Training, Human Decision Making and Control
J. Patrick and K.D. Duncan (Editors)

THE ESSENTIAL HUMAN CONTRIBUTION TO BICYCLE RIDING

A.J.R. Doyle

Department of Psychology, University of Sheffield,
Western Bank, Sheffield, S10 2TN

Bicycle riding is a universal skill which is traditionally surrounded by some degree of mystery. The old saw says that once learned it is never forgotten but what exactly is learned has been by no means clear. From the psychologist's point of view one of the most important questions about motor skills is to what extent they necessarily involve the higher functions of the cerebral cortex. Decisions take time, information must be stored and accessed, and in complex skills these requirements often seem hard to reconcile with what is known of the brain's capacity. Whatever control system is proposed for the bicycle it must be sufficiently flexible and simple to account for the fact that children can learn the skill in a very short time and that, once acquired, no retraining seems necessary to ride a wide range of different types under very different conditions. This study aimed to analyse bicycle riding as a motor skill to determine how much could be accounted for without involving higher cerebral functions.

1. THE ANALYSIS TECHNIQUE

There have been a number of studies of two-wheel vehicle control but most of them are concerned with improving the handling performance of motor-cycles. Weir and Zellner [1] derived descriptive equations for the relationship between the roll rate of the machine and the torque input to the handle bars for motor cycles travelling in a straight line in the speed range 30 to 40 mph. There are however some significant differences between such a task and that of riding a pedal bicycle at slow speed and a question that needs to answered is whether they are different skills or merely different versions of the same skill.

There are some difficulties in trying to apply mathematical time-series analysis to bicycle control. First the rider's body and arms constitute an important part of the uncontrolled structure. Regardless of any deliberate movements made by the muscles, the weight and damping resistance due to the resting tonus of the muscles have a critical effect on the response characteristic. This, combined with the gross instability of the system, makes an 'open-loop' run virtually impossible. Second, mathematical models are intolerant of intermittent inputs that have their origin outside the system and it was apparent that part of the human control at least was intermittent. Third the autostability properties of bicycles are closely interwoven with the human contribution making it difficult to separate one from the other. This latter limitation is not important from the designer's point of view but it is critical to the psychologist.

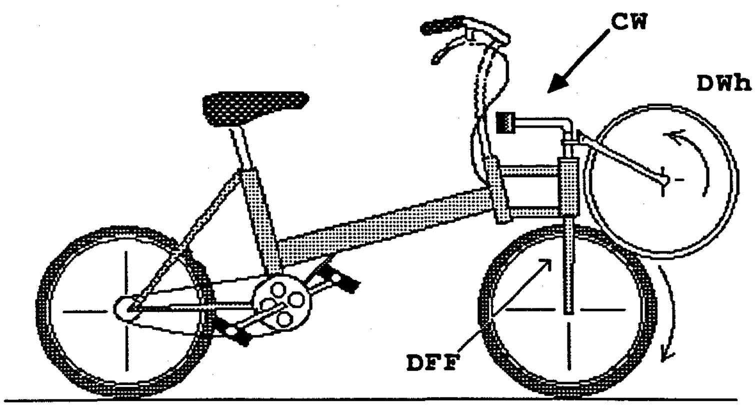


FIGURE 1

The destabilized bicycle. The straight vertical front forks (DFF) remove primary and secondary castor effects. The counter rotating wheel (DWh) removes gyroscopic precession effects. This wheel is counterbalanced (CW).

To overcome these difficulties this study took a different approach. Following the initiative of Jones [2] who attempted to construct an unrideable bicycle, a machine was constructed that had all the inherent roll stability removed. Figure 1 shows how the straight vertical forks do away with both rake and trail, removing the castor effect and the counter-rotating wheel cancels out the gyroscopic effect. Without these all movements of the front wheel come exclusively from the human control system.

To get round the intermittent control problem the bicycle was modelled in a computer simulation that worked by reiterating in small discrete steps. Each section of the rider/machine is modelled independently and the consequences of the input state over a very small time step is calculated for every part. The output states are then used to make the next wave of changes. Such a model can be tuned to give a very faithful imitation of the real machine over the range of values found in normal riding and will accept intermittent control inputs. The roll angle and front-wheel steering angles of the bicycle are recorded during free riding both with a normal bicycle and the destabilized machine. Because the system is so unstable there is very little freedom of choice for effective control systems. By carefully trimming the control values in the model to match the output in the actual traces it is possible to indicate in some detail the actual control being used.

2. UPPER-BODY CONTROL

Upper-body movement has been put forward as a possible means of controlling direction and/or roll.(Nagai,[3], Van Lunteran & Stassen,[4]).). Weir and Zellner [1], on the other hand, concluded from experiments that rider lean played only a minor part in control and immobilized lateral upper body movement in their subjects with a brace without adversely affecting their performance. Both recording and analysis are complicated by this additional input so it is desireable to remove it if possible. In considering this problem it is essential to bear in mind that the only way the rider can move the upper body one way is by pushing the bicycle frame in the other. It is possible to establish theoretically that the resulting movement of the centre of mass, following an upper body bend, depends on the relative masses of the upper and lower part of the combined man/machine, their relative positions and the speed of the movement. More telling, however, is the fact that, regardless of which way the centre of gravity moves during bicycle riding, at quite a small lean angle maximum upper body movements cannot bring the centre of mass onto the correcting side of the support point. This is confirmed by attempting to balance on a stationary bicycle either holding onto the cross bar instead of the handle-bar, or with the chain removed to prevent dynamic forces being transferred through the front wheel. No amount of body movement can prevent a fall in the direction of first disturbance. Thus it can be seen that upper body movement on its own cannot exert control in the rolling plane.

2.1 Indirect Lean Control

Despite the ineffectiveness of lateral body movement as a direct means of control the automatic stability conferred on bicycles by virtue of the front fork design does allow lateral upper body movement to control both roll and direction. Rolling the upper body to one side rolls the frame in the opposite direction. This roll is converted by the gyroscopic effect into a steering couple towards the frame roll, which in turn will push the centre of mass in the original direction of lean. A permanent lean to one-side will also generate a steering torque due to the castor effect. With the destabilized machine there are no secondary effects so upper body movements can be ignored.

3. CONTROL SYSTEMS

A single-track vehicle is so laterally unstable that there must be a continuous input to the front wheel steering to contain accelerations in roll. Any steering movements of the front wheel will produce a strong rolling couple in the opposite direction and, unless this is balanced by previously ensuring that the machine is leaning in the desired direction, the initial turn will have to be immediately reversed or the machine will fall. Thus it can be seen that an effective control system must translate all demands for changes in heading into some form of demand to the lateral control system. Figure 2 shows a formalised box diagram of such a nested feedback loop system.

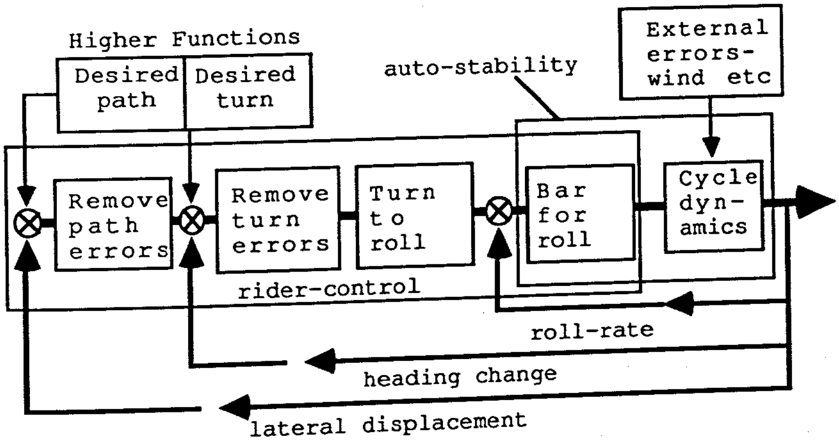


FIGURE 2

A formalized box diagram showing the relationship between the essential functions for bicycle control.

The two outer loops, control of heading and displacement, are common to the control of similar movements man makes in the world, whether driving a car or walking. A study by Smiley, Reid and Fraser [5] in 1980 explored the application of these two stages to car driving and they were able to show that beginners tended to run the two stages in parallel and experienced drivers nested the loops as shown in the proposed bicycle system. Although the two higher stages in the bicycle system could also run in either series or parallel their output must always be in series with the final loop. Thus, because the bicycle is so unstable, even beginners must learn to perform the inner loop function before extending their skill to the others. Consequently it is reasonable to consider this inner loop as the essential bicycle riding skill onto which other more general control skills can then be grafted.

4. THE ANALYSIS OF RIDER TECHNIQUE

The analysis will be presented in two parts. The first part will give the rider technique for controlling a normal bicycle at a speed where the autostability is making a full contribution and the second will explore the technique for riding the destabilized machine. Finally the way these two techniques relate to each other will be considered.

4.1 Autostability in the Normal Bicycle

Due to the design of the front forks three couples act continuously on the front wheel. Whenever the frame is rolling the gyroscopic action of the front wheel produces a couple trying to turn it in the direction of that roll. Due to the primary castor action any increase in the angle between the front wheel and the direction of its local travel will produce a restraining couple that inhibits the movement. For moderate angles of lean the secondary castor action gives a couple trying to turn the wheel in the direction of lean. The higher the speed the stronger the first two couples. The greater the angle of lean the smaller the last two couples but this effect is not of major importance at normal riding angles. These effects can only apply if the front wheel assembly is quite free to turn under the influence of the couples.

Thus at a moderately fast riding speed, say 15 mph, a bicycle will run in a straight line with a feeling of good stability. Any sudden disturbance of the front wheel due to bumps will be rapidly damped out and any angle of lean will be equally rapidly reversed with only a very small change in direction. The rider may safely remove his hands from the bar without any change in control.

4.2 General Observation of Normal Riding

A general observation of rider behaviour in the above regime reveals the following control technique. The design automatically ensures that roll disturbances are damped out and that, allowing for a certain amount of low frequency oscillation, lean and turn are always equated.

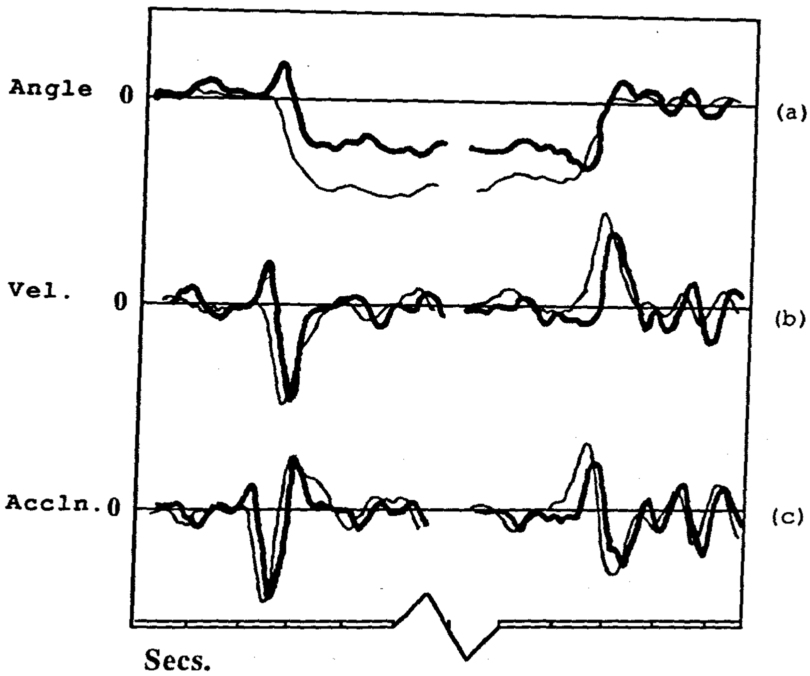


FIGURE 3

Rider manoeuvring on a normal bicycle. Speed approx. 8 mph. Entry and exit to turn shown. Handle-bar dark line. Roll fine line.

An angle independent pressure on the left handle bar, added to the autocontrol couples, will cause the bicycle first to roll and then to turn to the left. Releasing the push causes the bike to recover to the upright. It will be appreciated that this control movement is exactly the opposite to that used for a tricycle. A push to the right in fact turns the handle-bar to the left. The reason the bar then turns into the fall is due to the autostability couple not the rider's push which is actually opposing it. If the rider were to overpower this and turn the bar in the desired direction the result would be a violent fall out of the turn.

4.3 Matching the Real Trace

The first example is one of a number of recordings made while the rider was manoeuvring at approximately 8 mph. The machine first goes into into a steady turn, which is held for approximately ten seconds and then recovers back to straight running. Figure 3 shows the roll and handle-bar relationship during the critical entry and exit phases.

If the same situation is set up on the computer model it can be established that a short pulse of pressure on the handle-bar, increasing from zero to the final value in about 0.25 secs, will produce the same front assembly acceleration and initial roll rate. However, as will be seen in figure 4(a), the subsequent behaviour of the system is not the same. The roll angle increases initially to a much larger angle, around 15 degrees, and then recovers back to about 10 degrees where it more or less settles down. If, in the same way, the recovery is initiated by removing the bar tension then there is a very sharp recovery rate and fall over to the other side which gradually damps down to zero.

It is evident that the rider in the trace in figure 3 is using a more sophisticated control than the one described above. The initial fall, which is quite fast at about 10 degs a second, is stopped more or less at once with no hunting about a mean as there would if a single pressure had been held after the initial application. In the same way the recovery, although not absolutely dead-beat, does not go over the top to a large lean angle on the opposite side as it would if the pressure was just released.

Figure 4(b)shows the computer readout when the technique has been modified to match the two traces. The initial push gives the correct entry rate but it must be reduced to prevent too large an angle of lean accumulating. An ON/OFF pulse using the same acceleration rate, namely 0.25 secs to peak value and then 0.25 secs back to zero, gives the desired check of lean at about 5 degrees. This pulse is shown at A on the diagram. If however the push is left OFF the system will recover rapidly back to the upright under the unmodified influence of the autostability forces. To hold the lean angle, and thus the turn, some push must be reapplied. In the example shown the holding push is approximately half the original initiating value. The force of these pushes is not very critical but the timing is. The reapplication of the holding push must come as the steering acceleration, (Sdot), crosses the zero marked as C in figure 4, if it is to reproduce the dead-beat performance of the recorded rider.

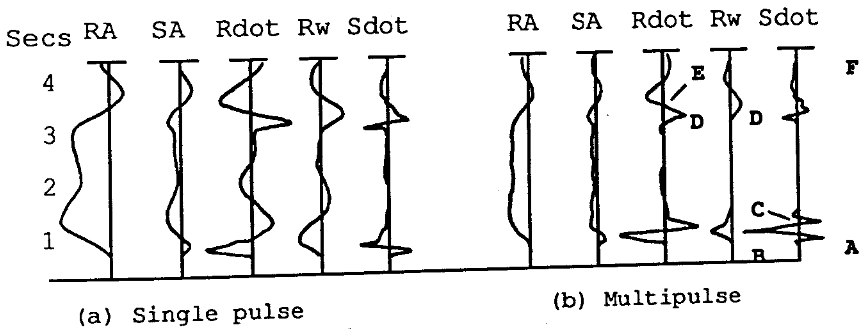


FIGURE 4

Simulation output showing effect of single pulse control (a) and multi-pulse control (b). T bar on VA & SA = +/- 5 degs.
Key:- RA=roll angle; SA=bar angle; Rdot=roll accln; Sdot=bar accln; Rw=roll velocity.
Normal bike; 12 stone rider; 12 fps (8.18 mph)

A very smooth dead-beat recovery can be achieved by removing the pressure at a very low rate over several seconds, but this is not what the rider in figure 3 has done. The strong initial recovery requires a rapid release of the pressure holding the bike in the turn. Since this does not lead to an overrun then pressure must have been reapplied at some subsequent point to damp it out. The trace shown was achieved by setting the pressure to zero within the standard time increment thus starting a strong recovery, shown at D in figure 4. Half the original value held during the turn is reapplied just before the roll acceleration (Rdot) crosses the zero line from right to left (E in fig.4) thus facilitating the autocontrol response to the rising roll which is checked as the bike reaches the upright rather than going beyond it. The pressure can be completely removed anywhere in the region marked F without making much difference to the behaviour.

There is no way of telling from the recording traces whether these extra control movements come directly from the rider's arms or are induced via the autostability with upper body rolling movements. The same result can be achieved by either means. Thus an upper-body roll out of the turn just after the application of the initial push would produce the required check at a lower angle of lean, and in the same way an upper body roll during the recovery would produce the observed dead-beat check at the vertical. This establishes the inputs that are necessary from the rider to produce the time course of events actually recorded on the normal bicycle.

5. THE DESTABILIZED BIKE

Figure 5 shows a short section from a series of runs in which the subjects are riding the destabilized bicycle at approximately 4 mph., with instructions to make no special attempt to maintain direction. It was found early in the study that depriving a rider of vision seemed to make no difference to riding ability so these runs were made with the subject blindfolded to try to reduce the tendency to steer a definite course. In the event all subjects tended to remove any turns automatically so that the general direction of the start was maintained for the run without any conscious intention.

The angle movement (Fig.5a) shows a low frequency wave of about 0.2 hertz with a shorter frequency wave of approximately one hertz superimposed on it. The handle bar movement, shown as the darker line, follows the roll line closely at a mean delay of 120 msecs. The angular velocity (Fig.5b) emphasises the short frequency movement and the lag delay between the channels can be clearly seen. In the angular acceleration curves (Fig.5c) the slow wave movement is invisible to a casual inspection, but the intimate relation between the bar and roll movement is at its clearest.

The basic tendency of the bar to follow the roll has two opposite effects. It reduces the roll acceleration when it is in the same direction and increases it when it is in the opposite direction. Which of these effects dominates depends on the combination of two factors. The length of the delay and the degree to which the bar value responds to the roll value. If the delay is very short indeed then the bar movement is almost all used in containing the roll and the roll divergences are damped out rapidly to zero. In this case the higher the multiplication factor the quicker the damping.

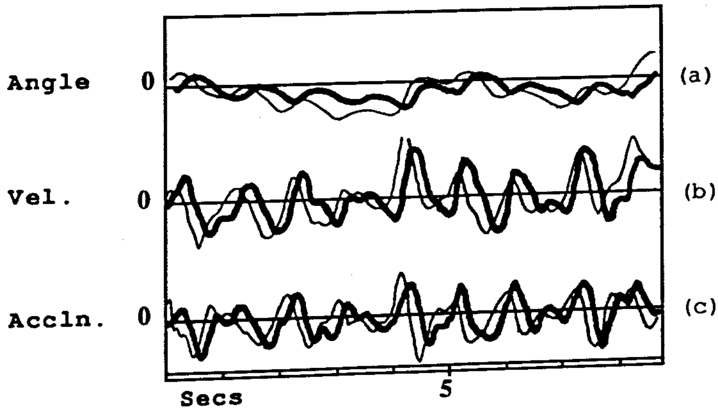


FIGURE 5

Blindfolded rider on destabilized machine. Speed approx. 4 mph. Handle bar dark line, roll fine line.

If the delay was long, say as long as the time it would take the bicycle to fall all the way to the ground, then the bar movement would fail to reduce the roll at all, regardless of the multiplication factor. However there is in practice a much shorter limit period for the lag, for, even if it is substantially less than that given above and manages to contain the fall by virtue of a high multiplication factor, it will then force the roll in the opposite direction during the lag period and will be faced with a much worse condition on the reverse as the bicycle will then be falling the other way at a speed that is a combination of both the gravity effect and the velocity it acquired during the reverse thrust.

Consequently it can be seen that to successfully contain the roll acceleration, the lag-follow technique demands a careful matching of the amplitude multiplication factor and the delay period, and that the delay period cannot exceed some quite short limit. There are differences between subjects, but within subjects the value is very stable. The rider in the run illustrated here has a delay of approximately 120 milliseconds though a delay of half this has also been recorded. There must be some minimum delay period that is dictated by the time taken for the human mechanism to extract, process and transmit the information to the operating muscles and for those muscles to respond. The shorter the delay the nearer this system comes to imitating the autocontrol bestowed on a normal bicycle by its front fork design, where, due to the direct nature of the mechanism, the delay is comparatively very short indeed.

5.1 The Acceleration Control Mechanism

Because the bar acceleration values follow the roll acceleration in the trace it can be established that the system is responding to acceleration changes. If it were only able to sample say velocity at some discrete interval then the slopes in the acceleration channel would not match and the reversals at the peaks would not show this regular form. In fact if such a system is tried out on the computer it is unable to produce a stable containment of the roll acceleration. If it has enough power to prevent the first fall it cannot help driving the reverse so far that it cannot be stopped before the machine goes out of control.

Thus the basic control mechanism takes the roll acceleration value and applies it, after multiplication by some constant, as an angle independent force at the handle-bar. Taking the delay at the same value as the run in the illustration, the computer model shows that, when the multiplication constant exceeds a certain value the system becomes unstable. If, on the other hand, the value is set too low then the system has insufficient power to contain quite small initial disturbances.

The fact that any particular combination of delay and multiplication factor gives a characteristic wave length in the acceleration channels can be used to 'tune' the multiplication factor in the computer simulation since the delay is already known. Once trimmed the computer simulation gives a stable wave response that contains the roll acceleration to a mean of zero for combinations of roll angle and turn in the same range as the actual run.

However when the multiplication factor in the model is so tuned then the resulting short period wave has a weaker amplitude response and a shallow rounded wave rather than the near triangular one seen in the actual traces. This regular triangular wave shape indicates that the force on the handle bar producing the angular acceleration is itself accelerating to a peak at a constant rate which is repeated from wave to wave. This is interesting as, first, the pulse input as a form of control has already been identified in the autocontrol run and second, the zero-crossing, being the point at which the sign changes, is an easily identified event in neurological terms. Experiment shows that putting in a small 'ballistic' pulse of arm-force during each wave reversal, timed to start at the change of sign at the zero crossing point gives a more characteristic wave shape and a better response.

This seems to suggest that the human control is 'pumping' energy into the system regardless of control requirements. If so this is quite possibly a reflection of the preference of all control systems for a reasonable error signal. When the signal gets too weak the system becomes swamped by noise and then 'dithers' about the zero, waiting for something to appear that is definite enough to work on. Gently hunting to and fro between detectable values is one way of overcoming this problem.

5.2 Pulse Control and Discrete Error Detection

The control system that has been developed so far is straightforward. The run shows an energetic acceleration wave at about 1 hertz with the bar following the roll at a delay of approximately 100 milliseconds. The regular triangular shape of the bar wave and the behaviour of the computer simulation indicates that the bar is being driven by a combination of the lagged value in the roll channel and a 'ballistic' burst of muscle tension timed with the zero-crossing. This control response will damp out the roll acceleration so that its mean is zero and this is clearly indicated by the fact that the acceleration trace is centred about the zero line. The velocity and angle traces (Figure 5.(b),(a)) are also centred about the zero although there is more local departure in the latter. It is evident that to keep the velocity and angle traces averaging zero, information from these channels must be also be fed back into the system as error signals.

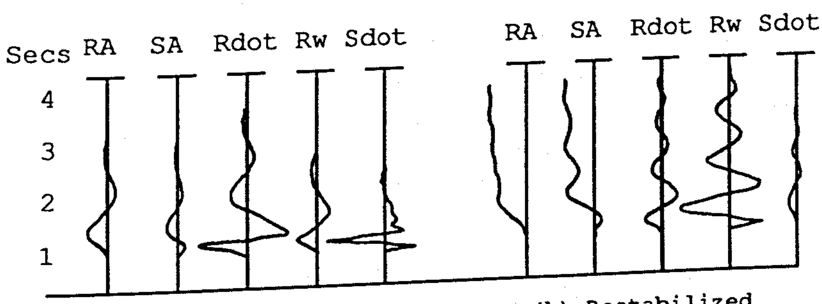
There does not seem to be much difficulty over the detection of roll velocity. Since the vestibular system is responding adequately to small acceleration changes then an integration, which in neuronal terms is a simple accumulation, will give a fair analogue of the velocity. However a further integration for roll angle is likely to be inadequate as errors accumulate. The riders in the experiment were unsighted so they cannot have used the obvious visual clues about angle of lean, and since this deprivation seems to cause no great subjective difficulty, and since the riders maintained a mean straight course even without consciously intending to, then absolute angle of lean must have been available from some sensory clue. The most obvious would be a filtered form of the rate of turn as small local oscillations average about the larger movements when the bicycle corrects lean by turning into it. There are at least two direct sensory clues to turn, first the mean handle bar angle, which, unlike the lean angle, can be directly extracted from arm position relative to the body, and second the pressure on the contact points between the rider and the machine. Both these are functions of the rate of turn.

5.3 Possible Control Systems

If an attempt is made to control the system by responding to absolute angle without any velocity feed-back then after one or two reversals the velocity reaches such a high value that excessive lean angles are generated before control takes effect.

If the angular velocity is fed directly into the arm tension via a suitable trimming factor then any disturbance is contained with an oscillatory response in which both the mean acceleration and velocity values are zero. However any angle that accumulates during this damping remains in the system. Different values of the multiplication factor give different reponse characteristics. In common with the acceleration factor, too high a setting leads to overcontrol and a diverging fugoid, whereas too little will contain only small errors.

Once it is tuned appropriately this combination of acceleration and velocity feed-back responds to a handle-bar pressure pulse in much the same way as the autostable bicycle but with the following difference. With the autostable system a single on/off pulse produces only a short lean/turn excursion before damping back to the upright, whereas the destabilized system responds to the same input with a marked permanent change in lean/turn. The secondary castor effect feeds absolute angle back into the former system but the latter is only controlling on velocity and acceleration and therefore allows angle to accumulate.



(a) Autostable (b) Destabilized

FIGURE 6

Simulation output showing effect of single ON/OFF pulse on the normal bicycle (a) & the destabilized machine (b).
T bar on first two columns = +/- 5 degs.
Key:- RA=roll angle; SA=bar angle; Rdot=roll accln; Sdot=bar accln; Rw=roll velocity.

Figures 6.(a) & (b) compare the effect of a single GO-LEFT pulse on the two systems. The pulse length is the same in both cases but the amplitude must be reduced by a factor of almost 20 in the destabilized system to produce a similar initial excursion of the steering acceleration, SDOT. This is due to the heavy damping of the primary castor effect.

It is a general characteristic of all the runs that the short waves in the velocity channel nearly always recross the zero line after every excursion. This is a certain indication that the system is feeding back the actual velocity value and not some filtered or averaged version of it. If the running mean, or a time interval sample, of the velocity channel is fed back as the error signal then the whole of the velocity wave moves clear of the zero line in sympathy with the long wave movements. This is also clear evidence that the control of angle change is achieved with a sudden short pulse and not a steady pressure. It is possible to achieve very good control with a steady pressure but the characteristic of the output is completely different. The rate of angle change is much slower with none of the rapid reversals observed in the actual traces and the velocity curve goes well away from the zero for a whole series of waves as the change is taking place.

5.4 The Proposed Destabilized Control System

All the ingredients are now available for constructing a simple, self-contained control system for riding the destabilized bicycle in a straight-line. The acceleration in roll is detected and integrated. Both these values, appropriately loaded by a constant multiplication factor, are applied as a force to the handle-bar which in turn produces an angular acceleration of the front wheel assembly. Because this takes time there is a lag between detection and application of something around 100 milliseconds. These two feed-back values enable the system to oppose accelerations and accumulated velocities in roll but because the system is not dead-beat there are two oscillations, one at about 1 hertz and another at about 0.2

hertz. These represent the balance between the delay, the multiplication factor and the natural frequency of the rider/machine in roll.

Since the above two feed-back corrections do not prevent an accumulation of absolute lean angle, and since it is seen that riders do remove the lean, even when briefed not to bother, it can be argued that there is a third level of automatic control working on absolute angle feed-back.

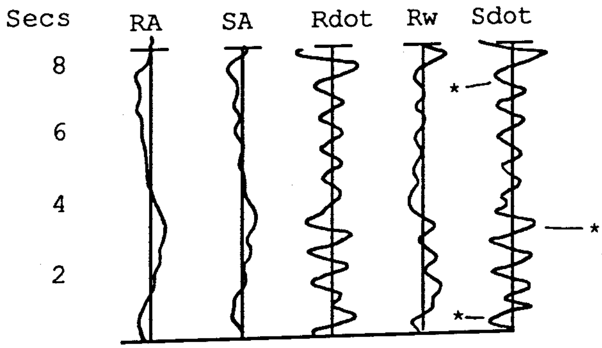


FIGURE 7

Computer model being driven by full control. Roll accln. and velocity continuous, absolute angle when 1.6 degree threshold is exceeded. Pulses in bar accln. shown by '*'. T bar on first two colums = +/- 2 degs.
Key:- RA=roll angle; SA=bar angle; Rdot=roll accln; Sdot=bar accln; Rw=roll velocity.
Destabilized bicycle; 12 stone rider; 6 fps (4 mph)

It can also be seen from the traces that when the correction to the lean angle is applied it reduces the lean to zero almost within one of the short wave lengths. This is clear evidence that the angle control is discrete not continuous. When the angle, or rate of turn, exceeds some threshold value the system responds with a fairly strong pulse of pressure applied to the handle-bar, timed as a wave of about the same length as the short oscillations. This leads to a rapid change in the lean angle within about one second and is followed by a more gentle series of alternating reversals. Such a pulse if applied at about 2 degs angle of lean to one side will give sufficient force to push the machine up to somewhere near the vertical, from which position it will then gradually fall either back to the same side or over in the opposite direction until the threshold lean angle is again exceeded.

Figure 7 shows the output trace of this control system riding the simulator on a similar course to the real-life example. With the simple rule, 'Make a pulse against the lean whenever it gets bigger than 1.6 degrees' this control system manages the totally destabilized bike in the same way as humans set the same task.

6. SPEED EFFECTS

In the model described above a change in bicycle speed leads to a change in the response characteristic. The reason is that the force generated at the wheel/road contact points is dependent on both angle of slip and speed, whereas the force required to balance a particular angle of lean depends solely upon weight and angle. The relationship is a simple one and is accounted for in the model by making the gain factor inversely proportional to speed. That humans are able to trim a multiplication or 'gain' factor in a control system to achieve a desired output is already well established. The Cross-Over model of operator performance of McRuer and Krendal which resulted from a study of a selection of compensatory tracking tasks (Summary in [5]) shows how the operators adjusted the gain factor in the various tasks to allow for different error sources. The cue for such a change in the bicycle riding task is more likely to be the change in response than absolute speed. The idea of 'pumping in' energy to get a good signal to noise ratio has already been mentioned, and this action would allow an estimate of the power of the selected gain factor to be made at the same time. If it is too high the responses will be diverging, but it would have to be very high indeed to send the machine out of control immediately, so the gain factor can be reduced to get control.

7. FULL NAVIGATIONAL CONTROL

Once the system is able to control the angle of lean in this way it has the necessary power to implement navigational instructions. It will noted that the roll-follow at a delay' system described above, although slower and more oscillatory, is in essence the same as the autostability control. In both systems the roll acceleration and velocity are damped out and the absolute angle is controlled by integrating a pulse input of angular acceleration with the other inputs to the steering head.

Since beginners start riding at the lowest possible speeds, and often on bicycles with poor autostability, it seems most likely that the fully-manual system is the one which is first learned. There is no conflict between the two systems. As riding speeds increase and autostability forces begin to make themselves felt, the much lower control forces of the basic system will merely fail to disturb the machine from its upright running. The much faster acting autostability of the front forks removes the roll error before the human system can react to it. Harder pushes will be tried and at first the on/off pulse steering technique will produce shorter duration turns than before because autostability tends to remove angle as well as acceleration and velocity. However, an experienced rider will learn to modify the basic directional control either by reapplying the push and holding it once the required angle of lean has been achieved, or making appropriate upper body roll movements to supplement bar control.

8. CONCLUSION

Bicycle riding is a commonly found, easily learned, manually operated skill that can be divided into two levels of operation. First navigation skills common to other forms of movement and second specialist balancing skills associated uniquely with two wheel machines. This underlying skill, on which the other depends, can be further divided into two levels; a basic control where the rider has to supply both the continuous control of roll rate as well as intermittent pulses which initiate a turn in the direction of push, and a simpler control where the autostability of the front fork design removes the roll errors and the rider is only required to supply the directional pulses. With growing experience these pulses are carefully timed to achieve a smooth 'dead-beat' performance. Because the system delay in the roll rate system is so short it is evident that the output from the vestibular system must go almost directly to the controlling muscles making little or no demand on higher cortical processes for this part of the system.

REFERENCES

[1] Weir, D.H. and Zellner, J.W., Lateral-Directional Motorcycle Dynamics and Rider Control, (Society of Automatic Engineers, Paper 780304, 1979).

[2] Jones, D.E.,The Stability of the Bicycle, Physics Today, (April 1970) pp.34-40.

[3] Nagai, M.,Analysis of Rider and Single-track-vehicle System; Its Application to Computer-controlled Bicycles, Automatica, Nol 19.(1983) pp 737-749.

[4] Van Lunteran and Stassen, H.G., Investigations of the Characteristics of a Human Operator Stabilizing a Bicycle Model, International Symposium of Ergonomics in Machine Design, Prague(1967) pp.349-369.

[5] Smiley, A., Reid, L. and Fraser, M., Changes in Driver Steering Control with Learning, Human Factors, 22(4) (1980) pp.401-415.