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From bipedalism to bicyclism: evolution in energetics and biomechanics of historic bicycles

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We measured the metabolic cost (C) and mechanical work of riding historic bicycles at different speeds: these bicycles included the Hobby Horse (1820s), the Boneshaker (1860s), the High Wheeler (1870s), the Rover (1880s), the Safety (1890s) and a modern bicycle (1980s) as a mean of comparison. The rolling resistance and air resistance of each vehicle were assessed. The mechanical internal work (W_{INT}) was measured from three-dimensional motion analysis of the Hobby Horse and modern bicycle moving on a treadmill at different speeds. The equation obtained from the modern bicycle data was applied to the other vehicles. We found the following results. (i) Apart from the Rover, which was introduced for safety reasons, every newly invented bicycle improved metabolic economy. (ii) The rolling resistance decreased with subsequent designs while the frontal area and, hence, aerodynamic drag was fairly constant (except for the High Wheeler). (iii) The saddle-assisted body weight relief (which was inaugurated by the Hobby Horse) was responsible for most of the reduction in metabolic cost compared with walking or running. Further reductions in C were due to decreases in stride/pedalling frequency and, hence, W_{INT} at the same speeds. (iv) The introduction of gear ratios allowed the use of pedalling frequencies that optimize the power/contraction velocity properties of the propulsive muscles. As a consequence, net mechanical efficiency (the ratio between the total mechanical work and C) was almost constant (0.273 ± 0.015 s.d.) for all bicycle designs, despite the increase in cruising speed. In the period from 1820 to 1890, improved design of bicycles increased the metabolically equivalent speed by threefold compared with walking at an average pace of *ca.* $+0.5\,\mathrm{m\,s^{-1}}$. The speed gain was the result of concurrent technological advancements in wheeled, human-powered vehicles and of 'smart' adaptation of the same actuator (the muscle) to different operational conditions.

Keywords: cycling history; energetics; mechanics; efficiency

1. INTRODUCTION

The struggle for mobility and communication, which is particularly apparent nowadays, has constituted a major evolutionary push for all terrestrial species. In most cases, the adopted solution for a change favoured a higher progression speed and economy. These two variables are in a way linked because, for the same engine or muscle power, the lower the cost of locomotion the better the performance. Notable examples have been the development of different gaits (walk, trot and gallop) within a single species and a wealth of diverse locomotion strategies across species, from the snake crawling to the cricket jumping. A novelty was introduced whenever the twofold problem of how to cope with the increased resistance of the medium and how to maintain the efficiency of the same actuator (muscle) at higher speeds was solved.

The same process can also be observed when humans, aware of the irreducible mismatch between 'slow' biological evolution and 'fast' socio-technological progress, rely on the mechanical appendages of their bodies, active (e.g. human-powered vehicles) or passive (automobiles), for increasing their mobility speed. Among all such stories (and we have to remember that cross-country skiing started as a means of transport more than 4000 years ago), the evolution of cycling represents a milestone in the application of ingenuity for overcoming the limiting constraints to speed on land imposed by bipedalism. During the whole of the nineteenth century, the combination of the need for individual mobility at an affordable price in urban/industrial settlements and the current technological advances produced a rapidly flourishing 'evolution' of the bicycle towards higher speeds and better riding economy and comfort (the last two concepts are somewhat related).

The aim of this paper is to quantify the improvements in the performance and economy of cycling evolution by studying the energetics and biomechanics of riding the most relevant historic bicycles, from the very beginning to the modern bicycle. The analysis of the first model, the Hobby Horse (1817), where the rider still pushed their feet against the ground, will help in understanding the transition from purely biological locomotion to modern technology-assisted progression. A case will also make the point of 'evolutionary' choice contradicting the energy-saving criterion in favour of a higher safety factor.

2. MATERIAL AND METHODS

(a) *Subjects*

The experiments were carried out using five recreational cyclists (mean ± s.d., age 56.2 ± 11.6 years, stature 1.72 ± 0.39 m

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Table 1. *The bicycles, technical data*
(Abbreviations: DFS, diamond-frame safety; PTS, pneumatic-tyre safety.)

	Hobby Horse	Boneshaker	High Wheeler	Rover (DFS)	Safety (PTS)	modern bicycle
abbreviation	HH	BS	HW	RO	SA	MB
year[b]	1820s	1860s	1870s	1880s	1890s	1980s
mass (kg)	23.7	24.5	15	20	16.5	12.1
handlebar height (m)	1.26	1.22	1.40	1.20	1.30	0.95
saddle height (m)	0.86	0.99	1.31	0.95	1.01	0.90
front wheel diameter (m)	0.725	0.89	1.27	0.75	0.71	0.64
rear wheel diameter (m)	0.725	0.74	0.44	0.75	0.71	0.64
distance travelled per pedal revolution (m)	—	2.80	3.99	4.45	5.50	5.02[c]
tyre thickness (mm)	20	20	20	20	40	45
rim or spokes	wood	wood	metal	metal	metal	metal
tyres	metal	metal	solid rubber	solid rubber	pneumatic[a]	pneumatic[a]
brakes	no	rear	front	front	front	front or rear
bike + subject frontal area (m^2)	0.46 ± 0.02	0.44 ± 0.02	0.55 ± 0.01	0.48 ± 0.01	0.49 ± 0.03	0.46 ± 0.01
rolling resistance, Cr	0.0268 ± 0.0018	0.0284 ± 0.0026	0.0158 ± 0.0020	0.0200 ± 0.0029	0.0083 ± 0.0037	0.0084 ± 0.0037
air density, ρ ($kg\,m^{-3}$)	1.193	1.192	1.186	1.200	1.195	1.201

[a]Front and rear wheel pressure during the experiments: 4 bar (405 kPa).
[b]Period of production/introduction of the model. For details see Dodge (1996).
[c]This distance corresponded to the chainwheel/cog choice of the subjects at all the investigated speeds.

and body mass 68.0 ± 2.5 kg). All subjects were experienced riders of historic bicycles (high wheelers, mainly), were informed about the methods and aims of the study and gave their written consent to the experimental procedure.

(b) *The bicycles: technical and historic data*

The bicycles used in this study were original pieces with the exception of the Hobby Horse, which was a very accurate reproduction. Their technical characteristics are reported in table 1. For further details on these and other historic bicycles, the reader is referred to the books of Sharp (1896), Whitt & Wilson (1974) and Dodge (1996).

(i) *The Hobby Horse*

Also called a 'draisine', it was the oldest bicycle tested, dating back to the 1820s. It consisted simply of two wooden wheels connected by a wooden beam on which a saddle, arm and chest support and a handlebar were fixed. It was also called a 'running machine' because forward propulsion was obtained by an alternate push on the ground of the lower limbs, as occurring in walking or running. However, unlike walking and running, the Hobby Horse supported some of the subject's weight with the saddle, and thus afforded substantial energy savings. The Hobby Horse represented an amusing toy for the very rich and was never used as a true means of transportation.

(ii) *The Boneshaker*

Also called a 'velocipede', this was developed in the 1860s. The most important technological improvement with respect to the Hobby Horse was the addition of pedals and cranks to the front wheel. The Boneshaker was the British name for those velocipedes with wooden wheels and metallic rims (like the one used in this study) to distinguish them from later models equipped with a rubber tyre fitting over the metallic band. The Boneshaker had a fairly primitive steering mechanism, and riding it on the poorly conditioned roads of that time required high skill, strength and balance. By 1868, some Boneshaker models allowed the crank length to be adjusted to suit the rider's leg length.

(iii) *The High Wheeler*

Also called a 'high bicycle', 'ordinary' and 'penny-farthing', the High Wheeler was developed in the early 1870s when the manufacturers of the velocipede began to enlarge the front wheel and use better and lighter materials. The rationale for this evolutionary step was that each pedal revolution translated into a greater distance of forward movement. As a by-product, the high wheels provided a flywheel effect and, well before the invention of pneumatic tyres, the elasticity of its long spokes helped in reducing the jolting caused by the rough roads. The High Wheeler was made completely of steel, was little more than half the mass of velocipedes and had wheels with solid rubber tyres. While intended as an improvement on the efficiency and safety of velocipedes, they were difficult machines to ride, requiring great courage and a good physical condition. Improved versions of the High Wheeler (like the one used in this study) comprised an adjustable ball bearings axle, trap pedals and toe clips. In order to offer an easier and safer ride to a widely increasing number of potential users, later versions of the High Wheeler (e.g. the 'xtraordinary' and the 'kangaroo') were also equipped with levers and gearing.

(iv) *The diamond-frame Safety* (*Rover*)

The Rover appeared in the 1880s and featured a chain-driven rear wheel. The advantages of the rear drive and smaller wheels were the ease of bicycle mounting/dismounting and the steering of a non-driving wheel. It was the first widely available design where the pedalling frequency was different from that of the wheels. While the diamond-frame, rear-driven bicycle was much easier to ride than the High Wheeler (hence its name), it suffered increased mass and vibrations, the last due to both the reduced length of the load-bearing spokes and the persistence of solid tyres. In order to attenuate this problem, manufacturers adopted a variety of spring suspension systems in the saddle, forks, bearing shackles and even in the frame itself. However, the Rover tested in this study had solid tyres and no springs (apart from in the saddle).

(v) *The pneumatic-tyred Safety* (*Safety*)

After the diamond-frame Safety the overall design of the bicycle would not dramatically change for nearly three-quarters of a century, apart from the introduction of pneumatic tyres in the 1890s. This step in bicycle evolution constituted a major improvement, since these tyres absorbed road irregularities more effectively than springs. Rubber pneumatic tyres made the Safety a lighter and more comfortable vehicle to ride, which was accessible to all. The Safety tested in this study had no springs (apart from in the saddle), an adjustable saddle and a shaft-driven transmission. The Safety was the first vehicle to make cycling available to women, although the drop frame, which was designed to accommodate skirts, introduced *ca.* 5.0 kg of extra mass.

(vi) *A modern bicycle*

As a means of comparison with the historic bicycles, we also performed the following procedures on a recent bicycle. The modern bicycle tested in this study (Arrowhead, GT; Santa Ana, CA, USA) had a frame similar to a mountain bike but with smoother tyres (a 'city bicycle'). Mountain bikes, which were developed in the 1980s as a result of the desire to ride off-road, represent 95% of adult bicycles currently sold in the USA (Dodge 1996). While being equipped with 24 different sprocket/chainwheel combinations, which are designed for coping with a wide range of inclines and speeds, our subjects used just one of these (in order to match the perceived exertion of riding the other historic bicycles).

Data referring to a modern racing bicycle (Capelli *et al.* 1998) are also reported in the study.

(c) *Experimental procedure*

The experiments were performed on a rough concrete surface where the subjects were asked to cycle around a path 170 m long at different, constant, submaximal speeds. All the tests took place on days with calm winds. The bicycles were equipped with bicycle computers (MSC 3DX, Cateye; Osaka, Japan) in order to allow the subjects to maintain the requested speed. The initial speed, which was selected according to the bicycle to be tested, ranged from 1.11 to 2.78 m s^{-1}. The speed was increased by 0.56 m s^{-1} every 6 min, with maximum speeds ranging from 3.33 to 5.56 m s^{-1}. The time to cover each lap was recorded and the average speed was calculated from these measurements.

(i) *Bioenergetic measurements*

The subjects were equipped with a portable metabograph (Cosmed K4b^2; Rome, Italy) that measured their pulmonary ventilation (VE) (l min^{-1}), heart rate (HR) (bpm), carbon dioxide output ($\dot{V}CO_2$) (l min^{-1}) and oxygen uptake ($\dot{V}O_2$) (l min^{-1}) on a breath-by-breath basis. Oxygen uptake at rest was measured while the subjects were sitting quietly in the laboratory before each experimental session. The VE, HR and $\dot{V}O_2$ values collected during the last 2 min of each run at constant speed were averaged and used for further analysis.

The energy cost of riding each bicycle (C) (J m^{-1}) (assuming 1 ml O_2 was equivalent to 20.9 J) was obtained from the ratio between steady-state oxygen uptake (when resting, as above) and average speed.

(ii) *Biomechanical measurements*

The total mechanical work of riding a bicycle can be divided into two components: the external work, due to overcoming aerodynamic drag and rolling resistance and the internal work, due to the linear and angular accelerations of the limb segments with respect to the body centre of mass.

The total resistance opposing the motion of a cyclist on the level (R_t) is the sum of the rolling resistance (R_r) due to energy losses as the wheels roll along the road and the air resistance (R_a) or drag, i.e. $R_t = R_r + R_a$ (e.g. Di Prampero *et al.* 1979*a*). In turn,

$$R_a = 0.5 \times \rho \times A \times C_a \times v^2 \qquad (1)$$

and

$$R_r = C_r \times M \times g, \qquad (2)$$

where ρ is the air density (kg m^{-3}), A is the frontal area (m^2), C_a is the air resistance coefficient (which is dimensionless, depending on three-dimensional shape), v is the average speed (m s^{-1}), C_r is the rolling resistance coefficient (dimensionless), M is the total mass (of the subject plus the bicycle) (kg) and g is the acceleration due to gravity (9.81 m s^{-2}).

(i) R_a was calculated by assuming that $C_a = 1.1$ (Di Prampero, 1986), from the frontal area of each cyclist riding each bicycle. The procedure involved digital photography (Cybershot DSC-F505, Sony; Tokyo, Japan), automatic pixel counting of a manually selected outline and metric unit conversion by using a reference grid of known size (NIH Image 1.62, USA; http://rsb.info.nih.gov/nih-image). During the metabolic sessions barometric pressure (P) (mmHg) and air temperature (T) (K) were recorded for each subject and each bicycle tested. The air density was therefore calculated from these measurements according to $\rho = \rho_0 \times P \times T$, where $P = 760$ mmHg, $T = 237$ K and ρ_0 is the density of dry air at standard temperature and pressure DRY (STPD, 1.293 kg m^{-3}).

(ii) The term R_r was calculated by means of a simplified deceleration method during 'coasting down' experiments performed on the same ground surface as that used for the metabolic tests. At low speeds of progression, the R_a term is negligible. Hence, the force opposing motion could be derived from $F = M\mathrm{d}v/\mathrm{d}t = -C_r \times M \times g$, which, when integrated, gives $v = v_0 - C_r \times g \times t$, where v_0 is the initial velocity and t is time (s). The subjects were therefore asked to ride the bicycles at a speed of *ca.* 3 m s^{-1} (2.81 $\pm$ 0.7 m s^{-1} on average), then to stop pedalling and remove their feet from the pedals. The decreasing speed was then recorded at 1 Hz by means of a bicycle computer (Power Control, SRM; Jülich, Germany), the data from which were uploaded from a PC. The decay in speed was fitted by a linear regression of the form $v = a + b \times t$, where the slope was the deceleration ($\mathrm{d}v/\mathrm{d}t$) due to rolling resistance. These measurements were repeated several times and the average slope (which corresponded to the product $-C_r \times g$) was divided by g in order to yield C_r.

(iii) In order to measure the internal work of cycling, three-dimensional motion capture was performed on one subject while riding a modern bicycle on a treadmill (Woodway ErgoLG; Weil Am Rhein, Germany). Eighteen reflective

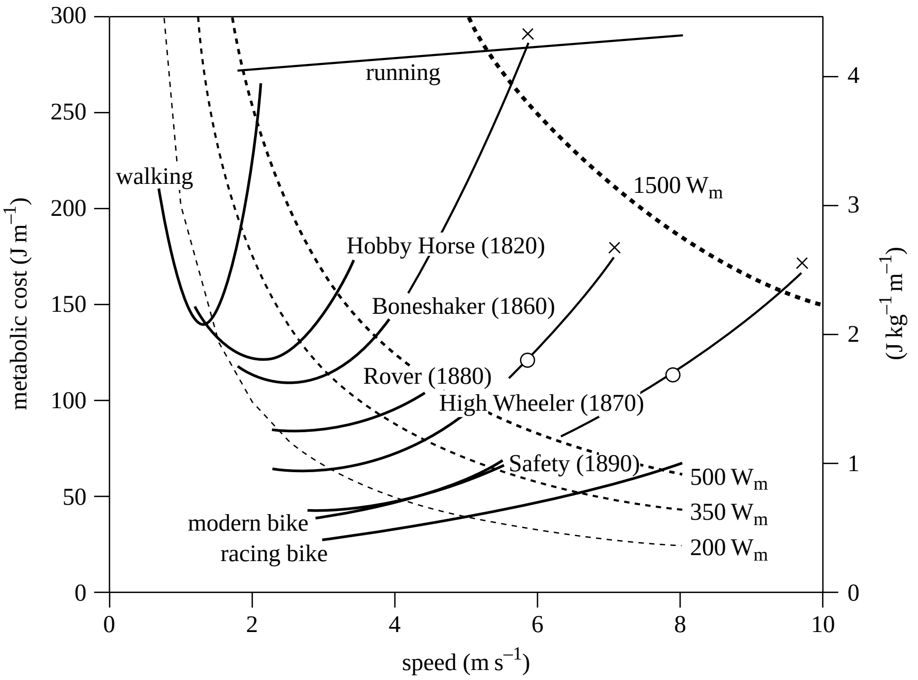

Figure 1. Metabolic cost versus progression speed for all of the bicycles tested. For the sake of comparison, data for walking, running (Minetti 1998*b*) and riding a modern racing bicycle (Capelli *et al.* 1998) are also shown. The descending dashed curves represent isometabolic power hyperbolas (power = cost × speed) (W_m represents a metabolic watt), while the asterisks refer to the 1-h (crosses) and 24-h (circles) records achieved in 1870–1876–1893 (Boneshaker–High Wheeler–Safety) and 1876–1894 (High Wheeler–Safety), respectively. Their vertical placement in the graph reflects the extrapolation on the regression second-degree polynomials at the speed record (thin curves). The metabolic cost indicated on the right-hand side ordinate is expressed per kilogram of body mass.

markers were put on relevant joints on both sides of the subject, who was asked to pedal unrestrained at a constant speed (3 and 5 m s^{-1}) and at several frequencies. For each of these a session of video sampling (100 Hz) lasting 5 s was executed by a four-camera motion analysis system (ELITE, BTS; Milan, Italy). The three-dimensional coordinates and standard anthropometric tables obtained allowed calculation of the position of the body centre of mass and the linear and angular speed of each body segment. A software package designed in our laboratory then computed the internal mechanical work (W_{INT} in J kg^{-1} m^{-1}) (Minetti 1998*b*), which was defined as the work needed in order to accelerate the limbs with respect to the body centre of mass (Cavagna & Kaneko 1977).

The same procedure was applied to the video capture data of a subject riding a Hobby Horse on the treadmill at different speeds (range of 1–3 m s^{-1}).

In order to estimate the pedalling W_{INT} for the other bicycles investigated we needed a model equation that was capable of predicting over a wider speed/frequency range with respect to the modern bicycle. For this purpose the following rationale was used. The internal work of a single revolution is expected to be speed independent because, as a first approximation, the body centre of mass is supposed to move forward at a constant speed (the relative linear speed of the limbs should depend on frequency only). Being strictly related to the changes in the angular kinetic energy of body segments, we could expect a dependence on the squared frequency. Thus,

$$W'_{INT} = q \times m \times f^2, \tag{3}$$

where W'_{INT} is expressed in joules per revolution, q is related to the inertia parameters of the moving body segments, m is the body mass (kg) and f is the pedalling frequency (Hz). In order to express the mechanical internal work in customary units (W_{INT} in joules per kilogram of body mass and per metre travelled), the above equation has to be modified to

$$W_{INT} = W'_{INT}/m \times f/s = q \times f^3/s, \tag{4}$$

where s is speed (m s^{-1}). Thus, we used a multiple nonlinear regression for the mechanical internal work where only q had to be estimated (Systat 5, SPSS Inc., Chicago, IL).

The model equation provided by the previous rationale could not be used to fit the experimental data when analysing the W_{INT} related to riding the Hobby Horse and a model proposed in the literature (Minetti 1998*a*) for walking and running (the closest gaits) was also not applicable because of the lack of a strict relationship between the stance and the swing time. In addition, since a given stride frequency was associated and there was no need to extrapolate beyond the investigated parameter range for each progression speed of the Hobby Horse, a descriptive (rather than a model) equation was used to fit the experimental data.

The net mechanical efficiency of riding each bicycle was calculated at any given speed and for any given subject and bicycle from the ratio of the total mechanical work ($W_{TOT} = W_a + W_r + W_{INT}$) (J m^{-1}) to the energy cost (C) (J m^{-1}).

3. RESULTS

(a) *Bioenergetic results*

The energy costs of riding the bicycles investigated are reported in figure 1 as a function of the progression speed. For the purpose of comparison, the energy costs required for covering a unit of distance are also reported

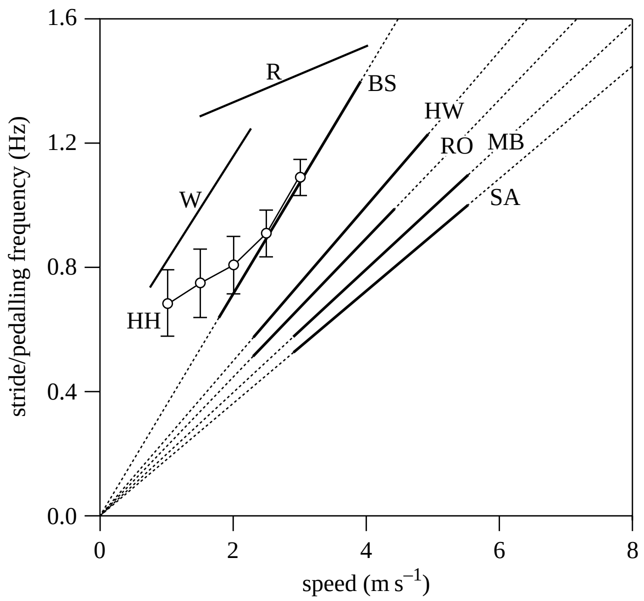

Figure 2. Stride (walking, running and Hobby Horse) and pedalling frequencies as a function of speed for all of the vehicles tested. The solid line segments represent the ranges investigated in the present study. The data for the Hobby Horse (open circles) are shown with standard deviations.

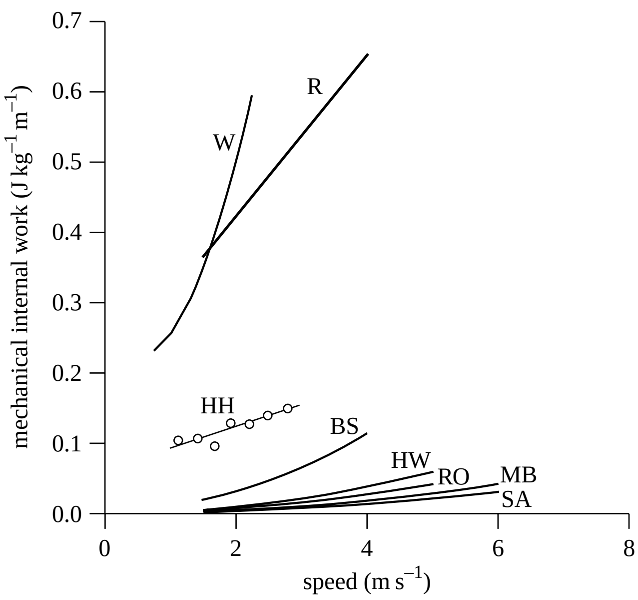

Figure 3. The mechanical internal work associated with oscillating the lower limbs (walking, running and Hobby Horse) and to pedalling as a function of speed plotted for all of the vehicles tested. The solid line segments represent the ranges investigated in the present study. The data for the Hobby Horse (open circles), which were obtained in one subject, have been fitted by linear regression.

for walking, running (Minetti 1998*b*) and riding a racing bicycle in an outdoor velodrome (Capelli *et al.* 1998).

The cost of riding the Hobby Horse ($C = 31.54v^2 - 133.71v + 263.94$, $n = 29$ and $r = 0.491$) was found to be less expensive than both walking and running, with a curvilinear relationship between C and v (as in walking). At the optimum speed (*ca.* 2 m s^{-1}) the energy expenditure of riding the Hobby Horse was half that of walking or running. The energy cost associated with the Boneshaker ($C = 16.75v^2 - 84.05v + 215.32$, $n = 22$ and $r = 0.402$) was on average 15% lower than with the Hobby Horse (between 1.67 and 3.33 m s^{-1}). The economy further improved with the High Wheeler ($C = 5.71v^2 - 30.76v + 105.23$, $n = 29$ and $r = 0.834$), the average cost of which was half that of the Boneshaker (at speeds of between 2.22 and 3.89 m s^{-1}). While the Rover certainly represented an improvement in safety, its economy was lower than that of the High Wheeler ($C = 5.71v^2 - 28.67v + 127.01$, $n = 13$ and $r = 0.807$). Nevertheless, riding the Rover was 20% less expensive than the Boneshaker (at speeds of between 2.22 and 3.89 m s^{-1}). Finally, the introduction of pneumatic tyres (the Safety and modern bicycle) further decreased the energy cost of cycling, and the energy expended in riding a Safety ($C = 1.99v^2 - 6.31v + 40.60$, $n = 15$ and $r = 0.837$) was very similar to that needed for riding a modern bicycle ($C = 3.67v^2 - 20.89v + 73.19$, $n = 27$ and $r = 0.786$).

(b) *Biomechanical results*

Apart from the Rover, the rolling resistance decreased with each subsequent bicycle design (see C_r in table 1). In contrast, the frontal area was almost constant (the High Wheeler was an exception because of the larger wheel size). Thus, the relationship between the work needed to overcome air resistance (W_a) (J m^{-1}) and speed was essentially the same for all bicycles. The stride/pedalling frequency is plotted in figure 2 as a function of the progression speed for all the vehicles investigated (data for walking and running are included for comparison). The mechanical internal work during pedalling on a modern bicycle was fitted by

$$W_{\mathrm{INT}} = 0.153 \times f^3/s \tag{5}$$

($n = 10$ and $r = 0.989$), while for the Hobby Horse the experimental data was fitted by

$$W_{\mathrm{INT}} = 0.058 + 0.031s \tag{6}$$

($n = 7$ and $r = 0.914$). Figure 3 reports the W_{INT} measured for the modern bicycle and the Hobby Horse, together with the estimated W_{INT} for the other vehicles obtained by substituting the bicycle-specific speeds and frequencies into equation (5).

The partitioning of the total mechanical work into its components (internal and external) (= air + rolling resistances) at metabolically equivalent speeds is reported for each bicycle in figure 4.

(c) *Mechanical efficiency*

The decrease in W_{TOT} from the Hobby Horse to the modern bicycle was matched by a proportional decrease in C so that the efficiency remained fairly constant from the 1820s to modern times (average (±s.d.) peak value 0.273 ± 0.015). As shown in figure 5*a*, the relationship between mechanical efficiency and progression speed for each new bicycle is a downward parabola, horizontally shifted to the right-hand side, with the maximum value in approximately the middle of the speed range investigated. Only geared vehicles (the Rover, Safety and modern

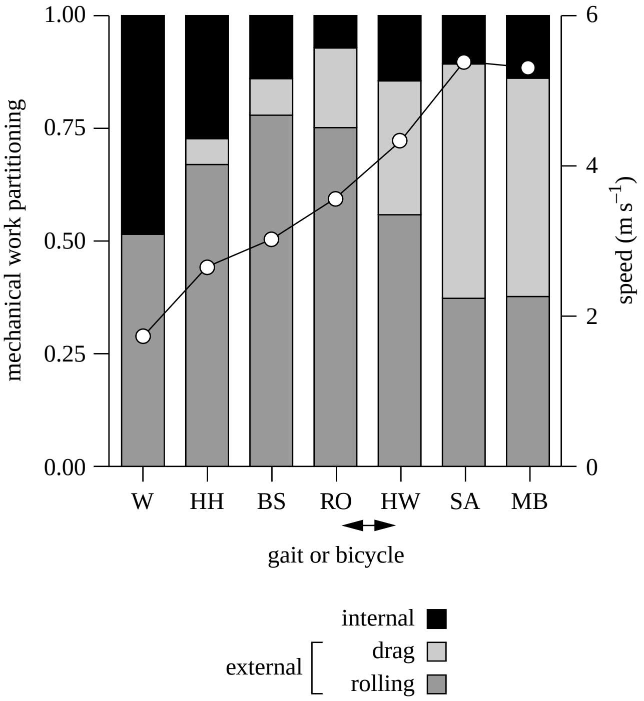

Figure 4. Mechanical work partitioning for each gait or vehicle moving at metabolically equivalent (350 W) speeds (open circles). For walking (W), the lower bar refers to the external work necessary for accelerating and lifting the body centre of mass. The chronological order has been reversed for the Rover and High Wheeler only in order to preserve the increase in economy. The histogram can also be referred to as the partitioning of the mechanical work due to drag, rolling resistance and limb movement (internal work) within a unit distance travelled.

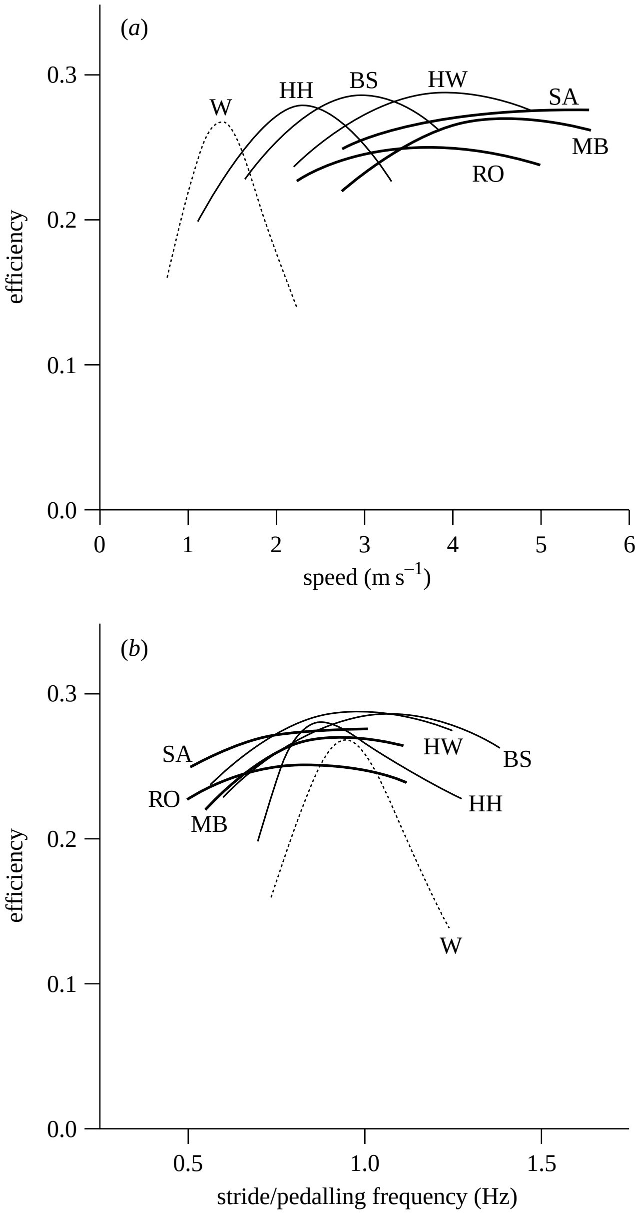

Figure 5. The efficiency of locomotion (the ratio between the total mechanical work and the metabolic energy cost) as a function of (*a*) progression speed and (*b*) stride/pedalling frequency. Thick curves represent vehicles where a transmission device (chain or shaft) is interposed between the feet and the wheel. The mechanical work used to calculate walking efficiency (W) was obtained by allowing complete energy transfer between body segments.

bicycle) (thick curves) reported slightly lower efficiency curves.

4. DISCUSSION

Some technical and methodological aspects of the present measurements are discussed in Appendices A–F in order to avoid overloading this section.

Our study shows that the introduction of wheels for personal use (the Hobby Horse) improved terrestrial locomotion economy. With the Hobby Horse, the saddle supported *ca.* 65% of the body weight (from preliminary measurements of vertical ground reaction force) and, as a result, doubled the metabolically equivalent speed compared with walking. In addition, the process of dramatically and progressively reducing the mechanical internal work in cycling evolution started with this bicycle (see figure 3 and Appendix A). In fact, despite the similarity with walking and running, the limbs could be accelerated less during the swing phase. This was caused by the decoupling of the duty factor (the portion of the stride at which each foot was in contact with the ground) from the stride frequency, which was allowed by the capability for proceeding just on the wheels. The related reduction in stride frequency (see figure 2) also accounts for the decrease in internal work (Minetti 1998*a*). The invention of the Boneshaker represented another milestone in cycling history since it was realized that, in order to increase progression speed, the feet need not be in direct contact with the ground. The pedals did not just slightly decrease the revolution frequency, their rotary movement also contributed to minimizing the relative speed change (with respect to the body centre of mass) of the lower limb segments and to further reducing the mechanical internal work (figure 3). The High Wheeler, which extended this concept by enlarging the driven wheel, succeeded in improving the progression economy (see figure 1) by lowering the rolling resistance (see table 1 and Appendix B for details). This was the combined effect of solid rubber tyres and long, elastic spokes. The

Table 2. *Summary of the results*

(Each symbol (upward arrow, increase; equals sign, no change; downward arrow, decrease) represents the comparison with respect to the preceding bicycle or gait. Metabolic changes are boxed to discriminate them from mechanical results.)

	C	W_{int}	W_{ext} vertical	W_{ext} horizontal	muscle efficiency	main novelty
walking and running						
1820s Hobby Horse	↓	↓↓	↓↓	=	=	body mass suspension
1860s Boneshaker	↓	↓↓	↓	↓	↑	lower limb position, less speed oscillation, gear ratio
1870s High Wheeler	↓	↓	=	↓	↑	gear ratio, rubber tyre
1880s Rover	↑	↓	=	↑	=	safety, uphill/downhill
1890s Safety	↓↓	↓	=	↓	↑	gear ratio, pneumatic tyre
1980s modern bicycle	=	=	=	=	↑	(multiple gear ratio)
race bicycle	↓	↓	=	↓↓	↑	rolling resistance and drag
		ca. frequency, limb posture	*ca.* body, suspension	*ca.* drag and rolling resistance	*ca.* gear ratio	

trend of enlarging the front wheel should have come to a stop, both because of the inevitable anatomical limitations and for sensible safety reasons. Injuries reported due to falling from such a height (an anecdotal skull fracture) prevented wide diffusion of the High Wheeler as a means of transportation and stimulated the invention of something safer, even at the cost of economy loss (see the Rover in figure 1). However, in order not to give up the speed achieved, a way of decoupling the pedal movement from the rotation of a smaller wheel was invented. Nevertheless, the persistence of solid rubber tyres and the shortening of spokes raised the rolling resistance (see table 1), and with the poor chain efficiency made the Rover a safe but (metabolically) expensive bicycle to ride. This makes an interesting case in evolutionary terms, since in 'pure' biology the criterion for success could also be different from just energy minimization or power maximization (Alexander 1996). The next milestones in bicycle history (the Safety and modern bicycles) showed just such an improved rolling resistance (inflatable tyres and smaller mass) and a further lowering of pedalling frequency at the same progression speed with the expected reduction in the mechanical internal work (see figure 3).

In order to obtain insight into the evolution of cycling economy and cruising speed, we need to consider the metabolic power required. If each bicycle were ridden at the same metabolic power required for walking at a fast pace (*ca.* 350 W at 1.75 m s^{-1}) (see the hyperbola in figure 1), the estimated speeds range from 2.66 (the Hobby Horse) to 5.32 m s^{-1} (the Safety and modern bicycle), resulting in a more than threefold increase. The metabolically equivalent speeds are reported in figure 4, together with the partitioning of the unit distance travelled into the different mechanical work components (external = air drag + rolling resistance (internal)) analysed in the present study. It is apparent how the aerodynamic cost kept on growing with the progression speed (see Appendix C), while the mechanical internal work was almost continuously decreasing (the High Wheeler and Rover are reversed in the chronological order of the abscissa in order to emphasize progression economy).

One of the questions we were interested in at the beginning of the study was how the efficiency of bicycles depended on technological solutions and on musculoskeletal system adaptations. We expected to observe a slow convergence towards the complete exploitation of the actuator involved, i.e. the muscle. Instead, we found that, when the total measured mechanical work (see Appendix D) was divided by the metabolic energy expenditure, the efficiency values were closer to the theoretical maximum and were bicycle independent (see figure 5*a* and Appendix E). Parallel trends existed in reducing resistance to motion and in adapting the propelling muscles to working efficiently despite the increase in progression speed. It is interesting to note that, for each vehicle, the maximum efficiency (0.273 ± 0.015) occurred at mid-speed with respect to the range investigated (for the thick curves see Appendix F). This behaviour is entirely similar to the efficiency/revolutions per minute relationship in internal combustion engines (Newton *et al.* 1983) when a single gear is used. The whole bicycle evolution, as well as modern bicycles allowing multiple gears, can be seen as an attempt to adapt the same actuators to a progressively increasing speed, and the adoption of multiple gears in automotives confirmed that this applies also to different actuators. Thus, what could be the unifying characteristic of all the vehicles studied? It is known in muscle physiology that maximum efficiency will only be reached at a given contraction velocity (e.g. Woledge *et al.* 1985). While we did not directly measure the contraction speed of the lower limb extensor muscles for each bicycle, it is reasonable to assume that the pedalling frequency, which could be seen as proportional to radians per second, is strongly associated with it. When the mechanical efficiency is plotted against the pedalling frequency, as in figure 5*b*, all the curves are clustered around 1.0 Hz (maximum efficiency at 0.97 ± 0.08 Hz for all bicycles),

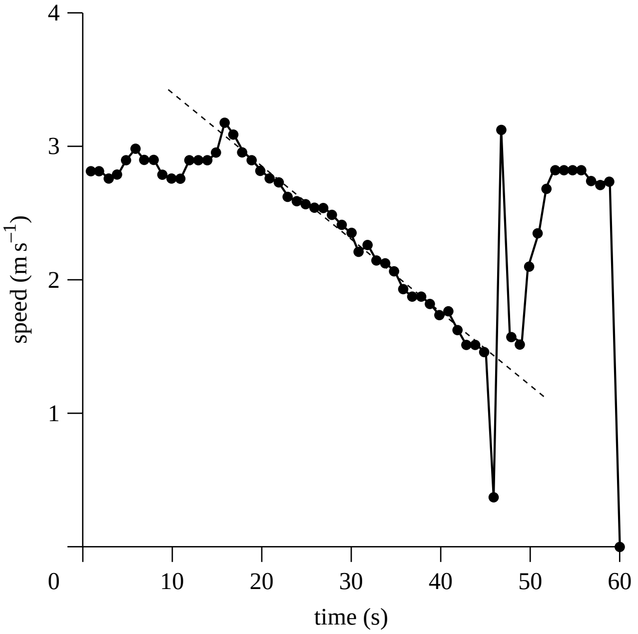

Figure 6. A typical coasting down experiment designed for estimating a bicycle's rolling resistance. Vehicle speed is plotted as a function of time, after having been collected by an SRM (Germany) at 1 Hz. The descending part has been fitted by a linear regression (see the text).

which is widely referred to as the optimum frequency in modern cycling (for a review of sources see di Prampero 2000). In addition, all the curves (except for walking and the Hobby Horse, where the above assumption does not hold) seemed to belong to the same overall function representing the efficiency/velocity relationship of extensor muscles working at a low–mid power regime (1.0 Hz has been suggested as the optimum frequency for type I fibres in cycling) (Sargeant & Jones 1995). From another perspective it can be said that each newly introduced bicycle decreased the overall resistance to progression and succeeded in increasing the muscle efficiency at the top speed of the predecessor. By comparing the metabolic and mechanical characteristics of each new bicycle with respect to its predecessor, table 2 summarizes the above discussion about the determinants of cycling evolution.

Our work shows how the early part of cycling evolution (1820–1890) allowed individuals to increase their personal mobility at a remarkably fast pace, by *ca.* 0.5 m s^{-1} per decade. Apart from the widespread use of the multi-geared bicycle (*ca.* 1913), which optimizes muscle efficiency over the whole speed range, twentieth-century research into human-powered terrestrial locomotion on wheels has mainly dealt with an extreme reduction in rolling resistance, aerodynamic drag and overall mass (Kyle 1995). However, those types of vehicle are not yet available for public transportation.

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APPENDIX A

W_{INT} measurement from motion capture resulted in a coefficient (see equation 5) that was 50% higher than previously investigated (di Prampero *et al.* 1979*b*) by using graphical analysis. It is likely that the difference between the measurements and estimates resides in a different body mass partitioning among segments, in the motion of the body centre of mass (which was assumed to be fixed in the graphical analysis) and in the slight pelvic tilt during real pedalling.

In spite of the slightly different posture of subjects with respect to the crank centre of rotation in the bicycles investigated, we estimated W_{INT} according to the actual speed and pedalling frequency by applying equation (5) to all of them, the coefficient of which ($q = 0.153\,\mathrm{J\,s^2\,kg^{-1}}$) was obtained from three-dimensional analysis of the lower limbs rotation in the modern bicycle only. Such a decision was taken in order to avoid subjects unsafely riding historic bicycles on the treadmill. However, since the crank length did not change significantly in the different bicycles (*ca.* 0.17 m), the approximation mentioned can be regarded as reasonable.

APPENDIX B

Different methods (e.g. De Groot *et al.* 1995; Candau *et al.* 1999) have been proposed for estimating the coefficient of rolling resistance (C_{r}) by means of coasting down experiments. Figure 6 shows a typical tracing of this experimental protocol. We chose a simpler computational method that did not involve the wind effect on deceleration because of the low speeds associated with the bicycles investigated in the present study. In order to compensate for eventual terrain gradients, the measurements were repeated along the two main directions of the circuit (formerly a tennis court) and the average values of C_{r} were calculated over an even number of trials.

As pointed out by Kyle (1986), the rolling resistance of cycle tyres is nearly speed independent, mainly proportional to the total load on the tyre and related to the vehicle structure deformation at the contact point with the surface. Thus, it could be lowered by increasing the wheel diameter, the tyres' smoothness and the inflating pressure and/or by decreasing the tyres' thickness (at the same bicycle-plus-subject mass). Rolling resistance will also increase the higher the bicycle mass and the lower the ability of the vehicle/ground interface (the wheel, the tyre and the road surface) to exchange elastic energy (Kyle 1986). The data reported in this study are in agreement with these principles. Indeed, W_{r} was found to be dependent on the total mass and on the elasticity of the wheels/tyres: it was higher in the Hobby Horse and Boneshaker (wooden wheels with metal rims) than in the Rover, High Wheeler (both with solid rubber tyres), Safety and modern bicycle (both with pneumatic tyres). Finally, the rolling resistance of the High Wheeler was found to be lower than that of the Rover (at a paired weight and type of tyres) due to its higher wheel diameter.

The C_{r} values for the Safety and the modern bicycle measured in the present study were higher than those reported in the literature for conventional bicycles over smoother surfaces (e.g. Gross *et al*. 1983; di Prampero 1986). However, because of the irregular terrain, the higher tyre width (40 and 45 mm, respectively) and lower pneumatic pressure (4 atm) with respect to the literature, the present C_r values seem quite reasonable. The twofold difference reported by Whitt & Wilson (1974) for bicycles with solid and pneumatic tyres was confirmed by the C_r values reported in this study, with the High Wheeler and Rover doubling the values for the Safety and modern bicycle.

APPENDIX C

The mechanical work against wind resistance was calculated from measures of frontal area and air density and assuming a drag coefficient (C_a) of 1.1 for all bicycles, a value applicable to walking, running (thus to a Hobby Horse) and cycling with traditional bicycles with the rider in the upright position (di Prampero 1986).

The values of frontal area reported in this study were comparable with those reported in the literature for a modern bicycle (Gross *et al*. 1983; di Prampero 1986) and historic bicycles (Sharp 1896). The lower values in the modern bicycle can be attributed to the partially crouched posture adopted by the riders (because of the lower height of its handlebar) and to the different elbow position, which was more 'open' in the older bicycles due to the larger dimensions of the handlebar (which were introduced in order to improve lateral balance).

However, the differences in frontal area were not big enough to lead to remarkable differences in wind resistance at the same speed among all the bicycles investigated ($W_a = 0.306\ (\pm 0.013) v^2\ \mathrm{J\,m^{-1}}$) with the exception of the High Wheeler ($W_a = 0.363 v^2\ \mathrm{J\,m^{-1}}$), the high value of which was in agreement with the greater wind resistance experienced by the Ordinary's riders since its development in the 1870s. From the 1890s onward, dropped handlebars and crouched positions in racing were adopted for the purpose of reducing wind resistance (Kyle 1995). The early streamlined vehicles date back to the 1920s even though streamlining cycling components (such as multispoked aerodynamic wheels) had been previously described (Sharp 1896).

APPENDIX D

In this paper, total mechanical work was partitioned into internal work, horizontal external work and vertical external work (see table 2). In contrast to legged locomotion, where it is widely debated whether external and internal work have to be calculated separately and summed (assuming no energy transfer between the two) or jointly computed in a total work allowing any possible energy transfer, no doubts are posed about wheeled human locomotion. Since most of the vertical displacement of the body centre of mass was eliminated by the introduction of the saddle and most of the horizontal speed oscillations disappeared by adding a circular rim to our (natural) spokes (the lower limbs), the uncertainty about energy transfer is less crucial and the three components can be regarded as independent. In order to make walking efficiency comparable with the bicycles investigated, its mechanical work was calculated according to complete energy transfer between external and internal work.

APPENDIX E

At moderate speeds the low efficiency of the Hobby Horse can be explained by a higher metabolic cost due to the co-contractions required for balancing. In fact, the subjects reported balancing problems and discomfort for each bicycle at the slowest speed, which was chosen to allow some overlap with the previous one. For the fastest vehicles, the top speed in the range was limited by the geometry of the track, which imposed sharp turns. A further reason for the increase in metabolic cost in the older bicycles (Hobby Horse, Boneshaker and Rover) at the top speed tested was the increased mechanical energy loss due to vibration. Whitt & Wilson (1974) mentioned that vibration loss increases proportionally with speed and, according to Sharp (1896), a significant part of a rider's effort is lost to vibratory effects when riding a bicycle with solid rubber tyres.

APPENDIX F

While most of the mechanical measurements were carefully made, the potential energy loss due to the transmission cascade from the pedals to the driven wheel (in the Rover, Safety and modern bicycle) was not quantified. This is also suggested by the overall lower efficiency curves of the geared vehicles (thick lines in figure 5) due to underestimation of the mechanical external work. The shaft-driven Safety and the modern bicycle seemed to suffer this approximation less, which was also because of the almost negligible energy loss (2–3%) associated with the transmission gearing (Kidd *et al*. 1996). Rather, the Rover we tested had an original 'Humber block chain' mounted, which probably generated substantial energy degradation. The reasons for this lower efficiency reside in (i) the irregularity and paucity of the teeth (double the spacing among them) in the chainwheel and the cog and (ii) higher friction, as witnessed by the wear on the faces of the blocks in contact with the teeth. The problem was solved in successive bicycles by replacing the Humber block chain with the 'roller chain' (Sharp 1896) in which loose rollers were mounted around the rivets inside each chain link in order to reduce friction with the teeth.

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