Experimental Optimization of Pivot Point Height for Swing-Arm Type Rear Suspensions in Off-Road Bicycles

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Towards the ultimate goal of designing dual suspension off-road bicycles which decouple the suspension motion from the pedaling action, this study focused on determining experimentally the optimum pivot point height for a swing-arm type rear suspension such that the suspension motion was minimized. Specific objectives were (1) to determine the effect of interaction between the front and rear suspensions on the optimal pivot point height, (2) to investigate the sensitivity of the optimal height to the pedaling mechanics of the rider in both the seated and standing postures, (3) to determine the dependence of the optimal height on the rider posture. Eleven experienced subjects rode a custom-built adjustable dual suspension off-road bicycle, [Needle, S., and Hull, M. L., 1997, "An Off-Road Bicycle With Adjustable Suspension Kinematics," Journal of Mechanical Design ***119****, pp. 370–375], on an inclined treadmill. The treadmill was set to a constant 6 percent grade at a constant velocity of 24.8 km/hr. With the bicycle in a fixed gear combination of 38×14, the corresponding cadence was 84 rpm. For each subject, the pivot point height was varied randomly while the motions across both the front and rear suspension elements were measured. Subjects rode in both the seated and standing postures and with the front suspension active and inactive. It was found that the power loss from the rear suspension at the optimal pivot point height was not significantly dependent on the interaction between the front and rear suspensions. In the seated posture, the optimal pivot point height was 9.8 cm on average and had a range of 8.0–12.3 cm. The average optimal pivot point height for the seated posture corresponded to an average power loss for the rear suspension that was within 10 percent of the minimum power loss for each subject for 8 of the 11 subjects. In the standing posture, the average height was 5.9 cm and ranged from 5.1–7.2 cm. The average height for the standing posture was within 10 percent of the minimum power loss for each subject for 9 of the 11 subjects. While the optimum height was relatively insensitive to pedaling mechanics in both the seated and standing postures, the choice of the optimal pivot point height in production bicycles necessitates some compromise in performance given the disparity in the averages between the seated and standing postures.* [DOI: 10.1115/1.1427701]

Introduction

Over the past decade the development of dual suspension off-road bicycles has greatly improved the off-road riding experience. Benefits from advances in bicycle suspension technology, aside from comfort, include diminished rider fatigue, improved braking, cornering, and line holding, and higher downhill speeds [2]. As a result of these benefits, the use of such bicycles has become increasingly popular. While the benefits are numerous, there are some drawbacks. Aside from a weight penalty, the primary drawback is suspension motion 'coupled' to the pedaling action [3]. Since the pedaling action is periodic, so too is the coupled suspension motion with the consequence that the suspension bobs as the rider pedals. This bobbing is disadvantageous because energy is lost in overcoming the dissipative forces in suspension systems and also because pedaling mechanics may be affected. Accordingly much attention has been devoted by the off-road bicycle industry in developing designs which either minimize or eliminate the coupling between the pedaling actions of the rider and the motion of the suspension.

For single swing arm-type rear suspensions, which is one common design, arguably the most important single design variable affecting the amount of pedaling induced suspension travel is the height of the pivot point above the bottom bracket. This variable is sensitive to pedaling action for three reasons [4,5]. Two reasons are traced to variation in the crank torque which causes two separate and independent effects. One is the moment created by the chain force about the pivot point and the other is the fore-aft accelerations (i.e., weight transfer). For a high pivot point location, an increase in the tension in the chain will create a moment which extends the suspension (Fig. 1(*a*)) whereas the suspension will compress for a low pivot point location (Fig. 1(*b*)). In either case, increasing chain tension will cause some forward acceleration of the rider-bicycle system which will cause the suspension to compress (i.e., suspension squat). The final reason is inertial loading due to the pedaling action of the rider's legs. Because all of these three reasons working in concert would cause suspension motion, it is reasonable to expect that an optimal pivot point height exists which minimizes the suspension motion and hence associated energy losses.

Previous studies in our laboratory have investigated the relationship between rider induced energy loss and the design variables of dual suspension bicycles incorporating the single swing-arm design. Wang and Hull [4,6] used a two-dimensional dynamic model of the bicycle and rider to compute suspension motion for a seated rider pedaling up a constant grade at a constant mean

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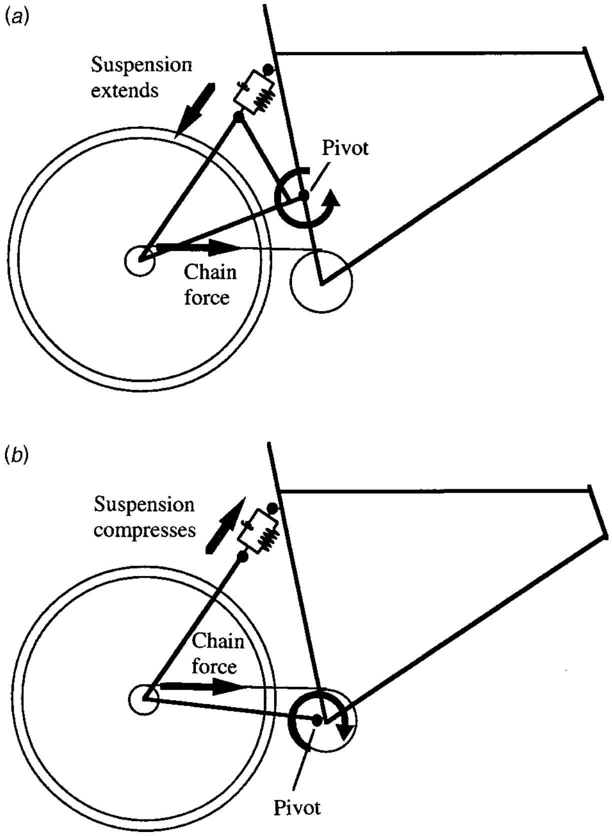

Fig. 1 Diagram illustrating how the height of the pivot point affects the suspension motion induced by changes in the chain tension: (A) The suspension extends for a high pivot point, and (B) the suspension compresses for a low pivot point.

velocity on a smooth surface and optimized the pivot point location in the plane of the bicycle. To assess the sensitivity of the optimal pivot point height to rider pedaling mechanics, the optimal pivot point was determined for four riders in a weight range of 68–91 kg. The resulting range of optimal pivot point locations was 10.5–12.5 cm above the bottom bracket. The relatively small 2.0 cm spread for the four cyclists indicated that the optimal pivot point was relatively insensitive to pedaling mechanics.

In a parallel effort, Needle and Hull [1] designed and fabricated a custom dual suspension bicycle which allowed adjustability in various design variables including the pivot point height above the bottom bracket spindle along the seat tube. Considering that the model of Wang and Hull [6] relied on several assumptions (e.g., rider loads do not vary substantially with suspension motion), one intended purpose of the custom bicycle was to provide a tool which could be used to verify analysis predictions. To demonstrate the usefulness of the custom bicycle, the optimal pivot point height was determined to be 8.4 cm for a single subject in the seated posture. Considering the use of only a single subject, the insensitivity to pedaling mechanics predicted by the model of Wang and Hull [6] remains unverified experimentally. Further, the experiment conducted by Needle and Hull [1] locked out the front suspension which could have affected the optimal pivot point location of the rear suspension as a result of interaction. However, in the model by Wang and Hull [6], the front suspension was included and the motion was minimal thus suggesting that any interaction would not be significant. Thus, using the custom bicycle developed by Needle and Hull [1], the first two objectives of the present study were: (1) to test the hypothesis that interaction between the front and rear suspensions did not affect the action of the rear suspension and hence determination of the optimal pivot point height, and (2) to test the hypothesis that the optimal pivot point height is insensitive to pedaling mechanics in one posture (either seated or standing).

Although the analysis of Wang and Hull [4] focused on determining the optimal pivot point location in the seated posture, the standing posture is also an important posture in off-road cycling. This is because off-road trails and particularly single-track trails are not graded. As a result, riders are often presented with steep sections which can best be negotiated in the standing posture. Because the rider loads in the seated and standing postures are fundamentally different [7], it could be speculated that the optimal pivot point locations for the two postures would be different as well. This speculation is based on an understanding of the reasons which affect the optimal pivot point location as described above. Accordingly the final objective of this study was to test the hypothesis that the optimal pivot point locations were different in the seated and standing postures.

Methods

Experiments. An existing test bicycle was used in this project [1]. This frame was built with roughly the same basic geometry as a 45.7 cm (18 in) Specialized M2 Mountain Bike (Morgan Hill, CA). The frame was designed with a 71 deg head tube angle, 73 deg seat tube angle, 4.1 cm fork rake, 104.6 cm wheelbase, 42.9 cm chainstay length, and a 29.8 cm bottom bracket height. The rear suspension was a single swingarm design, where the pivot point is located on a collar which can be clamped anywhere along the seat tube from the bottom bracket to 22 cm above the bottom bracket in 0.42 cm increments. The rear suspension element was an AMP rear shock (Laguna Hills, CA) with a 96.3 N/mm coil spring in parallel with a hydraulic damper which provided 3.75 cm of total travel. The oil was drained from the damper to prevent the system from being overdamped [1]. The front suspension fork was a 1997 Judy SL (RockShox, San Jose, CA) with green (medium stiffness) springs in series with an elastomer bumper and oil damping (factory setting) which provided a total travel of 2.8 cm. Assembled using commercially available conventional components, the final weight of the entire bicycle was 13.3 kg (29.4 lb).

Eleven experienced test subjects, who ranged in weight from 72–84 kg (Table 1), rode the test bicycle on a treadmill. The grade of the treadmill was 6 percent, the velocity was 24.8 km/hr, and the gear combination was 38×14 yielding a pedaling cadence of 84 rpm. Before any data collection on the treadmill, both the seat height and handlebar position were adjusted for the preference of the subject and each subject practiced on the treadmill to become comfortable riding in that environment.

Table 1 Test subject information

Subject	Age (yr)	Height (m)	Weight (kg)	Riding Experience a. years cycling b. racing category
CM	28	6'0" 1.83	84.3	a. 6 b. category 5/4 road
DM	34	5'11" 1.80	79.9	a. 6 b. sport mountain
DB	21	5'9" 1.75	71.8	a. 2.5 b. beginner mountain
MD	41	5'11" 1.80	75.3	a. 20+ b. beginner mountain
KK	37	5'11" 1.80	81.6	a. 19 b. category 2 road/expert mountain
RS	36	5'10" 1.78	87.4	a. 14 b. category 4 road/expert mountain
MG	27	6'1" 1.85	78.7	a. 13 b. category 3
RW	29	5'10" 1.78	74.7	a. 22 b. class B road
JC	21	6'3" 1.90	81.7	a. 6 b. category C road
EF	33	6'1" 1.85	76.7	a. 16 b. pro road
FM	25	6'0" 1.83	77.5	a. 10 b. sport mountain

The pivot point height along the seat tube (adjusted with the movable collar) was randomly selected from 5.04–12.18 cm above the bottom bracket for a total of 18 pivot points. To avoid interference with the chain, two swingarms were used, one for pivot points above the chainline and one for pivot points below the chainline. Because of the time required to perform the swingarm changeover (about 15–20 minutes), the four pivot points below the chainline were randomly selected at one time and the 14 above the chainline were randomly selected at another time

To provide data for testing the various hypotheses, each subject rode the test bicycle for four test conditions at a particular pivot point. Two of the test conditions were with the front suspension locked out (i.e., preload dial set completely positive to maximally compress the spring), and not locked out (i.e., preload dial turned completely negative to unload the spring and then backed out two turns). Once a pivot point height was selected, the front suspension element condition (i.e., locked or unlocked) was randomly selected. The remaining two test conditions were that each subject performed each data trial in two postures: seated and standing. The total number of trials for each subject was 72 (18 pivot point heights $\times 4$ test conditions/height). The time required to change the pivot point height was about 2 minutes so that subjects rested between every four trials. Prior to data collection, each subject pedaled for about 30 seconds as the treadmill speed was increased from 12.4 km/hr to 24.8 km/hr. Once at the proper speed, the subjects pedaled for an additional 20 seconds to reach steady state pedaling after which data were collected for a total of 14 seconds (to provide 12 seconds of usable data). All trials were completed in one day during a period of 3–4 hours.

Data were collected from several transducers. Linear potentiometers were used to measure the displacements across both the front and rear suspension elements. An optical encoder connected to the frame through a coupler and a 1:1 gear system attached between the coupler and crank indicated the crank angle. All data were acquired via a 12 bit A/D board (AT-MIO-64E-3, National Instruments Corporation, Austin, TX) inserted in a PC. National Instruments Labview 4.1 provided the acquisition user interface. Data were sampled at 100 Hz.

Data Analysis. Pertinent quantities were extracted from the raw data first. The amplitudes of motion across the front and rear suspension elements were calculated by computing the difference between the maximum and minimum displacements for each element. This difference was computed for each crank cycle for each subject. The average displacement was then calculated over all crank cycles.

To determine the power dissipated from the rear suspension element for arbitrary amplitudes, a regression model was developed. The range of test amplitudes from all subject testing conditions and the power loss was divided into 13 equally spaced increments. The power loss for each of the 14 amplitudes in the regression model was determined by measuring the force-displacement of the rear suspension element with the spring removed. Force-displacement was measured with a materials testing system (Model 858, MTS, Minneapolis, MN) under displacement control for a constant frequency equal to the testing condition. Inasmuch as the primary resistive force was Coulombic, the average force measured was used to calculate the power loss for each particular rear suspension displacement. This calculation was verified by computing the average power loss from integration. The relationship between the average power loss and the amplitude was modeled well by simple linear regression (R-squared$=$0.997). The regression was used subsequently to determine the power loss for each subject for each testing condition by interpolating the amplitude corresponding to a test condition and finding the corresponding power loss.

The optimal pivot point height for minimum average power loss was determined for each subject. To determine the optimal pivot point height, the power loss for each subject across the range of pivot point heights was determined from the aforementioned regression and plotted for the front suspension active and inactive test conditions. The power loss data as a function of pivot point height were then low pass filtered with a four-point moving average filter passed in both directions to eliminate any phase shift. The optimal pivot point height for that rider was then determined as the height corresponding to the lowest power loss (Fig. 2).

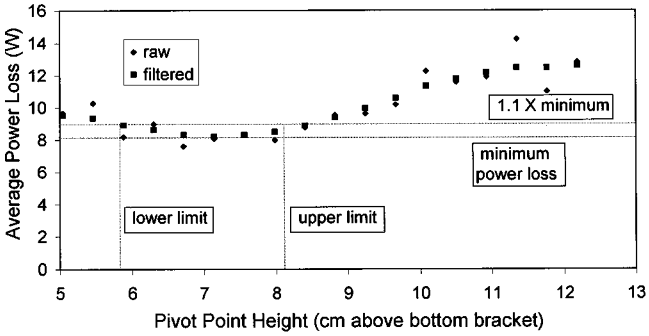

Fig. 2 Example plot of the average power loss versus the pivot point height (standing posture). The plot illustrates how the optimal pivot point height and the limits for pivot point heights corresponding to a 10 percent increase in the minimum average power loss were determined.

To test the first hypothesis, a paired student t-test was performed. The difference was between the minimum power dissipated for each rider with the front suspension fork active and inactive. This analysis was performed for both the seated and standing rider postures.

To test the second hypothesis, the lower and upper limits for the pivot point height corresponding to a 10 percent deviation from the minimum power loss were determined (Fig. 2). Using this range in pivot point heights for each subject, the plot of the minimum pivot point heights for each subject with corresponding error bars was developed. Again, plots were developed for both seated and standing postures.

Similar to the first hypothesis, a paired t-test analysis was performed to test the third hypothesis. Here, the paired difference was between the optimal pivot point height for the seated and standing postures.

Results

There was wide variability in the minimum power loss at the optimal pivot point height among the subjects. In the seated posture, the average minimum power loss was only 0.89 W but ranged from a low of 0.59 W to a high of 1.25 W (Fig. 3). In the standing posture, the average minimum power loss was much greater than in the seated posture with an average of 6.49 W and a range of 0.70 to 13.48 W with the front suspension active (Fig. 4). The motion of the rear suspension was 0.5 mm and 3.3 mm corresponding to the average power losses of 0.89 W and 6.49 W, respectively.

Although the minimum power loss was higher on average with the front suspension active in both the seated and standing postures, the difference was not statistically significant for either posture indicating that there was no interaction between the front and rear suspensions. In the seated posture, the average minimum power loss over all subjects was 0.89 and 0.86 W for the inactive and active front suspensions respectively ($p=0.431$). In the standing posture, the average minimum power loss was 6.49 and 6.28 W for the inactive and active front suspension respectively ($p=0.369$).

Notwithstanding the wide variability in the minimum power loss, the optimal pivot point was surprisingly consistent among the subjects. In the seated posture, the range of pivot point heights corresponding to the 10 percent increase in power loss above the minimum overlapped for the majority of the riders (Fig.

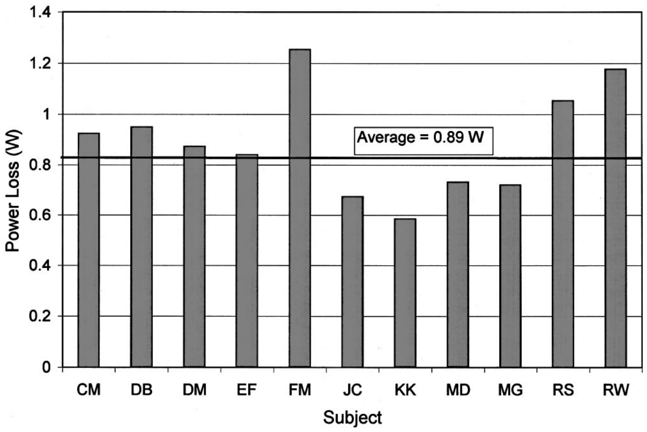

Fig. 3 Minimum rear suspension power loss for all subjects in the seated posture (front suspension active)

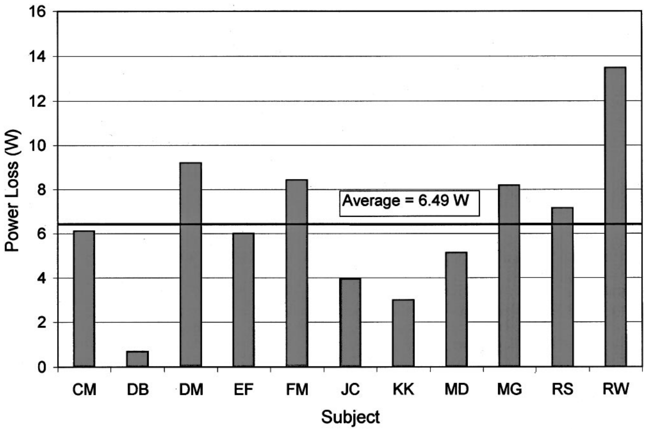

Fig. 4 Minimum rear suspension power loss for all subjects in the standing posture (front suspension active)

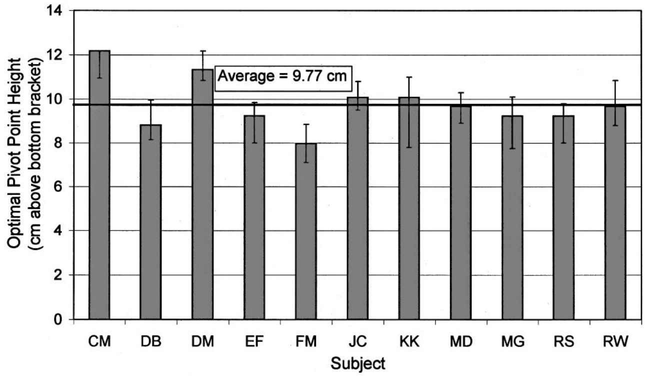

Fig. 5 Optimal pivot point height corresponding to minimum rear suspension power loss for all subjects in the seated posture (front suspension active)

5). The average minimum pivot point height was 9.8 cm and passed through the ranges of 8 of the 11 subjects. In the standing posture, the 5.9 cm average optimal pivot point height was in the range of pivot point heights corresponding to the 10 percent increase in power loss above the minimum for 9 of the 11 subjects (Fig. 6). Increasing the pivot point height to 6.6 cm passed through the ranges for all of the subjects.

Because the optimal pivot point was consistently higher for all subjects in the seated versus the standing posture (Figs. 5 and 6), the statistical test revealed that the difference was significant ($p < 0.0001$).

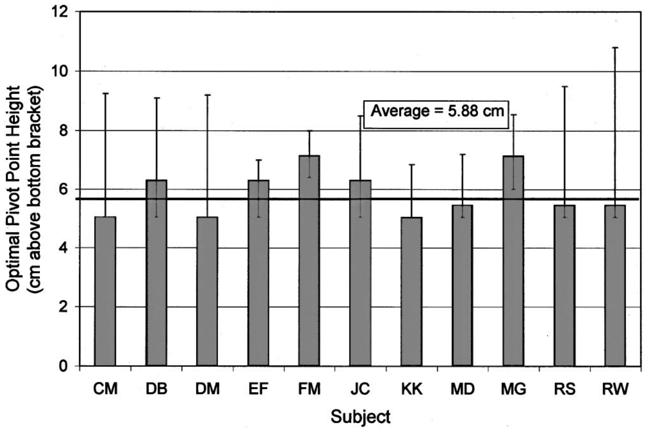

Fig. 6 Optimal pivot point height corresponding to minimum rear suspension power loss for all subjects in the standing posture (front suspension active)

Discussion

Considering the benefits of the dual-suspension bicycle in the off road environment, the popularity of the single swing-arm design for the rear suspension, and the disadvantages of pedaling induced suspension action, the two primary objectives of this study were to investigate the effects of pedaling mechanics and posture on the optimal pivot point height. To satisfy these objectives, an experimental approach was taken where eleven test subjects pedaled a test bicycle on an inclined treadmill. The most important findings were that (1) the same pivot point height in both the seated and standing postures could be considered near optimal (within 10 percent) for the majority of the test subjects, and (2) the optimal pivot point height was higher on average for the seated than the standing posture. Before discussing the practical implications of these findings, it is worth critically examining any methodological issues which could have influenced the results.

Methodological Issues. Ideally the leverage ratio of the rear suspension would have remained constant as the pivot point height was changed. The leverage ratio is the ratio of a differential displacement at the shock absorber to a differential displacement at the rear wheel [1]. The leverage ratio (LR) relates the effective spring (k_e) and damper (c_e) characteristics of the rear suspension to the spring (k_s) and damper (c_s) characteristics of the shock through the following equation $k_e/k_s = c_e/c_s$ if the leverage ratio is constant. Thus, the effective spring and damping would be independent of the pivot point height if the kinematics of the suspension met the requirement of constant leverage ratio. However, for the rear suspension design, $(\mathrm{LR})^2$ was a linear function of the pivot point height [1]. Consequently the variable of pivot point height was not completely isolated in the experiments since the effective suspension properties varied as well. Considering that the results of the present study verify the analysis by Wang and Hull [4] (see below) and that the optimal pivot point height is relatively insensitive to the leverage ratio [4], the inability to isolate the pivot point height did not markedly affect the results of the present study.

The rear shock was modified for the purposes of the experiments. To prevent the rear suspension from being overdamped hence rendering the suspension motion minimal, the oil was drained from the rear shock. This changed the mechanism of dissipation from Coulombic plus viscous to primarily Coulombic. As with the leverage ratio, this change did not affect the results for the optimal pivot point height because of insensitivity to suspension properties [4]. However, it did affect the determination of the power loss. Considering that the frequency of pedaling was constant, any effect was systematic and hence did not affect relative comparisons.

In analyzing the data to evaluate the second hypothesis, a methodology was necessary to determine the acceptable range of pivot point heights for each subject. Both a relative approach (i.e., limits based on a percent increase in the power loss relative to the minimum) and an absolute approach (i.e., limits based on a fixed increase in the power loss) were considered and evaluated. The primary reason that the relative approach was chosen was because it allowed the results of this study to be more broadly applicable than the absolute approach. Although the optimal pivot point height is not particularly sensitive to suspension parameters [4], the amount of power loss could be. Consequently the absolute approach would have provided results applicable only to the parameters particular to the test bicycle used herein.

In using the relative approach, a value for the percent increase in the power loss at the optimal pivot point height had to be chosen to determine the acceptable range of pivot point heights for each subject. The goal was to select a value that provided lower and upper limits on the pivot point height that included the ‘‘trough’’ region of the power loss versus pivot point height plot (e.g., Fig. 2). While the selection of this value was somewhat arbitrary, it had to be small in relation to the extreme values of the curve. In this application, the 10 percent value satisfied this requirement considering that the maximum power loss increase was about 140 percent when averaged over all subjects in both postures. Moreover, for several subjects, the ‘‘trough’’ region was actually quite flat over a wide range of pivot point heights. For these subjects, the 10 percent value yielded limits on the pivot point height that included most if not all of the flat region. A smaller percentage (e.g., 5 percent) would have been too restrictive because it would have yielded limits that did not span the flat region whereas a higher percentage (e.g., 15 percent) would have yielded limits that were unnecessarily generous to include the flat region.

Although testing was conducted at a relatively high output power of approximately 300 W and over an extended period, the effects of fatigue are not a concern for several reasons. First, although the tests consumed 3–4 hours, the data were collected in 72 trials each of which lasted 14 seconds. Inasmuch as each subject pedaled as the treadmill speed was increased to the test speed and then typically pedaled for approximately 20 seconds at test speed immediately prior to data collection, the total time of high power output at test speed was about 41 minutes. Assuming a testing duration of 3 hours (the worst case), the subjects pedaled at high power only for 25 percent of the total time of the test and rested during more than half of the test duration. Given this amount of rest, only two of the subjects requested additional time to rest. Second even if a subject did become fatigued, then he still produced constant power because the speed and grade of the treadmill never varied. Finally, the order of the pivot point heights was randomized across subjects. So the effects of fatigue, if any, were random and not systematic.

Interpretation of Results. Since one of the primary motivations for undertaking this study was to validate the optimization findings of Wang and Hull [4], the results from the seated posture should be viewed in this context. For a chainring with 38 teeth, the analysis of Wang and Hull [4] predicted an optimal pivot point height 13.0 cm above the bottom bracket spindle. In comparison, for the eleven subjects tested herein, the optimal pivot point height had an average value of 9.8 cm and varied from a minimum of 8.0 cm to a maximum of 12.3 cm. Thus the average value for the experiments was lower than the value for the analysis.

The higher average for the analysis was most likely the result of overestimating the inertial loads in the fore-aft direction [4]. This overestimation would cause a greater tendency for suspension squat which would need to be counterbalanced by a greater moment about the pivot point tending to increase the extension of the rear suspension. Accordingly, the pivot point height would have to be increased to provide this greater moment. Although the analysis overestimated the inertial loads hence influencing the absolute optimal pivot point height, this influence was systematic and hence would not be expected to markedly affect the sensitivity of the optimal pivot point height to the variables studied.

Because Wang and Hull [4] also studied the sensitivity of the optimal pivot point height to pedaling mechanics, this sensitivity affords another comparison to the experimental results obtained herein. The range of variation in the optimal pivot point height reported by Wang and Hull [4] was 2.0 cm whereas for the experiments reported herein the range was 3.5 cm. The wider range is not surprising considering that the number of subjects used in the experiments (i.e., eleven) was considerably greater than the number of subjects used in the analysis (i.e., four).

Notwithstanding the fact that the range in the experimentally determined optimal pivot point height for the seated posture was wider than that determined from the analysis, the optimal pivot point height was remarkably robust. Eight of the eleven subjects contained the average value within the 10 percent limits. To include the three subjects whose 10 percent limits did not contain the average optimal pivot point height, the limits would need to be expanded to 20 percent for two subjects and 35 percent for the final subject. Nevertheless, observing that more than 70 percent of the subjects included the average optimal pivot point within the limits, the results of the experiments confirm the analysis result of Wang and Hull [4] that the optimal pivot point height is relatively insensitive to pedaling mechanics.

Considering the fact that results from the experiments reported herein validate the analysis predictions by Wang and Hull [4] for the sensitivity to pedaling mechanics lends credibility to other comparative aspects of the analysis. For example the analysis showed that the optimal pivot point location was insensitive to the suspension stiffness and damping parameters. This observation was used to support statements made earlier in the Discussion section that the variability in leverage ratio of the test bicycle and the dissipation of the rear shock absorber did not affect the determination of the optimal pivot point in the experiments reported herein.

When the subjects changed from the seated to the standing posture, the optimal pivot point in standing shifted to a lower height than seated. Again this shift can be explained by considering the influence of the crank torque. For the 38×14 gear combination, the chainline was 7.5 cm above the bottom bracket spindle axis. Thus the 9.8 cm average height of the optimal pivot point location for the seated posture was well above the chainline whereas the 5.9 cm average height for the standing posture shifted to below the chainline. The shift in optimal pivot point location occurred in part because the peak instantaneous crank torque is greater in the standing posture than the crank torque in the seated posture [7]. For a pivot point located above the chainline, the increased chain force in standing would cause an increase in the tendency of the suspension to extend. Thus, to counteract this tendency, a downward shift in the pivot point was necessary. Although the increased peak crank torque would also increase the fore-aft accelerations thus increasing the tendency of the suspension to compress, the effect on the suspension motion was evidently less important than that due to the moment created by the increased chain force. Also the difference in inertial loads due to the motion of the rider between the seated and standing positions could account in part for the shift in the optimal pivot point location.

Interestingly, the optimal pivot point height was even more robust in the standing posture than the seated posture because more subjects (9 versus 8) included the optimal pivot point height within the 10 percent limits. Moreover, a pivot point height of 6.6 cm, which is slightly higher than the average optimal height of 5.9

cm, was identified which was included in the limits for all of the subjects. While the increased robustness might seem at first to be surprising since the loading during standing cycling might be expected intuitively to be less consistent than the loading during seated cycling, keep in mind that the minimum power loss in standing was more than 7 times greater than in seated. As a consequence, the pivot point limits for a 10 percent increase in the minimum power increased accordingly thus making the optimal pivot point height in standing more robust than in seated.

Because the average optimal pivot point location for standing was almost 4 cm lower than that for seated, clearly some compromise must be made in practical off-road bicycle design. One issue worthy of consideration in making this compromise is that most extended climbing is done in the seated posture because of increased energy expenditure in the standing posture for equivalent average power output [8]. Therefore, even though greater power would be lost in shifting the optimal pivot point from the standing to the seated location, it would probably be to the rider's advantage to have the pivot point optimized for seated rather than standing.

Not only is the optimal pivot point height sensitive to the posture, but the analysis by Wang and Hull [4] also demonstrated that the height was sensitive to the size of the front chainring. This is because the size of the chainring dictates the direction of the chain force and hence the moment developed by the chain force about the pivot point. Accordingly the relationship is linear with the optimal pivot point being higher for larger chainrings. This finding in conjunction with the experimentally determined finding reported herein that the optimal pivot point height is also sensitive to posture complicates the choice of the pivot point height in production bicycles [4]. However, as noted above, the complexity can be reduced somewhat by focusing on the optimal pivot point height in the seated posture.

Once the decision is made regarding the posture for optimization, a similar decision must be made regarding the size of the chainring. Although the present study as well as that of Wang and Hull [4] decided to base the optimization on the middle chainring, arguments could be offered that the smallest chainring is the more appropriate choice depending on the region and riding style. For example riders in mountainous areas with steeper, slower, and more technical trails would likely spend considerable time climbing in the smallest chainring. Moreover, rear suspension coupling problems are amplified in the smallest chainring since chain tension is higher and bike speed and hence inertia are reduced. If chainring size were reduced from 38 teeth used herein to 24 teeth which is a typical size for the smallest chainring, then the optimal pivot point height would decrease from 9.8 cm above the bottom bracket to 6.2 cm which is a substantial reduction.

Table 2 Pivot point heights above the bottom bracket for four production bicycles. The optimal pivot point height found in the present study was 9.8 cm using a 38 tooth front chainring for the seated posture.

Manufacturer	Model	Type	Pivot Point Height (cm)
Cannondale	Jekyl	Swingarm	6.6
Haro	Extreme EX3	Swingarm	9.8
Marin	B17	Swingarm	7.9
Proflex	N/A	Swingarm	10.0

Inasmuch as the variation in the optimal pivot point height is substantial depending on the chainring size, it was of interest to examine the pivot point heights of some production bicycles to ascertain the chainring size on which the industry is deciding to base the optimization. As summarized in Table 2, the pivot point heights for two of the four production bicycles examined are very close to that found herein while the pivot point heights for the other two production bicycles are lower (one by about 2 cm and the other more than 3 cm). Considering these variations, the two designs with the lowest heights are optimized for use in the smallest chainring while the two designs with the highest heights are optimized for use in the middle chainring. If the manufacturers intentionally decided to optimize their designs for the respective chainring size, then it is evident that there is no consensus in the industry regarding the philosophy for the optimization.

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