily thrown upon the calorific value of the potassic chlorate.

The mean of the above five experimental numbers was in all cases deducted from the actual numbers read off in the following determinations.

It was ascertained by numerous trials that all the potassic chlorate was decomposed in the deflagrations, and that but mere traces of carbonic oxide were produced.

Joule's mechanical equivalent of heat was employed, viz. 1 kilog. of water raised 1° C. =423 metrekilogs.

The following results were obtained :—

Actual Energy developed by 1 grm. of each substance when burnt in Oxygen.

Name of substance (dried at 100° C.).	Heat-units.					Metre-kilogs. of force. (Mean.)
	1st Exp.	2nd Exp.	3rd Exp.	4th Exp.	Mean.	
Beef muscle purified by repeated washing with ether ...	5174	5062	5195	5088	5103	2161
Purified albumen...	5009	4987	......	......	4998	2117
Beef fat	9069	......	......	......	9069	3841
Hippuric acid	5330	5437	......	......	5383	2280
Uric acid	2645	2585	......	......	2615	1108
Urea..................	2121	2302	2207	2197	2206	934

It is evident that the above determination of the actual energy developed by the combustion of muscle in oxygen represents more than the amount of actual energy produced by its oxidation within the body, because when muscle burns in oxygen its carbon is converted into carbonic acid, and its hydrogen into water, the nitrogen being to a great extent evolved in the elementary state; whereas when muscle is most completely consumed in the body the products are carbonic acid, water, and urea: the whole of the nitrogen passes out of the body as urea, a substance which still retains a considerable amount of potential energy. Dry muscle and pure albumen yield, under these circumstances, almost exactly one-third of their weight of urea; and this fact, together with the above determination of the actual energy developed on the combustion of urea, enables us to deduce with certainty the amount of actual energy developed by muscle and albumen respectively when consumed in the human body. It is as follows :—

Actual Energy developed by 1 grm. of each substance when consumed in the body.

Name of substance (dried at 100° C.).	Heat-units. (Mean.)	Metrekilogs. of force. (Mean.)
Beef muscle purified by ether ...	4368	1848
Purified albumen	4263	1803

Interpolating the data thus obtained into the results of Fick and Wislicenus's experiments, let us now compare the amount of measured and calculated work performed by each of the experimenters during the ascent of the Faulhorn, with the actual energy capable of being developed by the maximum amount of muscle that could have been consumed in their bodies, this amount being represented by the total quantity of nitrogen excreted in each case during the ascent and for six hours afterwards.

	Fick.	Wislicenus.
Weight of dry muscle consumed	37·17 grms.	37·00 grms.
Actual energy capable of being produced by the consumption of 37·17 and 37·00 grms. of dry muscle in the body	68,690 metrekilogs.	68,376 metrekilogs.
Measured work performed in the ascent (external work)	129,096 metrekilogs.	148,656 metrekilogs.
Calculated circulatory and respiratory work performed during the ascent (internal work)	30,541 metrekilogs.	35,631 metrekilogs.
Total ascertainable work performed .	159,637 metrekilogs.	184,287 metrekilogs.

The actual energy capable of being produced by the consumption of 37·17 and 37·00 grms. of dry muscle in the body was *estimated* by Fick and Wislicenus at 106,250 and 105,825 metrekilogs.

The experimental determination of the actual energy developed by muscle-oxidation renders it now abundantly evident that the muscular power expended by these gentlemen in the ascent of the Faulhorn could not be exclusively derived from the oxidation either of their muscles or of other nitrogenous constituents of their bodies, since the maximum of power capable of being derived from this source, even under very favourable assumptions, is in both cases less than one-half of the work actually performed; but the deficiency becomes much greater if, as Fick and Wislicenus have done, we take into consideration the fact that the actual energy developed by oxidation or combustion cannot be wholly transformed into mechanical work. In the best-constructed steam-engine, for instance, only one-tenth of the actual energy developed by the burning fuel can be obtained in the form of mechanical power; and in the case of man, Helmholtz estimates that not more than one-fifth of the actual energy developed in the body can be made to appear as external work. The experiments of Heidenhain, however, show that under favourable circumstances a muscle may be made to yield, in the shape of mechanical work, as much as one-half of the actual energy developed within it, the remainder assuming the form of heat. Taking, then, this highest estimate of the proportion of mechanical work capable of being got out of actual energy, it becomes necessary to multiply by 2 the above numbers representing the ascertainable work performed, in order to express the actual energy involved in the production of that work. We then get the following comparison of the actual energy capable of being developed by the amount of muscle consumed, with the actual energy necessary for the performance of the work executed in the ascent of the Faulhorn.

	Fick.	Wislicenus.
	metrekilogs.	metrekilogs.
Actual energy capable of being produced by muscle-metamorphosis .	68,690	68,376
Actual energy expended in work performed	319,274	368,574

Thus, taking the average of the two experiments, it is evident that scarcely one-fifth of the actual energy required for the work performed could be obtained from the amount of muscle consumed.

Interpreted in the same way, previous experiments of a like kind prove the same thing, though not quite so conclusively. To illustrate this, I will here give a summary of three sets of experiments,—the first, made by Dr. E. Smith upon prisoners engaged in treadmill labour; the second, by the Rev. Dr. Haughton upon military prisoners engaged in shot drill; and the third, adduced by Playfair, and made upon pedestrians, pile-drivers, men turning a winch, and other labourers.

Treadwheel Experiments.

A treadwheel is a revolving drum with steps placed at distances of 8 inches, and the prisoners are required to turn the wheel downwards by stepping upwards. Four prisoners, designated below as A, B, C, and D, were employed in these experiments; and each worked upon the wheel in alternate quarters of an hour, resting in a sitting posture during the intervening quarters. The period of actual daily labour was 3½ hours. The total ascent per hour 2160 feet, or per day 1·432 mile. The following are the results:—

Treadweel Work. (E. Smith.)

	Weight in kilogs.	Ascent in metres.	Days occupied in ascent.	External work performed in metre-kilogs.	Total nitrogen evolved.	Weight of dry muscle corresponding to nitrogen.
					grms.	grms.
A	47·6	23,045	10	1,096,942	171·3	1101·2
B	49	23,045	10	1,129,205	174·5	1121·7
C	55	20,741	9	1,140,755	168·0	1080·1
D	56	20,741	9	1,161,496	159·3	1024·3

In these experiments the measured work was performed in the short space of 3½ hours, whilst the nitrogen estimated was that voided in the shape of urea in twenty-four hours. It will therefore be necessary to add to the measured work that calculated for respiration and circulation for the whole period of twenty-four hours. This amount of internal work was computed from the estimates of Helmholtz and Fick as follows:—

Internal Work. (Helmholtz and Fick.)

	Work performed.	Actual energy required.
	metrekilogs.*	metrekilogs.
Circulation of the blood during 24 hours at 75 pulsations per minute	69,120	138,240
Respiration for 24 hours at 12 pulsations per minute	10,886	21,772
Statical activity of muscles	Not determined.	Not determined.
Peristaltic motion	" "	" "
	80,006	160,012

Taking this estimate for internal work, the average results of the treadwheel experiments may be thus expressed:—

* Since making use of this number I find that Donders estimates the work of the heart alone for twenty-four hours at 86,000 metrekilograms, a figure which is higher than that used above for the combined work of circulation and respiration.

Treadwheel Work.

Average external work per man per day	119,605 metrekilogs.
Average nitrogen evolved per man per day	17·7 grms.
Weight of dry muscle corresponding to average nitrogen evolved per day	114 "
Actual energy producible by the consumption of 114 grms. dry muscle in the body	210,672 metrekilogs.

Average actual energy developed in the body of each man, viz.

External work	119,605 × 2 = 239,210	metrekilogs.
Circulation	69,120 × 2 = 138,240	"
Respiration	10,886 × 2 = 21,772	"
	399,222	"

In these experiments the conditions were obviously very unfavourable for the comparison of the amount of actual energy producible from muscle-metamorphosis with the quantity of actual energy expended in the performance of estimable work, since, during that portion of the twenty-four hours not occupied in the actual experiment, a large amount of unestimable internal work, such as the statical activity of the muscles, peristaltic motion, &c., was being performed. Nevertheless these experiments show that the average actual energy developed in producing work in the body of each man was nearly twice as great as that which could possibly be produced by the whole of the nitrogenous matter oxidized in the body during twenty-four hours. It must also be remarked that the prisoners were fed upon a nitrogenous diet containing 6 ounces of cooked meat without bone—a diet which, as is well known, would favour the production of urea.

Shot-drill Experiments.

The men employed for these experiments were fed exclusively upon a vegetable diet, and they consequently secreted a considerably smaller amount of nitrogen than the flesh-eaters engaged in the treadwheel work; the other conditions were, however, equally unfavourable for showing the excess of work performed over the amount derivable from muscle-metamorphosis.

In shot drill each man lifts a 32-lb. shot from a tressel to his breast, a height of 3 feet; he then carries it a distance of 9 feet and lays it down on a similar support, returning unloaded. Six of these double journeys occupy one minute. The men were daily engaged with

Shot drill	3 hours.
Ordinary drill	$1\frac{1}{4}$ "
Oakum-picking	$3\frac{1}{2}$ "

The total average daily external work was estimated by Haughton at 96,316 metrekilogs. per man. The following is a condensed summary of the results of these experiments :—

Military Vegetarian Prisoners at Shot Drill. (*Haughton.*)

Average external work per man per day	96·316 metrekilogs.
Average nitrogen evolved per man per day	12·1 grms.
Weight of dry muscle corresponding to average nitrogen evolved per day	77·9 „
Actual energy producible by the consumption of 77·9 grms. of dry muscle in the body	143,950 metrekilogs.

Average actual energy developed daily in the body of each man, viz.

External work 96,316 × 2 . . .	=192,632 metrekilogs.
Internal work	=160,012 „
	352,644 „

Owing chiefly to the vegetable diet of these prisoners, this result is more conclusive than that obtained upon the treadwheel, the amount of work actually performed being considerably more than twice as great as that which could possibly be obtained through the muscle-metamorphosis occurring in the bodies of the prisoners.

Playfair's Determinations.

In these determinations the number 109,496 metrekilograms was obtained as the average amount of daily work performed by pedestrians, pile-drivers, porters, paviours, &c.; but as the amount of muscle-consumption is calculated from the nitrogen taken in the food, the conditions are as unfavourable as possible with regard to the point I am seeking to establish; for it is here assumed, not only that all the nitrogen taken in the food enters the blood, but also that it is converted into muscle, and is afterwards oxidized to carbonic acid, water, and urea.

The following are the results, expressed as in the previous cases :—

Hard-worked Labourer (Playfair).

	Work performed.	Actual energy required.
	metrekilogs.	metrekilogs.
Daily labour (external work)....	109,496	218,992
Internal work	80,006	160,012
	189,502	379,004

Actual energy capable of being produced from 5·5 oz. (155·92 grms.) of flesh-formers contained in the daily food of the labourer ...... metrekils. 288,140

Thus, even under the extremely unfavourable conditions of these determinations, the actual work performed exceeded that which could possibly be produced through the oxidation of the nitrogenous constituents of the daily food by more than 30 per cent.

We have seen, therefore, in the above four sets of experiments, interpreted by the data afforded by the combustion of muscle and urea in oxygen, that the transformation of tissue alone cannot account for more than a small fraction of the muscular power developed by animals; in fact this transformation goes on at a rate almost entirely independent of the amount of muscular power developed. If the mechanical work of an animal be doubled or trebled, there is no corresponding increase of nitrogen in the secretions; whilst it was proved, on the other hand, by Lawes and Gilbert as early as the year 1854, that animals under the same conditions as regarded exercise, had the amount of nitrogen in their secretions increased twofold by merely doubling the amount of nitrogen in their food. Whence, then, comes the muscular power of animals? What are the substances which, by their oxidation in the body, furnish the actual energy whereof a part is converted into muscular work? In the light of the experimental results detailed above, can it be doubted that a large proportion of the muscular power developed in the bodies of animals has its origin in the oxidation of non-nitrogenous substances? For, whilst the secretion of nitrogen remains nearly stationary under widely different degrees of muscular exertion, the production of carbonic acid increases most markedly with every augmentation of muscular work, as is shown by the following tabulated results of E. Smith's highly important experiments upon himself, regarding the amount of carbonic acid evolved under different circumstances*.

Excretion of carbonic acid during rest and muscular exertion:—

	Carbonic acid per hour.
During sleep	19·0 grams.
Lying down, and sleep approaching .	23·0 ,,
In a sitting posture	29·0 ,,
Walking at the rate of 2 miles per hour	70·5 ,,
Walking at the rate of 3 miles per hour	100·6 ,,
On the treadwheel, ascending at the rate of 28·65 feet per minute. . .	189·6 ,,

It is admitted on all hands that food, and food alone, is the ultimate source from which muscular power is derived; but the above determinations and considerations prove conclusively, first, that the non-nitrogenous constituents of the food, such as

* Phil. Trans. for 1859, page 709.

starch, fat, &c., are the chief sources of the actual energy which becomes partially transformed into muscular work; and secondly, that the food does not require to become organized tissue before its metamorphosis can be rendered available for muscular power, its digestion and assimilation into the circulating fluid (the blood) being all that is necessary for this purpose. It is, however, by no means the non-nitrogenous portions of food alone that are capable of being so employed—the nitrogenous also, inasmuch as they are combustible, and consequently capable of furnishing actual energy, might be expected to be available for the same purpose; and such an expectation is confirmed by the experiments of Savory upon rats*, which show that these animals can live for weeks in good health upon food consisting almost exclusively of muscular fibre. Even supposing these rats to have performed no external work, nearly the whole of their internal muscular work must have had its source in the actual energy developed by the oxidation of their strictly nitrogenous food.

It can scarcely be doubted, however, that the chief use of the nitrogenous constituents of food is for the renewal of muscular tissue—the latter, like every other part of the body, requiring a continuous change of substance; whilst the chief function of the non-nitrogenous is to furnish, by their oxidation, the actual energy which is in part transmuted into muscular force.

The combustible food and oxygen coexist in the blood which courses through the muscle; but when the muscle is at rest, there is no chemical action between them. A command is sent from the brain to the muscle, the nervous agent determines oxidation. The potential energy becomes actual energy, one portion assuming the form of motion, another appearing as heat. *Here is the source of animal heat, here the origin of muscular power!* Like the piston and cylinder of a steam-engine, the muscle itself is only a machine for the transformation of heat into motion; both are subject to wear and tear, and require renewal; but neither contributes in any important degree, by its own oxidation, to the actual production of the mechanical power which it exerts.

From this point of view it is interesting to examine the various articles of food in common use, as to their capabilities for the production of muscular power. I have therefore made careful estimations of the calorific value of different materials used as food, with the same apparatus and in the same manner as described above for the determination of the actual energy in muscle, urea, &c. The results are embodied in the following series of Tables;

* The Lancet, 1863, pages 381 and 412.

but it must be borne in mind that it is only on the condition of the food being digested and passed into the blood, that the results given in these Tables are realized. If, for instance, saw-dust or paraffin oil had been experimented upon, numbers would have been obtained for these substances, the one about equal to that assigned to starch, and the other surpassing that of any article in the Tables; but these numbers would obviously have been utterly fallacious, inasmuch as neither sawdust nor paraffin oil is, to any appreciable extent, digested in the alimentary canal. Whilst the force-values experimentally obtained for the different articles in these Tables must therefore be understood as the maxima assignable to the substances to which they belong, yet it must not be forgotten that a large majority of these substances appear to be completely digestible under normal circumstances.

TABLE I.—Results of Experiments with Food dried at 100° C., in heat-units.

Name of food.	Heat-units. 1st Exp.	Heat-units. 2nd Exp.	Heat-units. 3rd Exp.	Heat-units. (Mean.)
Cheshire cheese	6080	6149	......	6114
Potatoes	3752	......	......	3752
Apples	3776	3562	......	3669
Mackerel	5994	6134	......	6064
Oatmeal (not dried)	4143	4018	3857	4004
Lean beef	5271	5260	5410	5313
White of egg	4823	4940	4927	4896
Carrots	3776	3759	......	3767
Pea-meal (not dried)	3866	4006	......	3936
Flour (not dried)	3941	3931	......	3936
Arrowroot (not dried)	3923	3902	......	3912
Butter	7237	7291	......	7264
Ham boiled and lean	4188	4498	......	4343
Lean veal	4459	4595	4488	4514
Hard-boiled egg	6455	6187	......	6321
Yelk of egg	6460	......	......	6460
Isinglass	4520	4520	......	4520
Cabbage	3809	3744	......	3776
Whiting	4520	4520	......	4520
Ground rice (not dried)	3802	3824	......	3813
Cod-liver oil	9134	9080	......	9107
Cocoa nibs (not dried)	6809	6937	......	6873
Residue of milk	5066	5120	......	5093
Bread crumb	3984	3984	......	3984
Bread crust (not dried)	4459	......	......	4459
Lump sugar (not dried)	3403	3294	......	3348
Commercial grape-sugar (not dried)	3277	3277	......	3277
Residue from bottled ale	3776	3744	......	3760
Residue from bottled stout	6348	6455	......	6401

TABLE II.—Actual Energy developed by 1 gram of various articles of Food when burnt in Oxygen.

Name of food.	Heat-units.		Metrekilograms of force.		Per cent. of water.
	Dry.	Natural condition.	Dry.	Natural condition.	
Cheese (Cheshire)	6114	4647	2589	1969	24·0
Potatoes	3752	1013	1589	429	73·0
Apples	3669	660	1554	280	82·0
Oatmeal	......	4004	......	1696	
Flour	......	3936	......	1669	
Pea-meal	......	3936	......	1667	
Ground rice	......	3813	......	1615	
Arrowroot	......	3912	......	1657	
Bread crumb	3984	2231	1687	945	44·0
Bread crust	......	4459	......	1888	
Beef (lean)	5313	1567	2250	664	70·5
Veal	4514	1314	1912	556	70·9
Ham (boiled)	4343	1980	1839	839	54·4
Mackerel	6064	1789	2568	758	70·5
Whiting	4520	904	1914	383	80·0
White of egg	4896	671	2074	284	86·3
Hard-boiled egg	6321	2383	2677	1009	62·3
Yelk of egg	6460	3423	2737	1449	47·0
Isinglass	4520	......	1914		
Milk	5093	662	2157	280	87·0
Carrots	3767	527	1595	223	86·0
Cabbage	3776	434	1599	184	88·5
Cocoa-nibs	......	6873	......	2911	
Beef fat	9069	......	3841		
Butter	......	7264	......	3077	
Cod-liver oil	......	9107	......	3857	
Lump sugar	......	3348	......	1418	
Commercial grape-sugar	......	3277	......	1388	
Bass's ale (alcohol reckoned)	3760	775	1599	328	88·4
Guiness's stout ,,	6401	1076	2688	455	88·4

TABLE III.—Actual Energy developed by 1 gram of various articles of Food when oxidized in the Body.

Name of food.	Metrekilograms of force.	
	Dry.	Natural condition.
Cheshire cheese	2429	1846
Potatoes	1563	422
Apples	1516	273
Oatmeal	......	1665
Flour	......	1627
Pea-meal	......	1598
Ground rice	......	1591
Arrowroot	......	1657
Bread crumb	1625	910
Lean of beef	2047	604

Table (*continued*).

Name of food.	Metrekilograms of force.	
	Dry.	Natural condition.
Lean of Veal	1704	496
Lean of ham (boiled)	1559	711
Mackerel	2315	683
Whiting	1675	335
White of egg	1781	244
Hard-boiled egg	2562	966
Yelk of egg	2641	1400
Gelatin	1550	
Milk	2046	266
Carrots	1574	220
Cabbage	1543	178
Cocoa-nibs	......	2902
Butter	......	3077
Beef fat	3841	
Cod-liver oil	3857	
Lump sugar	......	1418
Commercial grape-sugar	......	1388
Bass's ale (bottled)	1559	328
Guiness's stout ,,	2688	455

Table IV.—Weight and Cost of various articles of Food required to be oxidized in the body in order to raise 140 lbs. to the height of 10,000 feet.

External Work = one-fifth of Actual Energy.

Name of food.	Weight in lbs. required.	Price per lb.	Cost.
		s. *d.*	*s.* *d.*
Cheshire cheese	1·156	0 10	0 11½
Potatoes	5·068	0 1	0 5¼
Apples	7·815	0 1½	0 11¾
Oatmeal	1·281	0 2¾	0 3½
Flour	1·311	0 2¾	0 3¾
Pea-meal	1·335	0 3¼	0 4½
Ground rice	1·341	0 4	0 5½
Arrowroot	1·287	1 0	1 3½
Bread	2·345	0 2	0 4¾
Lean beef	3·532	1 0	3 6½
Lean veal	4·300	1 0	4 3½
Lean ham (boiled)	3·001	1 6	4 6
Mackerel	3·124	0 8	2 1
Whiting	6·369	1 4	9 4
White of egg	8·745	0 6	4 4½
Hard-boiled egg	2·209	0 6½	1 2½
Isinglass	1·377	16 0	22 0½
Milk	8·021	5*d.* per qrt.	1 3½
Carrots	9·685	0 1½	1 2½
Cabbage	12·020	0 1	1 0¼
Cocoa-nibs	0·735	1 6	1 1¼
Butter	0·693	1 6	1 0½
Beef fat	0·555	0 10	0 5½
Cod-liver oil	0·553	3 6	1 11¼
Lump sugar	1·505	0 6	1 3
Commercial grape-sugar	1·537	0 3½	0 5½
Bass's pale ale (bottled)	9 bottles.	0 10	7 6
Guiness's stout ,,	6¾ ,,	0 10	5 7½

TABLE V.—Weight of various articles of Food required to sustain Respiration and Circulation in the Body of an average Man during twenty-four hours.

Name of food.	Weight in ozs.	Name of food.	Weight in ozs.
Cheshire cheese	3·0	Whiting	16·8
Potatoes	13·4	White of egg	23·1
Apples	20·7	Hard-boiled egg	5·8
Oatmeal	3·4	Gelatin	3·6
Flour	3·5	Milk	21·2
Pea-meal	3·5	Carrots	25·6
Ground rice	3·6	Cabbage	31·8
Arrowroot	3·4	Cocoa-nibs	1·9
Bread	6·4	Butter	1·8
Lean beef	9·3	Cod-liver oil	1·5
Lean veal	11·4	Lump sugar	3·9
Lean ham (boiled)	7·9	Commercial grape-sugar	4·0
Mackerel	8·3		

These results are fully borne out by experience in many instances. The food of the agricultural labourers in Lancashire contains a large proportion of fat. Besides the very fat bacon which constitutes their animal food proper, they consume large quantities of so-called apple dumplings, the chief portion of which consists of paste in which dripping and suet are large ingredients; in fact these dumplings frequently contain no fruit at all. Egg and bacon pies and potatoe pies are also very common *pièces de résistance* during harvest time, and whenever very hard work is required from the men. I well remember being profoundly impressed with the dinners of the navigators employed in the construction of the Lancaster and Preston Railway; they consisted of thick slices of bread surmounted with massive blocks of bacon in which mere streaks of lean were visible. These labourers doubtless find that from fat bacon they obtain at the minimum cost the actual energy required for their arduous work. The above Tables affirm the same thing. They show that ·55 lb. fat will perform the work of 1·15 lb. cheese, 5 lbs. potatoes, 1·3 lb. of flour or pea-meal, or of 3½ lbs. of lean beef. Donders, in his admirable pamphlet 'On the Constituents of Food, and their relation to Muscular Work and Animal Heat,' mentions the observations of Dr. M. C. Verloren on the food of insects. The latter remarks, "many insects use, during a period in which very little muscular work is performed, food containing chiefly albuminous matter; on the contrary, at a time when the muscular work is very considerable, they live exclusively, or almost exclusively, on food free from nitrogen." He also mentions bees and butterflies as instances of insects performing enormous muscular work, and subsisting upon a diet containing but the merest traces of nitrogen. The following conclusions may therefore be drawn from the foregoing experiments and considerations:—

1. A muscle is a machine for the conversion of potential energy into mechanical force.

2. The mechanical force of the muscles is derived chiefly, if not entirely, from the oxidation of matters contained in the blood, and not from the oxidation of the muscles themselves.

3. In man, the chief materials used for the production of muscular power are non-nitrogenous; but nitrogenous matters can also be employed for the same purpose, and hence the greatly increased evolution of nitrogen under the influence of a flesh diet, even with no increase of muscular exertion.

4. Like every other part of the body, the muscles are constantly being renewed; but this renewal is scarcely perceptibly more rapid during great muscular activity than during comparative quiescence.

5. After the supply of sufficient albuminoid matters in the food of man to provide for the necessary renewal of the tissues, the best materials for the production both of internal and external work are non-nitrogenous matters, such as oil, fat, sugar, starch, gum, &c.

6. The non-nitrogenous matters of food which find their way into the blood yield up all their potential energy as actual energy; the nitrogenous matters, on the other hand, leave the body with a portion (at least one-seventh) of their potential energy unexpended.

7. The transformation of potential energy into muscular power is necessarily accompanied by the production of heat within the body, even when the muscular power is exerted externally. This is doubtless the chief, and probably the only, source of animal heat.