The Physiological Basis of Athletic Records.[1]

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FATIGUE AS THE DETERMINING FACTOR.

AN important and interesting problem for any young athlete is presented by the question: "How fast can I run some given distance?" The maximum speed at which a given distance can be covered is known to vary largely with the distance. What are the factors determining the variation of speed with distance? How far, knowing a man's best times at two distances, can one interpolate between them for an intermediate distance, or extrapolate for a distance greater or less?

Obviously the answer to such questions depends upon the factor which in general terms we designate fatigue. Fatigue, however, is a very indefinite and inexact expression; it is necessary to define it quantitatively before we can employ it in a quantitative discussion such as this. There are many varieties of fatigue, but of these only a few concern us now. There is that which results in a short time from extremely violent effort: this type is fairly well understood; there is the fatigue, which may be called exhaustion, which overcomes the body when an effort of more moderate intensity is continued for a long time. Both of these may be defined as muscular. Then there is the kind which we may describe as due to wear-and-tear of the body as a whole, to blisters, soreness, stiffness, nervous exhaustion, metabolic changes and disturbances, sleeplessness, and similar factors, which may affect an individual long before his muscular system has given out. Of these three forms of fatigue the first one only is as yet susceptible of exact measurement and description. The second type may quite possibly come within the range of experiment at no distant date. The third type is still so indefinite and complex that one cannot hope at present to define it accurately and to measure it. Undoubtedly, however, all these types of what we call "fatigue" influence—indeed, determine—the results which are to be presented.

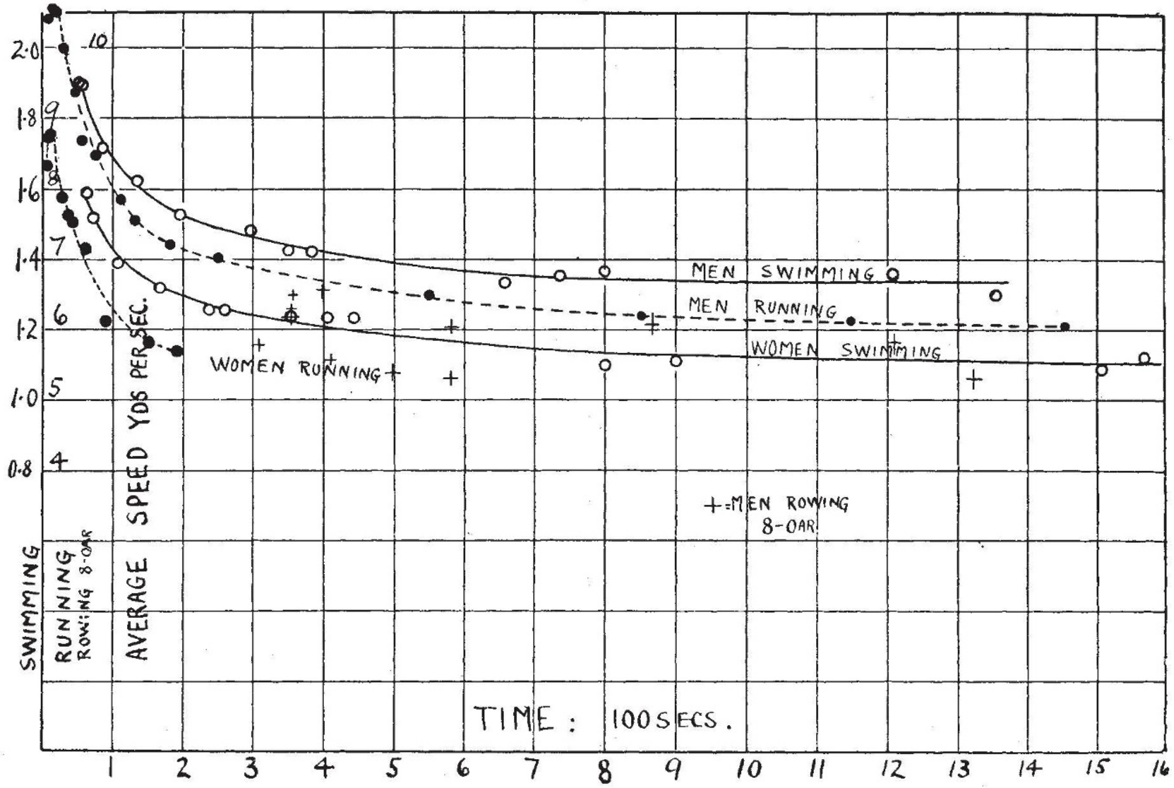

FIG. 1.—World's records for men and women swimming and running: average speed in yards per second against time in seconds. *Note.*—The scale for swimming is five times as great as for running. The observations for men rowing an eight-oar boat are on the same scale as running and are referred to later in the text.

In Fig. 1 all the important world's records are presented, average speed against time, for men and women running and for men and women swimming. The crosses representing men rowing in an eight-oar boat will be discussed later. It is obvious in all four cases that we are dealing with the same phenomena, a very high speed maintainable for short times, a speed rapidly decreasing as the time is increased and attaining practically a constant value after about 12 minutes. There are no trustworthy records, in the case of swimming, for times of less than about 50 seconds, so that the curves cannot be continued back so far as those for running. There can, however, be no doubt that the curves for running and swimming are essentially similar to one another and must depend upon the same factors. The phenomena shown in Fig 1 are susceptible of a fairly exact discussion.

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[1] From the presidential address delivered at Southampton on August 31 before Section I (Physiology) of the British Association.

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OXYGEN INTAKE, OXYGEN REQUIREMENT, AND OXYGEN DEBT.

In recent papers my colleagues and I have tried to emphasise the importance of a clear distinction between the oxygen intake and the oxygen requirement of any given type and speed of muscular effort. When exercise commences, the oxygen intake rises from a low value characteristic of rest to a high value characteristic of the effort undertaken. This rise occupies a period of about 2 minutes; it is nearly complete in 90 seconds. The oxygen used by the body is a measure of the amount of energy expended: one litre of oxygen consumed means about five calories of energy liberated, enough to warm 5 litres of water 1° C.—expressed in mechanical energy, enough to raise about 1 ton 7 feet into the air.

It has been established, however, that the oxygen need not necessarily be used during the exertion itself. The muscles have a mechanism, depending upon the formation of lactic acid in them, by which a large amount of the oxidation may be put off to a time after the exercise has ended. The recovery process, so called, requires this delayed oxidation: it is just as important to the muscle as recharging to an electrical accumulator. The degree, however, to which the body is able to "run into debt" for oxygen, to carry on not on present but on future supplies, is limited. When an "oxygen debt" of about 15 litres has been incurred the body becomes incapable of further effort: it is completely fatigued. In anything but the shortest races our record-breaking athlete should finish with something near a maximum oxygen debt, otherwise he has not employed all his available power, he has not done himself full justice. The maximum effort, therefore, which he can exert over a given interval depends upon the amount of energy available for him, upon (*a*) his maximum oxygen intake (that is, his income), and (*b*) his maximum oxygen debt (that is, the degree to which he is able to overdraw his account). These maxima are fairly well established for the case of athletic men of average size—about 4 litres per minute for the one, about 15 litres or rather more for the other.

It is possible for a man to make an effort far in excess of any contemporary supply of oxygen. This effort will require oxygen afterwards, and the total oxygen needed per minute to maintain the exercise can be measured. It is what we call the "oxygen requirement" characteristic of the effort involved. Now experiments have shown (see Fig. 2) that the oxygen requirement varies very largely with the speed: it increases far more rapidly than the speed, more like the second, third, or even some higher power of the speed, so that high speeds and intense efforts are very wasteful. These facts enable us approximately to deduce the general form of Fig. 1. . . .

It is obvious, however, that we must not pursue the argument too far. A man cannot exhaust himself completely in a 100 or a 200 yards race: a quarter-mile, in the case of a first-class sprinter, is enough, or almost enough, to produce complete inability to make any immediate further effort. We have found an oxygen debt of 10 litres even after a quarter-mile in 55 seconds, and one of 15 litres after 300 yards at top speed. It is obvious, therefore, that we cannot pursue our argument below times of about 30 to 40 seconds, and that the maximum speed for very short distances is limited by quite other factors than the amount of energy available. Neither can the argument be applied to very long races, where other types of exhaustion set in.

COMPARISON OF MEN AND WOMEN; SWIMMING AND RUNNING.

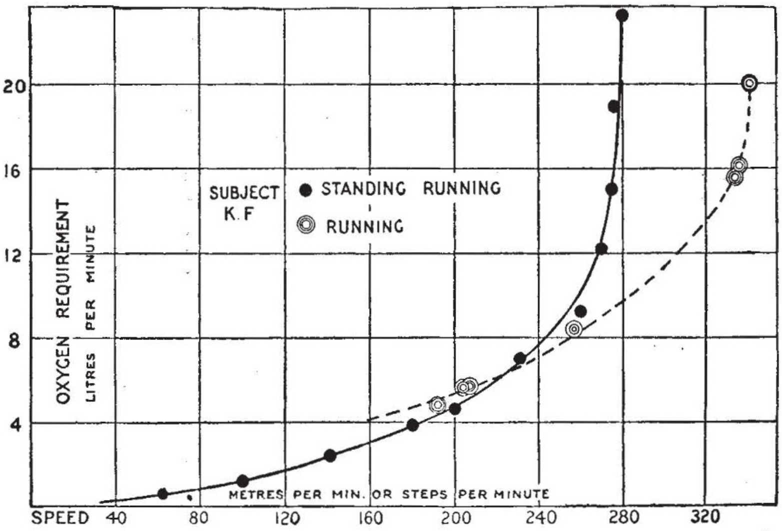

FIG. 2.—Observations of oxygen requirement of K.F. running and standing-running at various speeds. Horizontally, speed: running, metres per minute; standing-running, steps per minute. Vertically, oxygen requirement per minute, litres.

There are certain characteristics of these curves which are of interest. In the first place, those for men and women are almost precisely similar. For a given time of swimming the maximum speed for a woman appears, throughout the curves, to be almost exactly 84 to 85 per cent. of that for a man. If we assume what is roughly true, that the energy expenditure rises approximately as the square of the speed, we may conclude that a woman swimming is able to exert, per kilogram of body weight, about 72 per cent. of the power expended by a man. Women are well adapted to swimming: their skill in swimming is presumably just as great as that of men; the difference in the maximum speed for any given time can be a matter only of the amount of power available.

In running, the same type of comparison may be made, and it is found that a woman running is able to liberate in a given time only about 62 per cent. of the energy expendible by a man of the same weight. It is probable that this ratio as determined by swimming and by running respectively is really the same in either case, and that the apparent difference depends upon an inexactness in the simple laws assumed. It would seem fair to take the mean of these two values, 67 per cent., as the ratio of the amount of energy expendible by

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a woman in a given time as compared with that by a man of the same weight. It would be of great interest —and quite simple—to test this deduction by direct experiment on women athletes.

THE CHARACTERISTIC OXYGEN-REQUIREMENT-SPEED CURVE AND SKILL.

The curves given in Fig. 2 define the economy with which movements are carried out. By such means can be shown the amount of energy required, in terms of oxygen used, in order, say, to run or swim for a minute at any given speed. The curves will vary largely from one individual to another. It is obvious, however, that such a curve must exist for any person performing any kind of continuous muscular exercise. In it we have a characteristic of that given individual for that particular form of work.

Some people are much more skilled than others. To a large degree, of course, the skill and grace associated with athletic prowess is natural and inborn; to a large degree, however, it can be produced by training and breeding. All the movements required in the violent forms of muscular exertion here discussed are rapid ones, far too rapid to be directly and continuously subject to the conscious intelligence: they are largely, indeed mainly, reflex, set going by the will, but maintained by the interplay of proprioceptive nervous system and motor apparatus.

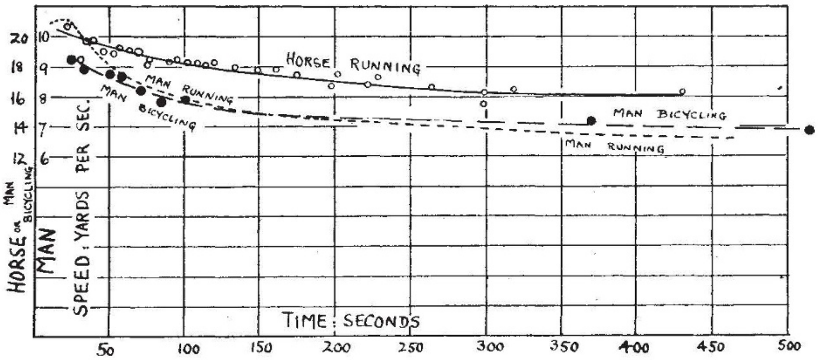

FIG. 3.—Records for horse running and man bicycling; dotted curve for comparison, man running, taken from Fig. 1. Horizontally, time in seconds; vertically, average speed yards per second. *Note.*—The horse and the man bicycling are shown on half the scale of the man running. The records for bicycling are the unpaced professional records against time. The records for horses were made in America.

The forms of the characteristic curves of Fig. 2 depend upon the skill of the subject in ordering his movements, just as the "miles per gallon" of the motor-car depends upon the skill of those who designed and adjusted its timing gear and its magneto. Given incorrect adjustment due to lack of skill, given imperfect timing of the several parts of the mechanism, given unnecessary movement and vibration, the whole system will be inefficient. Fundamentally the teaching of athletics for anything but the shortest distances consists in training the performer to lower the level of his characteristic curve, to carry out the same movements at a given speed for a smaller expenditure of energy.

BICYCLING AND HORSE-RUNNING.

Not all forms of muscular exertion are so violent, involve so great an expenditure of energy, when carried out at the highest speed, as running and swimming. In Fig. 3 are two examples of this fact, horse-running and bicycling. It is obvious at once that neither of these two curves falls anything like so rapidly as does that of a running man; fatigue does not so soon set in; the amount of energy expended at the highest speed must be much less than in a running man. This conclusion, indeed, is obvious to any one who has tried to ride a bicycle fast. It is impossible to exhaust oneself rapidly on a bicycle. The curve for horse-running is almost parallel to that for bicycling; presumably, therefore, the movements of a horse are so arranged that the extreme violence of effort possible in a human "sprinter" is unattainable.

SHORT AND LONG RACES.

Let us pass now to a consideration of the last diagram, Fig. 4. Average speed in a race is plotted against the logarithm of the time occupied in it, the logarithm being employed for the purpose of including all records from 75 yards to 100 miles in the same picture. Fig. 4 presents the data of athletics perhaps more clearly than any other. The initial rise of the curve for men running, which is due to starting inertia, is very obvious. The rapid fall beyond 220 yards is clearly seen. It is obvious that the 100 and the 220 yards (⅛ mile) records are better than those lying in their neighbourhood, that the quarter-mile record is extremely good, the 500 yards record very bad, by comparison with its neighbours. This diagram should enable any enterprising and scientific athlete to select the records most easy to break: let him try those for 120 yards, for 500 yards, for three-quarter-mile, for three miles, but not for 220 yards, quarter-mile, one mile, and six miles.

In Fig. 1 we saw that the speed fell to what seemed to be practically a constant level towards the right of the diagram: this fall represents the initial factor in fatigue. On the logarithmic scale, however, where the longer times are compressed together, the curve continues to fall throughout its length. This later fall is due to factors quite different from those discussed above. Consideration merely of oxygen intake and oxygen debt will not suffice to explain the continued fall of the curve. Actually the curve beyond 10 miles seems to some degree doubtful. Apparently the same extent of effort has not been lavished on the longer records: the greatest athletes have confined themselves to distances not greater than 10 miles. The most probable continuation of the running curve would seem to be somewhere between the lines B and C.

The continued fall in the curve, as the effort is prolonged, is probably due either to the exhaustion of the material of the muscle, or to the incidental disturbances which may make a man stop before his muscular system has reached its limit. A man of average size running in a race must expend about 300 gm. of glycogen per hour; perhaps a half of this may be replaced by its equivalent of fat. After a very few hours, therefore, the whole glycogen supply of his body will be

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exhausted. The body, however, does not readily use fat alone as a source of energy: disturbances may arise in the metabolism; it will be necessary to feed a man with carbohydrate as the effort continues. Such feeding will be followed by digestion; disturbances of digestion may occur—other reactions may ensue.

The women's curve, so far as it goes, is very similar to the men's. An enterprising woman athlete who wants to break a record should avoid the 300 metres; she would be well advised to try the 500 metres. It would be very interesting to have an intermediate point between 100 and 220 yards.

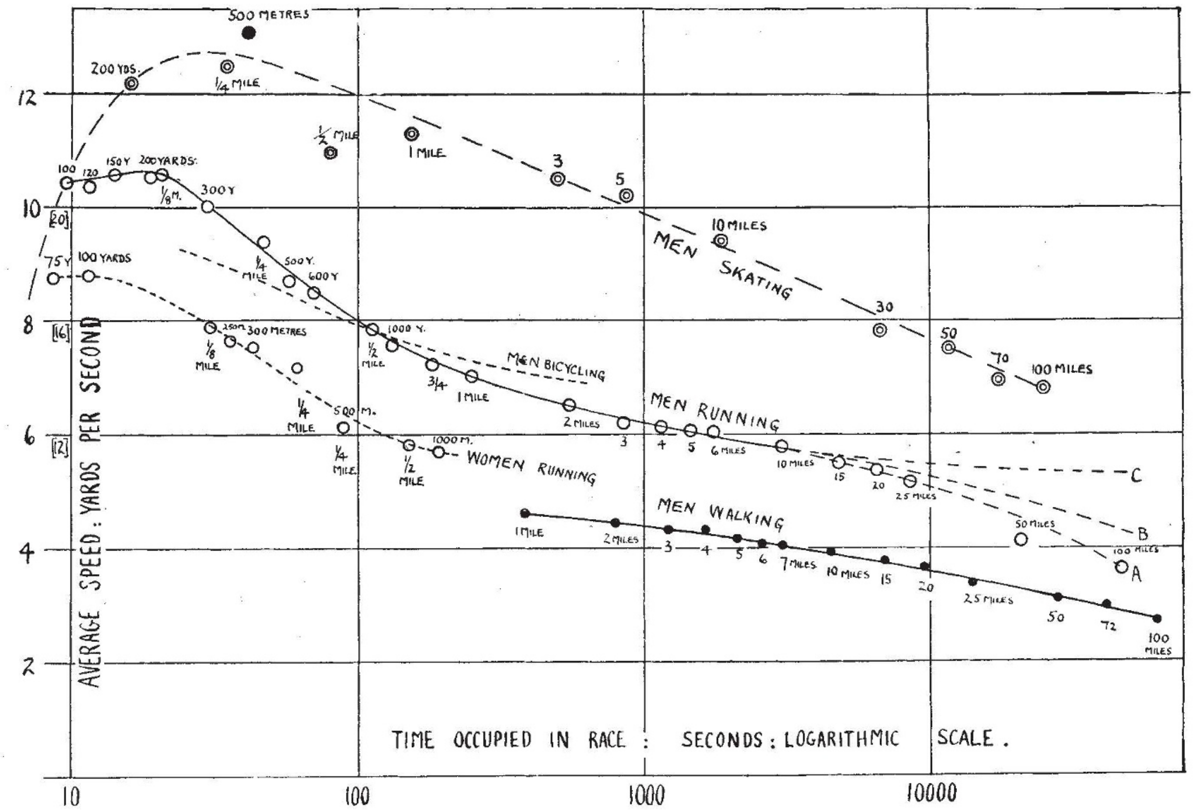

Fig. 4.—Records for men skating, bicycling, running and walking, and for women running. Horizontally, logarithm of time occupied in race; vertically, average speed in yards per second. The same scale is used throughout, except for bicycling, where half the scale is employed, as shown in square brackets. The curve for men running appears to be somewhat doubtful beyond 10 or 15 miles, and three alternative curves are shown by broken lines.

Bicycling and Walking.

As before, the curve for men bicycling, which is drawn on twice the scale vertically of the running curves, is far less steep than they are. The conclusion from this was emphasised above. The walking curve is interesting—it is approximately straight. Physiologically speaking, there is not much interest in the shortest walking races, since here walking is artificial and extremely laborious; running at a considerably higher speed is much more easy. For longer distances, however, say from 10 miles onwards, we have probably in walking the most trustworthy data available for long-continued muscular effort. If we wish to study the exhaustion produced by exercise of long duration, walking-men may well provide the best subjects for our experiments.

Rowing.

There are only a few records available, and those lying between rather narrow limits, for the case of rowing. Taking the case of an eight-oar boat, the most reliable of the data have been plotted in Fig. 1 on the same scale as the running, on five times the scale of the swimming. The observed points, shown by crosses, are somewhat scattered. So far as they go, a mean curve through them would lie practically along the curve for women swimming, but, of course, on five times the scale. The interesting part of the curve to the left is lacking: it is obviously impossible to make observations on an eight-oar boat for periods of 20 seconds; starting inertia is too great and no result of any value could be obtained.

In rowing the movements are slow: in an eight-oar boat, from 30 to 40 strokes per minute. According to observations by Lupton and myself, the maximum efficiency of human muscular movement is obtained at speeds of about one maximal movement per second. In rowing, experience and tradition alike suggest that such a speed is about the optimum. In an eight-oar boat the recovery takes almost as long as the stroke, both occupying about one second. It is of interest how practical experience has gradually evolved a speed of movement which is almost exactly what a physiologist might have predicted as the most efficient. At

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a stroke of about 32 per minute the mechanical efficiency is apparently near its maximum.

An enormous amount of work has to be done in propelling a boat at speeds like 10 to 12 miles per hour. According to Henderson, each member of the crew of an eight-oar boat must exert about 0·6 of a horse-power. Clearly, if this enormous amount of external work is to be done, it must be accomplished by working under efficient conditions: those conditions necessitate a stroke of a particular frequency; only when the race is very short is it permissible, in order to obtain a greater output, to work less efficiently by adopting a more rapid stroke. The stroke may rise to 40 per minute for a short distance: in such an effort the oxygen debt is accumulating rapidly and exhaustion will soon set in. The amount of work, moreover, will not be proportionately greater, probably only slightly greater, than at the lower frequency. The conditions which determine the speed of movement, the "viscous-elastic" properties of muscle, are what ultimately decide the length of the oars and the speed of movement in a racing-boat.

Wastefulness of High Speeds.

This last discussion leads us to the question of what determines the great wastefulness of the higher speeds. Why, returning to Fig. 2, does a speed of 280 steps per minute require 24 litres of oxygen per minute, while a speed of 240 steps per minute requires only eight litres of oxygen? The answer depends upon the variation of external work with speed of muscular movement. In a series of recent papers it has been shown that in a maximal muscular movement the external work decreases in a linear manner as the speed of shortening increases. At sufficiently high speeds of shortening no external work at all can be performed.

In most of these athletic exercises, apart from the case of rowing, a large proportion of the mechanical work is used in overcoming the viscous resistance of the muscles themselves. At high speeds of running only a small fraction of the mechanical energy of the muscles is available to propel the body, once the initial inertia has been overcome. The work is absorbed by internal friction, or by those molecular changes which, when the muscle is shortening rapidly, cause its tension to fall off. When working against an external resistance, as in rowing, there is an optimum speed. If an effort is to be long continued it must be made at a speed not far from the optimum. When, however, the whole of the resistance to movement is internal, as in running, there is no optimum speed: the expense of the movement increases continually as the speed goes up; the faster we move, the greater relatively the price: our footsteps are dogged by the viscous-elastic properties of muscle, which prevent us from moving too fast, which save us from breaking ourselves while we are attempting to break a record.

Jumping.

One final point may be worthy of mention—this time connected with high-jumping and long-jumping. Recently I made a series of observations, with a stop-watch reading to 0·02 second, of the times occupied by a number of high-jumpers from the moment they left the ground to the moment they reached the ground again. With men jumping about 5 feet the time averaged about 0·80 second. Calculating from the formula

$$S=\tfrac{1}{2}gt^2,$$

where t is half the total time of flight, the distance through which the centre of gravity of the body was raised must have been about 2·5 feet. The men competing must have had an original height of their centre of gravity of about 2·9 feet. Thus, in the high-jump, their centres of gravity went about 5·4 feet high into the air. The world's record high-jump is 6·61 feet, the centre of gravity of the performer being presumably about 3 feet high at rest. He raises it therefore 3·61 feet into the air, from which we may calculate that the whole time occupied in the jump is about 0·96 second. All the characteristics of the proprioceptive system must be evoked in their highest degree in carrying out such a skilled, rapid, and yet violent movement in so short a time.

In long-jumping, it is well known that success consists in learning to jump high. The world's record long-jump is 25·48 feet. With the check provided by the vertical impulse in the last step we cannot well imagine the horizontal velocity to be greater, at this moment, than that of 100 yards completed in 10 seconds; that is, than 30 feet per second. Let us assume this value, then the performer remains in the air for 0·85 second: hence we may calculate that the vertical distance covered is about 2·9 feet. Assuming the centre of gravity of the subject to have been originally 3 feet high, this means that it must have reached a height 5·9 feet in the air, enough, in a high-jump, to enable its owner to clear 5·9 feet. It is interesting to find that the simple laws of mechanics emphasise so strongly the precepts of the athletic trainer.

A High-frequency Induction Furnace for making Alloys.

A PAPER on a high-frequency induction furnace for making alloys was presented by Mr. D. F. Campbell at the autumn meeting of the Iron and Steel Institute held in Birmingham on September 10. The early work in this field was carried out at Princetown University by Dr. Northrup, whose investigations of the physical laws governing induction from high-frequency equipment led to the evolution of the first metal-melting furnaces. As Mr. Campbell points out, low-frequency induction furnaces have been known for forty years, and twenty years ago it seemed possible that they would, to a large extent, replace the crucible process for high-grade steel making. This possibility, however, has for a variety of reasons not been fulfilled. Inductive heating has, however, found wide application in the non-ferrous trade in furnaces having a vertical slot worked on normal commercial frequencies. These furnaces have the disadvantage of requiring an iron core, in consequence of which the molten metal is contained in small channels surrounding the iron core as well as in the main bath of the furnace. This involves much wear and tear of the refractory material.

In the case of high-frequency heating the conditions

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