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GROWTH AND DEVELOPMENT

With Special Reference to Domestic Animals

XXXII. The Energy Cost of Horizontal Walking in Cattle and Horses of Various Ages and Body Weights

WARREN C. HALL AND SAMUEL BRODY

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ABSTRACT

This bulletin presents comparative data for heat production and cardiorespiratory activities during standing and horizontal walking in cattle and horses (and a few humans) of wide range in live weight and age. Analysis of the data showed that (1) the *percentage* increase in heat production of walking over standing varies directly with speed as represented for humans by the equation $Y = 74S$, in which Y is the percentage increase in metabolism at speed S in miles per hour. This means that at a speed of 1 mile per hour the heat production during walking is 74% above standing, at 2 miles it is 148% above standing etc. The percentage increase in horses is less than in humans; the percentage increase in cattle is of the same order as in humans. (2) The *net* energy expense of walking, which is the expense of walking above standing (not including the cost of standing at rest), is per unit of live weight and unit distance walked independent of speed. In terms of kilo-calories per 100 pounds live weight the net energy of walking one mile is, in round numbers, 40 for humans, 33 for cattle, and 28 for horses. In terms of gm-cal. per kilogrammeter the net expense is 0.544 for humans, 0.452 for cattle, and 0.385 for horses. (3) The total, or *overall*, cost of walking (including the overhead cost of standing) per unit live weight and unit distance decreases with increasing speed. The decrease is probably exponential, approaching the net energy expense of walking as a limit, as indicated by the equation for humans $Y = 44_{e}^{-0.268s} + 39.7$ in which Y is the Cal. per 100 pounds per mile, at speed S, and 39.7 is the net energy cost of walking as explained in (3) above. (4) The above relations (per unit live weight and per unit horizontal distance walked) are apparently independent of live weight for a given species. These relations do not apply to animals of extreme fatness. Horses spend less energy for moving unit body weight per unit horizontal distance than humans or cows. Cows and humans spend almost the same amounts of energy per unit live weight and unit distance. (5) As regards the influence of fast on metabolism, this decreased during standing and walking but the percentage increase due to walking tended to increase with increasing time after feeding. (6) Of the cardiorespiratory activities, the percentage increase in the ventilation rate followed closest to that of the oxygen consumption, followed by respiration rate, and pulse rate. The influence of walking on tidal air is uncertain.

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XXXII. The Energy Cost of Horizontal Walking in Cattle and Horses of Various Ages and Body Weights*

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INTRODUCTION

Paper XXVI of this series[1] † was concerned with the energy increment of standing over lying, and the energy cost getting up and lying down. This paper carries this research a step further to include the energy cost of walking on a horizontal platform. The following paper[2] extends this research to include the energy cost of work (pulling loads). The aim of this general research, as previously noted, is to catalog as completely as possible the energy expenses associated with the normal life processes of farm live stock during their life cycle and whenever possible to compute the efficiencies of these processes. As in the preceding paper[1] we shall also present the comparative data on the cardiorespiratory activities.

LITERATURE

With the exception of Huxdorf's preliminary reports on horses,[3] we are not familiar with any literature on this problem as it relates to energy expended for walking over standing by live stock. The best known researches on humans are by Benedict and Murschhauser[4] and by Smith[5] also from Benedict's laboratory. These papers present a full discussion of the literature on walking in humans. By way of orientation it may be noted that most of the literature on the energy cost of walking in humans is concerned with the energy cost of marching of soldiers. It is generally agreed that Zuntz and Schumberg's monograph[6] on marching, is the classic contribution in this field. More recently Waller[7] measured the cost of marching at various speeds and under various conditions; as did also Cathcart and associates[8]. Benedict and Parmenter[9] incidental to other aims measured the energy cost of walking in women. McClintock and Paisley[10] measured the energy cost of walking in boys and girls ages 11 to 14 years.

*Taken in part from a thesis by W. C. Hall.
†Numerals refer to references, Page 16.

Paper 77 in the Herman Frasch Foundation Series.

METHODS

The closed-circuit oxygen consumption method used for measuring the energy metabolism was previously described[11]. The animals walked on a treadmill, the treadle of which was actuated by a 5-HP motor. The motor was belted to the treadmill with pulleys of appropriate sizes to give the desired speeds. Sketches and photographs of the treadmill setup are given elsewhere[2]. Speeds of 1.15, 2.2 and 3.1 miles per hour were employed in this work. Only the slowest speed could be used for the heavy cattle, while all three speeds were used for the horses. For the sake of completeness a few trials were also carried out on humans. For purposes of comparative discussion we have graphed Smith's[5] data on walking in humans.

ANIMALS

The horses (Shetlands, American Saddle Horses, and Percherons) ranged in weight from about 200 lbs. to about 1500 pounds. The cattle(Holstein, Jersey, and Hereford) ranged in weight from about 850 to about 2,000 pounds. Their ages and weights are given in Table 1 together with the other data.

DEFINITIONS

To avoid circumlocution we shall introduce at this time a number of convenient terms that we shall use in this paper.

Units of Work Accomplished and Units of Energy Expended

Conventional units of work such as foot-pounds or kilogrammeters, can not be used to represent the work done in moving of the body (walking) in a horizontal direction, since such movement does not increase the potential energy of the body. We shall for this purpose adopt the unit employed by investigators of the energy cost of walking in humans ([1, 2]). This empirical unit represents work accomplished in terms of horizontal displacement of 1 kilogram body weight for a distance of one meter, and is called the hotizontal kilogrammeter. We shall supplement this customary metric unit by a unit based on the more familiar English system, namely, horizontal displacement of 100 pounds of body weight for a distance of one mile. (Note: 1 kilogrammeter = 7.236 foot-pounds = 0.0000137 mile-100-pounds; 1 mile-100-pounds = 528,000 foot-pounds = 72,968 kilogrammeters.)

As regards energy units, we shall use the small calories, or gram-calorie, in connection with the above metric work unit, and the large calorie, or kilo-calorie, or simply Calorie with a capital C, when used in connection with the above English unit.

Manner of Representing Cost of Walking

We shall represent the energy cost of walking in three ways as follows.

Overall Expense of Walking.—This expense is made up of (a) the overhead expense of maintenance during standing at rest and (b) the superimposed, or extra, expense of walking.

Net Expense of Walking.—This is item (b) above—the net cost of walking not including the overhead cost of standing at rest. The energy expense at rest is referred to as overhead expense since this goes on regardless of whether or not the animal walks.

Percentage Increment of Walking.—This is the percentage ratio of the net expense of walking (item b above) to the cost of the overhead expense of maintenance when the animal is standing at rest (item a above). In other words it is the percentage increase in energy metabolism due to walking with reference to the energy expense during standing as base.

RESULTS

Heat Production

The basic data are presented in Table 1. The statistical constants of the data are given in Tables 2 and 3. The measurements were made during all hours of the day, without reference to the time of feeding. The animals were fed in the usual manner (twice a day). An attempt was also made to determine the influence of fasting (time after feeding) on the heat increment of walking with results indicated in Table 4.

Table 4 shows, as might be expected, that the heat production during rest (standing) declines with increasing time of fast due, of course, to the disappearance of the so-called specific dynamic effect of feeding. The metabolism during walking declined with increasing fast in the very heavy steer 815, but not in (the medium weight) cows 206 and 669. The absolute heat increment of walking declined with increasing time of fast in the heavy steer 815 but increased somewhat in the cows. The percentage heat increment of walking increased with increasing time of fast in the steer and to a less extent in the cows.

The other data are presented in table 1. The more significant aspects of these data are also presented in graphic forms in Figs. 1 and 2, and it will be simplest to confine our discussion to the graphs rather than to the tables.

Fig. 1 presents the percentage increases in heat production during walking over standing as functions of speed. In addition to including our data on horses and cattle, we have, for comparative purposes, also

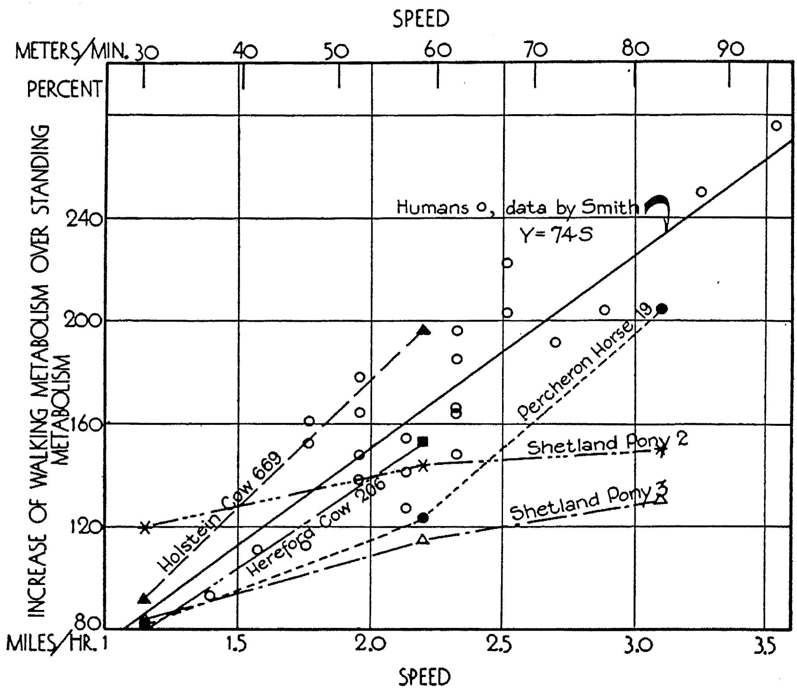

Fig. 1.—The *percentage* increase of walking over standing metabolism as function of speed. The light circles represent Smith's data on humans to which we have fitted (by method of least squares) the equation Y = 0.68 × 74.1S The other data are original.

included Smith's data[5] on humans. The percentage increase in metabolism due to walking naturally increases with speed. The rise is steeper in humans and cattle, than for horses, especially the very small ponies. The increase in heat production during slow walking is seen to be of the order of 100% above standing. During fast walking (3 miles per hour) the heat production of walking over standing is seen to be of the order of 230% for humans and perhaps cattle, and between 130 and 190% for horses. It seems that per unit of live weight and distance, horses spend least energy for walking especially at the rapid rates, while humans and cattle (which have the same order of efficiency in this respect) are relatively less efficient than horses.

One may generalize quantitatively by saying that the percentage heat increment of walking over standing increases with increasing speed in a roughly linear manner. In the case of humans, the heat increment of walking over standing is 74% for each one-mile increase in speed. That is, at a speed of 1 mile per hour, the energy expense during walking is 74% above that of standing; at 2 miles, it is 74 x 2 = 148% above

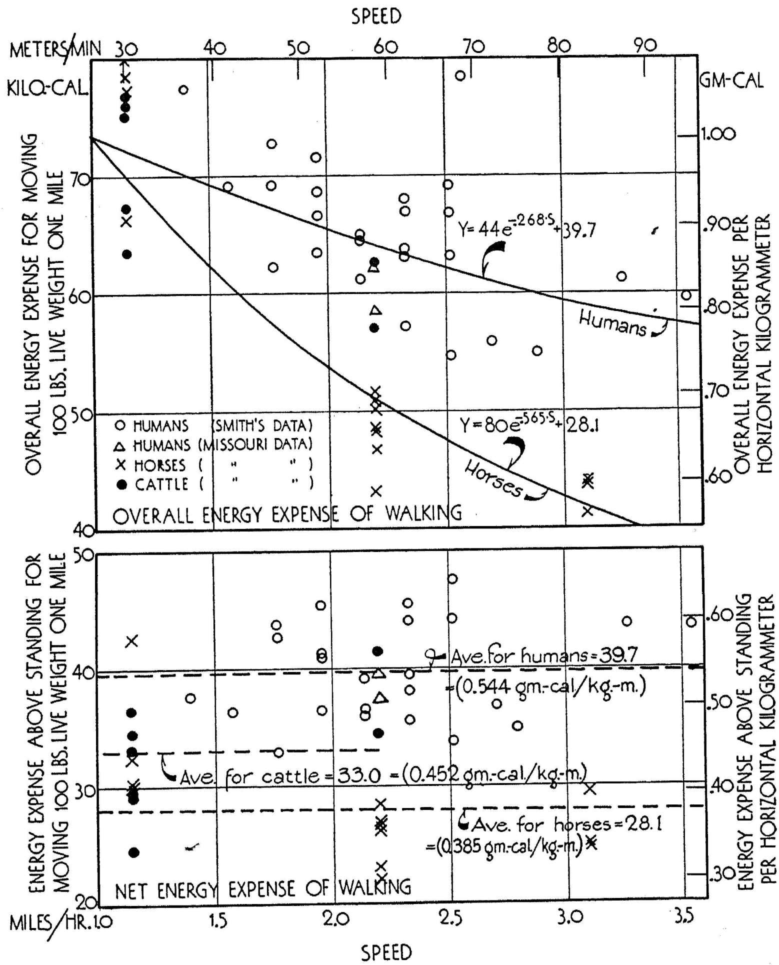

Fig. 2.—The data in the lower quadrangle represent the *net* energy expense of walking (i. e. of walking above standing into which the overhead cost of maintenance does not enter); the data in the upper quadrangle represent the *overall* energy expense of walking (into which is included the overhead cost of maintenance, that is, while standing at rest). All expenses are presented in terms of calories per unit live weight and unit distance walked (metric units on top and right; English units on bottom and left side).

standing and so on for other speeds. The equation relating the percentage heat increment of walking, Y, with speed, S, is, therefore, $Y = 74 \times S$. A somewhat better (least-square) fit of the equation to Smith's data[5] for humans is obtained with $Y = 0.68 + 74.1S$. For practical purposes the constant 0.68 may be ignored. The percentage increases with speed for horses is somewhat less than for humans.

As regards the *net* energy expenses of walking, the lower half of Fig. 2 represents the *net* energy of walking as a function of speed. The

TABLE 1.—COMPARATIVE DATA ON ENERGY METABOLISM AND

Animals	Age Mos.	Body Weight Kgs.	Surface Area Sq. M.	Number of Measure S	Number of Measure W	Metabolism Cal. per day S	Metabolism Cal. per day W	Heat Increments of Walking over Standing: Total Cal/day	Heat Increments of Walking over Standing: Cal/Kg/day	Heat Increments of Walking over Standing: Per cent Increase
(A) Walking Speed = 1.15 miles p										
Jersey Cow 834	43	384	4.20	17	20	9135	14876	5741	14.9	63
Hereford Cow 206	17	407	3.76	15	15	10383	18596	8213	20.2	79
Holstein Cow 669	19	416	4.39	22	22	10043	19308	9265	22.7	92
Guernsey Cow 427	59	460	4.65	15	17	11878	21513	9635	20.9	81
Holstein Cow 599	46	516	4.96	15	18	11909	21163	9254	17.9	78
Holstein Cow 601	44	535	5.06	15	14	14193	24686	9493	17.7	74
Hereford Steer 815	56	930	5.97	26	32	14698	43082	28384	30.5	193
Shetland Pony 1 Gelding	24	91	1.71	10	7	2629	4422	1793	19.7	68
Shetland Pony 2♀	54	265	3.36	6	6	5784	12648	6864	25.9	119
Shetland Pony 3♂	30	279	3.47	9	9	6168	11256	5088	18.2	83
Percheron Colt 37♂	6	338	3.92	28	31	9637	15845	6208	18.4	64
Percheron Horse 19 Gelding	52	688	6.38	31	31	15352	27716	12364	18.0	81
(B) Walking Speed = 2.2 miles p										
Hereford Cow 206	17	407	3.76	11	11	10668	27034	16366	40.2	153
Holstein Cow 669	19	417	4.40	15	16	10260	30389	20128	51.4	196
Shetland Pony 2♀	48	272	3.42	25	33	6264	15288	9024	33.2	144
Shetland Pony 3 Gelding	24	267	3.38	34	37	6240	13440	7200	27.0	115
Percheron Colt 31♂	6	338	3.92	26	29	9776	20325	10549	31.2	108
Percheron Colt 37♂	10	476	5.05	24	22	13200	27792	14592	30.7	111
Percheron Horse 19 Gelding	51	673	6.29	34	34	17048	38098	21050	31.3	123
American Saddle Horse 1♀	12	215	2.95	19	17	7186	12747	5561	25.9	77
American Saddle Horse 2♀	24	328	3.85	25	22	8907	17769	8862	27.0	99
Human, F. C. ♂	23 yrs.	70	----	10	15	1615	4762	3047	43.5	195
Human, W. O. ♂	21 yrs.	75	----	5	5	1978	5426	3448	46.0	174
(C) Walking Speed = 3.1 miles p										
Shetland Pony 2♀	60	281	3.53	5	5	7603	19031	11428	40.7	150
Shetland Pony 3 Gelding	36	299	3.63	5	5	9385	21566	12181	40.7	130
Percheron Horse 19 Gelding	53	708	6.50	27	27	16872	51111	34239	48.4	204

Footnotes S = Standing; W = Walking.

net energy of walking, as defined in the preceding section, is the total energy expended less the energy expense of maintenance when standing at rest. In other words, it is the energy of walking above that of standing. This net energy cost of walking per unit live weight and horizontal distance is seen in Fig. 2 to be roughly independent of speed. For humans it is of the order of 39.7, for cattle 33.0, and for horses 28.1 kilo-calories per 100 pounds live-weight per mile (or in terms of gram-calories per kilogrammeter, 0.544 for humans, 0.452 for cattle and 0.385 for horses).

If, however, the *overall* energy (including the expense of maintenance at rest) is considered, then, naturally, the energy expense declines with increasing speed because the overhead cost of maintenance for walking a given distance declines with increasing speed. Taking an extreme hypothetical case, if the speed of walking were to become infinitely great, then the overhead expense of standing for walking a finite distance would become infinitely small because the time interval would approach zero so that the only remaining expense would be the net energy of walking. But we have seen that the net energy for walking

CARDIORESPIRATORY ACTIVITIES DURING STANDING AND WALKING

er hour (30.85 meters per minute).

Gram-calories per horizontal kilogrammeters		Kilo-calories to move 100 lbs. for one mile		Pulse Rate per minute			Respiration Rate per minute			Tidal Air Liters			Ventilation Rate Liters per minute		
Total	Above Stand-ing	Total	Above Stand-ing	S	W	Per cent In-crease	S	W	Per cent In-crease	S	W	Per cent In-crease	S	W	Per cent In-crease
0.87	0.34	63.6	24.6	54	64	19	16.1	19.8	23	3.06	3.76	23	49	74	51
1.03	0.45	75.1	33.2	69	78	13	----	----	---	----	----	---	----	----	---
1.05	0.50	76.3	36.6	67	74	11	----	----	---	----	----	---	----	----	---
1.05	0.47	76.8	34.4	54	65	20	18.3	23.0	26	3 88	5.28	36	71	122	72
0.92	0.40	67.4	29.5	57	67	18	16.7	23.5	41	4.47	5.07	11	75	118	57
1.04	0.40	75.9	29.2	56	67	20	23.0	29.1	27	3.74	4.39	17	85	127	49
1.04	0.69	76.1	50.2	64	77	20	----	----	---	----	----	---	----	----	---
1.09	0.44	80.1	32.5	----	----	---	11.3	16.0	42	2.56	2.33	−10	29	37	28
1.07	0.59	78.5	42.6	40	43	8	14.8	21.9	46	5.50	5.67	3	81	122	51
0.91	0.41	66.3	30.0	43	43	0	16.9	23.6	38	5.23	4.98	−5	88	115	31
1.05	0.41	77.1	30.2	58	61	5	28.6	44.2	55	2.85	2.89	1	81	126	56
0.91	0.41	66.2	29.5	46	47	2	17.5	35.2	101	7.87	7.90	0	138	281	104
er hour (59.00 meters per minute).															
0.78	0.47	57.1	34.6	69	87	---	----	----	---	----	----	---	----	----	---
0.86	0.57	62.6	41.5	67	83	24	----	----	---	----	----	---	----	----	---
0.66	0.39	48.3	28.5	39	43	10	12.7	21.8	65	5.21	5.64	8	65	118	82
0.59	0.32	43.2	23.2	42	47	12	13.6	27.1	93	4.03	3.91	−3	59	111	88
0.71	0.37	51.7	26.8	59	62	5	28.5	54.1	90	2.92	3.19	9	81	168	107
0.69	0.36	50.2	26.3	52	55	6	19.7	35.0	78	5.83	6.06	4	115	213	85
0.67	0.37	48.6	26.9	45	49	9	17.3	38.5	123	8.02	8.61	7	135	325	139
0.70	0.30	50.9	22.2	49	55	12	16.6	27.4	65	3.14	3.09	−2	50	80	60
0.64	0.32	46.6	23.2	47	51	9	12.6	25.2	100	7.23	6.89	−5	90	170	81
0.80	0.51	58.6	37.5	64	66	3	15.3	13.2	−14	1.29	2.13	65	19	27	42
0.85	0.54	62.3	39.6	81	82	1	17.0	23.4	35	1.15	1.50	30	20	35	75
er hour (83.15 meters per minute).															
0.88	0.53	41.3	24.8	45	54	20	16.7	31.0	86	5.44	5.37	−1	91	166	82
0.60	0.34	44.0	24.8	43	53	23	19.6	46.8	139	5.05	4.46	−12	99	208	110
0.60	0.40	44.0	29.5	44	52	18	18.0	49.2	173	7.81	9.65	24	139	473	240

is about 39.7 kilo-calories per 100 pound live weight per mile; therefore, as the speed of walking becomes faster and faster, the *overall* energy of walking will approach closer and closer to the *net* energy of walking, i. e., to 39.7 Calories per 100 pound live weight per mile. This idea can be generalized quantitatively for humans in the form of the equation $Y = 44e^{-0.268s} + 39.7$ in which Y is the overall expense of walking, 39.7 is the net energy of walking, S is speed in miles per hour, and e is the base of natural logarithms.

Finally, it may be seen in Table 1, that the size of the animal is not an important influencing factor on the net energy expense per unit live weight and per unit horizontal distance walked. Thus from table 1, the small Shetland pony 3 expended the same number of overall and net calories per kilogrammeter of walking as the large Percheron horse 19. The difference between the two Shetland ponies 2 & 3 of the same live weight is much greater than between the ponies and the large horse. However the limited number of animals included in the results does not

Table 2.—Statistical Constants for the Metabolism and Pulse Rate Data

(A) Walking Speed, 1.15 miles per hour (30.85 meters per minute).

Animals	Metabolism, calories per day						Pulse Rate per minute					
	Standing			Walking			Standing			Walking		
	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %
Jersey Cow 834	9135±161	952	10.4	14876±235	1518	10.2	54.2±0.8	5.02	9.3	63.9±0.7	4.75	6.4
Hereford Cow 206	10383±176	974	9.4	18596±349	1936	10.4	68.9±0.9	5.11	7.4	78.1±1.2	6.86	8.8
Holstein Cow 669	10043±114	776	7.7	19308±295	2007	10.4	66.9±0.7	4.69	7.0	73.9±0.9	5.94	8.0
Guernsey Cow 427	11878±200	1110	9.4	21513±228	1355	6.3	53.9±1.3	6.80	12.6	65.2±0.7	4.81	7.4
Holstein Cow 599	11909±307	1701	14.3	21163±322	1966	9.3	56.8±1.4	7.75	13.6	67.1±1.4	7.27	10.8
Holstein Cow 601	14193±180	1000	7.1	24686±492	2632	10.7	55.9±1.4	7.41	13.3	67.0±1.0	4.96	7.4
Hereford Steer 815	14698±159	1179	8.0	43082±306	2522	5.9	64.1±0.5	3.70	5.8	77.1±0.7	5.94	7.7
Shetland Pony 1 C	2629± 58	260	9.9	4422± 60	217	4.9	----	----	----	----	----	----
Shetland Pony 2♀	5784±192	725	12.5	12648±216	792	6.3	40.3±0.5	1.89	4.7	43.4±0.8	2.75	6.3
Shetland Pony 3♂	6168±168	749	12.1	11256±288	1198	10.6	42.9±1.3	5.25	12.2	43.3±1.3	5.36	12.4
Percheron Horse 37♂	9637±194	1496	15.5	15845±192	1562	9.9	58.4±0.7	5.22	8.9	60.6±0.7	5.68	9.4
Percheron Horse 19 C	15352±258	2098	13.7	27716±264	2147	7.7	46.0±0.5	4.10	8.9	47.0±0.4	3.01	6.4

(B) Walking Speed, 2.2 miles per hour (59.00 meters per minute).

Animals	Metabolism, calories per day						Pulse Rate per minute					
	Standing			Walking			Standing			Walking		
	M	a	V, %	M	a	V, %	M	a	V, %	M	a	V, %
Hereford Cow 206	10668±153	715	6.7	27034±765	3588	13.3	69.4±1.2	5.51	7.9	87.3±2.1	9.72	11.1
Holstein Cow 669	10260±476	2640	25.7	30389±748	4294	14.2	66.7±0.8	4.37	6.6	83.1±1.0	5.16	6.2
Shetland Pony 2♀	6264±120	792	12.6	15288±216	1747	11.4	39.4±0.5	4.04	10.3	43.4±0.4	3.73	8.6
Shetland Pony 3 C	6240± 96	802	12.8	13440±168	1416	10.5	41.6±0.4	3.70	8.9	47.3±0.5	4.23	8.9
*Percheron Horse 37♂	9776±189	1400	14.3	20325±284	2229	11.0	59.1±0.7	5.46	9.2	61.8±0.7	5.42	8.8
**Percheron Horse 37♂	13200±144	1099	8.3	27792±312	2134	7.7	51.6±0.8	5.74	11.1	55.2±0.9	6.08	11.0
Percheron Horse 19 C	17048±142	1212	7.1	38098±352	2998	7.9	44.9±0.4	3.34	7.4	48.7±0.4	3.20	6.6
American Saddle Horse 1♀	7186±129	809	11.3	12747±302	1792	14.1	49.4±0.7	4.38	8.9	55.2±1.1	6.69	12.1
American Saddle Horse 2♀	8907±143	1039	11.7	17769±235	1596	9.0	46.7±0.8	5.63	12.1	51.0±1.1	7.11	13.9
Human, F. C. ♂	1615± 85	377	23.3	4762± 67	369	7.8	64.2±1.0	4.60	7.2	65.6±1.6	9.09	13.9
Human, W. O. ♂	1978±118	349	17.7	5426± 95	281	5.2	81.0±1.5	4.31	5.3	82.0±2.8	8.33	10.2

(C) Walking Speed, 3.1 miles per hour (83.15 meters per minute)

Animals	Metabolism, calories per day						Pulse Rate per minute					
	Standing			Walking			Standing			Walking		
	M	a	V, %	M	a	V, %	M	a	V, %	M	a	V, %
Shetland Pony ♀	7603 ±120	355	4.7	19031 ±368	1091	5.7	44.8 ±0.5	1.60	3.6	54.0 ±1.2	3.58	6.6
Shetland Pony 3 C	9385 ±365	1082	11.5	21566 ±385	1140	5.3	43.2 ±0.9	2.71	6.3	53.2 ±1.2	3.49	6.6
Percheron Horse 19 C	16872 ±205	1552	9.2	51111 ±479	3618	7.1	44.3 ±0.4	3.03	6.8	51.6 ±0.5	4.14	8.0

$$M = \text{Mean} = \frac{\Sigma X}{N}$$

$$a = \text{Standard Deviation} = \sqrt{\frac{\Sigma X^2}{N} - (Mx)^2}$$

$$V, \% = \text{Coefficient of Variation} = \frac{a}{M} \times 100$$

* = Colt 6 months old.
** = Colt 10 months old.
♀ = Female; ♂ = Male; C = Castrate.

TABLE 3.—STATISTICAL CONSTANTS FOR THE RESPIRATION DATA

(A) Walking Speed, 1 15 miles per hour (30.85 meters per minute).

Animals	Respiration Rate per minute						Tidal Air, Liters						Ventilation Rate, Liters per minute					
	Standing			Walking			Standing			Walking			Standing			Walking		
	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %
Jersey Cow 834	16.7±0.4	2.27	14.1	19.8±0.5	2.98	15.1	3.06±.06	.402	13.1	3.76±.09	.579	15.4	49.1±1.5	9.44	19.2	74.2±2.2	14.51	19.6
Guernsey Cow 427	18.3±0.4	2.34	12.8	23.0±0.4	2.45	10.7	3.88±.07	.383	9.9	5.28±.14	.784	14.9	71.1±2.1	11.92	16.8	121.5±3.8	21 23	17.5
Holstein Cow 599	16.7±0.9	4.64	27.8	23.5±0.7	3.76	16.0	4.47±.11	.592	13.2	5.07±.17	.995	19.6	74.8±4.4	23.35	31.2	118.4±4.7	26.89	22.7
Holstein Cow 601	23.0±0.8	3.88	16.9	29.1±0.4	2.03	7.0	3.74±.12	.614	16.4	4.39±.19	.945	21.5	85.4±3.4	17.40	20.4	126.8±5.0	24.57	19.4
Shetland Pony 1 C	11.3±0.2	0.93	8.2	16.0±0.1	0.46	2.9	2.56±.04	.188	7.3	2.33±.03	.095	4.1	28.7±0.0	1.92	6.7	37.2±0.0	1.59	4.3
Shetland Pony 2♀	14.8±0.6	2.36	15.9	21.9±1.2	4.28	19.5	5.50±.10	.374	6.8	5.67±.15	.534	9.4	80.9±3.3	11.95	14.8	122.4±5.4	19.64	16.3
Shetland Pony 3♂	16.9±0.5	2.26	13.4	23.6±1.5	5.72	24.2	5.23±.11	.472	9.0	4.98±.12	.468	9.4	88.1±3.1	13.19	15.0	115.3±4.5	17.50	15.2
Percheron Horse 37♂	28.6±0.5	3.45	12.1	44.2±1.0	8.18	18.5	2.85±.04	.295	10.3	2.89±.04	.357	12.3	81.0±1.5	11.31	14.0	125.5±2.2	17.94	14.1
Percheron Horse 19 C	17.5±0.2	1.93	11.0	35.2±0.6	5.09	14.5	7.87±.07	.583	7.4	7.90±.06	.500	6.3	138.1±1.7	13.45	9.7	280.5±4.0	32.53	11.6

(B) Walking Speed, 2.2 miles per hour (59 00 meters per minute).

Animals	Respiration Rate per minute						Tidal Air, Liters						Ventilation Rate, Liters per minute					
	Standing			Walking			Standing			Walking			Standing			Walking		
	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %
Shetland Pony 2♀	12.7±0.2	1.75	13.8	21.8±0.6	4.67	21.4	5.21±.08	.583	11.2	5.64±.12	.988	17.5	65.4±1.0	8.08	12.4	117.6±1.6	13.94	11.9
Shetland Pony 3 C	13.6±0.3	2.29	16.8	27.1±0.6	5.17	19.1	4.03±.09	.760	18.9	3.91±.09	.762	19.5	59.1±1.8	15.63	26.5	110.9±2.1	18.02	16.3
*Percheron Horse 37♂	28.5±0.5	3.54	12.1	54.1±0.9	6.86	12.7	2.92±.05	.339	11.6	3.19±.05	.354	11.1	81.2±1.5	11.31	13.9	168.3±2.8	21.81	13.0
**Percheron Horse 37♂	19.7±0.4	2.45	12.4	35.0±1.1	7.01	20.0	5.83±.08	.526	9.0	6.06±.12	.746	12.3	114.7±1.9	13.00	11.3	212.6±5.9	36.90	17.4
Percheron Horse 19 C	17.3±0.5	4.04	23.4	38.5±0.9	7.31	19.0	8.02±.17	1.435	17.9	8.61±.15	1.288	15.0	134.7±2.2	19.13	14.2	325.4±7.5	63.99	19.7
American Saddle Horse 1♀	16.6±0.7	3.94	23.7	27.4±2.0	9.33	34.0	3.14±.12	.640	20.4	3.09±.13	.620	20.1	50.1±1.2	6.30	12.6	80.1±3.6	16.70	20.8
American Saddle Horse 2♀	12.6±0.3	2.12	16.8	25.2±0.8	5.17	20.5	7.23±.09	.689	9.5	6.89±.14	.913	13.3	90.4±1.5	11.03	12.2	170.3±4.2	27.52	16.2
Human, F. C. ♂	15.3±0.5	2.32	15.2	13.2±0.4	2.07	15.7	1.29±.04	.165	12.8	2.13±.04	.228	10.7	19.4±0.3	1.12	5.8	27.4±0.4	2.35	8.6
Human, W. O. ♂	17.0±0.4	1.27	7.5	23.4±0.3	0.80	3.5	1.15±.02	.071	6.2	1.50±.05	.134	8.9	19.7±0.9	2.63	13.4	34.9±0.8	2.40	6.9

(C) Walking Speed, 3.1 miles per hour (83.15 meters per minute).

Animals	Respiration Rate per minute						Tidal Air, Liters						Ventilation Rate, Liters per minute					
	Standing			Walking			Standing			Walking			Standing			Walking		
	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %	M	σ	V, %
Shetland Pony 2♀	16.7±0.3	0.75	4.5	31.0±1.1	3.35	10.8	5.44±.04	.109	2.0	5.37±.11	.334	6.2	90.8±2.1	6.13	6.8	165.7±3.1	10.63	6.4
Shetland Pony 3 C	19.6±0.5	1.36	6.9	46.8±1.7	5.15	11.0	5.05±.06	.182	3.6	4.46±.13	.372	8.3	99.0±2.7	8.00	8.1	208.2±7.3	21.62	10.4
Percheron Horse 19 C	18.0±0.4	2.84	15.8	49.2±0.8	6.08	12.4	7.81±.14	1.000	12.8	9.65±.17	1.240	12.8	139 ±3	18.48	13.3	473 ±11	78.69	16.6

M = Mean = $\frac{mX}{N}$ a = Standard Deviation = $\sqrt{\frac{\Sigma X^2}{N} - (Mx)^2}$ V, % = Coefficient of Variation = $\frac{a}{M} \times 100$

* = Colt 6 months old ** = Colt 10 months old. ♀ = Female; ♂ = Male C = Castrate

TABLE 4.—INFLUENCE OF FASTING ON THE ENERGY COST OF WALKING AT THE RATE OF 1.15 MI./HR.

Holstein Cow 669, weight 406 kg. (896 lbs.)

Hours after feeding	Heat Production Cal./hr.		Difference	
	Standing	Walking	Absolute Cal./hr.	%
5	422	707	285	68
11	355	640	285	80
14	403	739	336	83
26	352	624	272	77
32	323	666	343	106
38	406	758	352	87
50	365	733	368	101
53	352	691	339	96
58	352	733	381	108
74	394	694	300	76
2	442	774	332	75
5	406	739	333	82
11	365	723	358	98
26	352	707	355	101
31	349	640	291	83
35	384	733	349	91
50	355	666	311	88
55	371	694	323	87
1	435	640	205	47
2	403	704	301	75
3	403	646	243	60
15	352	710	358	102
16	410	710	300	73
21	307	666	359	117
22	333	666	333	100
25	250	518	268	107
26	403	646	243	60
28	403	646	243	60
39	403	762	359	89
45	339	672	333	98
46	307	640	333	108
50	275	659	384	140
52	307	672	365	119
64	339	704	365	108
69	288	710	422	147
2	390	749	359	92
4	410	685	275	67
16	326	653	327	100
21	384	768	384	100
26	307	582	275	90
27	333	582	249	75
46	349	643	294	84
51	304	646	343	113
63	384	675	291	76
65	381	640	259	68
71	336	630	294	88

Hereford Cow 206, weight 399 kg. (878 lbs.)

Hours after feeding	Heat Production Cal./hr.		Difference	
	Standing	Walking	Absolute Cal./hr.	%
4	410	774	364	89
9	368	736	368	100
15	394	720	326	83
29	365	704	339	93
34	298	691	393	132
39	285	666	381	134
49	326	637	311	95
52	355	736	381	107
60	352	707	355	101
77	333	720	387	116
1	326	685	359	110
2	326	627	301	92
3	326	653	327	100
16	384	710	326	85
21	307	749	442	144
22	333	698	365	110
25	243	678	435	179
26	294	678	384	13
28	269	704	435	162
39	294	755	461	157
40	326	781	454	139
45	282	704	422	150
46	339	704	365	108
50	301	710	410	136
52	307	755	448	146
64	282	698	416	148
71	371	742	371	100
3	416	771	355	85
5	410	710	301	73
15	358	602	243	68
21	384	627	243	63
27	275	608	333	121
28	307	602	294	96
40	349	736	387	111
41	320	723	403	126
47	390	694	304	78
52	288	688	400	139
64	352	781	426	122
72	368	698	330	90
1	394	736	342	87
6	403	774	371	92
12	358	704	346	97
25	326	637	310	95
30	333	720	387	116
36	285	643	358	126
49	301	637	336	112
54	291	646	355	122

Hereford Steer 815, weight 930 kg. (2049 lbs.)

Hours after feeding	Heat Production Cal./hr.		Difference	
	Standing	Walking	Absolute Cal./hr.	%
1	605	1789	1184	196
4	659	1907	1248	189
15	595	1837	1242	209
20	598	1744	1146	192
39	544	1763	1219	224
47	570	1642	1072	188
50	605	1696	1091	180
64	518	1632	1114	215
66	458	1581	1123	245
69	461	1405	944	205
4	605	1856	1251	207
9	570	1837	1267	222
13	490	1744	1254	256
27	518	1696	1178	228
31	538	1632	1094	203
37	458	1587	1129	247
51	480	1619	1139	237
56	470	1555	1085	231

justify final conclusions. The unusually heavy steer 815 had a high net expense of walking due probably to his extreme fatness and clumsiness, and to sore feet rather than to his live weight as such.

The high cost of walking of pony 2 for the 1.1 and 2.2 mile speeds is probably due in part to a slightly sore shoulder at these times. Discomfort (sore feet in case of steer 815 and probably a slightly sore shoulder in case of pony 2) seemingly increases the energy expense of walking.

Cardiorespiratory Activities

In Table 1 are given the data for pulse rate, respiration rate, tidal air and ventilation rate during standing and walking. The percentage increments for ventilation rate approach most nearly in magnitude to the percentage increments for energy expense. The influence of walking on respiration rate is next in magnitude of percentage increment. Pulse comes third. The influence of walking on tidal air is uncertain.

The literature on the relation between energy metabolism and cardiorespiratory activities has been discussed in connection with the data on the energy increment of standing over lying (1).

The Statistical Constants

The statistical constants given in tables 2 and 3 are very irregular partly because in some cases the records going to make up the averages were obtained in close succession and therefore under nearly the same conditions; while others were obtained a year apart. The training factor might also have been an influencing factor. To simplify the situation we give below a tabulation of the averages of the coefficients of variability of all horses and cattle measured at all speeds.

	Coefficient of Variation	
	Standing Per cent	Walking Per cent
Metabolism	11.56	9.28
Pulse Rate	8.91	8.83
Respiration Rate	15.45	16.93
Tidal Air	12.30	13.91
Ventilation Rate	14.97	15.51

This tabulation shows that the coefficient of variation is of the order of 9% for pulse rate, 10% for heat production, 13% for tidal air, 15% for ventilation and respiration rates. It may be noted that these coefficients of variation are of the same order of magnitude as were found in the other physiological processes, such as milk secretion in cattle.

SUMMARY AND CONCLUSIONS

The energy costs of horizontal walking at speeds 1.15, 2.2, and 3.1 miles per hour (30.85, 59.00, and 83.15 meters per minute) were measured on seven cattle ranging in weight from 384 to 930 kilograms, and on seven horses ranging in weight from 91 to 688 kilograms. A few humans were also included in the experiments for comparative purposes, supplemented further by an analysis of Smith's[5] data on humans. Cardio-respiratory data are also presented for the sake of completeness. The results, together with their statistical constants, are presented in tabular and also in graphic forms.

The results may be summarized as follows: (1) The *percentage* heat increment of walking over standing increases in a roughly linear manner with speed. For humans the relation of the percentage heat increment of walking over standing, Y, to speed, S, is $Y = 74S$; which means that at 1-mile hr. speed the increase of walking over standing is 74%; at 2-mile hr. speed the increase is 148%; and so on. The percentage rise with increasing speed is less steep for horses. (2) The *net* energy expense of walking (expense above standing) per unit live weight and per unit horizontal distance is independent of speed. It is 39.7 Cal. per 100 pounds live weight per horizontal mile for humans, 33 Cal. for cattle, and 28.1 Cal. for horses (or 0.544 gm-cal. per horizontal kilogrammeter for humans, 0.452 cal. for cattle, and 0.385 cal. for horses). (3) The *overall* energy expense of walking (including the overhead cost of maintenance) per unit line weight and per unit horizontal distance decreases with increasing speed according to the equation $Y = Ae^{-ks}+C$ in which Y is the overall energy expense of walking for speed S, and C is the net energy expense of walking. (4) Per unit of live weight and distance walked, horses spend less energy than cattle, and cattle somewhat less than humans. In other words, humans are less efficient walkers than horses or cattle. These differences are apparently independent of size of animals since the differences between two small ponies were greater than between the small ponies and large horses.

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