Bicycle Rear Suspension Study

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ABSTRACT

The use of suspension on off-ride bicycles has proliferated in the past few years. Although such a proliferation may be partially attributed to a fad, bicycle suspension does have technical merits. Bicycles equipped with suspension result in increased rider comfort, enhanced wheel contact and control, and less net rolling resistance. The primary design consideration for suspension systems is to design the system so that it responds to bumps but does not respond to rider induced forces. If the suspension responds to the rider's forces, it may be absorbing valuable energy which could otherwise be helping to propel the rider and bike faster. In addition, such a suspension results in a strange, uncomfortable ride. To fulfill this design goal, free body analysis was done on the bicycle and suspension system. By examining the forces on the bicycle and suspension, frame configuration and pivot placement(the two primary factors that affect suspension performance) of the suspension swingarm were determined.

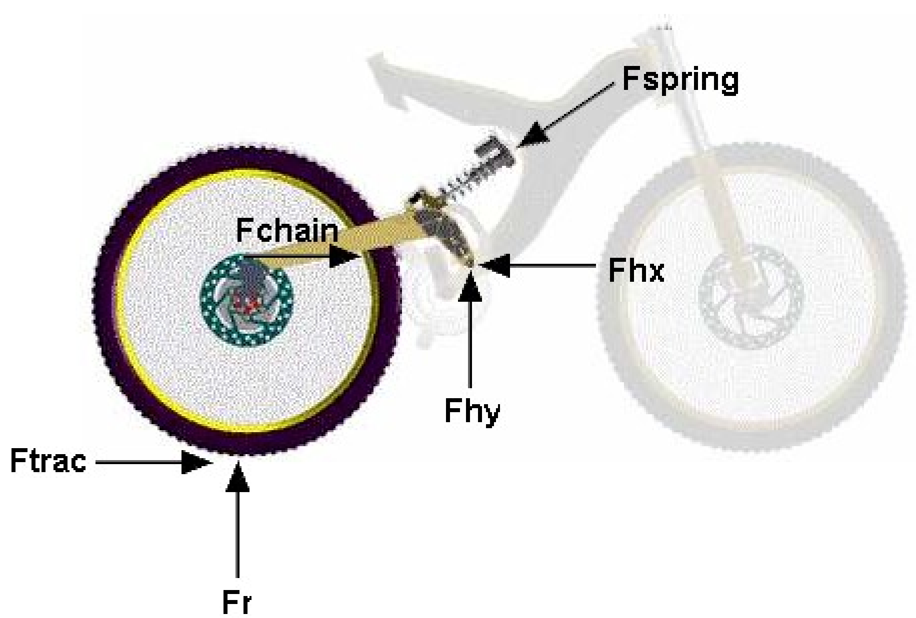
The next design consideration was what type of suspension component should be used. The accepted suspension component used on most production bicycles is a coil spring and oiled damper combination, but for our experimental purposes, a tension band was chosen as the suspension component. This provided strength and size adjustability, low cost, and simplicity. A full-scale working prototype bike designed with these principles was built and superficially tested.

METHODS & DISCUSSION

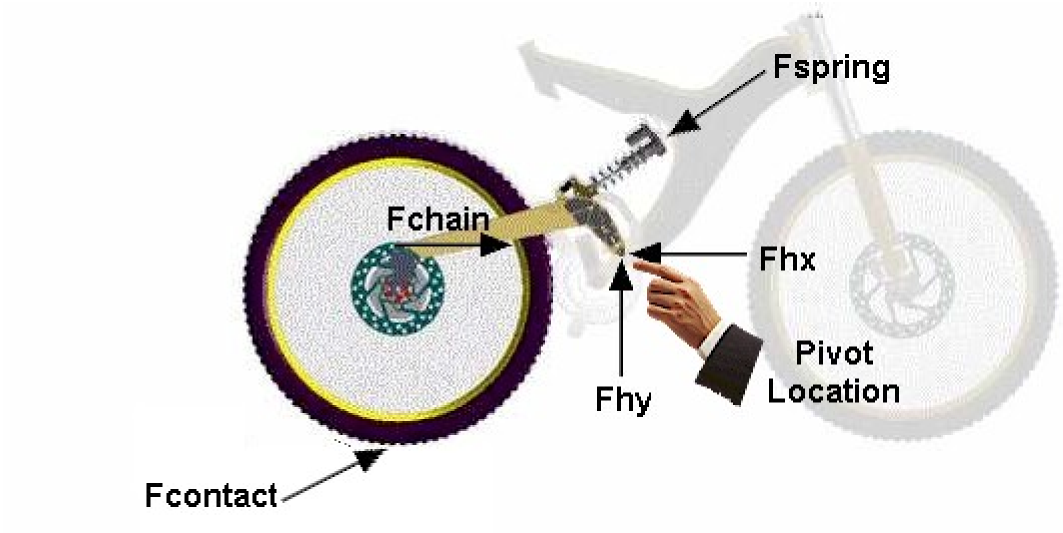
Forces between the rider, bike, and ground were analyzed using free body diagrams and applying laws of statics and dynamics. The analysis was done for a seated rider. The rider's temporary foot force at the pedal results in several temporary forces on the system: chain tension, traction force at the rear wheel contact, and an increase in the vertical force at the rear wheel due to weight transfer when the rider accelerates: all these forces can excite the suspension. Aerodynamic drag and rolling resistance were neglected because of their relatively small magnitudes. In our analysis, the rider was idealized as applying only a force on the downward stroke (no force exerted on the upstroke). All the rider-induced forces that may excite the suspension are all functions of the pedaling force. Thus when the pedaling force is greatest, during uphill climbing and sprinting, the suspension is most likely to be activated.

First we consider a conventional suspension design. The net temporary forces that result from the rider's cyclic pedaling motion, shown below, must not excite the suspension.

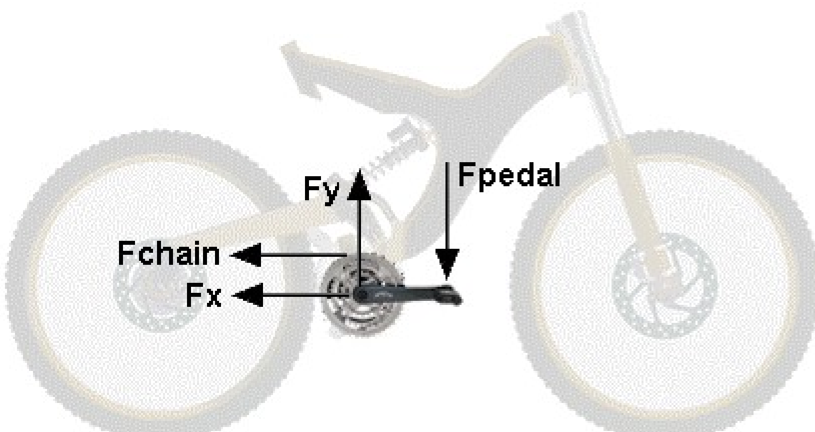
FBD of conventional suspension design - rear part of bike



For the rider-induced forces not to excite the suspension, the pivot must lie at the intersection of the rider-induced forces: the chain force (Fchain) and the rear wheel contact force ((Fcontact) The resultant of the rear wheel traction force and the rear wheel vertical force). With such a configuration, Fchain and Fcontact will not create a torque about the pivot. Hence the suspension will not be activated by the rider-induced forces. The only unresolved force remaining is the shock force(Fspring) that is left to respond to bump forces generated by the terrain.



To determine the magnitude and direction of the unknown forces (chain tension, traction force, and the vertical force at the rear wheel) free body diagrams were used. To determine the chain tension the following FBD was used:

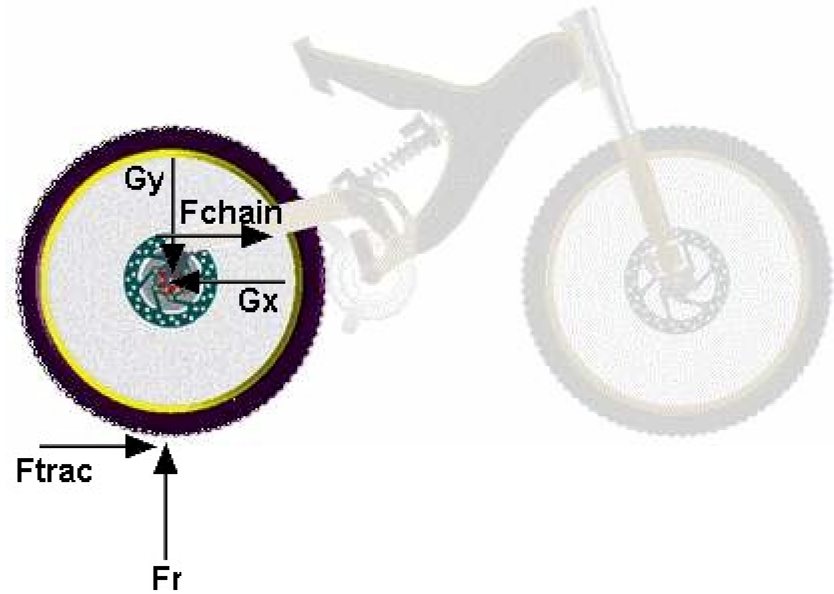


Summing the moments about the center of the front sprockets:

$$\sum M_{/fsprocketcenter} = 0 \qquad \Rightarrow F_{chain} = \frac{F_{pedal} \cdot R_c}{R_f}$$

R_c: crank arm length
R_f: Front cog radius

With the chain tension known, the rear traction force may be determined:

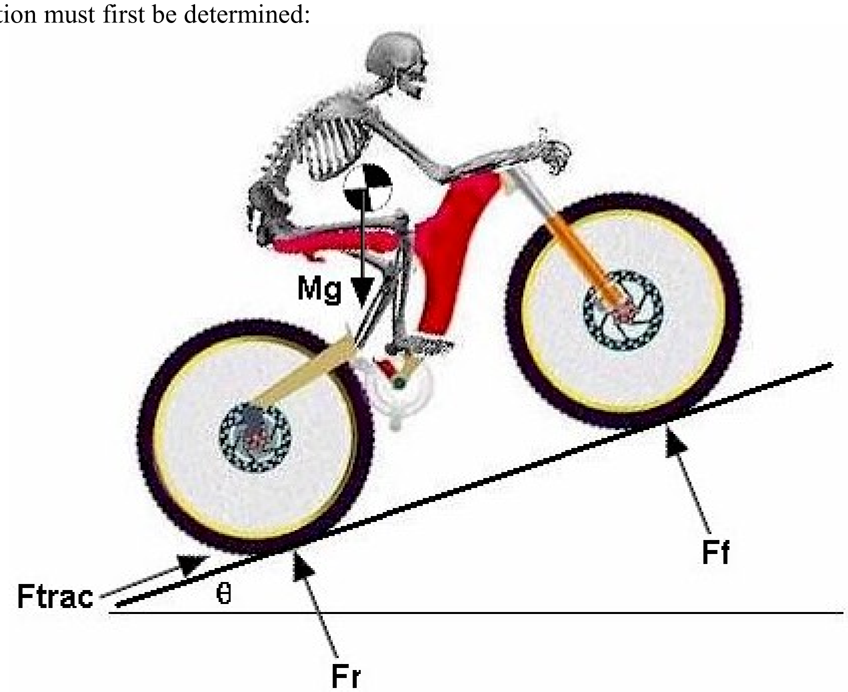


$$\sum M_{/\,rcogcenter} = 0$$

$$\Rightarrow F_{trac} = \frac{F_{pedal} \cdot R_c \cdot R_B}{R_f \cdot R_w}$$

R_b: rear cog radius
R_w: rear wheel radius

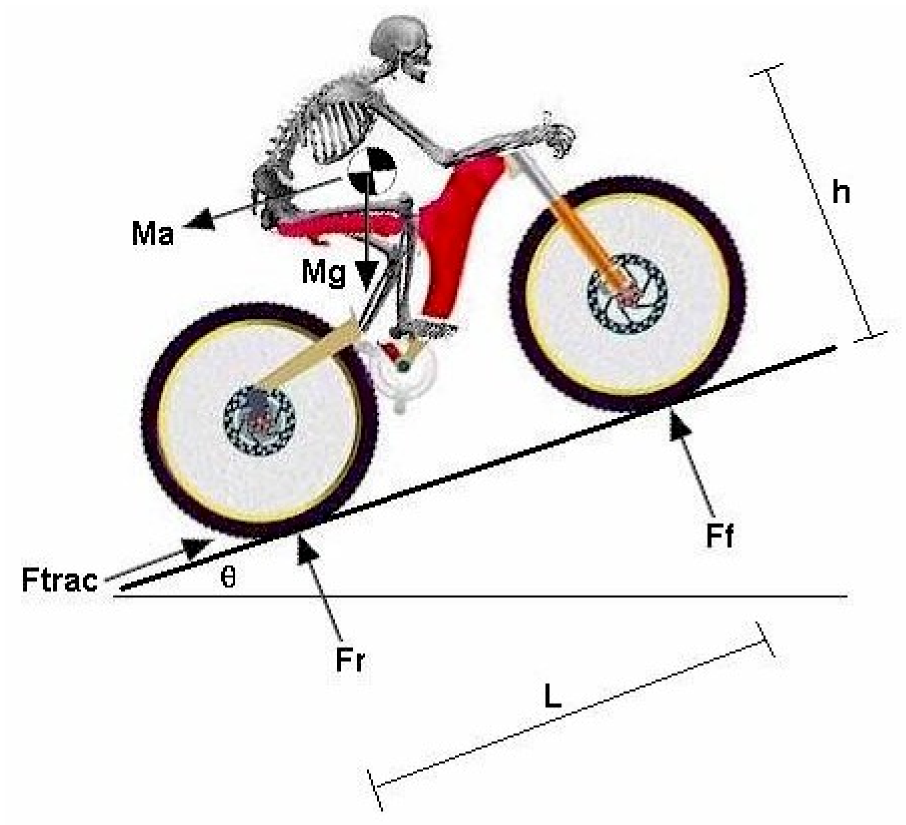
The vertical force at the rear wheel is the last force to be determined. To calculate the affects of weight transfer, the rider/bike acceleration must first be determined:



$$\sum F_{/\,hill} = M \cdot a_{hill}$$

$$\Rightarrow a_{hill} = \frac{F_{pedal} \cdot R_c \cdot R_B}{R_f \cdot R_w \cdot M} - g \cdot \sin\theta$$

To determine the total vertical force at the rear wheel, including weight transfer



$$\sum M_{/\,frontwheelcontact} = 0 \qquad \Rightarrow F_R = \frac{F_{pedal} \cdot R_c \cdot R_B \cdot h}{R_f \cdot R_w \cdot L} + \frac{m \cdot g \cdot l \cdot \cos\theta}{L}$$

L: wheelbase length
h: orthogonal distance from ground to center of mass of bike/rider

The first term in the above expression is due to weight transfer. The second term is due to gravity. The resultant of the two rear wheel contact forces may now be calculated. But first it is important to consider spring pre-stress (pre-load). A spring may be pre-stressed so that its length will not change until a certain force is applied. This concept is used in suspension bikes so that the spring pre-stress accounts for the rider's normal weight. When the rider sits on the bike, the spring is stiff and the suspension does not move. Theoretically, pivot placement could also account for the rider's normal weight, but the variety of rider's weights would necessitate a variety of pivot locations.

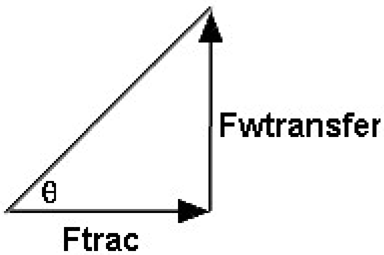
With the spring pre-stress used to account for the rider's weight, the remaining temporary forces which must be accounted for at the rear wheel contact are:

$$F_R = \frac{F_{pedal} \cdot R_c \cdot R_B \cdot h}{R_f \cdot R_w \cdot L}$$

Vertical force due to weight transfer

$$F_{trac} = \frac{F_{pedal} \cdot R_c \cdot R_B}{R_f \cdot R_w}$$

Traction force

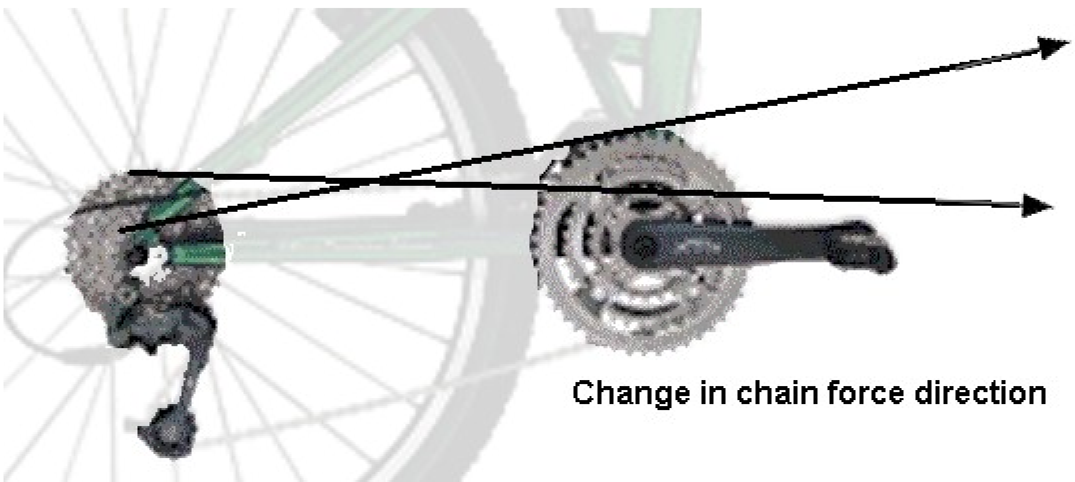


The angle at which the resultant force acts is:

$$a\tan\left[\frac{\left(\dfrac{F_{pedal}\cdot R_c\cdot R_B\cdot h}{R_f\cdot R_w\cdot L}\right)}{\left(\dfrac{F_{pedal}\cdot R_c\cdot R_B}{R_f\cdot R_w}\right)}\right]$$

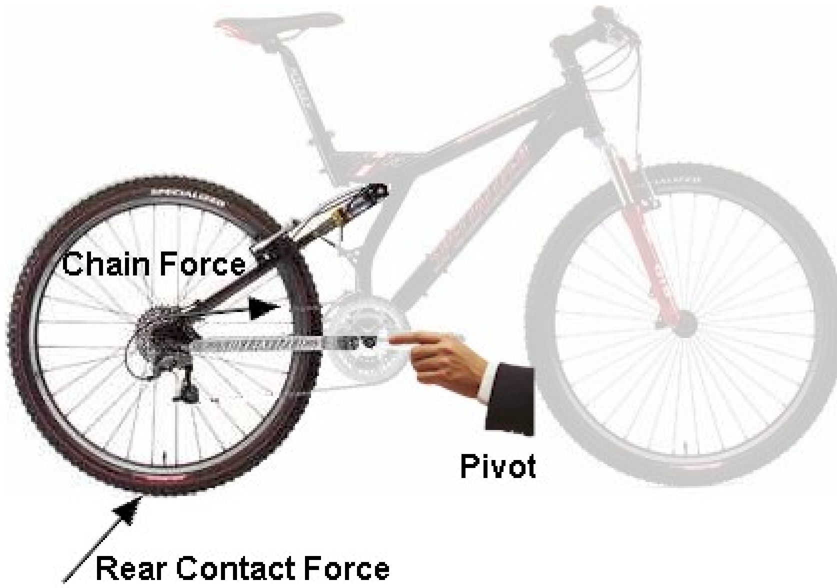
After canceling out most of the terms, θ = atan(h/L), where h is the height of the rider/bike center of mass and L is the wheelbase. These two dimensions are roughly equal and thus the angle of the resultant force at the rear wheel contact is always about 45 degrees.

With the direction of the chain tension and rear wheel contact forces known, the pivot location may be determined. Unfortunately, several problems arise. First, the intersection of the chain force and the rear wheel contact force do not intersect at a point on the bicycle frame (it actually lies in the area where the rear wheel is located). Secondly, the chain force direction changes and thus the ideal pivot location changes. As the chain is switched onto different rear wheel cogs and front sprockets, the direction changes.

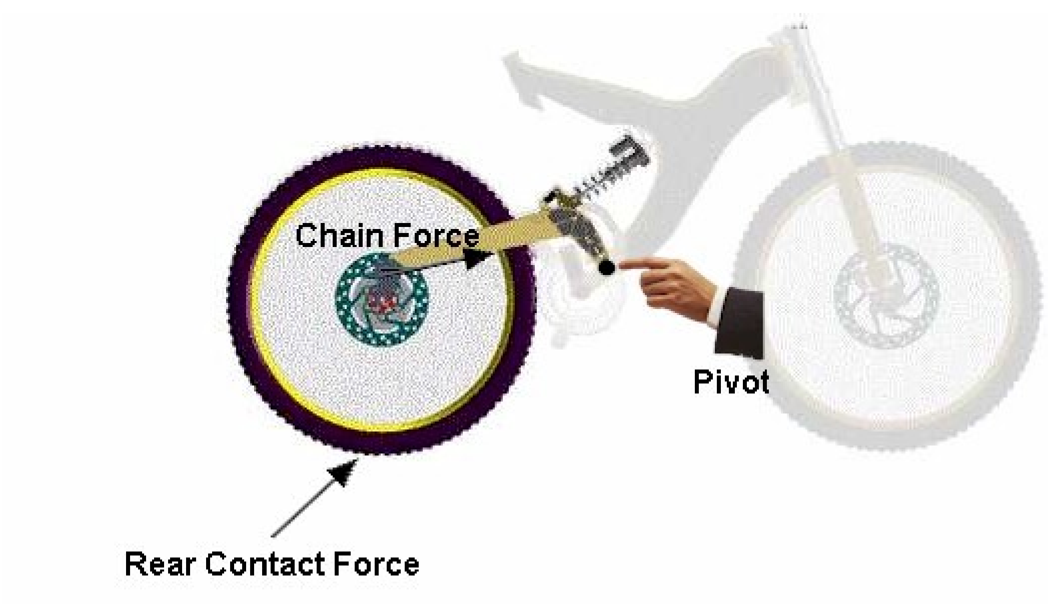


The chain force direction can also change, but to a lesser degree, when a bump is hit. The chain force changing direction can excite the suspension because the chain force is of such a great magnitude that even if it is acting slightly off the pivot location, a torque will be generated, exciting the suspension.

Most conventional suspension designs fit into one of two categories: either the pivot is located very close to the crank's center or it is located on the downtube in the general proximity of the chain force line of action. When the pivot is located near the center, biopacing is minimized because as the rear wheel moves up due to suspension activation, the chain length between the front and rear sprockets remains relatively constant. But such a pivot location is not good due to the fact that the rear wheel contact force and chain force excite the suspension because both create a torque about the pivot.

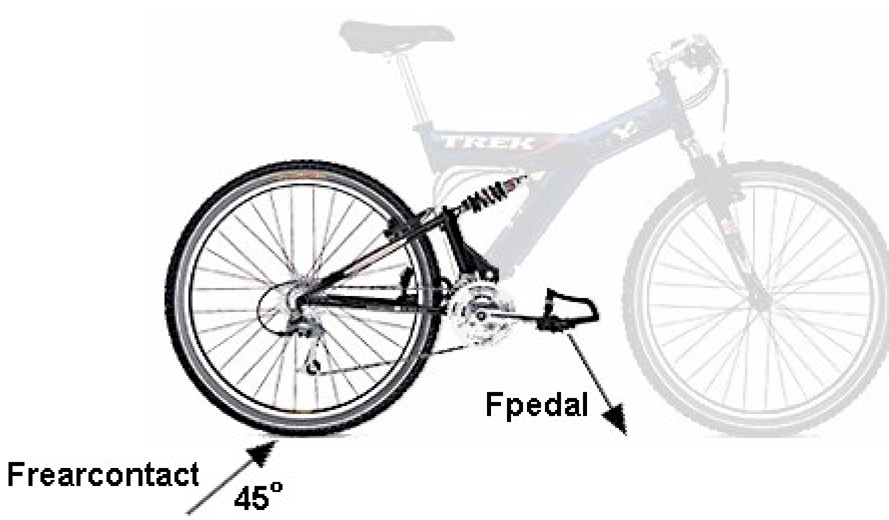


When the pivot is located on the downtube near the line of action of the chain force, it is intended that the chain force will not activate the suspension. But as explained previously, the chain force can change directions such that a torque will be generated about the pivot, and the suspension will be activated. In addition, biopacing is a problem. As the rear wheel moves upward, the chain length between the front and rear cog does not remain constant but instead changes. As this occurs, the riders pedaling rhythm is interrupted.

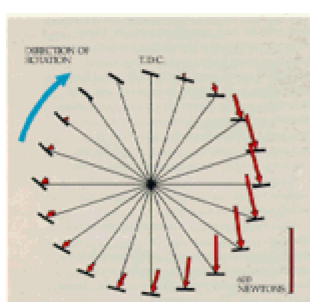


The use of a unified rear triangle(URT) greatly simplifies the rear suspension design problem. With a URT, the chain force is isolated from the suspension.

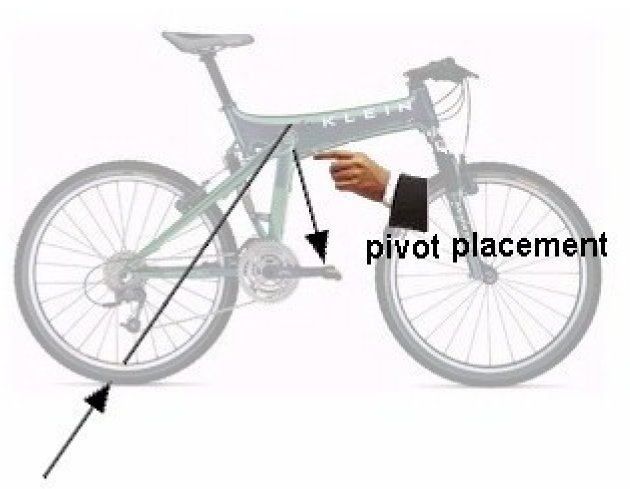
The pivot placement now depends on the rear wheel contact force, the pedaling force, and the bike frame geometry. The rear wheel contact force acts at about 45 degrees as explained earlier.



The direction of the pedal force is not as clear. During the downstroke, the pedal force acts at angles relative to the vertical ranging from 0 degrees to 15 degrees. The pedaling force seems to be greatest when this angle is 15 degrees.



By taking the point of intersection of the rear wheel contact force and the pedal force, the pivot location may be determined. This location is approximately positioned as shown below:



This is the ideal location for the rider-induced forces not to excite the suspension. This point, and only this point, will work for all gear ratios because the direction of the temporary rear wheel contact force is always acting at about 45 degrees even though its magnitude varies.

One final design consideration is biopacing. Although the chain length between the front sprocket and rear cogs remains fixed with a URT, biopacing can still occur. Biopacing occurs when a bump is hit and the rear suspension moves, along with the pedals. The pedal's movement depends on the pivot location. Such pedal movement is not wanted because the pedals actually "quicken" and it interrupts the rhythm of the rider's pedaling stroke. With the pivot location determined above, it is evident that biopacing would occur. A compromise must be made between limiting biopacing and rider activation of the suspension when choosing the pivot location. Biopacing is reduced if the pivot location is on the bottom tube where the pedal passes. With such a pivot location, when a bump is hit the downstroke pedal does not move.

This pivot location also results in canceling out the pedaling force when it is maximum (i.e the maximum pedaling force does not excite the suspension). This is the optimum pivot location for a unified rear triangle equipped bicycle, compromising between biopacing and rider suspension activation. The only rider-induced force that will excite the suspension is the rear wheel contact force. By increasing the spring pre-stress, this force may be accounted for.

A tension based suspension system was chosen for several reasons. The greatest attribute is the adjustability. Adjustability is very important because much of the suspension system's performance relies on the pre-stress. If the pre-stress is too high, the suspension system won't respond to the ground bumps. If the pre-stress is too low, the rider's forces (normal weight and temporary rear wheel contact forces) will activate the suspension. By having an easily adjustable suspension component, the pre-stress may be adjusted for optimum performance. The adjustability also allows compensation for some variables that are not easily quantified. For example, because the pivot location is designed for only one pedal force direction during the pedal cycle, the suspension may be activated when the pedal force is applied in a different direction during the pedaling cycle. This problem may be accounted for by adjusting the pre-stress accordingly. Also, when the rider is pedaling out of the saddle, his up and down accelerations may excite the suspension. Once again, adjustable pre-stress could remedy the problem. With tension based suspension, press-stress is easily adjustable by simply adding more "rubber band" components. The material and shape of such bands control the strength and dampening. This provides a simple, cost-efficient way to study and design optimum suspension design.

CONCLUSION

Mountain bicycle rear suspension results in increased rider comfort, enhanced wheel contact and control, and less net rolling resistance. Unfortunately, these benefits often come at a price. Poorly designed rear suspension can respond to the rider's forces, robbing the rider of valuable energy. In addition, strange pedaling rhythms, biopacing, may result thereby making for an uncomfortable ride. These two drawbacks can be greatly minimized and almost reduced with a properly designed URT suspension system with an optimum pivot location. Fortunately, the magnitude and direction of the rider-induced forces can be quantified. Using this information and incorporating design criteria to minimize biopacing, effective and comfortable rear suspension systems may be designed to respond independently of the rider's forces.