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The Basic Human Input to Bike Control

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Abstract

This study, completed in 1987, aimed to establish the essential input from a human bicycle rider to maintain vertical stability. A human rider on a bicycle is an example of an inherently unstable system. With only two points of support and a high centre of gravity it is not possible to maintain static balance. The special case of a skilled rider with a fixed wheel is discounted as being not entirely static. The reason the system is so unstable is that as soon as the centre of mass is displaced from the vertical the weight forms a disturbing couple about the support points and the greater the angle of lean the greater the moment arm. This produces an accelerating angular velocity into the fall. The modern bicycle has two built in aids to stability. Up to some angle determined by the design details, the raked steering axis produces a steering couple in the direction of lean when the machine is set at an angle to the vertical. When the bicycle is moving forward this produces a force at the front wheel ground contact point in the direction of lean which in turn rotates the frame in the horizontal plane thus producing a similar force at the rear wheel ground contact point. These two forces combine to produce two relevant effects. On the one hand it puts the system onto a curved trajectory in the horizontal plane in the direction of the lean which changes the direction of travel, and at the same time it acts about the high centre of mass to produce a couple that opposes the disturbing couple in the vertical plane. The other automatic stability factor is due to the gyroscopic effect of the wheels. Angular velocity in the vertical plane is precessed through ninety degrees to become a rotation in the horizontal plane in the direction of the lean. At typical bicycle speed this effect is not strong but it is enough to add another couple about the steering head tending to turn the front wheel into the lean. The combination of these two steering couples produces a tendency for a lean to be converted into a turn in which the centripetal couple opposes the fall couple. Both stability features depend on speed for the production of force at the wheel ground contact point so their effect changes with riding speed. Obviously how a bicycle or bicycle rider combination behave will depend on the specific design details but in general terms at around twenty miles per hour most bicycles will respond to disturbances in the vertical plane by a rapid short period turn into the fall which restores the upright running with very little change in direction. This is the sort of performance expected from a motor cycle where the gyroscopic effect is much more powerful and the normal operating speed much higher. As the speed reduces the automatic stability features get weaker until they are no longer strong enough to restore upright running. A riderless bicycle left free to run at walking speed will slowly collapse along a circular path. The same would happen to a 'no-hands' rider who was foolish enough to insist on remaining in the saddle. A bicycle with the front steering locked dead ahead will fall much faster showing that the stability features are still having some effect even at low speed. Since humans are able to ride bicycles at very slow speeds without falling it is evident that they are doing something in addition to the automatic stability and it was the intention of this study to find out as much as possible about this input.

The first thing was to remove the automatic stability features to ensure that all the steering input came from the rider alone. The trail angle was removed by mounting the steering axis vertically. The gyroscopic effect was removed by mounting a second front wheel vertically above the other and driving it at the same speed but in the opposite direction. The result was a bicycle with zero built-in stability and various tests were carried out to confirm this. Launched on its own it fell over as quickly as a bike with the steering locked dead ahead. If the rider took his hands off the bar the bike fell over. Though potentially dangerous at high speed the machine was pleasant to ride and easy to control.

The records consisted of roll rate and handle bar position on a common time base. Weight transference has been suggested as a means of control and this would have been a contaminating factor as there was no record of rider position. A chapter in the thesis dealing with this subject in detail shows that although shifting the rider's weight either side of the plane of the bicycle's frame will have an effect on the configuration of the system it cannot on its own alter the balance between the two major couples in the vertical plane. Front wheel movement is necessary for control and since a riderless bike can be made to run upright at high speed it is also sufficient. Riding 'no hands' depends on front wheel movement via the built-in stability of the bike and is not possible with a zero-stability bicycle. In addition to this both subjects made every effort to reduce body movements to a minimum during the recording runs.

It was realized from the start that analysis of the records was going to be much easier if as little as possible of the control input was caused by extraneous events. Consequently visual input was seen as a potentially contaminating factor because it was not possible to tell whether features in the surrounding scene might be influencing the rider to make control inputs. It was soon found that riding a bicycle blindfold was no harder than doing so sighted so all the runs were made with zero visual input. It was then possible to identify the information available to the rider. The semicircular canals respond to roll and yaw accelerations and integration would produce velocity information. A further integration would also yield some

angle information. There would be inputs from the otolithic organs but the linear accelerations would be very low. There would possibly be some information from the pressure changes at the seat but these were bound to be somewhat ambiguous as in a sustained turn the loading down the body axis is much the same as when upright. Finally the rider would have positional and rate information about steering angle via the bar position.

Since all the stability augmentation at the front wheel had been removed, any movement of the steering bar can have come only from the rider, consequently, since the blindfold riders were able to prevent the bike falling, the movements of the steering bar were both necessary and sufficient to prevent a fall. This meant that the record of the roll and bar activity was a complete record of how the subjects were responding to the roll changes to prevent the machine falling over. The next task was to analyze the traces with the aim of constructing a model that would account for their relationship. To assist in working out what was going a computer simulation of both a stabilized and zero-stable bike was written.

The values recorded were handle bar angle and roll velocity. Because the vestibular system responds to roll acceleration rather than velocity the roll velocity was differentiated to convert the trace into roll acceleration and the initial comparisons were between this and the steering angle traces. The high correlation between these two traces combined with the lack of any autocorrelation in the bar trace showed that the bar was following the roll continuously rather than timing internally generated pulses. By finding the peak correlations the time delay between signal and response were established in the range 60-120 milliseconds. These were fairly constant within but different between the two subjects.

When this control technique was applied to the computer model it showed that responding to the acceleration in this way removed the roll acceleration and produced a gently oscillating value either side of zero. However this did not contain the velocity so with this control the simulation continued to fall at a steady rate. The riders on the other hand did not, so it was evident that they were responding to velocity as well. When some velocity as well as acceleration feedback was added to the simulated control it produced a similar oscillation around zero velocity. When both acceleration and velocity were combined correlations between handle bar and roll activity were even higher. There was still something missing because the simulation showed that with this control the bike entered a continuous turn whereas the riders although they were briefed to make no attempt to maintain a straight course tended to correct turns and always maintained roughly the same direction. So they must have been able to detect and respond to turn as well.

The simulation allowed the exploration of some possible alternatives. Adding a continuous component of direction produced traces that were a good deal more stable than the actual traces. A closer study showed that there were places where the two curves seemed to fit rather badly so the residuals once the ‘fit’ between the two curves had been accounted for were extracted. These took the form of short pulses of input every now and then. When these were put on the same time trace as lean angle they coincided with the places where the turn was corrected back up to upright running. It appeared that when the turn rate exceeded some low value the riders were producing a short stab of handle bar input to push the bike back up towards the upright. This control technique, when applied to the computer simulation, produce a very similar output to that recorded on the real bike. The result of the above showed that given an unstable bicycle two riders of quite different build and riding experience were using their existing riding skills to ride blindfold in an approximately straight line and that the control they were using could be accounted for with the model outlined above.

Some unrecorded experimental runs made on a bike with full stability showed that given sufficient speed lean control was automatic and the bike ran upright without human contribution. A short push on the bar destabilized the bike momentarily but the combination of trail and precession rapidly brought the bike back to the upright on a slightly different heading. Smooth directional control was achieved by gently applying an angle independent torque to the steering head. This is interesting, as at first sight it appears contradictory. To go left the torque is applied as though to turn the handle bar to the right. To put it another way, to go left push on the left bar. This push produces a strong roll to the left and the reason riders do not easily appreciate what they have done is because the automatic control immediately responds to this rapid roll by turning the bar to the left to control the fall with a torque value greater than the rider’s input. Consequently the bar goes left even though the rider is pushing it to the right. When questioned riders almost always claim they turn the bar into the turn. If the rider were to apply an angle input instead of an angle independent torque then there would be a dramatic fall in the opposite direction. As soon as the rider removes the torque the bike returns to upright running. In effect, by adding a steering torque to the right the rider resets the zero position of the automatic control from ‘steady upright’ to ‘steady lean’ and the automatic control responds by turning so as to contain the resulting roll. The automatic stability on a bike depends on speed so it becomes less effective as the speed falls. Since, however, riders can remain in control down to very low speeds, it is evident that they must be supplementing the automatic stability as speed decreases. This makes sense as learning always takes place at low speed and most children’s bikes have poor automatic stability characteristics. The reason that there is no conflict between the two systems at intermediate speeds and above is almost certainly due to the considerable difference in response times. The system delay in the human response measured here was in the range 60-120 milliseconds but the two mechanical control features have literally no delay at all, consequently at high speed the automatic control removes any roll error before the human sensory system can detect it. As the speed falls there comes a point where the automatic system fails to contain the vertical angle and the human system picks this up and adds the required additional torque to the steering head. It is emphasized that neither control system deals in terms of steering angle. In both cases the controlling input takes the form of an angle independent couple or torque.