FORCES APPLIED TO A BICYCLE DURING NORMAL CYCLING*

P. D. Soden and B. A. Adeeafa

Department of Mechanical Engineering, The University of Manchester Institute of Science and Technology, Manchester, England

Abstract - Forces that the rider applies to the pedals, saddle and handlebars during speeding, hill climbing and starting are estimated from cine film records using elementary mechanics. The results are compared with force measurements obtained from an instrumented pedal. Pedal forces of up to three times bodyweight were recorded during starting. Handlebar loads were always significantly large.

INTRODUCTION

The object of this paper is to estimate the forces that the rider can be expected to apply to a bicycle in a variety of common racing cycling situations. This information is needed in order to assess the strength and performance of bicycle frames (Soden et al., 1979). Forces applied to the bicycle due to braking, irregularities in road surface and other circumstances where the rider is relatively inactive are not considered here.

The forces resisting motion of a bicycle include rolling resistance and aerodynamic drag, together with inertia forces during acceleration and gravity forces when climbing an incline. The rider overcomes these resistances by applying forces to the pedals which are transmitted by the mechanical drive to the rear wheel. Estimates of the magnitude of pedal forces derived from cine-film and from a pedal force transducer will be presented. Pedal loads are not the only forces which the rider applies to the machine; he may also exert forces on the handlebars and on the saddle. Furthermore, the distribution of forces varies as riders tend to adopt different positions and riding patterns in different situations.

CINE FILM RECORDS

A preliminary survey of the postures of riders and their change with riding conditions was carried out by studying 8 mm films shot for the Road Time Trials Council during the 1974 British racing season. Particular attention was paid to a sequence showing the motion of a rider climbing a hill during a long race (Fig. 1). Forty-eight consecutive frames from the sequence were developed into 30 × 42 mm negatives and studied using a slide projector. Sixteen of the 48 frames, covering a complete cycle of the crank rotation, were developed into pictures of 125 × 85 mm size. From these, measurements of the variation of the bicycle tilt with crank position were taken (Fig. 2).

At a later date, 16 mm cine films were recorded showing front, side and rear views of two cyclists, each climbing a ramp of 1 in 10 gradient, starting on level ground and speeding on a level road. Some photographs were also taken using a motor driven 35 mm camera.

Both subjects were 16 year old males with 'personal best' times of less than 24 min for 16 km (10 mile) time trials. Subject A weighed 570 N and subject B 660 N.

Using an analytical projector 'back projecting' onto a glass screen, the following measurements were taken from the 16 mm film:

<table>
<thead>
<tr>
<th>Subject</th>
<th>Case</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Climbing—(side view)</td>
<td>Displacement along the incline, from a reference point (Fig. 3)</td>
</tr>
<tr>
<td>B</td>
<td>Climbing (front view)</td>
<td>Variation of the angle of tilt</td>
</tr>
<tr>
<td>B</td>
<td>Climbing—(back view)</td>
<td>Vertical displacement of a label on the back of subject (Fig. 4)</td>
</tr>
<tr>
<td>B</td>
<td>Starting—(side view)</td>
<td>Horizontal displacement (Fig. 5)</td>
</tr>
<tr>
<td>A</td>
<td>Speeding—(side view)</td>
<td>Horizontal displacement</td>
</tr>
</tbody>
</table>

RESULTS AND ESTIMATION OF PEDAL LOADS FROM THE CINE FILMS

Climbing

As shown in Fig. 1, when climbing, riders tend to rise out of the saddle and stand first on one pedal and then the other, tilting the bicycle from side to side. Figure 2 shows that this rider tilted the bicycle up to 10° from...
the vertical. Maximum tilt occurs when the cranks are near vertical. The bicycle is nearly vertical when the cranks are horizontal and offering maximum leverage.

Similar climbing patterns were observed from the 16 mm films, although subject B appears to tilt the bicycle less than most riders. The maximum tilt recorded for subject B was $8^\circ$. In all the 16 mm films the riders gripped the bottom part of the handlebars (Fig. 6).

Figure 4 shows the vertical movement with respect to time of a spot on the lower back of subject B. The range of vertical movement was approximately 13 cm and the frequency of oscillation twice the frequency of pedalling; the rider's lower back reaching its highest point each time the cranks were horizontal (Fig. 4), and then following the descending leg to its lowest point when the crank was at the bottom dead centre (Figs. 6a–c). If the motion is assumed to be roughly simple harmonic, taking the range and frequency from Fig. 4 gives a maximum acceleration of approximately $16 \text{ m/s}^2$. The vertical movement of the rider's shoulders was relatively small (Figs. 6a and c).

Imperfect clarity and the relatively small scale of the pictures made all measurements taken from the cine film inaccurate. Measurements of objects of known size and inclination indicated accuracies in the order of $\pm 1 \text{ cm}$ and $\pm 1^\circ$. The above calculation gives only a very rough indication of the maximum acceleration.

From Fig. 3 the distance travelled along the inclined plane between one frame and the next (1/32nd sec) was found to be constant, within experimental errors, throughout the ascent. Scaling the measurements from the known diameter of the wheel, a climbing speed of 26.3 km/h was obtained.

**Estimation of pedal force during climbing.** Previous workers have estimated the magnitude of aerodynamic drag and rolling resistance of bicycles from wind tunnel and free wheeling experiments (Whitt and Wilson, 1974; Kyle and Edelman, 1974). Assuming on the basis of a rough assessment of frontal area that the drag force on the standing cyclist is no greater than that for a cyclist in the touring position, the total rolling and air resistance at 26.3 km/hr was approximately $16 \text{ N}$ (Kyle and Edelman, 1974). As the weight of rider was 660 N and the weight of bicycle 90 N, the component of total weight acting down the 1 in 10 incline and opposing motion was 75 N, hence total resistance to motion $= 75 + 16 = 91 \text{ N}$. The
Fig. 1. Sample prints from an 8 mm cine film showing a sequence of rear views of a rider climbing a hill during a long race (film by courtesy of RTTC). Note tilting of the bicycle (see also Fig. 2).
Fig. 6. Subject B climbing the 1 in 10 incline. Pictures taken with the 35 mm camera. (a) and (b) Cranks approaching horizontal. (c) and (d) Cranks approaching vertical.
Fig. 7. Subject D starting on level ground. Above: Sequence of rear views from the 16 mm cine-film, note tilting of the bicycle. Below: Side view with cranks horizontal, taken with the 35 mm camera.
Fig. 8. Subject B speeding on level ground.

Fig. 9. The instrumented pedal.
Forces applied to a bicycle during normal cycling

Figure 4. Vertical displacement of a spot on the subject's lower back measured relative to the bicycle frame. Data from a 16 mm cine film showing rear view of subject B, out of saddle, riding up the 1 in 10 incline. Estimated crank angles are indicated.

Total resistance was not sensitive to small errors in the assumed aerodynamic drag.

Tractive power = total resistance × forward velocity (26.3 km/hr) = 665 W.

The pedalling rate is a function of the gearing selected. For historical reasons (consider the Penny Farthing), bicycle gearing is usually quoted as the equivalent diameter of the driving wheel (in inches), i.e.

\[
\text{size of gear } = \frac{\text{no. of teeth on chainwheel}}{\text{no. of teeth on sprocket}} \times \text{wheel diameter.}
\]

For the hill climbing experiment under consideration, subject B chose a 72 in. gear.

Angular velocity of crank

\[
= \frac{\text{forward velocity}}{\text{effective driving wheel radius}} = 8 \text{ rad/sec} = 76 \text{ rev/min.}
\]

Ignoring the small power losses (Whitt and Wilson, 1974) in the mechanical drive,

mean torque = \(\frac{\text{tractive power}}{\text{angular velocity of crank}}\)

= 83 Nm.

A constant vertical force applied to the pedal during the down stroke would produce a sinusoidal variation in torque and a

maximum torque = \(\frac{\pi}{2} \times \text{mean torque}\)

= 130 Nm,

pedal force = \(\frac{\text{maximum torque}}{\text{crank radius (0.175 m)}}\)

= 750 N.

Starting

Figure 7 shows pictures of subject B starting on level ground. The rider's position and action is similar to that observed for climbing with the rider out of the saddle (Fig. 6).

Figure 5 shows that for the first complete revolution of the crank, the locus of horizontal displacement is approximately a parabola; the average acceleration being approximately 2.6 m/sec².

Estimation of pedal force during starting. The total weight of the rider and machine was again approximately 759 N. The horizontal force required at the rear wheel to produce an acceleration of 2.6 m/sec²

\[
= \frac{2.6}{9.81} \times 750 \text{ N} = 198 \text{ N.}
\]

In this case aerodynamic drag and rolling resistance were negligible (Kyle and Edelman, 1974). Inertia due to rotation of the wheels and cranks was insignificant. The rider selected an 81 in. gear.

Mean torque = tractive force \times effective wheel radius

= 203 Nm.

Assuming a sinusoidal variation in torque as before,

max. torque = \(\frac{\pi}{2} \times \text{mean torque}\) = 318 Nm,

pedal force = \(\frac{318}{0.175}\) = 1815 N.

(This is 2.75 times the rider's body weight.)

Spreading

The films of cyclists speeding on a level road showed that the riders sat in the saddle and adopted the
conventional crouched racing position (Fig. 8). There was very little movement of the body or tilting of the bicycle.

A plot of distance travelled with time for subject A showed that the rider maintained a constant speed of 37.2 km/hr throughout the sequence.

Estimation of pedal load for speeding. The total drag force for a rider in a crouched racing position travelling at 37 km/hr is approximately 25 N (20 N aerodynamic drag and 5 N rolling resistance) (Kyle and Edelman, 1974).

Power output at 37.2 km/hr
\[ = \text{drag force} \times \text{forward velocity} \]
\[ = 255 \text{ W}. \]

Subject A used an 87 in. gear so the angular velocity of the crank was 9.4 rad/sec or 89 rev/min.

Mean crank torque = 255/9.4 = 27.1 Nm.

It was assumed that a rider in the seated position would adjust his foot pressure to exert maximum vertical force when the cranks were horizontal and the lever arm was a maximum and only small vertical forces when the cranks were vertical and the lever arm was zero.

Assuming a sinusoidal variation of vertical pedal force during the down stroke results in a torque which is proportional to \( \sin^2 \theta \) when \( \theta \) is the angle of the crank to the vertical; hence in this case

maximum torque = 2 x mean torque = 54.2 Nm
maximum pedal force = 54.2/0.175 = 310 N.

**MEASUREMENT OF PEDAL FORCES**

*Force transducer and circuitry*

Pedal loads can be determined by measuring the forces applied to the pedals or to the cranks (Sharp, 1896; Moulton, 1973; Hoes et al., 1968).

Figure 9 shows the instrumented pedal (Adeyefa, 1978) used in this investigation. The upper platform of the transducer resembled a normal pedal, enabling normal shoes, shoe plates and toestraps to be used.

Two crossed beams transmitted the load from the platform to the pedal spindle. The beams were mounted below the pedal spindle where there was adequate clearance to avoid interference with normal pedalling.

Four electrical resistance strain gauges attached to each beam were connected to form a wheatstone bridge circuit, allowing separate monitoring of forces normal to the pedal and of the shear forces parallel to the pedal platform.

Power supply and bridge balancing were provided by two Fylde F3-492 BBS mini balances and the bridge outputs were connected via 12 m long cables, through Fylde type FE-251 6A mini amplifiers, to an U.V. recorder.

Calibration carried out with the pedal removed from the crank showed the load–strain relationships to be linear and repeatable throughout the entire operating range. There was some cross-talk, horizontal shear loads resulting in small readings on the normal force channel (Adeyefa, 1978). All results have been adjusted slightly to compensate for this effect.

*Crank position indicator*

To enable pedal load to be related to crank position, an aluminium disc with nine teeth cut on its periphery was attached to the bicycle chain-wheel. An electrical circuit was completed and a pulse displayed on the U.V. recorder whenever a tooth on the disc triggered a microswitch attached to the seat tube of the bicycle frame. Unequal tooth spacing allowed crank-top-dead-centre to be identified (Adeyefa, 1978).

*Dynamometer*

In indoor experiments the cyclist was mounted on a stationary bicycle with the rear wheel removed and replaced by a dynamometer to simulate resistance to motion. The Ergowheel dynamometer (Brook and Firth, 1971) consisted of an aluminium disc which could be rotated against eddy current resistance. The pole facing overlapping the disc and hence the flux, could be varied, and a calibrated scale indicated the power at a given speed and amount of overlapping.
A tachometer attached to the dynamometer gave the rider an indication of pedalling rate which could be checked more accurately from the time markers on the u.v. recorder traces.

Results of indoor experiments

The subject for the indoor tests was subject A referred to previously. He wore his normal cycling shoes and shoe plates which engaged with the pedal and the usual toestraps, and clips were fitted to both pedals. In all but one experiment the rider was seated in the saddle.

Figure 10(a) shows a copy of the force traces recorded during four complete crank revolutions with the rider pedalling at a steady rate of 90 rev/min and the dynamometer set to absorb 434 W at this speed.

The maximum push of approximately 450 N, or 78% of the rider's body weight, occurred near the 90° position (cranks horizontal). The normal force had decreased to approximately 50 N by the time the crank had reached bottom dead centre (180°). The small normal forces between 180° and 360° which produce negative torque were presumably due to the weight of the leg resting on the pedal. The normal forces were

![Diagram](image-url)
always greater than zero, indicating that the rider did not pull on the pedal at any time during the cycle, although the toestrap would have allowed him to do so. All these results are in general agreement with those of Hoes et al. (1968). The maximum fore-aft shear forces (75 N) were small compared with the maximum normal forces. The most notable peaks were associated with forward forces when the crank passed top dead centre and backward forces when the crank passed bottom dead centre, both contributing useful torque.

Tests at the same pedalling rate (90 rev/min) with the dynamometer set to a lower load of 325 W resulted in similar force patterns but reduced peak loads, the maximum normal force being approximately 380 N. Tests without toeclips and straps at the lower dynamometer setting resulted in no marked difference in force pattern (Adeyefa, 1978).

Figure 10(b) shows the results of a test at the higher load setting and with a pedalling rate of 120 rev/min, giving a power output of 772 W. Toestraps were worn and the force pattern was generally unchanged, although peaks appeared to be sharper and maximum loads increased to about 580 N, or approximately equal to the rider's body weight. Also, the rider tended to exert a very small pull on the pedal during the upwards movement.

When asked to pedal at maximum speed at this dynamometer setting, the rider was able to increase his pedalling rate to 130 rev/min (906 W) and the pull on the pedals increased to almost 100 N.

The rider was asked to adopt the hill climbing stance, standing on the pedals and gripping the lower part of the handlebars. In this position he could not maintain a steady pedalling rate of more than about 80 rev/min, generating 370 W, but the range of normal forces increased to 910 N, or 160% of body weight. Figure 10(c) shows a sample of the force traces which still exhibited marked peaks, but the period of low normal force was reduced and hence the total force supported by the two pedals was never less than body weight. The method of constraint prevented the rider from tilting or moving the bicycle in the manner usually adopted by a standing rider.

Outdoor experiments

The normal rear wheel was re-fitted to the bicycle. The wires from the transducer were secured to the rider's leg about 300 mm above the ankle, and at the recorder end the trailing wires were held about knee high by a helper. The travel of the bicycle was limited by the 12 m length of the cable, but the motion appeared to be otherwise unrestricted. The main objective of the outdoor experiments was to obtain information on the pattern of forces when the rider was out of the saddle.

Results of outdoor experiments

Subjects A and B both performed a number of starts (Adeyefa, 1978) on level ground and on the 1 in 10 incline. For a given rider the pattern of loads observed in these two situations was similar, but the loads developed tended to be larger when starting on the incline.

Figure 11(a) shows a typical load trace for subject A starting on the incline using a 67 in. gear. The normal force increased rapidly to a maximum value, remained nearly constant to the end of the first power stroke and then decreased to a small pull and remained negative to the start of the next down stroke. The force traces during the second and third revolutions were also flatter than during the indoor experiments and the forces were larger, the maximum range of normal force being 1780 N (3.1 times body weight). When starting on level ground, subject A developed a maximum normal push of 950 N and a maximum pull of 280 N.

The shear forces were small compared with the normal forces (note the different scales in Fig. 11) and were negative except for a forward peak near top dead centre, and a smaller forward peak at the end of the power stroke. The maximum shear forces were in the range 200–400 N.

Figure 11(b) shows that the shear forces for subject B starting on the incline followed a similar pattern, but the normal forces were consistently different from those for subject A. Subject B, who incidentally is known to be a good hill climber, developed a normal force which levelled out and then increased steadily to a large peak value in the second half of the power stroke, the maximum recorded push being 1990 N (3.0 times body weight). During the return stroke he pulled steadily 'upwards' and 'backwards' on the pedal. From the films it appeared that the pedal was inclined forwards during this period. The maximum recorded pull was 460 N.

Starting on level ground subject B developed a maximum normal push of 1580 N and a maximum pull of 350 N.

A third subject, a 20 year old male, body weight 727 N, developed a force of 2100 N (2.9 times body weight) when starting on the incline.

DISCUSSION OF RESULTS

The estimation of pedal loads for the case of the cyclist speeding on a level road assumed a vertical pedal force varying sinusoidally at 89 rev/min to develop 255 W. Applying the same assumptions to the experimental results of Fig. 10(a), 434 W at 90 rev/min gives a mean torque of 46 Nm, a maximum torque of 92 Nm and a sinusoidally varying force with a maximum value of 526 N. Comparing the assumed variation with the experimental results for the normal force on one pedal (see Fig. 10a) shows that it underestimates the normal force near to top dead centre, ignores the negative torque produced by the weight of the ascending leg resting on the pedal and makes no allowance for the small contribution of the fore–aft forces pushing forwards at top dead centre and backwards at bottom dead centre. It is perhaps fortunate that these effects tend to cancel out, with the
Forces applied to a bicycle during normal cycling

result that the theoretical maximum force of 526 N which occurs when the cranks are horizontal only slightly overestimates the experimental values of 430–500 N (see Fig. 10a).

When comparing the results it should be noted that the experimental measurements cannot strictly be regarded as vertical and horizontal forces because the angular position of the pedal relative to the crank was not recorded. The films showed that the forward pedal was usually horizontal, but the rear pedal was sometimes tilted up to 50° from horizontal.

The pedal loads for climbing and starting with the rider out of the saddle were calculated from the cine film by assuming a constant vertical force throughout each ½ cycle. Comparison with the experimental results shows that this was only roughly correct for subject A (Fig. 11a) and did not give a good description of the pattern of normal forces produced by subject B (Fig. 11b). Assumption of other than constant pedal force would, of course, predict larger peak loads.

The estimated pedal load for subject B, accelerating from rest at a rate of approximately 2.6 m/sec, was 1815 N or 2.75 times body weight, compared with experimentally measured maximum forces of 2.4 times body weight starting on level ground and 3.0 times body weight starting on the incline (accelerations not measured).

The predicted loads are clearly of the correct order of magnitude. Note, however, that if the rider pulls upwards on the rear pedal, the predicted load represents the sum of the push on the front pedal and the pull on the rear pedal. When the rider was seated the pull was small (see also Hoes et al., 1968) but the maximum pull recorded by subject B starting on the incline was 460 N or 0.7 times body weight. This will be allowed for in calculations which follow.

In all tests with the rider seated, the pedal loads were less than, or equal to, body weight leaving a fraction of body weight to be supported by the saddle.

In the climbing and starting tests the gravity and acceleration forces were large. The riders stood on the pedals but the maximum pedal loads were considerably greater than body weight. Possible sources of reaction allowing forces greater than body weight to be applied are (a) inertia forces due to vertical acceleration of the body, (b) pulling on the handlebars, (c) pulling on the rear pedal.

It is not uncommon for inertia forces to be significant in human body motion; for example, a man walking at 112 paces/min may exert foot—ground forces of up to 1.35 times body weight (Jacobs et al., 1972).

Assuming simple harmonic motion gave a rough estimate of the maximum acceleration of the rider's body during climbing as 1.6 times the acceleration due to gravity, but only a fraction of the rider's body (his lower trunk) was involved, so the associated forces are expected to be considerably less than 1.6 times body weight. Also it is important to note the direction of these forces. During the most effective half of the cycle when the pedals are near horizontal, the acceleration of the lower trunk is downwards (see Fig. 4), and the inertia forces upwards tending to reduce the thrust on the pedal. During starting the action appears to be similar, but vertical movements are slower, so inertia forces should tend to be smaller. A detailed study would be necessary to determine the exact contribution of inertia forces, but it seems unlikely that they
are the major factor allowing effective pedal forces to exceed body weight.

In the following analysis, vertical inertia forces will be ignored and the magnitude of forces applied by the arms will be estimated by considering the equilibrium of the bicycle and rider.

**ANALYSIS OF FORCES**

The three cases of starting, climbing and speeding will be analysed. Figure 12 shows a diagram of the bicycle together with the major dimensions and the simplified system of forces assumed to act. Additional simplifying assumptions are necessary in particular cases:

**Starting**

The co-ordinates of the riders' centre of gravity ($L_1$ and $L_2$ in Fig. 12) were calculated by the segmental method (Williams and Lissner, 1962; Cooper and Glasgow, 1968) which involves measuring from a photograph the approximate position of the centre of gravity of body segments and taking moments about a convenient point. For subject B standing on the pedals with the cranks horizontal (Figs. 6 and 7), $L_1 = 601$ mm, $L_2 = 1054$ mm (Adeyefa, 1978).

There were no forces on the saddle

$$S_H = S_V = 0.$$ Aerodynamic forces and rolling resistance were negligible.

The rider weighed 660 N and the horizontal force ($I$ in Fig. 12) required to accelerate the rider at 2.6 m/sec$^2$ was 175 N.

For simplicity, the weight and inertia of the bicycle itself are neglected. These forces are relatively small but could be readily incorporated in the analysis if required. The acceleration is produced by a horizontal force, $T$, of 175 N acting at the rear wheel and this force is transmitted to the rider's body by horizontal forces $F_3$, $F_4$ at the handlebars. Horizontal forces at the pedals are ignored.

Thus, for horizontal equilibrium of the bicycle

$$F_3 + F_4 = 175 \text{ N}. \quad (1)$$

The vertical reactions at the wheels can be determined by considering the equilibrium of the rider and bicycle together.

The vertical equilibrium

$$R_1 + R_2 = 660. \quad (2)$$

Taking moments about $B$ in Fig. 12

$$R_1 \times 1060 + I \times L_5 = 660 \times L_1, \quad (3)$$

hence

$$R_1 = 200 \text{ N} \quad \text{and} \quad R_2 = 460 \text{ N}. \quad (4)$$

Although the riders' centre of gravity was well forward, the horizontal inertia force increased $R_2$, the reaction at the rear wheel, and helped prevent wheel spin. In this case wheel spin would occur only if the coefficient of friction between the wheel and the ground was less than $175/460 = 0.38$.

The vertical forces applied to the handlebars ($F_1$, $F_2$) and the rear pedal ($P_3$) can be determined by considering the equilibrium of the bicycle alone.

The effective pedal force calculated previously was 1815 N. The experimental results (Fig. 11) indicated that the standing rider could exert a pull on the rear pedal. Hence the effective pedal force was taken as a combination of a vertical push, $P_1$, on the front pedal and a vertical pull, $P_2$, on the rear pedal,

$$P_1 + P_2 = 1815. \quad (5)$$

Considering vertical equilibrium of the bicycle

$$F_1 - F_2 - P_1 + P_2 + R_1 + R_2 = 0 \quad (6)$$

and substituting from equations (3) and (5),

---

**Fig. 12.** Forces acting on the bicycle. (a) Front view, bicycle tilted. (b) Side view, bicycle vertical. All dimensions in mm.
Forces applied to a bicycle during normal cycling

\[ F_1 - F_2 = 1155 - 2P_2 \]  \hspace{1cm} (7)

Taking moments about \( B \) in side view

\[ R_1 \times 1060 + (F_3 + F_4) \times 847 + (F_1 - F_2) \times 990 - P_1 \times 600 + P_2 \times 250 = 0 \]  \hspace{1cm} (8)

and substituting from equations (1), (4), (5) and (7) gives the pull on the rear pedal,

\[ P_2 = 367 \text{ N} \] (0.56 times body weight);

and a push on the front pedal,

\[ P_1 = 1448 \text{ N} \] (2.19 times body weight),

which compare favourably with experimental values for subject \( B \) starting on level ground \((P'_1 = 1580 \text{ N}, \ P'_2 = 350 \text{ N})\).

Substituting \( P_2 \) back into equation (7) gives the net pull applied to the handlebars

\[ F_1 - F_2 = 421 \text{ N} \] (0.64 times body weight).  \hspace{1cm} (9)

The vertical forces applied to the two handlebars are not equal. Consider the front view in Fig. 12. The pedal loads produce a couple which is resisted by the hands.

Taking moments about the line of contact of the wheels with the ground,

\[ F_1 \times L_{11} + F_2 \times L_{12} = P_1 \times L_9 + P_2 L_{10} \]  \hspace{1cm} (10)

If the bicycle is vertical, \( L_{11} = L_{11} = 220 \text{ mm} \) and \( L_9 = L_{10} = 122, \) and from equations (9) and (10)

\[ F_1 = 714 \text{ N} \] and \( F_2 = 293 \text{ N}, \)

so the rider is exerting a maximum pull of 1.08 times body weight with one arm, and a push of 0.44 times body weight with the other.

To demonstrate the effects of tilting the bicycle, consider a hypothetical situation where the maximum tilt of \( 8^\circ \) from the vertical is achieved when the pedals have only just passed the horizontal. Then \( L_{11} = 107 \text{ mm}, \ F_{12} = 330 \text{ mm}, \ F_9 = 91 \text{ mm}, \ L_{10} = 151 \text{ mm} \) (see Fig. 12). It is assumed that the rider’s weight remains over the line of support and that all forces remain vertical. Then, from equations (9) and (10),

\[ F_1 = 737 \text{ N (pull)} \] \hspace{0.5cm} and \hspace{0.5cm} \[ F_2 = 316 \text{ N (push)} \]

These handlebar forces are only slightly greater than when the bicycle was assumed to be vertical. All other forces remain unchanged.

As the forward crank approaches bottom dead centre with the bicycle tilted, \( L_9 \) and \( L_{10} \) increased to \( L_9 = 114, \ L_{10} = 174, \) so that for the same tilt and pedal loads the required handlebar forces increase to

\[ F_1 = 841 \text{ N} \] \hspace{0.5cm} and \hspace{0.5cm} \[ F_2 = 420 \text{ N}. \]

Thus for this case the simplified analysis fails to show any advantage to be gained from tilting the bicycle.

Taking moments in plan view would show the horizontal handlebar forces \( F_3 \) and \( F_4 \) to be equal when the bicycle is vertical and unequal when it is inclined. However, these forces are relatively small, all lateral forces on the bicycle have been ignored and no attempt has been made to achieve moment equilibrium of the handlebar–brakes–front wheel assembly which is free to rotate about the inclined axis of the steering tube.

**Climbing**

The cranks are assumed to be horizontal and the rider out of the saddle in the same position as for starting.

The analysis uses the same procedure and assumptions as for starting, but the inertia force \( I \) is replaced by the aerodynamic drag on the rider \((10 \text{ N})\) (Kyle and Edelman, 1974) and the component of the rider’s weight acting down the incline \((66 \text{ N})\), a total ‘horizontal’ force of \( 76 \text{ N} \) assumed to act at the rider’s centre of gravity. ‘Horizontal’ and ‘vertical’ directions in Fig. 12 are taken as parallel and perpendicular to the ramp. The inclination of the ramp was small. Equations (2) and (3) give the reactions at the front and rear wheels as

\[ R_1 = 299 \text{ N}, \quad R_2 = 361 \text{ N} \]

Due to the smaller horizontal force, the reactions are more evenly distributed between the two wheels than was the case for starting.

The effective pedal force for this climbing case was calculated previously as

\[ P_1 + P_2 = 750 \text{ N}. \]

hence from equations (6) and (8) the pull on the rear pedal is very small

\[ P_2 = 18 \text{ N}, \]

while the force applied to the forward pedal still exceeds body weight

\[ P_1 = 732 \text{ N}. \]

From equation (7) the net pull applied to the handlebars is small

\[ F_1 - F_2 = 54 \text{ N}, \]

but to prevent overturning, the separate handlebar forces are still quite large.

Assuming the bicycle is vertical, substitution into equation (9) gives

\[ F_1 = 235 \text{ N (pull)} \] \hspace{0.5cm} and \hspace{0.5cm} \[ F_2 = 181 \text{ N (push)} \]

Tilting the bicycle to \( 8^\circ \) while the cranks are near horizontal has the advantage of reducing the force on the handlebars slightly, to

\[ F_1 = 199 \text{ N} \] \hspace{0.5cm} and \hspace{0.5cm} \[ F_2 = 145 \text{ N}. \]

If the pedal loads and angle of tilt remained the same, as the cranks approached vertical, the handlebar forces would be

\[ F_1 = 239 \text{ N}, \quad F_2 = 185 \text{ N}, \]

which are similar to the values obtained with the bicycle vertical.
Speeding

In the case of speeding on flat ground, the only resistance acting on the rider is the aerodynamic drag force which is approximately 15 N at 37.2 km/hr (Kyle and Edelman, 1974). The bicycle is vertical and the rider seated with his back parallel to the ground (see Fig. 8). In this position his centre of gravity is nearer to the rear wheel, which thus carries about 60% of the weight.

Ignoring drag and gravity forces on the bicycle itself and taking, for subject B,

\[ W = 660 \text{ N}, \quad L_1 = 424 \text{ mm}, \quad L_5 = 1010 \text{ mm}, \]

equations (2) and (3) give the magnitude of the wheel reactions

\[ R_1 = 250 \text{ N}, \quad R_2 = 410 \text{ N}. \]

The drag force is assumed to be transmitted from the rider to the bicycle by a horizontal force \( S_H = 15 \text{ N} \) at the saddle. Horizontal forces at the handlebars are ignored, \( F_3 = F_4 = 0 \), making the remaining forces statically determinate.

Following the previous discussion and calculations, the maximum pedal force for this case is taken as \( P_1 = 310 \text{ N} \) when the cranks are horizontal. Horizontal forces at the peddles are offset from the points of support, toppling sideways had to be prevented by the rider pulling up on one handlebar (71 N) and pushing down on the other (101 N).

The maximum pedal load recorded for a seated rider was in an indoor experiment when a power of 770 W was dissipated in a dynamometer. The maximum push applied to the pedals was then approximately equal to the rider's body weight (570 N) and the maximum pull on the rear pedal was less than 100 N. At lower work rates the seated rider did not pull on the rear pedal.

In situations such as starting and climbing where the resistance provided by inertia forces and gravity can be ten times larger than the normal aerodynamic resistance, the riders tend to rise out of the saddle and tilt the bicycle from side to side applying forces in excess of body weight first to one pedal and then to the other.

Pedal forces in excess of body weight are produced by pulling on the handlebars and by pulling on the rear pedal, the latter producing additional useful torque.

A rider starting on level ground and accelerating at 2.6 m/sec² was estimated to apply a force of 1448 N or more than twice his body weight to the forward pedal and a pull of 267 N, 0.56 times body weight, to the rear pedal. These pedal loads were in good agreement with measured values. The need to apply a large net pull on the handlebars to counteract the large toppling moments produced by both pedals, in this case requires a pull of 714 N, i.e. greater than body weight, on one handlebar, together with a push of 293 N, or 0.44 times body weight, on the other.

A rider climbing a one in ten incline at 26 km/hr, and developing a power output of 665 W, was estimated to produce a maximum pedal force of 732 N, slightly in excess of body weight. The pull on the rear pedal was very small and the net pull on the handlebars only 54 N, but the push (235 N) and pull (181 N) on the handlebars to prevent toppling were still about one third of body weight.

The largest pedal forces recorded were for starting on an incline when three riders each applied maximum pedal forces of three times body weight.

When speeding on level ground the subjects sat in the saddle and pedalled steadily, keeping the bicycle vertical and adopting the usual crouched racing position to reduce aerodynamic drag which was the major resistance to motion. It was estimated that a rider travelling at a steady speed of 37 km/hr on level ground, and developing a power of 255 W, exerted a maximum push on the pedal of 310 N, about 50% of his body weight, and that about 50% of his body weight was supported by the saddle. As the pedal load was applied to the pedals was then approximately equal to the rider's body weight (570 N) and the maximum pull on the rear pedal was less than 100 N. At lower work rates the seated rider did not pull on the rear pedal.

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Forces applied to a bicycle during normal cycling

our experimental subjects, Mark Soden (subject A), and Nicholas Sharpe (subject B), and the British Road Time Trials Council for the use of their 8 mm cine film (Fig. 1).

REFERENCES


