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TYRANNOSAURUS REX RUNNING? ESTIMATIONS OF EFFICIENCY, SPEED AND ACCELERATION

I. Nesteruk*

Institute of Hydromechanics, National Academy of Sciences of Ukraine, Kyiv, Ukraine
Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

*Corresponding author: inesteruk@yahoo.com

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Background. The estimations of maximum speed of Tyrannosaurus Rex vary from 5 20 m/s and higher and still are the subject of scientific discussion. Some scientists consider T. Rex the largest terrestrial super-predator that needed speeds greater than 60 km/h (17 m/s) to capture its prey. Some recent publications indicate that it wasn't able to run at all due to its large mass and significant loads on the skeleton and limit its walking speed to 5–7.5 m/s.

Objective. We will try to answer the question of whether large animal or robot sizes are an obstacle to rapid running and to evaluate the maximum possible speed of T. Rex.

Methods. We will use: a) two energy efficiency indicators - the drag-to-weight ratio or the cost of motion and the recently developed capacity-efficiency (connected with the power-to-weight ratio or metabolic rate); b) the vertical acceleration estimations; c) the available data about the speed, the stride and the leg length of human and animals.

Results. The drag-to-weight ratio and the capacity-efficiency were estimated for running of different animals and humans. It was shown that the maximal running speed of T. Rex may reach the values 21–29 m/s. The values of its vertical acceleration are typical for bipedal running.

Conclusions. Large dimensions of Tyrannosaurus Rex couldn't be an obstacle to achieving rather high speeds during short intervals of fast running. Such conclusions allow us not to abandon the assertion that the dinosaur was a super-predator. Presented approach could be useful for studying locomotion in modern and fossil animals, human sport activity and for design of fast bipedal robots.

Keywords: biological data analysis; animal locomotion; bipedal running; fossil animals; cost of motion; metabolic rate; drag-to-weight ratio; power-to-weight ratio.

Introduction

The maximum speed of Tyrannosaurus Rex remains the subject of scientific discussion. Without going into detail, we note two opposite points of view. Some scientists consider T. Rex the largest terrestrial super-predator that needed speeds greater than 60 km/h (17 m/s) to capture its prey [1]. Some recent publications indicate that it wasn't able to run at all due to its large mass and significant loads on the skeleton and limit its walking speed to 5–7.5 m/s [2, 3]. However, the speed of the African Bush elephant (Loxodonta africana, the herbivorous animal of similar weight – 8 t) may exceed 11 m/s [4].

In this paper, we will try to answer the question of whether large animal or robot sizes are an obstacle to rapid running and to evaluate the maximum possible speed of T. Rex. For this purpose, energy efficiency indicators (the drag-to-weight ratio or the cost of motion and the capacity-efficiency, developed in [5, 6] and connected with the power-to-weight ratio or metabolic rate) and the vertical acceleration estimations will be used.

Materials and Methods

Drag-to-weight ratio and cost of motion. Since the aerodynamic drag can be neglected by running of humans and large enough animals [6, 7], the total drag $X \approx mg/k$ is connected with supporting the animal weight mg. The drag-to-weight ratio $1/k$ can also be treated as the cost of motion, i.e. how much energy is used to move 1 N of weight to the distance of 1 m. Usually in literature, this characteristic is related to the 1 kg of mass – $Jkg^{-1}m^{-1}$ (see, e.g., [8]). By dividing the values in $Jkg^{-1}m^{-1}$ by 9.8 ms^{-2} (the value of gravity constant), we obtain the dimensionless criterion $1/k$.

To estimate the efficiency of running, we shall modify the approach proposed in [7], which assumes running as series of jumps and the energy of the vertical motion as wasted to support the horizontal motion. Then this wasted kinetic energy equals $0.5mv^2$ (v is the vertical velocity in the beginning of the jump). By dividing this energy by the duration of the jump $2v/g$, we obtain the wasted capacity $0.25mgv$ and the drag coefficient $1/k = 0.25v/U$, where U is the velocity of a horizontal movement.

Since the aero-dynamical drag can be neglected, the vertical velocity just after (and before) the leg contact with the ground can be estimated from the simple relationship: $l_j = 2Uv/g$, where l_j is the length of the jump, or running stride. Then the drag-to-weight ratio can be estimated as follows [6]:

$$1/k = 0.25v/U = 0.125 l_j g/U^2. \qquad (1)$$

Power-to-weight ratio and capacity-efficiency. The power balance for the steady horizontal anaerobic motion can be written as follows:

$$q\eta mg = XU = \frac{mgU}{k} \qquad (2)$$

where q is total available power per unit of weight (metabolic rate), and η is the propulsion efficiency $(0 < \eta < 1)$. Then the maximum velocity of running is independent of mass and equals $U = kq\eta$. That means that the large mass of T. Rex cannot prevent its fast running. It must be noted that a long time running can be supposed as an aerobic activity with the energy release proportional to the lung surface (or $m^{2/3}$). Then from the balance similar to (2), we can conclude that $U \sim m^{1/3}$, i.e. small animals are faster long distance runners. The same is valid for human athletes. For instance, the body mass of 10 000 m runner champion – Kenenisa Bekele (55 kg) – is only 58.5 % of mass of 100 m one – Usain Bolt (94 kg).

Eq. (2) yields a new characteristic – capacity-efficiency (see also [5, 6]):

$$C_E = q\eta = \frac{U}{k} \qquad (3)$$

which with the use of (1) can be written as follows:

$$C_E = 0.25v = 0.125 l_j g/U. \qquad (4)$$

Results

Estimations of the drag-to-weight ratio. The estimations of the cost of motion (1) for humans and animals are presented in Table and in Figure by red markers. To estimate it dependence on the maximal running velocity, the simple relationships for male 100 m running: $U = 0.79 + 3.89 l_j$ and female 40 m one: $U = 0.53 + 3.71 l_j$ can be used (U is in m/s, l_j – in meters [9]). Then eq. (1) yields:

$$1/k = 0.0321(U - 0.79)g/U^2;$$
$$1/k = 0.0337(U - 0.53)g/U^2. \qquad (5)$$

The red solid and dotted lines show the relationships (5) in the Figure. They attain their maxima at velocities 1.48 m/s and 1.06 m/s respectively. At greater velocity, the cost of running diminishes with the increase of the velocity. For bipedal running, the experimental values (shown by red triangles) are in good agreement with the relationships (5). Only very small animals such as cockroaches, lizards and quails are the exceptions, since their stride-velocity dependences sufficiently differ from the human ones (their stride frequency U/l_j is much higher).

The real metabolic cost of human running is approximately 4 $Jkg^{-1}m^{-1}$ (e.g., [8]) or $1/k = 0.41$. This value is 10–15 times greater than shown in the Table estimations 0.027–0.042. It means that only a small part of the energy released in human body is transformed into the kinetic energy of the mass center movement, i.e., the propulsion efficiency is rather small.

Calcualtions of the capacity-efficency. The results of the capacity-efficiency calculations with the use of equation (4) are presented in the Table and shown by blue markers in the Figure. It follows from (3) and (5) that

$$C_E = 0.315–0.249/U;$$
$$C_E = 0.33–0.175/U \qquad (6)$$

for 100 m male and 40 m female running respectively.

Solid and dashed blue lines show the relationships (5) in the Figure.

For bipedal running, the experimental values (presented by blue triangles) are in good agreement with the relationships (6). Only very small animals such as cockroaches, lizards and quails are the exceptions, since their stride-velocity dependences sufficiently differ from the human ones.

It must be noted that real values of the power-to-weight ratio (or metabolic rate) are much greater than the capacity-efficiency. For example, the maximum metabolic rate of human athletes is

Table: Information about speed, lengths of stride and leg for humans and animals obtained from different sources. Estimations of drag-to-weight ratio, capacity-efficiency and vertical acceleration

N	Name	Primal information				Calculations		
		Maximal speed, m/s	Stride length, m	Leg length, m	Ref.	Drag-to-weight, $1/k$, eq. (1)	Capacity-efficiency, CE, m/s, eq. (4)	Vertical acceleration, a/g, eq. (8)
1	Cockroach, Periplaneta	1.5	0.029	0.016	[12, 16]	0.016	0.024	1.11
2	Bobwhite quail, Colinus virginianus	3.0	0.250	0.114	[12, 13, 15]	0.035	0.103	1.68
3	Guinea fowl, Numida meleagris	3.4	0.564	0.279	[12, 13, 15]	0.058	0.201	1.75
4	Lizard 1, dopsosaurus dorsalis	3.7	0.159	0.034	[12, 17]	0.014	0.053	2.87
5	Lizard 2, callisaurus draconoides	4.2	0.162	0.040	[12, 17]	0.011	0.047	2.51
6	Rhea, rhea Americana	5.5	1.383	0.809	[12, 13, 15]	0.055	0.306	1.65
7	Turkey, meleagris gallopavo	5.8	1.135	0.483	[12, 13, 15]	0.041	0.239	2.08
8	Male record 10 km, Kenenisa Bekele	6.3	1.650	0.800	[18, 19]	0.050	0.319	1.96
9	Emu, dromaius novaehollandiae	7.2	1.835	1.003	[12, 13, 15]	0.043	0.312	1.77
10	Fit female, 40 m run	7.4	1.850	0.790	[9]	0.042	0.307	2.17
11	Fit male, 100 m run	9.4	2.210	0.830	[9]	0.031	0.289	2.42
12	Female record, 100 m, Florence Griffith-Joyner	9.5	2.083	0.850	[20, 21]	0.028	0.268	2.23
13	Male record, 100 m, Usain Bolt	10.4	2.439	1.000	[22]	0.027	0.286	2.25
14	Hare	18.0	3.000	0.397	[4]	0.011	0.204	5.60
15	Ostrich	19.4	5.000	1.500	[4, 23]	0.016	0.315	3.02
16	Red kangaroo, macropus rufus	19.4	9.000	1.600	[4]	0.029	0.567	5.15
17	Horse record, Winning Brew	19.7	7.500	1.600	[24, 25]	0.024	0.467	4.29
18	Cheetah	31.0	7.000	0.610	[4]	0.009	0.277	8.48

approximately 2.9 m/s (28 W/kg) [8] and is 10 times greater than the capacity-efficiency of 100 m running and is in between the rate of standing 1.29 W/kg and walking 3.3 W/kg [10]. Similar large differences occur also in the case of vehicles (see [6]) and can be explained by a small value of the locomotion coefficient η.

We can assume that the capacity-efficiency of T. Rex cannot exceed the value 0.33 m/s, which follows from second equation (5) and experimental data for bipedal running. If Tyrannosaurus Rex had the values $C_E >$ 0.33 m/s, it would mean a higher metabolic rate or/and a bigger locomotion coefficient η in comparison with existing animals with the same running gait. There are animals with higher values of capacity-efficiency (e.g., horses and kangaroos, see the Figure and the Table), but they have different running gaits.

Estimations of the maximal running velocity. Inequality $C_E \leq 0.33$ m/s and formula (4) yield the estimation of the maximum running velocity in Tyrannosaurus Rex

$$U(m/s) \geq 3.71 \cdot l_j(m). \qquad (7)$$

Thus, to know its maximal speed, we need its maximal stride length. Unfortunately, information about T. Rex traces is very limited. Moreover, to use formula (7), we need the maximal length of the running stride, which is much larger and happens much less often in comparison with the strides corresponding to the comfortable running (see, e.g., the data about ostriches in [11]). We can

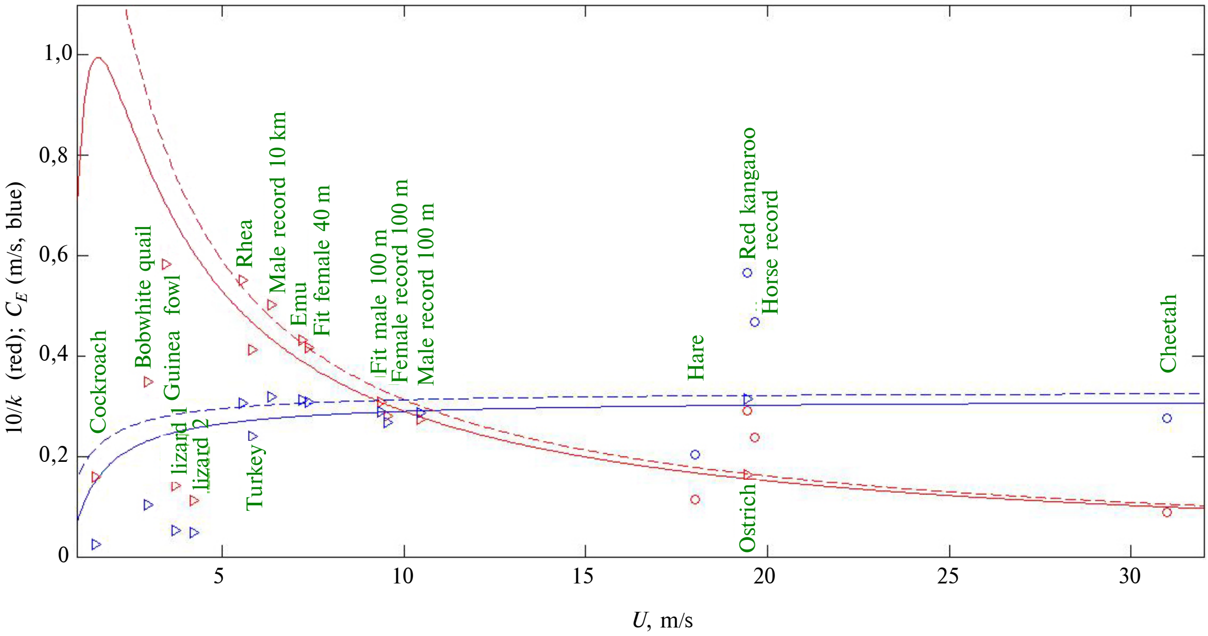

Figure: Drag-to-weight ratio (cost of motion) and capacity-efficiency for humans and running animals. Red lines correspond to $10/k$ values calculated with the use of formulae (2). Experimental values (formula (1)) are shown by red markers. Blue lines correspond to C_E values calculated with the use of formulae (5). Blue markers show the experimental values (formula (4)). Bipedal running animals are presented by "triangles"; other running gaits – by "circles"

use the information about the relative stride referred to the leg length. The maximum stride-to-leg ratio for humans and birds vary from 1.7 to 2.4 [12, 13]. Then taking the value 3.3 m as the maximal length of T. Rex leg [14], we can obtain from (7) the estimations of its maximum velocity: $U > 20.8$–29.4 m/s.

Such high speeds correspond to the maximum values of the capacity efficiency, i.e., are close to the asymptotical values in relationships (6). Thus, we can conclude, if T. Rex needed to run fast, its capacity-efficiency could be around 0.33 m/s and its maximum speed between 21 and 29 m/s. To be sure that such high velocities are possible, we will estimate the values of the vertical acceleration a as a measure of forces acting in skeleton.

Calculation of the vertical acceleration. We can use the simple relationship: $a \approx 2v/t_c$, where t_c is the duration of a leg contact with a ground and can be taken from [14], where the information about running of many animals were summarized as follows: $t_c = 0.8 l_l^{0.84}/U^{0.87}$ (the values of the leg length l_l must be taken in meters, speed in m/s). Using also (4), we obtain:

$$a \approx 8\frac{C_E}{t_c} \approx 10\frac{C_E U^{0.87}}{l_l^{0.84}}. \qquad (8)$$

The results of application of formula (8) are presented in the Table. For the bipedal running animals, the vertical acceleration doesn't exceed 3g. Bipedal hopping gait (kangaroo, hare) allows larger values of acceleration (5.2–5.6g), since the vertical load is distributed on two legs. The highest acceleration 8.5g occurs in cheetah, where four legs are in simultaneous ground contact. Putting in (8) values C_E = 0.33 m/s and l_l = 3.3 m, we can estimate the acceleration in T. Rex between 1.7g and 2.3g for speeds 21 and 29 m/s respectively. These values are typical for bipedal running and cannot destroy its bones.

Discussion

To be convinced of the correctness of our estimates, it is necessary to answer the question why the capacity-effectiveness of modern lizards is 6–7 times less than what is accepted for T. Rex (see the Table). Application of these small values of C_E to T. Rex could yield 6–7 times higher values of its speed (according to (4)) and 21–22 % lower values of its vertical acceleration (according to (8)). Such procedure looks incorrect due to the huge difference in sizes (e.g., the length of callisaurus draconoides is 69 times smaller than the length of

T. Rex [14, 17]). For very small animals, aerodynamic drag becomes essential and the presented formulae are no more valid. To be aware of this, we can use the critical value of k

$$k^{***} = 0.43 \frac{g(1-\alpha)\sqrt{V}}{\alpha\sqrt{\nu U^3}}; \alpha = \frac{\rho V}{m} \qquad (9)$$

at which the aerodynamic drag on an elongated body of revolution with a laminar unseparated shape becomes equal to the drag associated with supporting the weight, [6]. Here V is the volume of body; ρ is the density of air; $\nu \approx 1.46 \cdot 10^{-5}$ m^2/s is the kinematic viscosity of air. If $k^{***} >> k$, then the aerodynamic drag can be neglected.

Assuming the average density of animals to be close to the density of water ρ_W $(m \approx \rho_W V)$, we can use the available data about their mass and the value $\alpha \approx 1.2 \cdot 10^{-3}$. Then, for callisaurus draconoides (the lizard of average mass 9.5 g, [17]), formula (9) yields $k^{***} \approx 322$. This value is comparable with the estimation (4), presented in Table 1, $k \approx 91$. It means that air drag influences the running of small lizards. The same conclusions can be drawn about cockroaches and quails. Relatively small values of capacity-efficiency don't mean that very small animals are bad runners. Their drag-to-weight ratio and C_E was underestimated by neglecting the aerodynamic drag. In the case of T. Rex (U = 21–29 m/s, m = 8–14 t), eq. (9) yields values $k^{***} \approx 16000$–35000, which are much lager than $k = U/C_E \approx 64$–88 (eq. (3), $C_E \approx 0.33$ m/s). Therefore, the air drag in T. Rex running can be neglected and all presented formulae and estimations are valid.

Conclusions

The obtained results don't mean that T. Rex had to run at speeds 21–29 m/s. We claim only that its large dimensions couldn't be an obstacle to achieving such high speeds during short intervals of fast running. Such conclusions allow us not to abandon the assertion that the dinosaur was a super-predator. Such a popular animal couldn't only eat carrion.

Presented approach could be useful for studying locomotion in modern and fossil animals, human sport activity and for design of fast bipedal robots.

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І.Г. Нестерук

БІГ ТИРАНОЗАВРА РЕКСА? ОЦІНКИ ЕФЕКТИВНОСТІ, ШВИДКОСТІ ТА ПРИСКОРЕННЯ

Проблематика. Оцінки максимальної швидкості тиранозавра Рекса варіюються від 5 до 20 м/с і вище й досі залишаються предметом наукової дискусії. Деякі вчені вважають, що т. Рекс – найбільший наземний суперхижак, який, щоб захопити свою здобич, мав розвивати швидкість понад 60 км/год (17 м/с). У деяких недавніх публікаціях вказується на те, що він взагалі не міг бігати через велику масу і значні навантаження на скелет, і швидкість його ходьби обмежується значенням 5–7,5 м/с.

Мета. Ми спробуємо відповісти на запитання про те, чи є великі розміри тварин або роботів перешкодою швидкому бігу, та оцінити максимально можливі швидкості руху т. Рекса.

Методика реалізації. Ми будемо використовувати: а) два показники енергетичної ефективності – співвідношення опір до ваги, або витрати на рух, та запропоновану нещодавно потужність–ефективність (пов'язану зі співвідношенням потужність до ваги або швидкістю метаболізму); б) оцінки вертикального прискорення; в) наявні дані про швидкість, крок і довжину ноги людини й тварин.

Результати. Зроблено оцінки співвідношення опір до ваги та потужності–ефективності для бігу різних тварин і людей. Показано, що максимальна швидкість руху т. Рекса може досягати 21–29 м/с. Значення його вертикального прискорення характерні для бігу на двох ногах.

Висновки. Великі розміри т. Рекса не можуть бути перешкодою для досягнення досить високих швидкостей бігу за короткі проміжки часу. Такі висновки дають нам можливість не відмовлятися від твердження, що динозавр був суперхижаком. Запропонований підхід може бути корисним для вивчення руху сучасних і викопних тварин, спортивної активності людей, а також для розробки швидких двоногих роботів.

Ключові слова: аналіз біологічних даних; пересування тварин; біг на двох ногах; викопні тварини; витрати на рух; швидкість метаболізму; співвідношення опір до ваги; співвідношення потужність до ваги.

И.Г. Нестерук

БЕГ ТИРАНОЗАВРА РЕКСА? ОЦЕНКИ ЕФФЕКТИВНОСТИ, СКОРОСТИ И УСКОРЕНИЯ

Проблематика. Оценки максимальной скорости тираннозавра Рекса варьируются от 5 до 20 м/с и выше и до сих пор являются предметом научной дискуссии. Некоторые ученые считают т. Рекса крупнейшим наземным суперхищником, который, чтобы захватить свою добычу, должен был развивать скорость более 60 км/ч (17 м/с). В некоторых недавних публикациях указывается на то, что он не мог бегать вообще из-за большой массы и значительных нагрузок на скелет, и скорость его ходьбы ограничивается значением 5–7,5 м/с.

Цель. Мы постараемся ответить на вопрос о том, являются ли большие размеры животных или роботов препятствием для быстрого бега, и оценить максимально возможную скорость движения т. Рекса.

Методика реализации. Мы будем использовать: а) два показателя энергетической эффективности – отношение сопротивления к весу, или стоимость движения, и разработанную недавно мощность–эффективность (связанную с отношением мощности к весу или скоростью метаболизма); б) оценки вертикального ускорения; в) имеющиеся данные о скорости, шаге и длине ноги человека и животных.

Результаты. Отношение сопротивления к весу и мощность–эффективность были оценены для бега различных животных и людей. Максимальная скорость бега т. Рекса может достигать 21–29 м/с. Значения его вертикального ускорения типичны для бега на двух ногах.

Выводы. Большие размеры т. Рекса не могут быть препятствием для достижения довольно высоких скоростей бега в короткие промежутки времени. Такие выводы позволяют нам не отказываться от утверждения о том, что динозавр был суперхищником. Представленный подход может быть полезен для изучения локомоции у современных и ископаемых животных, спортивной активности человека и для разработки быстрых двуногих роботов.

Ключевые слова: анализ биологических данных; локомоция животных; бег на двух ногах; ископаемые животные; стоимость движения; скорость метаболизма; отношение сопротивления к весу; отношение мощности к весу.