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Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance

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The coefficient of rolling resistance (C_r) for pneumatic tyres is dependent on hysteresis loss from tyre deformation which is affected by the vertical force applied to the tyres (F_v) and the tyre inflation pressure (P_r). The purpose of this paper was to determine the relative influence of five different levels of P_r and four different levels of F_v on C_r and to examine the relationships of C_r with P_r and F_v during cycling locomotion. F_v was modified through carriage of additional mass by the subject. C_r was determined with the coasting deceleration method from measurements performed in a level hallway. Iterations minimizing the sum of the squared difference between the actual deceleration distance and a predicted deceleration distance were used to determine C_r. This latter distance was computed from a derivation based on Newton's second law applied to the forces opposing motion. C_r was described by a hyperbolic function of P_r ($C_r = 0.1071\ P_r^{-0.477}$, $r^2 = 0.99$, $p < 0.05$), decreasing 62.4% from 150 kPa ($C_r = 0.0101$) to 1200 kPa ($C_r = 0.0038$). F_v was related to C_r by a polynomial function ($C_r = 1.92 \cdot 10^{-8} F_v^2 - 2.86 \cdot 10^{-5} F_v + 0.0142$, $r^2 = 0.99$, $p = 0.084$), with an added mass of 15 kg ($C_r = 0.0040$) resulting in an 11.4% increase in C_r compared with no added mass ($C_r = 0.0035$). From this study, it is concluded that the relationships of P_r and F_v with C_r for cycling are non-linear. Furthermore, a simulation model shows that changes in P_r and F_v of the magnitude examined here have an important effect on competitive cycling performance.

1. Introduction

Decreases in rolling resistance (R_r, N; see appendix for the list of abbreviations) have been a major contributing factor to the improvements in cycling performance observed during the past 20 years. R_r has been reduced through the development of tyres allowing higher inflation pressures (P_r, kPa) and lighter bicycles which have reduced the vertical force applied to the tyres (F_v, N). It has been established that the major source of R_r in a pneumatic tyre is from hysteresis, or non-elastic deformations, occurring to the tyre when compressed on a solid surface (Tabor 1955, Schuring 1980, Kauzlarich and Thacker 1985,

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Ménard 1992). The magnitude of this deformation determines the tyre coefficient of rolling resistance (C_r, unitless). The two main factors that affect tyre deformation are P_r and F_v. When rolling, some slippage also occurs, but its contribution to the total R_r is negligible. Other energy-dissipating mechanisms such as adhesion between the tyre and roadway, air pumping in the tyre cavity, and road deformation are generally estimated as insignificant relative to the hysteresis phenomenon (Schuring 1980).

In contemporary cycling, the main force opposing motion of the cyclist is from aerodynamic drag (R_a, N), while R_r represents a minor part of the total resistance (R_T, N). At a typical race speed (V_c) of 14 $m \cdot s^{-1}$, R_r constitutes only 10% of R_T, although at a lower V_c (7 $m \cdot s^{-1}$), R_r could reach 30% of R_T (Pugh 1974, Kyle and Edelman 1975, Di Prampero *et al.* 1979, 1986, Gross *et al.* 1983, Ménard *et al.* 1990, Ménard 1992, Capelli *et al.* 1993, Grappe *et al.* 1997). In most previous studies, R_r has been reported to be independent of V_c and equal to the product of C_r and F_v (Pugh 1974, Di Prampero *et al.* 1979, Kyle and Burke 1984, Davies 1980, Ménard *et al.* 1990, Ménard 1992, Capelli *et al.* 1993, Grappe *et al.* 1997, Candau *et al.* 1999):

$$R_r = C_r F_v, \tag{1}$$

where $F_v = Mg$, where M = transported mass (kg) and g = acceleration due to gravity (9.81 $m \cdot s^{-2}$).

A recent laboratory study conducted on cycling reported a positive linear relationship between C_r and F_v, and an inverse linear relationship between C_r and P_r (Ménard 1992). However, an earlier study conducted in the field using a tricycle reported C_r to be inversely, but not linearly, related to P_r (Kyle and van Valkenburgh 1985). Moreover, previous laboratory and field studies conducted on passenger car tyres have reported C_r to be related to P_r and F_v by numerous empirical equations (Schuring 1980).

It has been reported that a decrease in C_r of as little as 0.02% would have important impacts on racing performance (Kyle and van Valkenburgh 1985). This magnitude of change in C_r could result from an increase in P_r from 680 to 750 kPa. Yet, a recent laboratory study concluded that alterations in P_r from 550 to 960 kPa were too small to be detected by metabolic measurements (Ryschon and Stray-Gundersen 1993). Thus, changes in P_r or F_v could have important impacts on cycling performance without being detectable through physiological measurements. Additionally, to the best of our knowledge, it appears that no study has been conducted during actual cycling locomotion to determine the mathematical relationships for C_r with P_r and F_v, or to determine the effect of changes in P_r and F_v on cycling performance.

Thus, the purpose of this paper was to examine the relationships of C_r with P_r and F_v during actual cycling locomotion by using a previously described field method (Candau *et al.* 1996, 1999). In addition, the influence of changes in P_r and F_v on cycling performance during a 1 h event were estimated using a mathematical simulation model.

2. Method

2.1. *General procedure*

One trained male cyclist participated in this study. All of the risks associated with the experimental procedures used in this investigation were explained thoroughly during his first visit to the laboratory, and he provided written informed consent. The age, mass and height of the subject were 32 years, 66.2 kg and 1.72 m respectively.

The subject performed testing under two different conditions. For the first, the effect of five different levels of P_r (150, 300, 600, 900, 1200 kPa) on C_r was tested. Classical 32-spoked wheels were equipped with tubular tyres (Victoria Corsa Cx 22 mm, 220 g; Italy). P_r was adjusted and controlled with a classical foot pump (Silca, Italy; accuracy $\pm$20 kPa). For the second test condition, the effect of four different levels of F_v on C_r was tested. Classical clincher wheels were equipped with clincher tyres (Techno Kevelar 23 mm, 250 g, Vittoria). P_r was maintained constant at 1000 kPa while F_v was modified by loading the subject with additional mass (0, 5, 10, 15 kg) in a backpack. To maintain a constant effective frontal area for the cyclist (AC_d, m^2), the size of the backpack was kept constant (perimeter of trunk and backpack = 1.1 m) by the insertion of light foam plastic material into the backpack. Since the maximal change in backpack dimensions was kept to $<$ 0.5 cm, AC_d was assumed to be constant. For all tests, a classical racing bicycle of 9.8 kg was used.

2.2. *Determination of* C_r

C_r was determined through coasting deceleration tests. The reproducibility (mean absolute error = 0.70%; coefficient of variation = 0.59%) and the sensitivity of this method have been previously reported (Candau *et al.* 1996, 1999). To eliminate disturbances due to variations in weather conditions, testing was performed on a level 60 m indoor hallway with tiled flooring. Acceleration was achieved during the first 40 m of the hallway. The cyclist then decelerates while maintaining a constant upright position (the hands on the upper part of the handlebars) while rolling across three timing switches. To simulate actual cycling conditions with turbulence induced by movement of the lower limbs, the subject continued to pedal without transmitting propulsive force to the rear wheel during each coasting trial. The timing switches were linked to a chronometer system with an accuracy of 30 μs (Electronique Informatique du Pilat, Jonzieux, France) from which the time ($T_{initial}$) to travel between the first two timing switches ($D_{initial}$ = 1 m) and the time (T) to travel between the second third timing switches (D = 20 m) were determined. The system included specific software, an interface and a PC-like computer. Each timing switch was 51 mm wide, with the central 15 mm measuring 1.5 mm thick and the remainder being 1 mm thick.

Two marker strips separated by 0.5 m were placed on the floor between the timing switches for the cyclist to use as guides to maintain straight tracking during deceleration. The strips helped the cyclist avoid steering corrections which could cause the tyres to side-slip and elicit a slight braking force that would elevate the measured C_r. When tracking was not straight, the trial was discarded. One test procedure consisted of 30 acceptable coasting decelerations across different initial velocities (v_0) ranging from 2.5 to 12.8 m s^{-1}. For the first test conditions, five test procedures were performed (i.e. $5 \times 30 = 150$ trials), and for the second test conditions, four test procedures were performed (i.e. $4 \times 30 = 120$ trials).

C_r was calculated using techniques previously detailed (Candau *et al.* 1999). Calculations were based upon a derivation from Newton's second law describing the two forces opposing motion of the cyclist, and iterations minimizing the sum of the squared difference between the actual deceleration distance (D) and a calculated deceleration distance (D^*):

$$D^*(v_0, T) = 1/(2\beta) \cdot \ln\left[\left(1 + \tan(\sqrt{\alpha\beta} \cdot T - \text{atan}(\sqrt{\beta/\alpha} \cdot v_0))^2\right) / (1 + (\beta/\alpha) \cdot v_0^2)\right], \quad (2)$$

where $\alpha = -g\ C_r$ and $\beta = -\rho\ AC_d/2\ M$, and

$$v_0 = V(D_{initial}, T_{initial}) = \sqrt{\alpha/\beta} \cdot \left(\cos(\sqrt{\alpha\beta} \cdot T_{initial}) - e^{\beta.Dinitial}\right) / \sin(\alpha\beta \cdot T_{initial}). \quad (3)$$

2.3. *Simulations*

The influence of changes in P_r and F_v on simulated cycling performance during 1 h of cycling was estimated using a simulation model to compute the mean V_c sustained ($\overline{V}_c$). Simulations were performed by considering an elite cyclist riding in an aero-posture (aerodynamic position) on a covered track velodrome with no wind, a mean external mechanical power output ($\overline{P}_{ext}$) of 400 W and air density (ρ) of 1.19 kg·m^{-3}. In the conditions of the simulation, the two forces opposing motion of the cyclist are R_a and R_r. Thus, $\overline{P}_{ext}$ can be described by:

$$\overline{P}_{ext} = R_a\, \overline{V}_c + R_r\, \overline{V}_c, \quad (4)$$

where the first and second terms represent the mean power outputs to overcome R_a ($\overline{P}_{Ra}$, W) and R_r ($\overline{P}_{Rr}$, W) respectively.

R_a was calculated from $R_a = 0.5\ \rho\ AC_d\ \overline{V}_c^2$ and based on results from previous studies (Kyle and Burke 1984, Ménard 1992, Grappe *et al.* 1997). $AC_d = 0.2$ m^2 was used in the calculations. Then, according to equation (1), $\overline{V}_c$ was computed by iterations of the following equation:

$$\overline{P}_{ext} = 0.5\ \rho\ AC_d\, \overline{V}_c^{\,3} + C_r M g\, \overline{V}_c. \quad (5)$$

2.4. *Statistical analysis*

The data are presented using ordinary descriptive statistics of mean and SD. A power regression and a second-order polynomial regression were used to describe the relationships of P_r with C_r and F_v with C_r respectively. These types of regressions were chosen according to their better r^2 and level of statistical significance. The level of statistical significance was fixed at $p < 0.05$.

3. Results

3.1. *Influence of changes in* P_r *on* C_r

The relationship between C_r and P_r is presented in figure 1. C_r was 0.0101 ± 0.0003, 0.0069 ± 0.0004, 0.0050 ± 0.0005, 0.0040 ± 0.0003 and 0.0038 ± 0.0003 with increasing P_r levels of 150, 300, 600, 900 and 1200 kPa respectively. C_r was well described ($r^2 = 0.99$, $p < 0.05$) as a function of P_r by the hyperbolic power equation:

$$C_r = 0.1071\, P_r^{-0.477}. \quad (6)$$

In the present study, C_r decreased by 62% between 150 and 1200 kPa. The greatest decrease (50%) was observed between 150 and 600 kPa. Between 600 and 1200 kPa, the magnitude of the decrease was 24%. Within the range of P_r levels usually used by road cyclists (i.e. between 600 and 900 kPa), C_r could vary by 20%. For track cycling, where P_r usually ranges from 900 to 1200 kPa, C_r could vary by 5%.

3.2. *Influence of changes in* F_v *on* C_r

The additional loads of 0, 5, 10 and 15 kg resulted in F_V = 743, 794, 843 and 892 N respectively. Thus, the overloads of 5, 10 and 15 kg involved 22.7, 30.3 and 37.8% increases in F_V from the unloaded condition. The relationship between C_r and F_V is presented in figure 2. C_r increased from a baseline value of 0.0035±0.0004 to

Table 1. Mean cyclist speed sustained during 1 h ($\overline{V}_c$) at different tyre pressures (A) and loads (B) predicted from the simulation model. Also reported are associated values for the coefficient of rolling resistance (C_r) and mean power output to overcome aerodynamic drag ($\overline{P}_{Ra}$) and rolling resistance ($\overline{P}_{Rr}$). For all simulations, it was assumed that there was no wind, the effective frontal area of the cyclist was 0.2 m^2, the mean external mechanical power provided ($\overline{P}_{ext}$) was 400 W, and air density (ρ) was 1.19 $kg \cdot m^{-3}$.

(A)

Pressure (kPa)	1.5	3	6	9	12
C_r	0.0101	0.0069	0.0050	0.0040	0.0038
$\overline{P}_{Ra}$ (W)	298	328	347	357	359
$\overline{P}_{Rr}$ (W)	102	72	53	43	41
$\overline{V}_c$ ($km \cdot h^{-1}$)	48.9	50.5	51.5	52.0	52.1

(B)

Overload (kg)	0	5	10	15
C_r	0.0035	0.0036	0.0037	0.004
$\overline{P}_{Ra}$ (W)	362	359	355	350
$\overline{P}_{Rr}$ (W)	38	41	45	50
$\overline{V}_c$ ($km \cdot h^{-1}$)	52.2	52.0	51.9	51.6

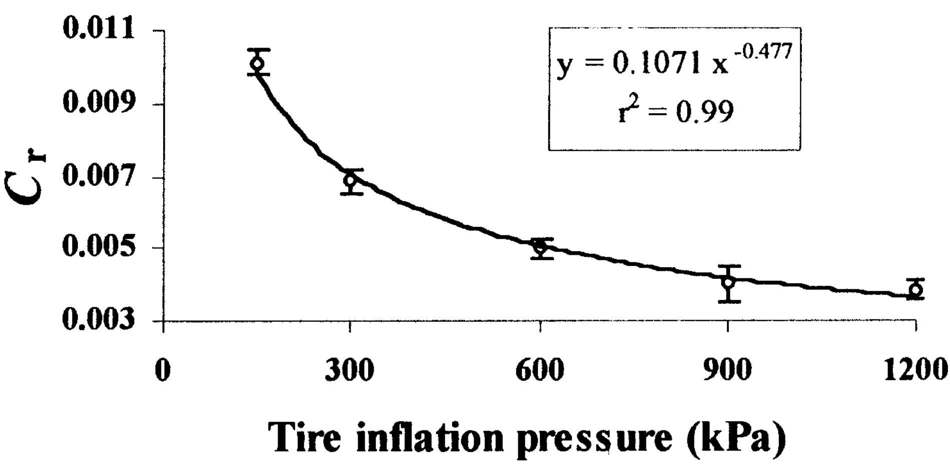

Figure 1. Coefficient of rolling resistance (C_r) as a function of tyre inflation pressure. Brackets= 1 SD.

0.0036±0.0002, 0.0037±0.0001 and 0.004±0.0003 with the overloads of 5, 10 and 15 kg respectively. The relationship between C_r and F_v was well described ($r^2 = 0.99$, $p = 0.084$) by the second-order polynomial equation:

$$C_r = 1.92 \cdot 10^{-8} F_v^{\ 2} - 2.86 \cdot 10^{-5} F_v + 0.0142. \tag{7}$$

A Spearman test indicated that there was no significant linear relationship between C_r and F_v ($r^2 = 0.91, p = 0.084$).

3.3. *Influence of changes in* P_r *and* F_v *on cycling performance*

The influence of alterations in C_r on $\overline{V}_c$ during a 1 h ride under the different experimental conditions of this study are summarized in table 1. Changes in C_r were associated with large variations in $\overline{P}_{Ra}$ and $\overline{P}_{Rr}$. As compared with a $P_r = 150$ kPa, P_r of 300, 600, 900 and 1200 kPa resulted in an estimated increase in distance that would be travelled during 1 h of 1600, 2600, 3100 and 3200 m respectively. With overloads of 5, 10 and 15 kg, the predicted distance that would be covered during 1 h decreased by 200, 300 and 600 m respectively. At 150 kPa, $\overline{P}_{Rr}$ was predicted to represent 25.5% of $\overline{P}_{ext}$. At 150, 300, 600, 900 and 1200 kPa, $\overline{P}_{Rr}$ was predicted to represent 25.5, 18, 13.2, 10.7 and 10.2% of $\overline{P}_{ext}$ respectively.

4. Discussion

The most important findings of this study are that the effects of P_r and F_v on C_r are non-linear in nature. C_r decreased curvilinearly with increases in P_r and increased curvilinearly with increases in F_v. The simulation model demonstrates that small changes in P_r and F_v can have large affects on cycling performance.

4.1. *Comparisons of* C_r *with previous studies*

The C_r observed here were in line with those reported previously (table 2) when considering a similar surface, tyre, P_r and F_v. Table 2 shows that C_r have been found to range between 0.001 and 0.0081. This C_r variability is partly explained by

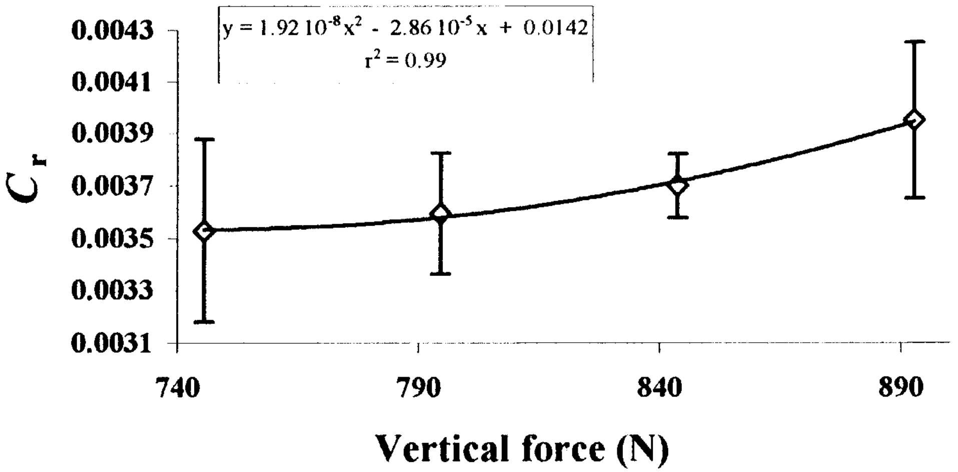

Figure 2. Coefficient of rolling resistance (C_r) as a function of the total vertical force applied to the bicycle tyres. Brackets= 1 SD.

Table 2. Summary of previously reported values for rolling resistance (R_r) and coefficient of rolling resistance (C_r) in cycling according to the type of surface, tyre inflation pressure and vertical load.

Studies	R_r (N)	C_r	Place and type of surface	Type of tyre	Inflation pressure (kPa)	Vertical load (kg)
Pugh (1974)	6.9	0.0081	aerodrome, asphalt surface	tubular 220 g	630	86
Kyle and Edelman (1975)	NA*	0.0019–0.0039	NA	different tubulars	NA	NA
Di Prampero *et al.* (1979)	3.2	0.0046	car track, asphalt surface	NA	700	70
Davies (1980)	0.76	0.001	treadmill, linoleum surface	NA	NA	79
Gross *et al.* (1983)	NA	0.0030–0.0045	NA	NA	NA	NA
Kyle and Burke (1984)	NA	0.0016–0.035	hallway, smooth surface	different tubulars	500–1100	NA
Kyle and van Valkenburgh (1985)	NA	0.0017–0.0043	road, smooth asphalt	different tubulars	540–1500	NA
				clincher	400–820	
Ménard (1992)	1–3	0.0028–0.0058	treadmill	different tubulars	300–500	20–61
Capelli *et al.* (1993)	2.43	0.0031	indoor velodrom, wood surface	NA	1000–1100	80
Grappe *et al.* (1997)	1.95	0.0030	outdoor velodrom, synthetic surface	tubular Corsa Cx section, 22 mm	800	78
Present study (changes in inflation pressure)	7.5–2.8	0.010–0.0038	hallway, tiled floor	tubular Corsa Cx	150–1200	76
Present study (change in weight added)	2.6–3.5	0.0035–0.0039	hallway, tiled floor	clincher Techno kevlar	1000	76–91

*Data not reported.

variations in the surface compactness and roughness, the tyre material properties, P_r and F_v. The measurement methods used to determine C_r must also be taken into account. C_r has been previously determined in cycling locomotion through the dynamometric technique (Di Prampero *et al.* 1979, Capelli *et al.* 1993), coast-down tests (Kyle and Edelman 1975, Gross *et al.* 1983, Kyle and Burke 1984, Kyle and van Valkenburgh 1985), direct measurement of power input to the rear wheel (Grappe *et al.* 1997) and indirectly through metabolic measurements (Pugh 1974, Davies 1980). C_r has also been previously measured in the laboratory (Shuring 1985, Ménard 1992). The dynamometric technique involve air turbulence set up by the towing vehicle and alterations in weather conditions, especially wind, can affect the results with this technique. The precision of the direct measurement appears limited by poor linearity of the transducer (mounted in the hub of the rear wheel), and the effects of alterations in ambient conditions. In the indirect measurement methods the determination of C_r is difficult and, thus, can give rise to measurement errors. With the coasting deceleration method, some variables can degrade the test precision to the point where repeat tests have shown variations of $>10\%$ (Candau *et al.* 1999). The potential error sources could be due to: (1) irregular grades; (2) behaviour of the subject during the deceleration test. Indeed, in our study, the simulation of actual cycling conditions with turbulence was induced by movement of the lower limbs, the subject continuing to pedal without transmitting propulsive force to the rear wheel during each coasting trial; (3) the cyclist to use as guides to maintain straight tracking during deceleration. In this study, two marker strips separated by 0.5 m were placed on the floor between the timing switches to help the cyclist avoid steering corrections during deceleration. That allows the reduction of the braking force that would elevate the measured C_r; and (4) the procedure to take into account a coasting deceleration. In our study, when tracking was not straight, the trial was discarded and the cyclist performed another deceleration. Previously, it has been observed that when all the above parameters are not well controlled that could involve significant changes in C_r.

4.2. *Influence of changes in* P_r *on* C_r

The decreases in C_r with increases in P_r observed in this study were in line with those previously reported by Kyle and van Valkenburgh (1985). They reported a 27% decrease in C_r between 540 and 1080 kPa for silk road tubular tyres, a 37% decrease in C_r between 680 and 1500 kPa for kevlar track tubular tyres, a 23% decrease in C_r between 400 and 820 kPa for touring wired-on tyres and a 15% decrease in C_r between 540 and 950 kPa for cotton utility tubular tyres.

In the present study, C_r was inversely and hyperbolically related to P_r (figure 1). Equation (6) describing this relationship was similar to empirical equations reported in previous studies conducted on passenger car tyres (Schuring 1980). Thus, the effect of P_r on C_r in cycling appears similar to that which has been observed for passenger cars. To the best of our knowledge, no previous study conducted in actual cycling locomotion has reported such a relationship between C_r and P_r. However, through coast-down tests with a loaded tricycle, Kyle and van Valkenburgh (1985) found a curvilinear decrease in C_r with increases in P_r. In contrast, from a laboratory study, Ménard (1992) reported that C_r for road cycling tyres was well described as an inverse linear relationship with P_r.

It has been reported that C_r is dependent on the characteristics of the tyre material at energy dissipation (Schuring 1980, Ménard 1992). For a given F_v, the tyre bulges and its deflection produces a 'footprint' (Schuring 1980, Ménard 1992). The leading part of the footprint stores energy, whereas the trailing part dissipates this stored energy (Kauzlarich and Thacker 1985, Schuring 1980, Ménard 1992). As the tyre material is not perfectly elastic, some of the stored energy is lost due to hysteresis, the extent of which varies with the strain and stress on the tyre and the elastic properties of the tyre material (Tabor 1955, Schuring 1980, Ménard 1992). The hyperbolic relation between C_r and P_r observed in this study is probably accounted for by the manner in which P_r affects the tyre footprint and the elastic properties of the tyre material, and in turn alters the amount of energy loss due to hysteresis.

4.3. *Influence of changes in* F_v *on* C_r

In the present study, a 15 kg overload added to the 66 kg cyclist and 9.8 kg bicycle resulted in an 11.4% increase in C_r. This result indicates that C_r for an 81 kg cyclist would be 11.4% greater compared with a 66 kg cyclist using the same bicycle. Thus, the influence of F_v on C_r cannot be neglected in cycling.

C_r was well described by F_v with a second-order polynomial equation (equation 7; figure 2). As was the case for the relationship of P_r with C_r, the relationship observed between F_v and C_r was similar to that previously reported for passenger car tyres (Schuring 1980). In contrast, previous studies of cycling have described the relationship between C_r and F_v as linear (Kyle and Burke 1984, Kyle and van Valkenburgh 1985, Ménard 1992).

The non-linear increase in C_r with F_v observed in this study could be similarly explained by the hysteretic loss phenomenon proposed to account for the effect of changes in P_r on C_r. Indeed, the tyre footprint is affected by F_v, and therefore the extent of energy loss due to hysteresis would also be expected to be affected by F_v. Furthermore, changes in F_v could alter the elastic properties of the tyres. It has been reported that the tyre elastic input energy per unit distance is proportional to the load to the four-thirds power (Schuring 1980). Thus, the non-linear increase in C_r relative to F_v observed in this study could be accounted for by the effects of F_v on the tyre footprint as well as the elastic properties of the tyre.

4.4. *Influence of changes in* C_r *on cycling performance*

Table 1A and B demonstrates that during a 1 h ride, cycling performance can be improved from decreases in C_r produced through increases in P_r. Furthermore, cycling performance can be adversely affected from increases in C_r produced through elevations in F_v. For a given load, a 300 kPa increase in P_r from 900 to 1200 kPa would predict a 100 m increase in the distance travelled during 1 h. For a given P_r, a 5 kg load increase from 76 to 81 kg would predict a 200 m reduction in performance. These findings indicate that P_r and the weight of both the bicycle and the subject are important factors affecting performance.

Kyle and van Valkenburgh (1985) have previously estimated that for a cyclist travelling 48.3 km during 1 h, increases in C_r of 10 and 20% would result in reductions in the distance travelled of 377 and 754 m respectively. According to the simulation model used in the present study (equation 5), it appears that the affect reported by these authors is slightly overestimated. The present model predicts that the distance travelled would be reduced by close to 200 and 400 m for increases in C_r of 10 and 20% respectively.

The results of this study demonstrate that within the P_r range usually used by road cyclists, an increase in P_r from 600 to 900 kPa could result in an improvement in performance of 0.5 km·h^{-1}. Recognizing the important impact of P_r on performance, the 1984 US Olympic team reportedly used a tyre pressure of 950 kPa in the 100 km time trial on the road (Kyle and van Valkenburgh 1985). Interestingly, within the P_r range used by track cyclists, an increase from 900 to 1200 kPa would be predicted to improve performance by 0.1 km·h^{-1}. These results indicate that variations within higher levels of P_r result in smaller improvements in performance. Nevertheless, the 1984 US Olympic cycling team reportedly used pressures of 1500 kPa in their tyres for track cycling (Kyle and van Valkenburgh 1985). When first and second places are determined by <1 s, even such relatively small effects on performance are important.

C_r has previously been reported to be on the order of 0.0001 for trains (Schuring 1980). This is due to the minimization of hysteresis loss that occurs through steel rolling against steel. It is interesting to consider how such a low C_r might affect cycling results. The present simulation model predicts that an elite cyclist could maintain an average speed of 53.9 km·h^{-1} for 1 h with $C_r = 0.0001$. This could determine a gain of 1800 m during a 1 h ride compared with a C_r of 0.0038 correspondent to a P_r of 1200 kPa. Thus, it is apparent that considerable gains in cycling performance are conceivable through further reduction in C_r.

4.5. *Conclusions*

This study demonstrates that the relationships of C_r with P_r and F_v for cycling are similar to those previously reported for passenger cars. The non-linear effects of P_r and F_v on C_r probably result from the manner in which these variables alter the tyre footprint and elastic properties of the tyre material. The tyres used for the two experimental conditions of this study were 'standard' tyres, and it is possible to generalize the findings of the effect of tyre pressure and load on these tyres. The simulation model used in this study shows that the effect of P_r and F_v on cycling performance cannot be neglected.

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Appendix. Glossary of abbreviations

AC_d	effective frontal area (m^2)
C_r	coefficient of rolling resistance (unitless)
D	distance between the second and third timing switches = 20 m
D^*	calculated distance between the second and third timing switches
$D_{initial}$	distance between the first and second timing switches = 1 m
F_v	vertical load applied on the tyre (N)
g	acceleration due to gravity = 9.81 $m \cdot s^{-2}$
M	transported mass of the bicycle (kg)
P_r	tyre inflation pressure (kPa)
$\overline{P}_{ext}$	mean external mechanical power provided by the cyclist (W)
$\overline{P}_{Ra}$	mean power output to overcome aerodynamic drag (W)
$\overline{P}_{Rr}$	mean power output to overcome rolling resistance (W)
R_a	aerodynamic drag (N)
R_r	rolling resistance (N)
R_T	total resistance opposing motion of a cyclist (N)
T	time to travel between the second and third timing switches (s)
$T_{initial}$	time to travel between the first and second timing switches (s)
V_c	cyclist speed ($m \cdot s^{-1}$)
$\overline{V}_c$	mean cyclist speed ($m \cdot s^{-1}$)
v_0	initial speed of the cyclist between the first and second timing switches ($m \cdot s^{-1}$)
ρ	air density ($kg \cdot m^{-3}$)