THE SKILL OF BICYCLE RIDING

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SUMMARY

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The principal theories of human motor skill are compared. Disagreements between them centre around the exact details of the feedback loops used for control. In order to throw some light on this problem a commonplace skill was analysed using computer techniques to both record and model the movement. Bicycle riding was chosen as an example because it places strict constraints on the freedom of the rider's actions and consequently allows a fairly simple model to be used. Given these constraints a faithful record of the delicate balancing movements of the handlebar must also be a record of the rider's actions in controlling the machine.

An instrument pack, fitted with gyroscopic sensors and a handlebar potentiometer, recorded the roll, yaw and steering angle changes during free riding in digital form on a microcomputer disc. A discrete step computer model of the rider and machine was used to compare the output characteristic of various control systems with that of the experimental subjects. Since the normal bicycle design gives a measure of automatic stability it is not possible to tell how much of the handlebar movement is due to the rider and how much to the machine. Consequently a bicycle was constructed in which the gyroscopic and castor stability were removed. In order to reduce the number of sensory contributions the subjects were blindfolded.

The recordings showed that the basic method of control was a combination of a continuous delayed repeat of the roll angle rate in the handle-bar channel, with short intermittent ballistic acceleration inputs to control angle of lean and consequently direction.

A review of the relevant literature leads to the conclusion that the proposed control system is consistent with current physiological knowledge. Finally the bicycle control system discovered in the experiments is related to the theories of motor skills discussed in the second chapter.

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CONTENTS

Chapters

1	Introduction	1
2	Motor Behaviour Research	4
3	Bicycle Riding as an Example of Human Skill	25
4	The Computer Model	55
5	The Calibrated Bicycle	85
6	Simulation of the Destabilized Bicycle Control	119
7	Control of the Autostable Bicycle	168
8	The Biological Correlates of the Control System	198
9	The Organization of Control	234
References		254

Appendices

1(a)	The Simulator Programs	260
1(b)	Scale Drawing of the Destabilized Bicycle.	272
2(a)	Roll and bar angles.	274
2(b)	Roll and bar rates.	281
2(c)	Histograms of lag, half-wave & area.	294
3(a)	Effect of Gain on Stability.	300
3(b)	Regression residuals plots.	305
3(c)	Relation between residuals & roll angle.	312

1. INTRODUCTION

Much of the research into motor behaviour starts from some theoretical position and explores the adequacy of this experimentally. A task is chosen either because it offers some specific advantage in the laboratory in terms of ease of recording the variables or because it focuses on some detail of particular interest to the theoretical argument. Most naturally arising skills are too complex and loosely defined to be examined in toto. The hope is that rules of operation will appear in the laboratory experiments which can then be used as primitive building blocks from which complete skills can be synthesized.

This study starts from the opposite position. It takes a naturally arising skill and attempts to analyse it so that a determinate system model will accurately predict the behaviour, over time, of a selected set of variables measured on the real machine. Bicycle riding was chosen because its inherent unstability allows only a few alternative strategies of operation.

The word *system* appears frequently in the following text in a number of different contexts. In its normal use, such as in *nervous system* it is rather loosely defined to mean a large number of parts connected together in a determinate way to act as a complex whole. When it applies to the bicycle control problem I will attempt to follow Ross Ashby's tighter definition (1952, 2/4, page 15) by using the word to refer to that particular set of variables chosen by the experimenter to represent some event in the real world. Thus the changes in lean angle and steering angle over time recorded from a bicycle constitute a system representing that particular part of its behaviour, although, as will be shown, this system is too limited to be state-determined and other variables must be added to form a system capable of accurate predictions.

The first chapter is a review of the various general theoretical approaches to skilled motor movements to which the particular details of this study will be related in the final chapter.

The second chapter deals with the specific control problems that arise from the nature of the rider/bicycle combination regarded as a mechanical system. It reviews some of the engineering research that has been done into the bicycle and touches on the psychological research into feedback control loops in humans.

Chapter three describes in detail the computer simulation of the bicycle which is used to test various control systems for their effect on the general characteristics of the bicycle/rider unit in later chapters.

The next two chapters use the records from a specially constructed bicycle to show in detail what a control system must do to achieve slow-speed, straight-line riding. In order to guarantee that all the control movements of the riders were recorded and that these were the only movements being used for control, the automatic stability provided by the front forks of the normal bicycle was removed to create a 'zero-stable' bicycle. It was found that in the absence of built-in stability the riders themselves provided sufficient for control. The analysis shows that the principle control of roll velocity for lateral stability was continuous but argues that there is strong evidence that an intermittent movement superimposed upon this underlying action was being used to control the angle of lean. When the proposed control solution was implemented on a simulation of the destabilized bicycle it produced an output characteristic almost identical with that obtained from the real riders.

Chapter six considers how the control system suggested by the runs with the destabilized bicycle relates to riding a normal bicycle. A comparison with an exactly similar set of runs on an unmodified bicycle indicated that there was little difference between the two in the slow straight-ahead case, the automatic control being relatively ineffective at very low speed. The general interest in bicycle control must obviously focus on manoeuvring at normal riding speeds and the original hope had been to examine the effects of increased speed and manoeuvre on both types of machine. Unfortunately, lack of time prevented any further recording, and the only successful record of a manoeuvring run available was one made during the early pilot tests. The information from this run together with some general observations of control technique at speed and the predictions from the computer model are used to hypothesize the most likely technique for normal bicycle control. Once again the predictions of the simulated bicycle using the proposed technique show a close similarity with the output from the real run.

The penultimate chapter discusses the requirements of such a control system at the biological level and reviews some of the research into human postural control to illustrate the similarity between this and the control used to balance the destabilized bicycle. The final chapter relates the bicycle control revealed by the study to the theoretical approaches discussed in the first chapter and briefly discusses the problem of learning the skill in the first place.

2. MOTOR BEHAVIOUR RESEARCH

Introduction

It is rather surprising, considering the experimental effort that has been brought to bear on the subject over the past twenty five years, that a more comprehensive and detailed theory of motor skill is not available. Before considering why this should be, and examining some of the theories that have been offered, it is useful first to establish the basic form of the problem to be solved.

The distinction between movement, motor behaviour and skilled behaviour is not a rigid one. The word skilled entails a suggestion of intent on the part of the subject but it is evident that there are many examples of complex predictable behaviour which the psychologist would wish to explain, and yet where the intent of the subject for the end state is either absent or open to question. It is therefore better to redefine the class of movements under investigation as predictable movements where the end state can only be reached by virtue of the precise application of forces generated by the subject's muscles.

The study of motor skills embraces animal activities as widely separated as the flight of a locust (Wilson,1961) and piano playing (Shaffer,1980). In the former case a full explanation can be made of the actual behaviour by showing how oscillations in the controlling neuronal cell lead, via activity in the connecting nerves and muscles, to effective flight. Such an explanation, however, says nothing about the origins of this relationship, nor is it obliged to deal with symbolic cognitive activity in the brain of the locust. At the piano-playing end of the scale, although we find peripheral events which seem very similar to the locust wing movements such as the lowering and raising of a digit, there are also essential mental acts directing and modifying the action in such a way as to preclude a description of the total behaviour in the same simple terms.

Two major problems may be identified:-

1. How are the apparently almost limitless degrees of freedom of the structure constrained?
2. How do complex behaviours develop?

Skilled motor behaviour always involves some predictable goal or end-state but the exact route taken from start to finish is seldom exactly defined. Articulated limbs have a wide range of possible movement and any independent change in one segment affects all the others. For example there is a very large range of possible trajectories for the upper and lower arm in moving the hand from one fixed point to another. Boylls & Greene (1984) quote Bernstein's comment that when the disposition of the soft tissue in relation to the rigid skeleton is also taken into account there is an even greater degree of freedom. Skilled movements have to synchronize with both internal and external changes during action and the problem is what is controlling these changes?

The problem of development is no easier. This may be considered on two time scales. In the first place how does a fully mature individual develop the ability to carry out a new skill? This cannot be viewed simply as a matter of memory or understanding. Knowing 'how' to hit a golf ball is not the same as being able to do so. During acquisition, performance changes take place which must be reflected in some physical change.

The longterm development from conception to maturity is even more problematical. Information processing theories postulate that central programs extract information about the current physical state from the sensory input in order to control output values to the muscles. To do this the program must possess the knowledge about interpretation and synchronization before the action takes place. The problem is, how and when does the system get this knowledge? Associated with this problem is the fact that changes of physical scale in the skeleton and tissues during growth require changes in the specific instructions at the muscular level to achieve the same overall movements (Kugler et al., 1982). Some theories see the simple movements present at birth as primitive units which combine later to make complex behaviour. If it is proposed that such movements are controlled by programs of instructions then they must alter during growth to achieve the same movements. It is also claimed that the simple programs present at birth modify themselves during development to produce the mature performance (Zanone & Hauert, 1987). The knowledge to achieve these changes must also be present at birth, and once again the problem is where does this knowledge come from?

The Mechanical Model

Almost all the research into motor behaviour so far has been based on a mechanical model. In its simplest terms this regards the skeleton as an articulated framework which is moved by the muscles acting as motors. When stimulated a muscle either contracts or, if movement is physically prevented, produces an increase in tension. The rate of change of contraction in the muscle is seen as being directly controlled by the rate of change of activity in the efferent nerves connected to it. The afferent nerves terminate in sensory devices which, operating as transducers, turn changes in stretch, shear and pressure into electro-chemical activity in the nerve pathways. This activity is seen as feedback giving information about the current state to the control centre.

In general three sources of efferent change are envisaged. First, activity in the afferent pathways from neighbouring muscle fibres, and possibly joint receptors, is fed more or less directly to the motor efferents to give coordinated changes. For example, to allow movement about a joint, the contraction of the muscle group on one side must be matched by an inhibition of the group which opposes it. Second, activity in a sensory afferent pathway due to some external change is fed, again more or less directly, to an appropriate muscle group to produce a rapid movement. A simple example of this sort of reflex action is the blinking response of the eyelid to a puff of air into the eye. The third class of efferent change comes from more remote sources in the central nervous system (CNS) where no simple direct pathway has been established linking it exclusively with the local afferent system.

Before dealing with the complexities of the last class of connections it is worth pointing out that the evidence from nearly a century of research does not unequivocally support the mechanical model. The neuronal pathways are so complex and extensive that they are able to support a great variety of schemes. Even the most straightforward reflex loops seem to be open to modification from changes originating at a higher level in the CNS and although the idea of synchronous exchange of control influences within groups of muscle fibres is well established the actual connections and method of operation is open to many different interpretations.

The State of the Art

Motor control research is not self-contained. At its boundaries it blends without clear distinction with neighbouring areas such as cognitive science, linguistics, artificial intelligence and neurophysiology. The body of research can be seen as dividing approximately into the three major classes of structure, behaviour and theory. These are not watertight divisions as all three are present to some degree in any research, but in most cases it is evident that the work is more directly orientated to one, particularly in the methodology.

Class I. Structure

Research into structure takes as its departure point a detailed description of some local part of an animal. The techniques are those of the neurophysiologist with an emphasis on staining, electro-chemical probes and micro-voltage recording techniques. Movement in the locality of interest is explored with in-vivo and in-vitro preparations and explanations take the form of mathematical or electro-mechanical analogue models which attempt to formalize the relationship between neural activity recorded at different sites. Some of this work has reached a very high degree of explication such as the relation between the vestibular system and the movements of the eye (Robinson, 1977; Boylls, 1980). It is with such explicitly described structures that all theories of central control must eventually interface.

Class II. Behaviour

Whiting (1980) laments that much research into motor performance is inapplicable to observed human behaviour. He quotes Kay as replying to the question 'What kind of system controls human skills?' with 'one must say exactly what we are trying to understand....the beginning lies in a precise description of the essential features of skilled performance.' Researchers with this view concentrate on those spontaneously arising accurately repeatable sequences of movements which may be unequivocally termed skilled behaviour. There are also a much larger number of experiments which investigate simple movements devised by the experimenter to tease out some particular point. An example of the former is given by Whiting's own use of the Selspot technique to record movement over time in games skills. Stelmach's (1980) experiments on the spatial location of arm movements provides a typical example of the latter. The problem with this last class of experiments, a criticism levelled by Whiting in his 1980 paper, is that the paradigm is often so limited that it is hard to see how it addresses the problem of spontaneous behaviour at all. Once again a theory of motor behaviour must eventually be reconciled with the complete descriptions of spontaneous behaviour. Truly objective observation, however, is never possible and some sort of initial theory is needed before the variables to be recorded can be chosen. As will be made clear later in this study the choice of variables can be critical to discovering the underlying mechanism in a way which can be interfaced with the next higher level of control in the hierarchy.

Class III. Theory

Theory, the final class, is something of a long-stop, because all theories will refer at some level or other to work already included in the two previous categories. The particular focus in this section is on work which starts with an attempt to give an overall framework into which the results from experiments can be fitted. Such comprehensive theories are obviously very useful for pulling together the mass of somewhat isolated experiments that inevitably mark the early stages of scientific exploration.

Cognitive and Non-cognitive Theories

Stimulus-response (S-R) theory attempted to explain all movement, including skilled human behaviour such as speech, in the terms of the physical structures of the body. Small movements of the reflex type were linked together in S-R chains to form a skilled movement. The reluctance to deal with mental acts led to a position where all the most interesting problems were either ignored or rendered trivial.

It was evident that, in humans at least, sensory patterns received at one time could be stored in memory and used later to modify responses. Because feedback for control was central to the stimulus/response conception there was a tendency to identify any sort of feedback as implying this form of control. The discovery that accurate movements could be made without afferent feedback led Lashley (1917) to propose that the pattern of activity in the efferent pathways controlling the muscles was directed by a central motor program which synchronized the output of appropriate values over time to give the observed behaviour.

The acceptance of mental acts as an integral part of behaviour has produced a situation where theories of information, not related to physical structure, have to be interfaced with that part of the structure which has been thoroughly explored. Sometimes the interface disappears completely when all the structure is represented in informational terms. The main divisions in theory at present are arguments about the role of cognitive factors in the control of behaviour.

Central control was seen as using information from many sources, including memories of results from previous events, initially to form and subsequently update a central network of programs. These could run off short segments of movement in a motor program style. During the movement they compared the sensory feedback with a memory of what previous actions had produced. This knowledge of results enabled them subsequently to achieve an improved performance.

Schema Theories

Schema theory holds that there is a program-like source of knowledge in the brain that can furnish the muscles with the correct values from moment to moment to achieve intended movements. Where information about state is needed for success this is fed back from sensors via the afferent nerves to the controlling authority where it is integrated in the program. The main difficulty with this model is that the 'freedom' of the structure leads to prodigious demands on storage and computation.

An early proponent of this class of theories was Adams (1971, 1976) who envisaged a local control of movement using feedback which he called knowledge of results and a long term memory which could be updated by this called the perceptual trace. This was an open-loop concept where the values needed during a movement were supplied from a central program held in the memory. It had been generally observed that there seemed to be a minimum time delay of about 200 msecs when a subject was asked to react as quickly as possible to some stimulus (See chapter 3 for a fuller treatment of action latencies). It was therefore supposed that an internal 'instruction', following the detection of a change in the environment via the sensory system, could not produce a response in the motor system of less than this minimum reaction time. As a result control of movements taking less than one reaction time were considered as being under a form of 'ballistic' control similar to the firing of a shell at a target. During the actual flight no influence could be brought to bear on the missile, but a knowledge of where it fell in relation to the target led to a suitable correction for the next shot. This theory attempted to explain not only how a performance was achieved but also how it might have been learned in the first place.

Schmidt (1976) identified a number of serious difficulties with this model, the principal two being the amount of storage space required to deal with the large degree of freedom of the system, and the appearance of novel movements. He proposed a generalized motor program which possessed all the necessary knowledge about what should be activated and in what sequence but had no specific values. Schmidt proposed that sequences shorter than one reaction time were open-loop, or ballistic, using information supplied by a recall schema. A recognition schema checked the consequent afferent response against the correct one held in memory.

All versions of these two schema theories are descriptions at the information exchange level with virtually no explicit reference to structure, consequently they have almost unlimited freedom to chose alternative algorithmic paths between end points. It is difficult enough to see exactly how the neural structure at the muscles might produce the required movements but how the known structure of the brain might interpret sensory inputs in order to produce the output signals demanded by such central 'programs' is so far a complete mystery. Such models can only be rigorously tested by linking them via specific values to the inputs and outputs identified in some physical event, and even then, since they do not deal with specific structures, they can tell us nothing concrete about structural development. In general neither of these models, nor their many derivative versions, pay sufficient attention to the fact that there are many motor movements which show close coupling with the changes in the environment at less than 200 msecs

Quite apart from the difficulty of identifying appropriate interface values, the information-flow model of control suffers from another serious inadequacy. The model handles the logical flow of information from input to output but in itself it has no knowledge about this information. The knowledge about the sequence of events and what the values in the program represent is supplied by the programmer. Also the relationship between that knowledge and the representing values is arbitrary. If a central program-like operation in the brain 'knows' that a certain rate of activity in a nerve coming from a particular sensor must be fed at a modified rate of activity to a certain muscle at some exact time then HOW does it know this? The modelling program knows it because the experimenter already has a personal mental model of the whole situation which supplies this knowledge. The objection to this sort of explanation is that it leads to an infinite regress with respect to the origin of the knowledge needed to drive it, an objection which Bernstein characterizes as making *'borrowings from the bank of intelligence.... loans which it has no means of repaying'* (Kugler et al., 1982).

Despite these difficulties there can be no doubt that, providing the input and output interfaces do actually lie somewhere within the physical structure, the computer analogy is an important and powerful tool for imposing order on what happens between them. The further towards the periphery of action the model extends the less it explains as the problem of selecting the one desired path from amongst so many is referred back to the unknown source of initial knowledge. The success of such an enterprise depends on establishing an hierarchy of semi-autonomous levels of function which serve to reduce the degrees of freedom by placing constraints at the local level. Perhaps the real value of this approach is that once a theory has been developed as a running program it is possible to identify the penalties, in information handling terms, of the proposed algorithms.

The Return of Non-Cognitive Theory

Despite the dominance of cognitive central control theories there have been voices crying in the wilderness. Perception is the act of transforming sensory inputs from the external world into the knowledge base on which central control theory depends. Gibson (1950) not only objected to the combinatorial implications of a knowledge-based central control for locomotion, but produced the groundwork for a viable alternative which has gradually been taken up by an increasing number of workers. The main thrust of his position is that the visual system does not extract dimensional information such as angles and distances but non-dimensional values which can be used to control movement directly without the intervention of insubstantial mental percepts. Lee (1974 & 1980) subsequently developed equations for properties of the two-dimensional projections on the retina during movement which yielded such non-dimensional invariants as time-to-impact to or course for collision with a location. He showed that this could be derived from the velocity of the image with a dramatically lower order of processing than that demanded by even the simplest system for extracting knowledge. In addition it had virtually zero storage demands. Not only does such a finding posit a system which dramatically reduces the degrees of freedom at a low level in the control hierarchy but it also suggests that the traditional way of looking at the problem might be making it seem harder than it really is.

Another example is provided by the operation of the arm muscles to produce an accurate pointing movement. To control each muscle independently from a central program requires a great deal of information feedback about the progress of events at the periphery. There are endless combinations of limb positions possible between the initial and final positions defining a movement and each one will require a different sequence of control instructions. Computer programs can solve this sort of problem but in order to do so for complex movements they need prodigious amounts of storage space, very fast processing and a good deal of specific knowledge. Recently it has been proposed (Stelmach & Requin, 1980 p.49) that these two muscle groups operate together as a unit with properties similar to those of a linear mass-spring system. This requires a completely different input from the central control as a single length/tension ratio for flexor/tensor muscles regarded as a unit will specify a unique position in their plane of movement. Thus the central programs associated with these two different types of input will also be completely different. In the latter system the control problem is much simpler as the program can use the ratio as a primitive in combined movements without any of the previous overheads, its output specification being simply a destination regardless of the present state. In going to the new position the system may pass through a wide variety of trajectories, depending on where it started and what external conditions it experiences on the way, but this freedom does not alter the fact that it is uniquely constrained as to its end state by the single input value. (Kelso et al., 1980; Bizzi, 1980; Cooke, 1980).

In the above model the degrees of freedom are reduced at a low level in the hierarchy by a semi-autonomous local system which contains its 'knowledge' in the structure, leaving much less to be accomplished by the central control. There is a double disadvantage of leaving too much to a computer-like central program. On the one hand we cannot say from where it gets its knowledge and on the other, since the theory does not address the problem of what physical structure supports the program, nothing is said about its development either. When the advantages of a semi-autonomous hierarchical system are considered it is difficult to imagine anyone wishing to continue with any theory of non-hierarchical central control.

Recently a theory has been proposed which considers the structure of animals as acting like a thermodynamic engine in a state of non-equilibrium rather than as a mechanical engine. This view promises to have far-reaching effects on the whole theory of motor behaviour and is sufficiently new to warrant a longer exposition.

The Theory of Naturally Developing Systems

The mechanical analogy described in the previous sections forces the view that each unit of the system, such as a single muscle fibre, is controlled for change of position over time by the incoming nerve impulse which takes its value from some central controlling system. The integration of the behaviour of this unit with that of other units is achieved at the control location which further forces the view that information about the system's state must be fed back to the central control as well. All research into motor behaviour is either directly or indirectly related to the solution of this control problem.

Two main difficulties become apparent. First as the nerve pathways are traced back into the CNS the number of autonomous or semi-autonomous units becomes so great that it is increasingly difficult to isolate individual transmissions. The generality of involvement in the brain itself led to the idea of mass action initially proposed by Lashley (1929). This was not a theory in itself so much as an abandonment of the mechanical analogy. The second problem is that, although animals can show great precision in their ability to move a limb from one point in space to another the number of possible pathways which can achieve this are very large. The problem is how this very extensive freedom of choice is limited by the control system.

Kugler, Kelso and Turvey (1980) have put forward a new theory of naturally developing systems. This theory, further elaborated in later references (Kugler et al., 1982;1984), claims to draw principles from philosophy, biology, engineering science, non-equilibrium thermodynamics and the ecological approach to perception and action. The main thrust of their argument is that animal movement should be treated not as a mechanical but as a thermodynamic engine. The essential difference between these two systems is that in the latter a very large number of semi-autonomous units interact with each other, remote from any central control, in such a way that the statistical sum of their movements leads to a stable state at a higher level of organization. For ease of reference the idea of two associated states at different levels of organization will be termed micro and macro. Certain non-dimensional variables in the system, labelled 'essential' variables, are identified as having a controlling effect on this transition between states. When the essential variable is between two limiting values the system as a whole goes into a stable macrostate.

The Benard 'convection instability' phenomenon is given as a simple physical example of this sort of system. If a tank of fluid is heated from below but kept at the same temperature above, the heat is transported to the upper layers by conduction only, providing the temperature gradient is smaller than some fixed limit. When the gradient exceeds this critical value the organization of the fluid undergoes a radical alteration.

Large groups of molecules coalesce, breaking away from the lower layers to rise in a pattern of convection currents. Despite the freedom of the structure at the molecular level, the macrolevel is first in a stationary homogeneous state and then changes to one of well-ordered movement. A third state in which the convection patterns become oscillatory is reached if the gradient is increased beyond a second critical value. In this system the essential variable is the temperature gradient and changes here force the system into different locally stable states at the macrolevel of description. Nonessential variables such as the tank dimensions or externally introduced flow rates will alter the details of the rising convection patterns but will not change the stability condition.

Seen in this light the ordered behaviour of a biological system between two limit values of its essential variables is the same order of event as the volume, temperature and pressure states of gases as a result of the molecular activity at the microlevel. We are unable to argue to the macrostate from a knowledge of events at the microlevel. In fact nuclear physics declares that the appropriate macro quantities of position and velocity no longer mutually exist at the lower level. What we do in the case of the gas laws is accept that, however it may be done, the relationship between the three values is fixed as long as the essential variables are between the relevant critical values. Beyond this limit the gas liquefies or solidifies and different relationships appear. The reason we believe this is not because we can argue it logically from some other position but because it is always observed to be true. The essential difference between the physical and the biological cases at present is that we have not yet devised a dimension of measurement for the latter which reveals similar invariant laws.

One of the most important consequences of this view is that the order observed in the system at the macrolevel is an *a posteriori* fact resulting from the nature of the myriad interactions at the microlevel. No conception of what this order might be need exist prior to the realization of the state which produces it. This is a very telling point because it is evident that any attempt to describe the same process at the macrolevel in computer program or cybernetic feedback control terms requires specific a priori knowledge of the future steady state. Once such a description is offered as a theory of behaviour it begs the question 'where does the *a priori* knowledge come from?' The advantage of describing the events in terms of a thermodynamic engine is that no such prior knowledge is required. The emerging state of order is the inevitable consequence of the microscopic structure. Thus, at a blow, two of the most intractable problems of control are by-passed. First the very large number of degrees of freedom associated with the individual muscle fibres is no longer a problem because it is the very number that allow the statistical nature of their integration. Second since the relationship between microactivity and macrostate is embodied in the structure there is no need to postulate a controlling program and therefore the problem of where that program gets its knowledge also disappears.

Kugler et al. give details of a number of theories which deal with this relationship between structure and function, the two most important being 'Dissipative Structure Theory' and 'Homeokinetic Theory'. Although these two theories take different views in detail they agree in describing how a thermodynamic system may pass, at some macrolevel of description, in sudden steps through states of local equilibrium which exist by virtue of the complex interaction of many independent units at the microlevel. Systems of this sort are not closed and therefore do not obey the laws of equilibrium thermodynamics. Consequently they do not have to move always towards a state of maximum stability and chaos but by virtue of being open and having access to some external source of energy they can move to locally stable states of greater complexity and order. Furthermore it is the nature of non-equilibrium thermodynamics that systems tend to make such moves as sudden 'catastrophic' jumps to positions of local equilibrium which they maintain until the essential variables alter to a new critical value. Thus it can be seen that such a system can show development from a less organized to a more organized state, in a more or less short term jump, providing the 'essential' variables force it to do so. For example in relating such a system to the case of change of limb movements with age in the growing child, the essential variables would be seen as the length and weight of the skeleton and muscles, and the change in movement patterns would be the necessary consequence of the previous microactivity working at the new macrostable level.

This new theoretical approach of Kugler, Kelso and Turvey is very promising and serves as a reminder the relationship between the mechanical engine analogy and motor behaviour is still very tentative. Information theory and cybernetic theory are attractive because they offer ways of organising a wide range of observations in a form which allows discussion and promises a way into the problem. The Dissipative structure offers another way and makes different but equally interesting promises about its possible power. As the authors themselves agree (Kelso, 1980, pp 65-66) there are as yet no conclusive experiments to show that biological structures are organized as dissipative systems, but neither are there any to show that mental acts are organized along the lines of information theory. The latter runs into a major difficulty in that it says nothing about how the knowledge necessary for its operation becomes available at the natural level, whereas the former specifies that 'knowledge' is a by-product of man's mental model of the situation and that the function of the biological structure itself is completely specified by the way it is put together.

One weakness of the Kugler et al. approach is that it ignores the fact that AT SOME LEVEL humans do exhibit symbolic mental behaviour. This thesis is an example of symbolic activity only arbitrarily and remotely linked with the supporting biological structure. It is also evident that mental acts at this level can be very rapidly translated into specific physical acts. Consequently any theory of human behaviour must take account of the need for an interface between these two different forms of behaviour. Although the authors do not mention specifically that even abstract thought might be seen as the inevitable consequence of the physical structure of the brain in relation to the surrounding ecostructure it looms in the background as a logical extension of the basic idea. It is evident that even a hint of such a deterministic solution would be sufficient to alienate many workers in the human behaviour field (Zanone & Hauert, 1987). However even when fears of predestination and biochemical automata are set aside the model carries with it the disadvantage that the details of the link between the micro structure and the macro behaviour are seen as opaque and it therefore has less potential as a predictive theory.

Applying the Thermodynamic Engine Theory

It is fairly obvious that man's mental models of an external reality will never capture the detail on every dimension. A model is in effect a simplifying tool for making serviceable predictions at the level of interest despite lack of precise knowledge at some more complex level. Good predictions are usually associated with specialization and the more specialized the model the less well will it map onto other specialized models. For example a map which allows compass bearings to be represented as straight lines will have to distort other aspects such as area. No single two-dimensional map can faithfully represent all the surface features of the globe because there is a dimension missing. Scientific theories, like maps, are models for making useful predictions about future events from limited data.

Therefore in considering theories of behaviour we should not be too upset if we find that a theory which makes good predictions about mental acts does not map directly onto a theory which makes good predictions about physical movements. The Dissipative Structure theory promises good power in explaining the sort of behaviour that is not much influenced by cognitive operations. In fact since the theory makes no allowance for such interferences it might serve as a defining test for behaviours that are not so influenced. Where it is evident that cognitive activity is making a significant contribution to behaviour then the interface between the two systems becomes important.

Kugler et al. (1982, page 45) reject dualist theories which posit causes and effects between the environment, described in physical terms, and percepts, described in mental terms said to be 'in' the animal. Their objection is that the interface between these two regimes is arbitrary, whereas their view shows that the emerging order in the natural event is a by-product not a controlling cause. However the point is that, at the present state of the art, there is no chance at all of describing the sort of dissipative structures that might support existing cognitive abilities as an *a posteriori* by-product. In fact it is only a few short years since information and computer theory have allowed us to get a systematic grip on cognitive activities. However unsatisfactory the arbitrary interface between mental events and physical acts might be, it does exist. It is itself a by-product of our investigative tools and like the two-dimensional maps that will not quite fit together we must accept, for the present at least, this discontinuity if we wish to keep the power of the separate tools intact. Too much concern about exact mapping of one theory onto the other will merely lead in the direction of a futile attempt to build a model that is as complicated as the world it is meant to simplify.

The task facing the proponents of the dissipative structure theory is first to show that the internal logic is sound, as has already been shown for information theory, computer theory and cybernetics, and second how it may be applied experimentally. Like the gas laws, the theory does not expect to show how the activity at the micro-level leads to changes at the macro-level in detail. Consequently its power will lie in its ability to find invariant laws which operate at the latter level and identify the 'essential' variables which control them. A description of the biomechanical aspect of motor behaviour in these terms would certainly ease the interface problem but so far it is but a promise.

Summary

This chapter has discussed the current theoretical approaches to the problems of motor behaviour. The next chapter will introduce bicycle riding as an example of a skilled motor behaviour in which the freedom of movement of both the rider and the machine is severely constrained by the inherent instability. Subsequent chapters will show how this constraint allows a detailed record of the movement of the machine during free riding to specify what the rider must be doing to achieve it. The structural correlates needed to implement this control behaviour will be discussed before relating it to the theories introduced in this chapter.

3. BICYCLE RIDING AS AN EXAMPLE OF HUMAN SKILL

Choice of Skill

Bicyle riding is a very common skill found in all the civilised and semi-civilised parts of the world. It is usually learned at an early age and it must be supposed that most of this learning takes place without any formal instruction. It is principally a problem of delicate balance and the fact that it must be learned is an indication that although it may depend on the same basic structures as standing and walking the skill does not transfer automatically. There are two indications that it is very close to existing balance skills. First it is learned quickly; A confident and enthusiastic child will learn the rudiments in a day or two which represents only a few hours of actual practice. This can be compared to the skills associated with musical instruments where a year or more may be needed to acquire a good tone on a violin or an oboe. Second it is well learned. The old saw says that 'Once learned, never forgotten' and this again contrasts with musical skills which are usually lost after quite short periods with no practice.

It is possible to learn a certain amount about bicycle control from straightforward observations. By operating the handle bars with various parts of the lower forearms it is possible to glean that the skill does not depend on the sensory input at the hand's surface. In the same way a variety of extreme body positions such as standing on one pedal and leaning away from the machine, or leaning right over the front wheel seems to have little effect on control. Many riders can keep quite good control without holding onto the handle bars at all although some bicycles will not allow this form of riding. Very short or very long handle bars seem to make no difference but reversing the hands so the left is on the right bar and vice versa immediately produces a very strong disruption and if the steering is locked solid riding becomes completely impossible.

If we look at the tracks left on a dry surface by wet tyres, we see that the rear wheel leaves a gently weaving line while the front wheel traces a sinusoidal path with a higher frequency that oscillates either side of the rear track or near to it. If we enter a turn quickly at some marked position we can see that the front wheel turns momentarily away from the desired direction before making the turn and that this deviation does not appear in the rear track. In a steep turn the front wheel track is outside or at a greater diameter than that of the rear wheel. Without some method of recording simultaneous events it almost impossible to locate the relative positions in time of those events recorded on the surface with the changes in lean angle observed during the turn.

Bicycle riding shares an interesting feature with many movement skills. Although people can do it perfectly well they have no clear idea what it is they are doing. A survey of ten regular bicycle riders showed 9 of them claiming that a turn was initiated by rotating the handle bars in the direction they wanted to go. Six of these thought that they leaned in the direction they wanted to go at about the same time and three thought they did not lean. One person thought he leaned in the direction he wanted to go but did not turn the handle bars. As will be made quite clear in the following chapters a turn is initiated or increased by moving the handle bars in the opposite direction to the turn and that moving them in the same direction will contain or reverse it. Of course it is possible to initiate or increase a turn by failing to produce sufficient handle bar to contain the fall rather than actually turning the bar in the reverse direction but a simple study of wet tyre marks on a dry surface immediately reveals that the normal practise is to initiate a turn with a short reversal of the bar, even though it is evident that most riders are quite unaware of this. Richard Ballantine, author of the popular vade me cum, *Richard's Bicycle Book* (Ballantine, 1983), specifically mentions turning the bar in the wrong direction as a special way of entering a turn quickly but otherwise seems unaware that this is the normal way as well. Ross Ashby (1952) states quite clearly in his *Design for a Brain* not only that the handle bar must be initially be pushed in the opposite direction to the desired turn but also he remarks on the fact that even very experienced bicycle riders are rarely conscious of this despite having carried out the act thousands of times.

At high speed on a bicycle or a motor-bicycle it can be easily demonstrated that a steady push tending to turn the handle bars to the right produces a turn to the left and vice versa. As soon as the rider and bicycle start to fall to the left out of the initial turn the autostability forces twist the front wheel powerfully left to check it. Even when this is well understood it is very difficult not to attribute the large handle bar movement into the fall to the rider initiating the turn rather than the autostablity following the fall. In chapter 7 it will be shown that as soon as the push 'in the wrong direction' is released the autostability forces stop the turn and restore the bicycle to upright running. As for the underlying responses to the change in roll which guarantees lateral balance when autostability is low, these seem to remain quite opaque to the conscious mind even when its presence is thoroughly understood. The situation is similar to that found by Lishman & Lee (1973) when, in their swinging room experiments, they found that *knowing* that the visual movements were false did not enable them to *perceive* them as such. '*Finally we ourselves are still visually dominated despite having intimate knowledge of the apparatus and being subjects for many hours.*'

Essential Characteristics of The Bicycle

A bicycle is stable fore and aft, unstable from side to side (Roll) and has a complex directional stability depending on conditions of front wheel angle and roll angle. When stationary a riderless bike will rapidly diverge in roll under the influence of gravity but when moving faster than some minimum speed it will automatically limit this rate of divergence. Depending on the design of the bicycle there may be some higher speed beyond which the machine will not fall at all but will maintain straight ahead upright running. Of course in the absence of some means of sustaining this speed, such as a motor or running down a hill the bicycle will eventually slow down into the lower speed range. Turning the front wheel at an angle to its direction of travel produces a sideways force at the front tyre/road contact point and this by swinging the front of the frame leads in turn to a similar angle and force at the rear wheel. The effect of these two forces cannot be determined by a casual intuitive inspection of the resulting overall behaviour. This is due to the fact that as soon as the frame angle responds to the front wheel change the angle between the direction of travel and both wheels is immediately altered giving interactive changes of both rotational and turning forces. The combination of these two forces also produces a couple about the centre of mass in the mid-frontal (or coronal) plane which tries to roll the machine out of the turn and this couple can be balanced by leaning the bike into the turn (see figure 3.1). The essential feature of control is the management of the position of the centre of gravity in relation to the wheel contact points via the front wheel angle so that the two couples balance for lateral stability.

The Control Model

The ultimate aim of this study is to shed some light on the contribution which humans make to the control of bicycles. At this stage in the investigation, however, it is not clear exactly was is happening let alone who or what is causing it. At the level of action being investigated, it will be assumed that the functioning units controlling the rider's movements behave in a determinate way, that is the effect of similar external conditions on a particular internal state will always lead to the same behaviour, and that as a consequence both the bicycle and the human, for the purpose of analysis, may be considered as a 'machine'. Thus the bicycle on its own may be referred to as a system, or the combination of rider and bicycle where the former is producing one of the variables such as the rate of handle bar movement. When the system is spoken of as having a problem this is to indicate that a specific relationship over time between the variables chosen is necessary to account for the observed performance, regardless as to whether it is provided by the rider, the design of the machine or a combination of the two together.

The problem of bicycle control is to sense the change in the roll angle and use the front wheel angle to control this to a desired value. Merely reducing the rate of roll is simple but as soon as it is reversed an uncontrolled acceleration in the opposite direction can only be avoided in one of two ways. Either the exact rate of steering angle change required for that bike, at that speed, in those road conditions at that specific lean angle must be available to the system or it must apply some general procedure which will cover all normally encountered conditions. The latter solution is greatly to be preferred both on the grounds of parsimony and because of the difficulty of finding physiological structures to account for the sensing of some of the values required by the former. Also the output characteristic of each is different, the former giving a 'dead-beat' performance where changes in angle are stopped exactly at the target value whereas the latter always overshoots to some degree and shows regular fugoid divergences either side of the target, which, as will be shown later, is one of the identifying characteristics of human bicycle control.

There are usually quite a large number of different control arrangements which will produce similar performances from the same machine. One of the major advantages of bicycle riding as an experimental example of a skill is that the extreme instability in roll allows only a very limited number of possible control solutions making identification of the one actually used considerably easier than it would be with a more stable one.

Existing Studies of Bicycle Riding

The single-track vehicle is a very complex dynamic machine which is not easily reduced to manageable mathematical representations. There do not seem to be substantial commercial rewards for marginal improvements in a device which is already extremely successful as a cheap personal transport, which probably explains the comparatively small amount of research in this area. Weir and Zellner (1979) claim a comprehensive bibliography of 21 papers and of these only four deal specifically with the rider's contribution to control. In these latter papers the authors compare the performance of mathematical models of the motor-cycle rider/machine system with records of riding behaviour. Their main concern is to improve the handling performance of the vehicle and the human contribution is seen as an essential but secondary consideration. Both Weir and Zellner (1979) and Eaton (1979) considered that basic balance control was achieved through a simple delay repeat of the roll activity as a handle-bar torque force or upper body displacement. Eaton found that the latter seemed to contribute very little during actual experiments and subsequently immobilized the upper body of his subjects in a frame. Weir and Zellner provide models for both combined body and bar movement and bar movements alone. Neither seems to have considered that the powerful gyroscopic effect of the front-wheel design in motor-cycles converts lateral body displacements to front wheel steering movements, so that upper body movement may just be an alternative option to handle-bar control. A study by Nagai (1983) also considers these two forms of control without mentioning the automatic interaction between them in normally designed machines. The distinction is not very important from their point of view but is of prime interest as far as a study of rider skill is concerned. An investigation by Van Lunteran & Stassen (1967) used a static electro-dynamic bicycle model that ignored the contribution of centripetal forces altogether thus fundamentally changing the skill required to achieve balance.

Jones (1970) attempted to penetrate the mysteries of bicycle mechanics by constructing an unridable bicycle by systematically removing those features which were supposed to confer stablity. Despite a rather lighthearted treatment Jones' paper has been much quoted since and therefore deserves a slightly longer treatment. This however will be postponed until some aspects of bicycle design have been covered.

BASIC CONTROL

Bicycle riding has three basic requirements. These are hierarchical, that is A is necessary for the performance of B and B is necessary for the performance of C.

A. *Don't fall over.*

B. *Turn where and when you want to.*

C. *Avoid obstacles and go to desired places.*

This study is only concerned with the two lower levels of the hierarchy and aims to find out exactly what happens in the combined rider/bicycle machine between the top level instructions GO-LEFT/GO-RIGHT/GO-STRAIGHT and the resulting performance. In a way it can be regarded as a navigation task on top of a steering task on top of a postural task. However, as will be made quite clear, the demands of the former must be met on the terms dictated by the latter.

The simplest possible control would be to treat the handle bar as though the bicycle was a tricycle. When the request GO-LEFT is given the bar is moved left. The response to such a movement is a violent fall to the right. Some idea of the forces involved can be gained from the way a motorcycle combination will lift the full weight of its sidecar plus passenger off the road in quite a moderate turn towards the car. It can be seen that this at least is not a candidate for the control of an unsupported bicycle. The control problem in general terms is that although directional response can be achieved using the bar like a car steering wheel it will lead to instant loss of roll stability. In order to find solutions to this problem further analysis is needed.

There are two major influences on the roll stability, the couple due to the weight and the couple due to the turn. Figure 3.1 (b) shows how the weight acts about the horizontal distance 'd' between the centre-of-mass and the support-point of the tyres to produce a rotating couple 'W x d' in the rolling plane.

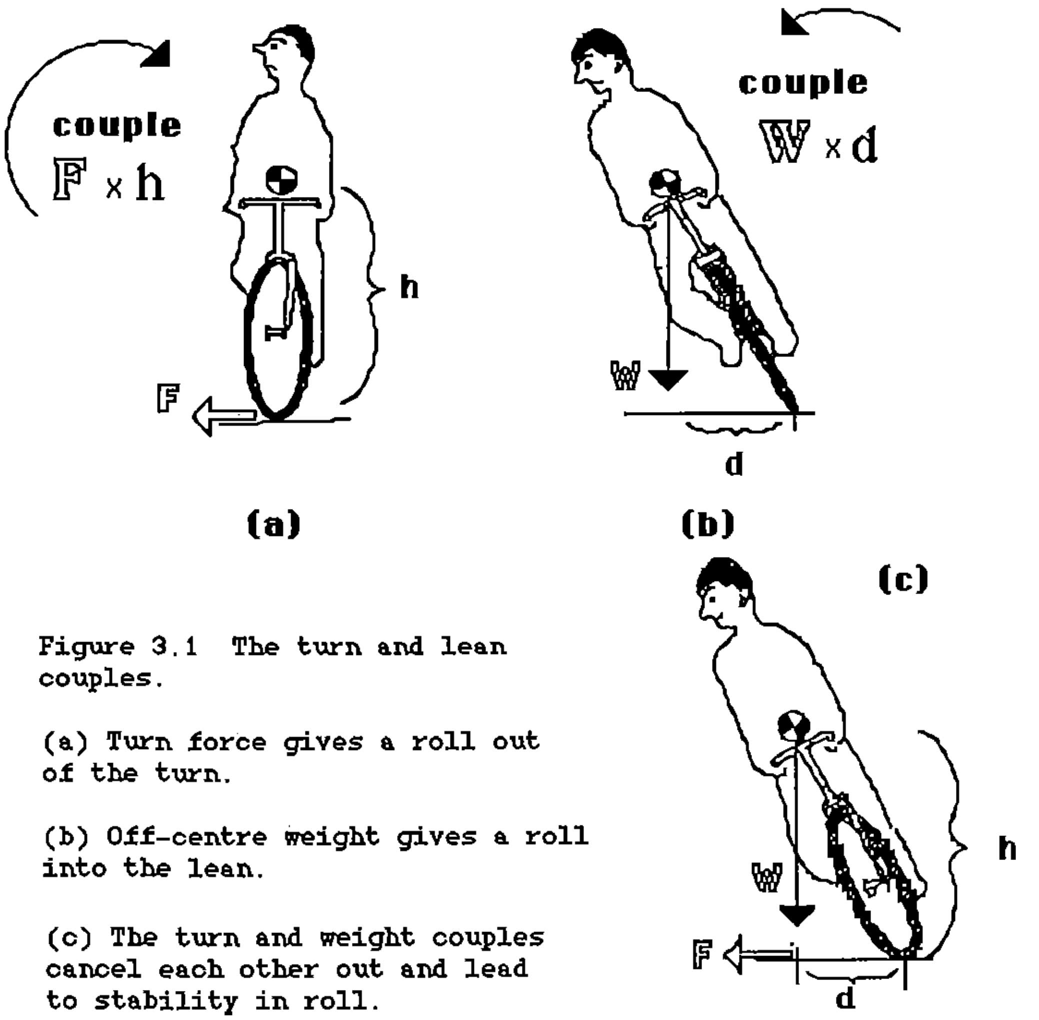


Figure 3.1 The turn and lean couples.

(a) Turn force gives a roll out of the turn.

(b) Off-centre weight gives a roll into the lean.

(c) The turn and weight couples cancel each other out and lead to stability in roll.

The greater the angle of lean the greater the rotating couple for any given weight. This is a sine relationship so the rate of change is small at first but gets rapidly bigger beyond 45 degrees. Since people can ride bicycles at an angle without falling over it must be possible to balance this with some other couple. There must always be a force present acting towards the centre of any turn, usually termed the *centripetal force*. On a bicycle this force comes from the strong sideways component of drag generated when the tyre runs at a slight angle to the direction of travel. Figure 3.1 (a) shows how this force at the tyre/road contact point produces a couple 'F x h' by acting over the vertical distance 'h' between the centre of mass and the ground. This couple is a cosine relationship and is at its greatest for a given force when the bike is vertical and gets rapidly less beyond 45 degrees lean.

Imbalance of Couples

It can be seen from the foregoing paragraphs that providing the bicycle is leaning into the turn the weight couple opposes the turn force couple. However it can also be seen that they are not well matched since the former gets bigger with increasing lean angle whereas the latter gets less. It is this mismatch that is at the heart of the bicyle control problem. Figure 3.2 illustrates the problem situations. In the first diagram, named 'The Fall', the distance 'd' is big so the weight forms a very large couple into the lean, but because of the exaggerated lean 'h' is small, so a very big force F would be needed to check the fall. It must be borne in mind that not only does this force have to match the couple formed by the weight times the distance from the support-point (W * d) but it must exceed it. Matching it will merely prevent there being any further acceleration in roll but the accumulated angular velocity, due to its having fallen from wherever it started, must also be dissipated or it will go on falling at that rate. During the time taken to overcome the residual velocity the angle of lean will have continued to increase so the imbalance situation will have got even worse. The second figure, named 'The Recovery', shows another problem area. Assume that the large increase in Force has successfully contained the fall and the machine starts to return to the upright. At first the return will be moderate as the couples are well matched but as the angle reduces the roles will be reversed and the rapidly increasing 'h/d' ratio produces a much bigger restoring couple than the disturbing one and the roll velocity becomes excessive so that when the machine passes the vertical and starts to fall the other way the recovery problem will be even greater than before. It can thus be seen that if the roll rate is to be controlled there must be a continuous and finely balanced relationship between the Weight and Turn Force couples.

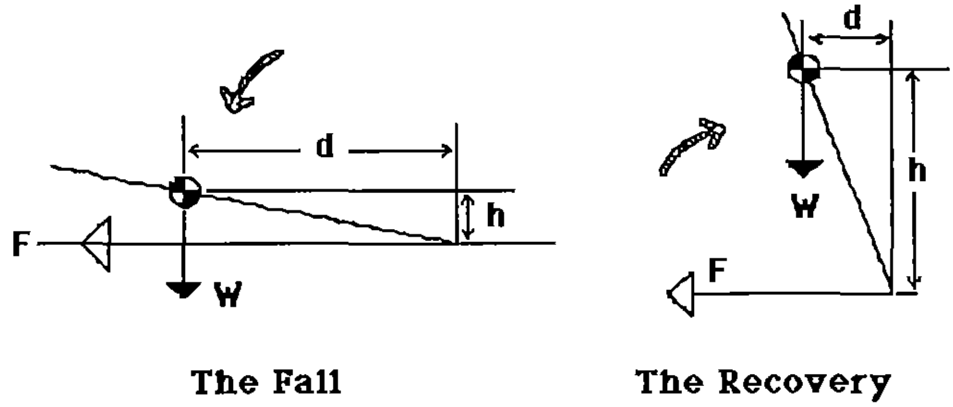


Figure 3.2 The two problem situations in balancing the disturbing and correcting couples. In the Fall the couple Wxd is very big and since 'h' is small then F must be very big to produce a correcting couple. In the Recovery the height 'h' is now big and 'd' is small. If the wheel force F is still big then the restoring couple Fxh is much bigger than the destabilising couple Wxd.

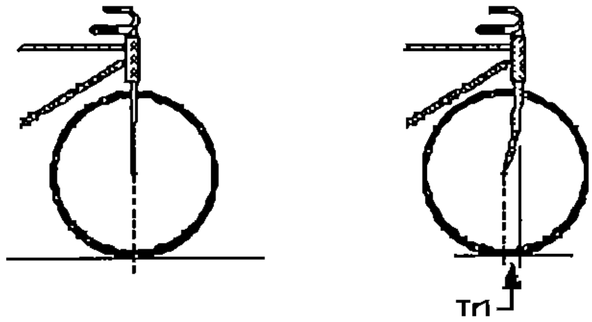
To achieve the minimum control requirement *'Do not fall over'*, it is necessary to use the unwanted rate of roll as the actuating signal which will drive the system so that roll rate is removed. Movement in roll may be considered as having two components, angular acceleration and angular velocity. The resultant of the weight and turn couples produces a change in acceleration and this, acting over time, changes the velocity.

The control exercises its influence through changes in the front wheel steering angle which in turn controls the side force at the tyre/road contact point, which in turn alters the turn couple. It has already been mentioned that merely reducing the acceleration to zero by balancing the roll couples is insufficient as it leaves the accumulated velocity unaccounted for. For a minimum solution the control must produce changes in the sideways wheel force via the steering angle that are dependent on both the acceleration and velocity in angular roll. This will remove any roll movement that arises giving a constant lean angle. Where this angle is other than vertical the bicycle will be turning towards the lean.

Autocontrol

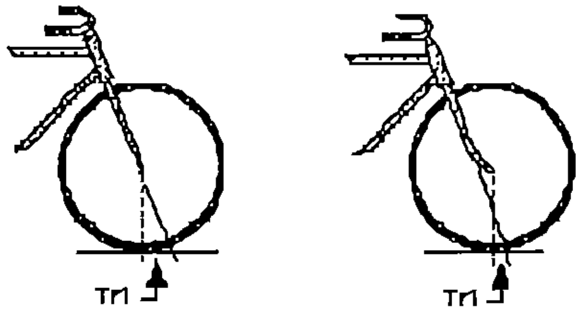
Over the years the front forks of the bicycle have evolved to a specialised form that provides a considerable degree of automatic directional and roll stability. Figure 3.3 shows four different front fork arrangements. In the first the hinge line is vertical and there is no offset of the front axle. The contact point of the tyre with the road is directly in the hinge line. In this configuration any force applied at either the contact point or at the frame/hinge junction cannot form a couple and will therefore have no influence on the steering angle.

In the second view the axle has been offset to the rear forming the trailing castor arrangement familiar in the wheels of movable furniture. Here any sideways force at the road contact point will form a couple over the distance marked Trl and drive the wheel steering angle back towards zero, thus damping out the effect. Any side force at the frame/hinge joint will also act over this distance so that when the bike is leaning to the left, say, the weight of the machine and rider will give a force to the left which will produce a couple rotating the wheel into the direction of lean. Since this will make the machine turn to the left, which will in turn produce an anti-lean couple, it is a stabilising movement in the roll plane.



(a) No rake & no offset, therefore no castor.

(b) No rake but rearward offset gives castor.



(c) Rearward rake, no offset gives a large castor.

(d) Offset axle reduces the castor effect.

Figure 3.3 Showing how variation in the geometry of the front forks gives different trail distances and thus different castor effects.

When the safety bicycle replaced the ordinary or 'penny-farthing' type the rearward movement of the rider necessitated a rearward movement of the control bar. This was almost universally accomplished by raking the hinge line back at an angle. Such an arrangement is seen in the third diagram. As can be seen the effect of such a design is a large distance between the ground-tyre contact point and the hinge line. (Marked Trl). This gives a powerful stabilising effect which makes it difficult to turn the wheel out of the dead ahead when upright and produces such a strong couple into the lean when tilted that, if allowed to dominate, it leads to overcompensation and a series of wobbles from one side to the other. This is not a desirable state of affairs for normal control and the 'stability' factor is reduced by offsetting the axle forward to reduce the distance Trl. This dimension is adjusted to give sufficient directional stability to prevent stray bumps jerking the steering into dangerously excessive angles and some assistance in turning the steering in the direction of roll changes without opposing volitional movements by the rider. This configuration is shown in the final diagram of fig. 3.3.

Gyroscopic Effect

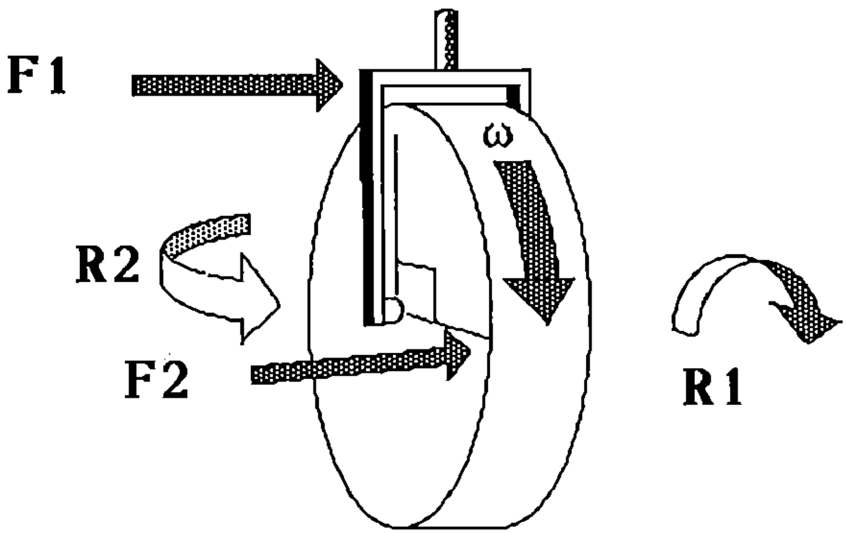


Figure 3.4 Showing precessional effect on a wheel acting as a gyroscope. A force applied at F1, tending to rotate the carriage in direction R1, will act as though it was applied at F2, ie at 90 degrees in the direction of rotation. The resulting yawing movement, R2, will be proportional to the angular velocity of R1, the moment of inertia of the wheel and its rate of rotation.

When a bicycle wheel rotates it acquires the properties of a gyroscope. When a couple is applied that tends to turn the wheel axle in one of the two planes at right angles to the plane of rotation, the precessional effect causes a turning movement in the other plane as though the force had been applied at a point at ninety degrees in the direction of rotation. This is shown in fig. 3.4. The result is that any roll velocity leads to a stabilising movement of the front wheel in the direction of roll. The greater the mass at the periphery of the wheel and the faster the road speed the greater is this effect. In a small wheel bicycle at walking speeds the effect is very slight whereas in a motorcycle travelling at normal road speeds the effect is very powerful.

Independent and Combined Control

The autocontrol features due to front fork design and gyroscopic effect described above provide a couple about the steering axis. A rider who moves the steering bar independently of this effect will feel the resultant couple as a resistance. In a light bicycle travelling at low speeds the effect is scarcely detectable.. At a good road speed, say fifteen miles an hour the effect on a normal bicycle is marked, giving a feeling of 'inevitability' to the roll stability. Removing the hands altogether has no immediate effect. At normal road speeds on a motorcycle the forces are so high that only a determined effort on the part of the rider could override the steering head couple. Thus it can be seen that two kinds of control must be considered for bicycle control. Whenever the steering head couple is weak the rider must provide all the movement necessary for stable control.

When, due to front wheel size and road speed, the machine provides a significant level of stability control the rider need supply only those control forces required to alter the angle of turn in the desired direction. In doing this the rider must not apply angle dependent forces on the handle bar as these will interfere with the automatic couples and autostability will be lost. What the rider must do is to contribute a further couple which will balance with the machine contributions to produce a resultant which gives the desired effect. The important point is that this couple MUST BE POSITION INDEPENDENT. This means that the arms must move with the bar as it alters its angle under the influence of the autocontrol but at the same time provide a steady push in the desired direction. In other words the force at the bar must be independent of the steering angle. At the anatomical level this means the rider is controlling the steering muscles for tension independent of length. At the experimental level it means that any record of changes in the steering angle will contain contributions from both the rider and the autostable effect of the front fork design in a proportion which depends up such factors as speed and individual design. Both the gyroscopic and castor autostability must be removed from the experimental bicycle if the record of handle-bar movement is to be an unadulterated version of what the human operator is doing but the description of how this is done will be left until chapter 5.

The Unridable Bicycle

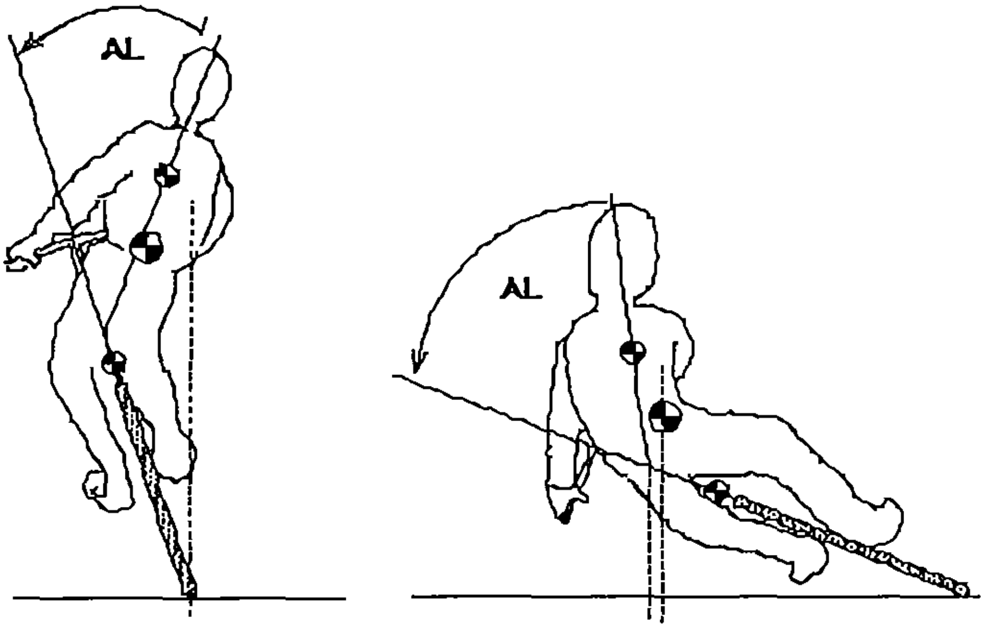
Before going on to consider the case of body movements as a means of control Jones 1970 paper will be considered in more detail now that the basic mechanics of the bicycle have been explained. Since Jones' thesis was that a bicycle without autostability would prove unridable it can be inferred that he regarded the human contribution to be of little importance. He used two tests to determine the unridablity of the bicycles he built. One was to try and make them travel on their own after being pushed off at a run and the other was a subjective account of how difficult he found them to ride. The actual words he used to describe the result of these latter test appear below in italics. The first unridable bicycle (URB1) had a second front wheel mounted alongside the first, just clear of the ground, so it could be spun up to speed by hand either in the same direction as the normal front wheel or opposite to it. When it was spinning in the same direction it enhanced the gyroscopic effect and when in opposition it diminished or reversed it. He confessed himself puzzled when the bicycle proved quite easy to ride at low speed in either condition. However the effect on the bicycle running on its own was quite clear. When the gyroscopic force was reduced the machine fell to the ground as soon as it was released and when the force was enhanced URB1 *ran uncannily in a slow, sedate circle before bowing to the inevitable collapse* (page 36). URB2 had a 1 inch furniture castor fitted instead of the front wheel. Despite problems with bumps and the bearing overheating Jones was able to ride this strange machine but was not surprised that it would not run on its own. URB3 had the normal front forks reversed, similar to the diagram in figure 3.3 (b). This machine was *amazingly stable* on its own, not only limiting the rate of fall but actually righting itself and turning in the opposite direction. But it was *strangely awkward* to ride, because it was too stable and resisted control inputs from the rider. Finally in URB4 Jones exaggerated the foreward curve of the front forks by mounting the wheel on 4 inch extension pieces producing a strong reverse castor effect. This machine would not run on its own but, although *very dodgy* to ride, it was not *as impossible* as he had hoped. The central part of Jones' paper is taken up with deriving a set of curves for the effect of lean angle on the castor. This is an alternative method of working out the effective trail distance which is dealt with in the next chapter using the geometrical method which Jones preferred to avoid.

Jones had hoped that, by removing the various features which were supposed to produce stability, he would be able to identify the contribution each made by finding when the bicycle became unridable. He confessed himself baffled by his own ability to overcome the obstacles he devised. The only modification which makes control impossible is to lock the steering solid. Since his modifications had the expected effect on the stability of the bicycles running without a rider it is evident that humans can deal not only with bicycles without any stablity but even manage those which have been quite seriously destabilized.

A more recent study by Lowell & McKell (1981) models some aspects of bicycle stability. The authors do not claim this as a serious investigation of bicycle or rider performance, but rather as a formal application of classical mechanics to a familiar problem. In order to keep their equations tractable they ignore both rider inputs and gyroscopic effects which lead to some rather strange conclusions about inherent stability which are not born out by the behaviour of bicycles, and particularly motor-cycles at high speeds. They quote Jones paper to support the claim that bicycles with small castor are *very difficult* to ride but in doing this they fail to distinguish between a zero castor and a negative castor. As will be seen later in this paper reducing the standard castor of a normal bicycle to zero produces no handling problems and actually gives the steering a rather pleasant 'light' feel. In any case they are misrepresenting Jones' report since he did not make a bicycle with zero castor and even found he could ride URB IV, with its large negative castor.

Lateral Weight Shift as a Control Input

Many studies have considered lateral body shift as a possible means of control. (Lowell & McKell, 1982; Nagai, 1983; Van Lunteran & Stassen, 1967; Weir & Zellner, 1979). Although there can be no doubt that bicycle riders do move their upper body from side to side during riding it does not follow that this movement is being used to control the machine either in roll or in direction. However, it is equally clear that rolling movements of the bicycle frame, induced by counter movements of the riders' body, will produce control effects via the autostability effect of the front fork design. Roll velocity is converted by the gyroscopic effect into a steering couple away from the upper body lean. The resulting turn will push the centre of mass in the direction of the initial lean. A permanent lean to one-side will also generate a steering torque in the same direction due to the castor effect. These effects are confirmed by the fact that riders can control bicycles with body movements alone when riding hands-off. As far as this study is concerned, it is important to get this point quite clear as the integrity of the recordings depend on the argument that when the autostability of the bicycle is removed body movements do not produce any significant control inputs. What must be established is that body movements in relation to the bicycle frame cannot in themselves produce controlling forces independent of their secondary effect via autostability. A preliminary examination might suggest that an unwanted displacement of the centre of mass to one side could be removed by leaning the body in the opposite direction. The dynamics of the system are, however, principally concerned with the position of the combined centre of mass in relation to the road support point and will be affected in a complex manner during the movement of the rider's mass in relation to that of the bicycle.



(a) (b)

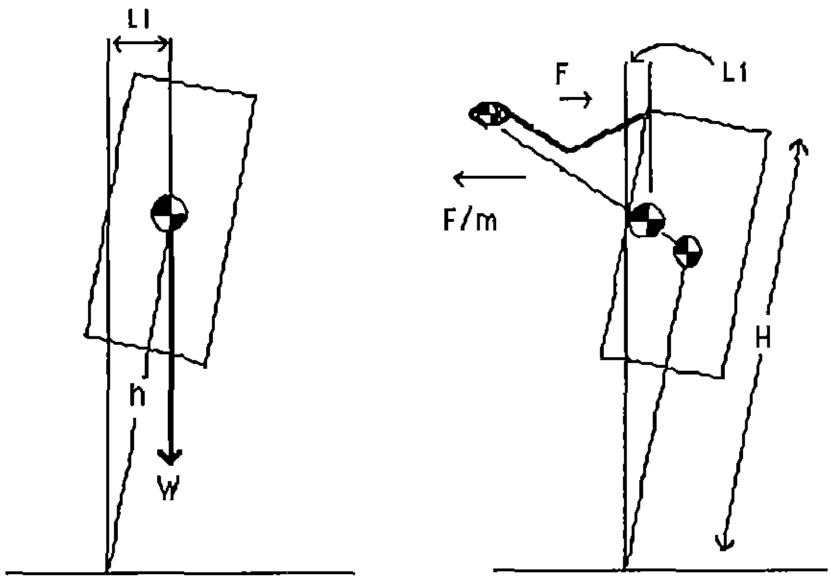
Figure 3.5 Despite the angle between the upper body and the bicycle frame (AL) the centre of mass, shown by the larger segmented circles, does not produce a restoring couple. Drawing (a) shows how even at quite small angles of lean a large AL fails to take the combined centre of mass onto the correcting side of the ground support point. Drawing (b) shows how, as the angle of lean approaches 90 degrees, the apparent sideways movement of the upper body produces very little change in the horizontal plane.

Exactly what happens when a rider moves his upper body laterally depends on the relationship between the masses of man and machine, their rate of movement and the angle of lean.

To deal with the simplest point first let us take the case of a rider, at some angle of lean, who has already moved his upper body towards the vertical in an attempt to restore the disturbance. Figure 3.5,(a) shows that there will be some fairly small angle of lean where the lateral movement of the body will not put the combined centre of mass on the restoring side of the vertical from the support point. In such a case the movement will have reduced the disturbing couple to the left but will not provide a restoring couple to the right. Figure 3.5,(b) shows that at large angles of lean the lateral movement has a decreasing influence on the disturbing couple as the movement lies increasingly in the vertical plane.

The above situation is static. How the rider achieves his displaced position and what happens during the movement have not been considered. For a start it takes time to move from the normal riding position to the position shown in figure 3.5,(a). During the time that the rider is moving right in relation to the bicycle everything will be falling left because the combined centre of mass is displaced to the left of the support point. This means that the angle of displacement to the left at which the rider started to make his correcting move will be less than the angle shown.

Given an initial displacement to one side, whether a rider can EVER produce a correcting movement in this manner depends on the interaction between two rates of movement and the relative moments of inertia of the masses moved, and this in turn depends on exactly how the rider carries out the movement.When the rider, seated normally on the bicycle, is displaced from the vertical so that the centre of mass is no longer vertically above the point of support the disturbing couple formed by the weight times the horizontal distance of displacement produces an accelerating roll about the support point.As the displacement increases so does the rate of acceleration. In order to check this movement two things are necessary. First either a couple must be formed that will oppose the accelerating couple or the couple must be removed. Second an additional couple must be formed temporarily which will decelerate the existing roll velocity to zero at which point it must then be removed to prevent its starting a fall in the opposite direction.

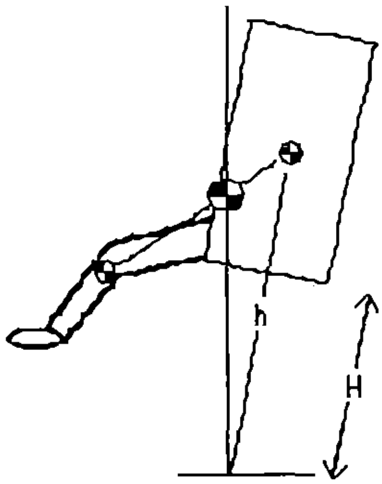


(a) Angular acceleration clockwise:-

W * L1 / M * Io

(b) Angular acceleration clockwise:-

(W * L1 / M * Io)+(F * H / (M-m)*Io)



(c) Leg movement

Figure 3.6 showing the effect on angular acceleration when a limb is moved to balance about a narrow support point. See text for details. M is total mass, 'm' is mass of arm.

In the case which is being considered here the only means the rider has of providing these couples is to alter the relative disposition of the physical parts, such as his limbs or torso, or the bicycle, to somehow move the centre of mass over to the other side of the support point. Nothing else will achieve the desired result. The start position is shown in figure 3.6,(a). The view is from the rear so that picture left is also left for the rider.

If it is assumed that in the start position the rider is sitting on the saddle then the only way he can shift the centre of mass to the left is by moving some part of his body in that direction. The argument is easier to follow initially if we consider the effects of moving first an arm and then a leg. Figure 3.6,(b) shows the effect of rapidly pushing the left arm out to the side. The force needed to accelerate the arm to the left will act against the shoulders in the opposite direction. The rate at which the arm moves is given by the force divided by the mass of the arm (F/m). The rate at which the remainder of the mass moves the other way is given by the rotating couple formed by the force times the height of the point of application above the ground (F*H) divided by the moment of inertia about the ground contact point (M*(h^2)/3). Thus the effect of flinging the arm out leads to its moving one way and the body moving the other, each at different rates. While this is taking place the whole is being rotated to the right under the influence of the original couple formed by the total weight times the lateral displacement (W*l) divided by the combined moment of inertia ((M+m)*(h^2)/3). Thus there are two couples driving the combined mass to the right but the movement of the arm out to the left brings the centre of mass out to the left with it so the lateral distance 'l' is being reduced. Because the arm is by comparison light and is going in a straight line it moves much quicker than the remainder of the mass. Whether this succeeds in moving the centre of mass onto the left hand side of the support point before it rolls out of reach or not depends on the actual masses and rates involved. To check the roll to the right the centre of mass must move not just back to the upright but beyond it in order to remove the accumulated angular velocity to the right.

An idea of how little control is available using this method may be gained by standing on one foot on a laterally unstable platform, such as a rolling pin, and trying to check an incipient fall by flinging out an arm. It is immediately evident that the movement of the centre of mass is not sufficient to overcome the roll. It is just possible with care to provoke a fall towards the flung out arm from the in-balance position but there is very little margin for error. When a leg is moved rather than an arm the result is more encouraging and there is certainly very little difficulty in preventing the initial fall from developing. It can be seen from figure 3.6,(c) that the thrust which pushes the leg out acts much lower down. The couple acting to the right now acts over the much reduced distance H and consequently more of the movement will take place at the leg. Because the leg is heavier it will have greater influence in bringing the centre of mass back towards the centre. Arm and leg movements are not being considered as candidates for bicycle control. The only other movement available to the seated rider is to bend at the waist and force the upper body to one side which will of course force the lower body and the bicycle in the opposite direction. If the balancing act described above is now tried using upper body lean to counter incipient roll by leaning away from the movement the task will be found to be impossible. In fact a careful attempt to initiate a fall from the balanced position by a sharp bend in the body will show that there is if anything a tendency to go the other way, that is the force applied has a greater effect on the lower mass than the upper. The masses of the two parts being moved are now more nearly equal and the thrust is being applied well up the body. None of these control movements has any chance of restoring balance once the combined centre of mass has moved more than a degree or two out of the vertical or when there is any amount of accumulated angular velocity.

Thus we can see that although a rider can control a bicycle entirely by moving his upper body away from a fall this is achieved via the autocontrol effect. Even at very small angles of lean such a movement cannot alter the position of the centre of mass to provide a restoring couple. A clear demonstration of this can be made by trying to balance on a stationary bicycle using upper body movements. Providing the chain is disconnected from the rear wheel to prevent dynamic forces being transferred through the front wheel this task is impossible and shows that upper body movement on its own cannot exert control in the rolling plane.

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 can only be achieved by rolling the machine in the opposite direction. This roll is converted by the gyroscopic effect into a steering couple away from the upper body lean. The resulting turn will push the centre of mass in the direction of the initial upper body lean. A permanent lean to one-side will also generate a steering torque in the same direction due to the castor effect. Since the roll and turn effects achieved in this manner can be equally achieved by handle-bar movement, and since only the movement of the handle bar is recorded on the experimental bicycle, it is preferable to avoid the influence of upper body movements in the analysis. As has already been mentioned above, it was necessary to remove the autostability from the experimental bicycle to prevent a confusion between automatic forces and human forces. By the same token, in the absence of automatic control, any body movements made by the subjects will not be translated into control movements thus forcing the subjects to depend on hand movements only for control.

The Psychological Point of View

In general the work that has been done on single track vehicles has been in the engineering field is therefore orientated towards vehicle design and performance leaving virtually untouched those aspects of bicycle-riding which interest the psychologist. Over the past thirty years a number of engineering theories such as feedback control and servomechanisms have been adopted by psychologists to describe the way limbs are controlled during skilled movements. In 1947 Craik found that people often made corrections in aiming and tracking tasks in steps rather than continuously and consequently described this behaviour as an intermittent servomechanism. Keele & Posner (1968) estimated that the minimum refractory period was 260 msecs. Many experiments used tracking or aiming tasks to explore control which led to a general conclusion that there is some minimum period required for central control to detect an error and implement a correction. When action followed stimulus at less than this interval it was supposed that control was via a local reflex. This idea became so well established that the 200-250 msecs latency was frequently taken as being the criterion for judging whether an action was under central control or not. However much shorter delays than this have been recorded in tasks where reflex control seems an inadequate explanation. For example Cordo and Nashner (1982), whose experiments will be dealt with in greater detail in chapter 8, found compensatory postural movements in humans in the latency range of 70-150 msecs which could not have been simple reflexes since they adapted to changes in the environment which could only have been processed centrally. These discoveries have led to the classification of responses into three speed categories. The fastest spinal, or myotatic, reflex acting in the 40-50 msecs range, the centrally controlled decision range starting at around 200 msecs and between these two there appears to be a range of reflex like movements, known as the Functional Stretch Reflex (FSR), which are nevertheless under some degree of central control.

It would unwise to assume that because intermittent control is used in some tasks that this is a general limitation in all tasks. Whether continuous or intermittent control is used depends initially on the exact details and in some cases at least it is evident that the experimental design itself forces a choice of technique. For example both Pew (1966) and McLeod (1977) used a tracking task in which the subjects were asked to keep a cursor in the middle of a VDU screen. The cursor was always accelerating at a fixed rate in a horizontal direction and the subjects were given two keys which selected the direction of this acceleration either left or right. Even if the subjects had been able to detect the rate of acceleration they had not the means to apply a proportional correction. If the acceleration was high when they switched directions they had to wait for it to produce a reversal and if they switched when the acceleration was still very small the result was a rapid reversal and a fast acceleration in the opposite direction. They were therefore committed to a particular form of control by the details of the task. In order to test this point of view the Pew task was rewritten to allow continuous control of the cursor acceleration with a joy-stick. It becomes immediately apparent that an operator can make use of the proportional response and in its new form the task is comparatively easy. A record of operator activity shows a continuous change rather than the previous intermittent control.

For continuous control it is necessary first that some variable, relevant to the reduction of error, is detectable by the operator and second that the means of continuous control is available. Where these two conditions are satisfied then any delay between detection and execution appears as a phase shift between the two continuous movements of the actuating signal and the manipulated variable. It is also necessary that the subject adopts an appropriate strategy since such variables could be detectable but ignored.

It appears from recent work with the mass-spring theory (Kelso et al. 1980; Bizzi, 1980 & Schmidt, 1980) that subjects in the sort of movement to a target task used for example by Keele (1968), might be setting the ratio of opposing muscle length/tension to achieve a final position, in which case a continuous monitoring and control of intermediate acceleration would not be necessary.

Bicycle riding was selected as a naturally arising complete skill which is so constrained that it was very unlikely to be amenable to intermittent control at the lowest level. Because the dynamics are non-linear it was difficult to see how the control could be linear. The main questions to answered were whether the control was intermittent or continuous, which actuating signal was being utilized and what form the output to the manipulated variable took. That continuous proportional responses are within the scope of human operators was shown in a study by McRuer and Kredel (1974) in which subjects were given tracking tasks with varying system dynamics. When the control device was of the non-linear acceleration form the subjects responded by making movements which were proportional to the rate of change of the system error, whereas for rate control the output was proportional to the system error itself. Regardless of the system in use the subjects adjusted the gain so that the input to the operator and the output from the machine were of equal amplitude giving a system gain of 1, thus limiting the input change to a rate which could be easily followed.

A close study of bicycle riding skill stimulates the interest of the psychologist in a number of ways. What exactly is the rider doing in terms of mental operations? How can the behaviour be so flexible as to allow a rider to move from a touring bicycle to a chopper or 1000cc motor-cycle without any apparent need for reshaping the basic skill? Is everyone doing the same thing, or are there distinctive versions of the skill? Why are even experienced riders so bad at describing the details of what they are doing? How do children learn to ride two-wheel bicycles so quickly? Why does convention say that once learned, bicycle riding is never forgotten and is this true? If the skill depends on the automatic stability built into the front forks of all commercially available two-wheel vehicles why could Jones ride his grossly destabilized bicycles without having to relearn his skill? And, central to the controversies surrounding Schema models, how much memory and computation does such a skill demand from the rider and to what extent is it 'ballistic' in the Schema sense of the word? The answers to such questions depend in the first place on finding out exactly what body movements are necessary and sufficient for normal bicycle control, and it is this question which this study aims at answering.

Summary

Bicycle riding was chosen as the subject for the study because it is acquired by many individuals and, being very constrained by its instability, it allows only a limited number of possible solutions. The design of bicycles which has evolved over the years provides a degree of autostability which varies from very little at slow speed to considerable at high cruising speed. The high centre of gravity and small lateral base of the rider/bicycle combination gives a bad balance between the destabilising and correcting couples. This severely constrains the way in which the correcting force provided by the handle-bar movement must be matched to the rate of roll if stability is to be achieved. When leg and upper body movements are ignored the freedom of movement of the rider is also severely constrained to the single plane of the handlebar. A record of handle bar movements and roll rate during free riding represents the input to and output from the human control system exercising the skill providing that they can be isolated from the autostable design of the bicycle.

4. THE COMPUTER MODEL

Mathematical Modelling of the Control System

One of the ways of 'understanding' a time-series such as the rates of roll and bar angle change during bicycle riding is to construct a mathematical model of the process, the model in this context being a formula which predicts the output values from the input. The best possible fit is obtained when the residual errors between the predicted values and the actual values sum to zero and are independently distributed, that is, the error value at any point in the series carries no information about the errors at other points, a characteristic known as 'white noise'.

The normal procedure for constructing a mathematical model of a process is to run it without any control under the stimulation of either a random, 'white-noise' generator or some easily modelled function such as sine wave oscillation. Thus the input is specified as an experimental variable and a model which predicts the output describes the nature of the system without control. This is known as running the system 'open-loop'. Modern control analysis techniques allow a very complete specification of many natural systems in this way including the regimes in which they are stable and unstable and thus the sort of control systems which would be successful in achieving stability.

There are a number of difficulties encountered in attempting to model bicycle riding in this way. The first is that such models are merely mathematical devices for 'joining' as it were the input values to the output and do not necessarily mirror the actual processes under observation. Such a model may be of great use to an engineer who wants to design an efficient control system but is of less assistance to the psychologist whose aim is to understand the human contribution in terms of mental processes and physical movements. In the engineering world the control system is a constructed machine and therefore well understood, the focus of interest being on adjusting its output so that it produces the desired performance. In the biological world it is the control structure itself which is being investigated and its interaction with the rest of the structure is the means of revealing it.

The second difficulty arises out of the nature of bicycle riding seen as a system. The 'open-loop' requirement for the bicycle is virtually impossible to meet because the behaviour of the machine is going to be quite different depending on whether there is a rider sitting on it and whether he is holding onto the handle bars or not. Although the rider's weight could be simulated a run would still be impossible because without control the machine will not stay upright. It might be possible to do very short runs under the influence of say a short wave sine oscillation accepting a fall at the end of each run. However the behaviour of the front wheel assembly, essential to the machine's response, would be quite different if free to turn than if the rider's arms were resting passively on the bar. Since human muscle has a resting 'tonus' or quiescent activity level, and is also capable of reflex responses to length changes and pressures it is virtually impossible to specify what a 'no-control' state in the rider might be.

Mathematical models of control systems are equations showing how the variables behave in relation to each other over time. The functions are continuous and the introduction of either discontinuous inputs or changes that are arbitrary or 'external' to the system invalidate them. It was strongly suspected from the first that bicycle control was at least partially intermittent and it was also seen that it would be virtually impossible to ensure that the rider did not introduce changes during a run which were independent of the feedback of the bicycle's movement.

As has already been mentioned in chapter 2 existing studies of bicycle dynamics have dealt mainly with the problem of trying to express the stability of the mechanical system in equation form with a minimum contribution from the rider. In the interests of simplicity various aspects not relevant to the particular study were omitted. For example Van Lunteran and Stassen (1969) ignored centrifugal forces and assumed a front fork assembly with zero mass and Lowell and McKell (1982) ignored both gyroscopic effects and rider inputs.

The Incremental Model

In order to meet these difficulties it was decided to construct a discrete step model of the mechanical aspects of the bicycle/rider unit which reproduced as nearly as possible the responses to handle bar movement in each time interval. The control sequence which moved the bar would be modified to test a variety of control solutions, including intermittent inputs. The output characteristic would then be compared with that from a real run.

The bicycle/rider combination was broken down into simple units and each of these was modelled independently to determine the movement over a single discrete time interval. The new state of each section at the end of the interval was then used as the starting point for the determination of the changes in the next interval. Where there was a lack of information about performance empirical values were taken from a real machine for the range of speeds and angles that were of interest.

The programs for the computer simulation are printed in appendix 1,(a). As is common with programs which have been developed over a period of time some of the variable names are somewhat cryptic. In the following text descriptions of operations will be kept as self-contained as possible using for the most part abbreviations local to the paragraph. When names are used which also appear in the programs they are in single quotes except in the body of equations where this convention is not followed to save space on the line. BBC basic uses the % sign after a symbol name to denote an integer. These are not shown in the text. The simulation can model either the normal bicycle or the experimental bicycle, which has all the autostability removed. A full description of the latter appears in the next chapter, but it will be referred to from time to time in this chapter as the 'destabilized bicycle'.

The programs were divided into a number of units because of limited memory in the graphics mode. There are several versions of the main program to accommodate differences in control and output printing. Initial variables for a run are set up in the program BIKE and passed to the main program either via the data file VALS or the BBC universal integer set, A to Z. Data specific to the bicycle model being run are in the files BIKE_A, BIKE_B etc. These files also contain the moments of inertia which are calculated separately in the programs BIKEIN and MOMENTS. The details of any bike can be printed with the routine CBIKE. The routine SCALES draws the axes for the main program.

The input to the main program consists of changes to the force applied to the handle bar. These are either fully automatic or can be introduced from the keyboard. The output takes the form of a five axis graph with selected values, such as roll angle, velocity or acceleration plotted vertically against time. The program can be stopped as required and the screen contents printed. Many examples of the output appear in this and in the following three chapters. It should be noted that the names for the variables printed in these figures are different from the names used in the computer program. The convention followed is to use a single quote mark to denote the first derivative of the angle, ie velocity, and two for the second, ie acceleration. Thus, for example, roll velocity is written as R' and steering acceleration as S''.

The rider/bicycle system is considered to consist of two parts, the frame and rider as one unit and the front wheel, forks and handle bar as the other. Within the latter part the rotation of the front wheel was also modelled for the precessional effects on steering. The difference in moment of inertia of the frame between having the steering straight ahead and at some large angle is small so it is ignored. Throughout the text the convention applies where rotation about the fore and aft axis is called roll and that about the vertical plane, yaw. The speed was a constant which could be altered at the start of any run. No account was taken of linear accelerations or retardation forces.

The difficulty in modelling the movements of the bicycle in three dimensions is finding tractable equations. One way to circumvent this problem is to model some limited part of the action only. If, however, all the main ingredients are to be represented then something else has to go. In this model that something is the strictly accurate relationship between the various contributing forces. In the rolling plane this is not very critical as small accumulating errors only give a change in degree. That is, insufficient contribution from the steering angle will lead to a 'sloppier' response in correcting for unwanted roll angle. When the two couples balance to produce zero roll velocity then the system will be re-zeroed. In the yawing plane however the relationship between the planes of rotation of the two wheels and their local relative movement over the ground is very critical as errors here can lead to a reversal of sign which plays havoc with the turning performance. Hence it will be seen that much greater attention has been given to the yawing forces in the main program. The same applies to the calculation of the effective trail distance with changes in roll and steering angle as this is critical for the autostable forces.

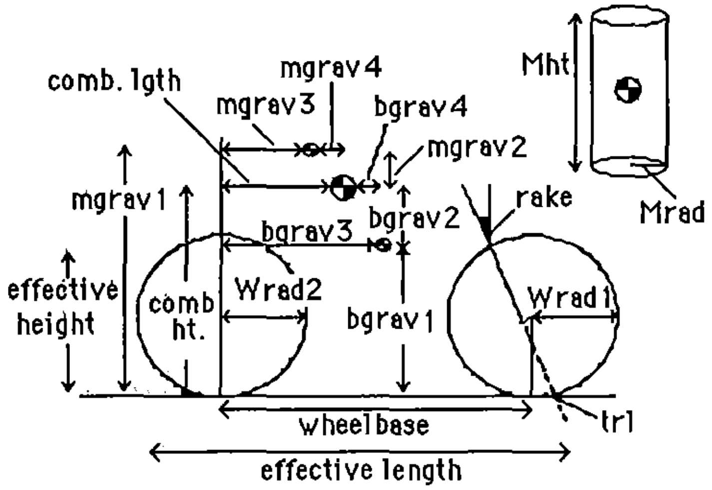


Figure 4.1 Showing the location of the values stored in the bicycle data files.

Rider and Bicycle Dimensions

The Triumph 20 bicycle used for the experimental runs was dismantled, the parts measured and weighed using a steel rule and a spring balance. The rider was regarded as a regular vertical cylinder with no allowances made for limb movements. The weight used for the illustrations in this thesis, at 11.5 stones was the mean weight of the two subjects involved in the experiments. The centre of mass of this cylinder was positioned 6 inches above the saddle. The coordinates for the positions of the centres of mass were taken from a scale drawing of the bicycle which is reproduced in appendix 1,(b). For the calculation of the moments of inertia the bicycle was considered to be a flat plate with no lateral dimension. Since the wheels are considerably lighter than the rest of the frame the effective length and height of this plate were taken from the 0.6 radius point of the wheels. The figure 0.6 was taken as a compromise between the radii of gyration of a solid disc and a wheel with all the weight at the rim, ie 0.5 and 0.7 respectively. All the above values were fed into the file BIKE_C using the routine BIKEIN.

Moments of Inertia

The routine MOMENTS uses the data for the specific bicycle to calculate the moments of inertia used in the main program and store them with the other dimensions in the BIKE_A type files. Figure 4.1 shows the dimensions used in this routine and table 4.1 shows the values for the Triumph 20 bicycle used in the experimental runs. Where the same names are used in the following text they appear in single quotes, except in the equations.

Measurement	Program name	Value	Units
Wheel base	WB	3.28	ft
Front wheel radius	Wrad1	0.85	ft
Rear wheel radius		0.85	ft
Effective height of bike		2.79	ft
Effective length of bike		4.26	ft
Rake angle	rake	20.0	degs
Trail (trl)	trl	0.15	ft
Bike mass		1.0	slugs
Front wheel mass		0.1	slugs
Bgrav1		1.39	ft
Bgrav2		1.89	ft
Bgrav3		1.39	ft
Bgrav4		0.13	ft
Man ht.		6.0	ft
Man rad.		0.75	ft
Man mass		5.00	slugs
Mgrav1		3.64	ft
Mgrav2		0.36	ft
Mgrav3		1.23	ft
Mgrav4		0.00	ft
Combined mass	Mass	6.00	slugs
Combined weight	WT	192.0	lbs
Combined C of G height	HG	3.28	ft
Combined C of G length		1.27	ft
Bar effective length	bar	1.70	ft
Bar mass		0.10	slugs

<u>Moments of Inertia</u>

Vertical about road.	WIo	84.53
Vertical about C of G.	FIo	20.57
Horizontal about C of G.	HIo	2.935
Horizontal about rear wheel	LIo	12.42
Front wheel assembly	FwIo	0.060

Table 4.1 The dimensions for the Triumph 20 bicycle used in the runs. These data are stored in the file BIKE_C. The moments of inertia are generated by the program MOMENTS.

The moments of inertia about the centres of mass for the cylinder representing the man and the plate representing the bicycle are worked out first as follows:-

Vertical Moments

man mom = man mass * ('Mrad'^2)/4 + ('Mht'^2)/12
bike mom = bike mass * (bike ht^2)/12

Horizontal Moments

man mom = man mass * ('Mrad'^2)/2
bike mom = bike mass * (bike length^2)/12

Steering Moments

bar mom = bar mass * (bar length^2)/12
Fwheel mom = Fwheel mass *((wheel rad * DE)^2)/4

where DE is the conversion for a wheel with its mass at the rim to an equivalent uniform disc.(=1.4144)

The combined moments of inertia are now worked out using the parallel axis theory. The general equation is:-

Combined mom = mom about C of Mass + (mass * (PD^2))

where PD is the separation between the axis under consideration and a parallel axis through the centre of mass. The various combined moments are listed with their program names and the relevant values of PD:-

Vert. about road	'WIo'.............	'Mgrav1', 'Bgrav1'
Vert.about C of M	'FIo'.............	'Mgrav2', 'Bgrav2'
Horz. about C of M	'HIo'.............	'Mgrav3', 'Bgrav3'
Steering moment	'FwIo'.........	bar mom + Fwheel mom

Side Force at the Wheel/Ground Contact Point

Whenever an object runs in a curve a force at right angles to the direction of travel must be present. This force comes from the action of the wheels running at a slight angle to their direction of travel, dragging the tyre over the ground. The theory governing the forces produced at the tyre/road contact point is too complex and incomplete to allow its use in this part of the model. However it is evident that the general characteristic of more angle more force holds good up to some critical angle where the tyre stalls and the force becomes very large and is directed almost entirely backwards as drag opposing forward movement. It is also obvious that the force for a given angle is dependent on the speed. It was therefore possible to run a bicycle in a turn and, knowing the weight of the system, the radius of turn and the speed, calculate what the force towards the centre must be. This method was not very precise, but all that was required was some guidance of the size of force per wheel to ground angle and an idea of whether it varied directly as the speed and angle or in some more complex relationship. Once an approximate value was obtained it could be trimmed in the simulation to suit a range of useful speeds.

When a bicycle runs in a steady turn the radius for the front wheel is greater than that for the rear. This difference in turning radius was found by measuring the wheel tracks, allowing a reasonably accurate estimate of the angle at which the rear wheel was dragging to produce its contribution to the turning force. When the system is in a steady turn the force at the front wheel must be slightly in excess of that at the rear to maintain the rotation but this difference was ignored in establishing the force per wheel, that is the total force was divided equally between the two wheels.

The following measurements were made with a 170 lb rider on the Triumph bicycle (weight 30 lbs). The speeds were estimated approximately by timing the pedalling rate for a distance of 70 yards prior to entering the turn. The steering angles were estimated by eye against a marked scale fixed to the frame and are very approximate. These are not used in calculating the estimated flow angle for the rear wheels but served to confirm the fact that both wheels were dragging over the ground at approximately the same local angle. The runs were made on a newly swept sand surface and left very clear marks from which the radii of the turns were measured with a steel tape. Each turn was made through 360 degrees.

Speed (ft/sec)	Steer-angle (degs)	Radius (ft)	Rad.diffs (ins)	Drag-angle (degs)	Force per wheel (lbs)
15	5-10	26	2-3	0.5	27
10	10-15	18	3-4	1	17
10	15-20	11	4-5	2	28

The last run was almost at the adhesion limit for the tyres on the loose surface and when the turn was tightened the radius difference increased to about 5.5" and then the wheels slipped. The drag angles were measured from a large scale drawing of the radii and bicycle frame and are approximate. Because of tyre distortion under load the relationship of force to both angle and speed is not a simple straight line. To obtain an approximate relationship for these two factors it is assumed that the force increases directly with angle. If the first and last runs are then considered it can be seen that they generate much the same force since the larger radius turn is performed at a higher speed. If the same angle relationship is applied it will be seen that the speed factor must multiply the force effect by about 4. This is very approximately equivalent to a cube function of speed. Raising the speed to the power 2.7 gives a fairly consistent coefficient of .03 for the three runs but is of course very rough. However this was sufficient to guide a choice of values for the simulation which after some trimming was taken as speed raised to the power 1.8 with a coefficient of 0.2.

Force = drag angle(degs) * (VV^1.8) * CD

where 'VV' is the speed and 'CD' is the drag coefficient. This keeps the system stable within the speed range 2 to 15 mph which is all that was required.

The side-force is frictional and will therefore depend on weight. Because the tyre is not rigid it will distort with different loads so the exact relationship between weight and force is not known. In order to allow for this change the coefficient is made directly proportional to the weight. This is established in the line:-

CD = 0.0014 * WT

which must of course come before the line given above. This gives a satisfactory performance over the weight range 32 lbs (riderless bike) and 284 lbs (18 stone rider).

In reality it is obvious that there is much more to tyre behaviour than is captured here but the main point is that despite very large differences in tyre type and riding condition all bicycles behave in approximately the same way so exact details within those limits which allow a stable performance are not important for the model and did not justify a more exact measurement on the real bicycle.

Rotations in the Horizontal Plane

The linear speed of the machine is assumed to be constant and no account is taken of fore and aft retardation forces. The mass of the bicycle/rider unit will not travel in a curve unless there is an unbalanced force acting at right-angles to the local direction of travel. This force must be generated by the wheels 'dragging' at an angle to their local direction of travel. Once in a turn the relative movement between the ground and any point on the bicycle is represented by the tangent to the turning circle at that point. With any turning system whether it is a car, a bicycle, a boat or a ski, this relative angle will only be the same for all points when they lie on a common radius. Thus since all such systems are orientated normal to the radius and more or less facing the direction of movement it follows that there will be a difference between the local surface movement at the front of the object and that at the back. The controlling ratio is that of the length of the object compared with the radius of the turn, so for a given length the tighter the turn the greater the effect. This difference of surface to object velocity during turning manoeuvres is critical to the ability of all systems which use relative surface movement to generate the turning force, to sustain a controllable turn. Unless some angle difference is introduced between the front and rear of the system the increasing curvature of the flow as the turn develops will produce an out of the turn rotating couple which will back- off the generating angle and stop the turn. In every controlled turn the couple rotating the object must be exactly matched with the total force controlling the radius of turn in such a way as to preserve the wheel to ground angles and the forces they generate. It is the lack of tractable equations to represent this situation which has led to such limited models of bicycle performance.

Because this simulation uses a discrete step rather than a continuous solution it is able to establish these important angles geometrically. The principal reference is taken as the north axis in the conventional cartographic sense. Angles are measured as positive from north in the westerly direction and negative in the easterly. There is no anomaly in the southern segment as the model does not exceed 90 degrees either side of north.

At the start of any time interval, 'Ti', each wheel will have made some angle to the local relative ground movement in the previous interval. Whenever this angle is greater than zero a force at right angles to the plane of the wheel will have been generated, the value depending on the actual angle and the speed. During the new time increment the combination of these two forces is regarded as an impulse acting on the centre of mass which will then move during the interval under both this influence and the linear velocity which is defined as a constant. Any difference in size or direction of the two wheel side-forces will also cause a rotation during the interval. The combination of the linear and rotational movements will lead to different relative paths for the front and rear wheel contact points which must be used to find the new forces generated at each wheel during the new interval. The front wheel is free to rotate in relation to the frame so this relative movement will also produce a couple in the steering when the ground contact point lies anywhere but directly on the extended hinge axis. In the normal 'autostable' bicycle this is the effective trail distance. The front wheel, having mass, will also have its own inertia and angular velocity about the steering axis which will influence the angle it makes with the external reference and the frame. The precessional effect of the front wheel due to rolling movements of the frame must also be added to this couple.

Values required in the horizontal plane

'Ti' One increment of time (10 msecs)

'VV' The linear velocity of the centre of mass.

Mass WT Mass and weight of bicycle plus rider.

'RA' Angle between local direction of travel of the centre of mass and north.

'HA' Angle between the frame of the bicycle and north.

'SA' Angle between the front wheel plane and north.

'RSA' Angle between the front wheel plane and the frame. (RSA is written as R in the printout figures)

'L2' Angle between the frame and the local direction of travel at the rear wheel contact point.

'L1' Angle between the front wheel plane and the local direction of travel at the front wheel contact point.

'Hw' The angular velocity of the frame.

'Sw' The angular velocity of the front wheel, forks & bar. (Sw is written as S' in the figures)

'Roti' Angle of ground 'flow' to frame due to rotation.

'Si' Distance increment travelled by C of M in time Ti.

'RAi,HAi,SAi' angle increments in time interval Ti.

'HwDOT,Sdot' angular accelerations of frame and front wheel. (Sdot is written as S'' in the figures)

'F1,F2 & FF' The forces at the front and rear wheel and their addition.

'Trl' The effective trail distance.

The method of working out the movement of the ground relative to the front and rear wheel contact points (called the ground 'flow') is as follows:-

(i) 'F1, F2 and FF' are found using 'L1 and L2' from the previous increment:-

F1= (L1 * Ffac) F2=(L2 * Ffac) FF= F1 + F2

where 'Ffac' is the frictional coefficient for the tyre adjusted for speed and weight.

(ii) 'FF' is normal to the direction of travel by definition. This disregards the difference between the frame angle and direction of travel but is sufficiently accurate for the shallow turns under consideration. The error is a function of radius of turn and rear wheel ground flow angle. For a 26 ft radius turn with 1.5 degrees flow angle it is just over 1 degree. 'FF' is applied as an impulse over the time increment 'Ti' at right angles to the direction 'SA', giving an angle increment 'RAi':-

RAi = ATN(FF * Ti) / (Mass * VV)

(iii) The linear advance in one time increment:-
Si = VV * Ti

(iv) Any difference between the wheel forces 'F1' and 'F2' will form a couple rotating the frame. The increment of rotation ('HAi') is found by combining this couple with the angular velocity ('Hw') from the previous time increment:-

HwDOT =(F1-F2)*WB1/(HIo*COS(VA)+(FIo*SIN(VA)
HAi = (Hw * Ti) + (HwDOT * (Ti^2)*0.5

where 'HIo' and 'FIo' are the angular moments of inertia in the vertical and horizontal planes. 'VA' is the lean angle and 'WB1' is half the wheel base. Both moments of inertia have to be considered when there is an angle of lean. The couple arm 'WB1' is not exact as it will vary for different systems. For the Triumph 20 it is 0.43 of the wheelbase, for the Carlton it is 0.5. Now the new angular velocity may be found:-

```
Hw = Hw(previous) + (HwDOT * Ti)
```

(v) In a similar manner the change in the steering angle ('SAi') is established. The couples acting in the steering plane are the weight and 'F1' force acting through the trail distance of the castor effect, the steering force acting over the handle bar length and the precessional effect due to any roll angular velocity present:-

```
Sdot = (PC*Vw)+(SF*bar)+(F1*Trl)+(WT1*SIN(VA)*Trl)/FwIo
   SAi = (Sw * Ti) + (Sdot * (Ti^2) * 0.5)
```

where 'PC' is the precessional coefficient, 'SF' is the steering force, and 'FwIo' is the front wheel angular moment of inertia about the steering axis. Strictly speaking WT1 should be the proportion of the weight falling on the front end of the machine. In practice this is taken as being equally divided fore and aft, so WT1 is (WT/2). The force due to the precession of the front wheel is:-

Moment of Inertia * angular velocity of wheel
* roll velocity

The first two terms together are the angular momentum, 'PC', which is established with the line:-

PC = (FwIo*2) * (VV * Pi * 2 /(front wheel diam * Pi))

The moment of inertia is multiplied by 2 because the stored value is the inertia about the steering axis which is half that about the axis of rotation. The expression is only solved once for any run so, in the interests of readability in the program it has not been simplified any further.

The new angular velocity of front wheel unit is:-

Sw = Sw(previous) + (Sdot * Ti)

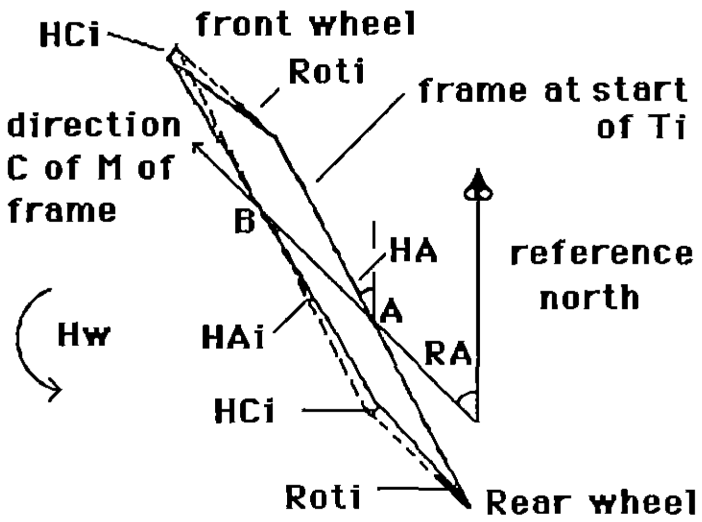


Figure 4.2 Finding the local ground/wheel 'flow' angles during a turn.

Finding the Front and Rear Ground Flow Angles

Figure 4.2 shows the translation and rotation of the frame during a time interval 'Ti'. During 'Ti' the frame advances in the direction 'RA' from A to B, a distance 'Si'. Without rotation it would end up in the position shown by the dotted lines with the front and rear extremities having traced out paths with the same angles to the direction of travel. In the situation envisaged it is supposed that an imbalance between 'F1' and 'F2' rotates the frame to the left through the angle 'HAi' and the front and rear of the frame move through the distance marked as HCi. The ground flow at the front of the frame alters by the angle 'Roti' so that it comes more from the left, that is the flow angle is increased while that at the rear is decreased by the same amount. The angles 'RA' & 'HA' have been exaggerated in the diagram for clarity, but for the small angles of flow normally encountered HCi may be regarded as the common arc of the two triangles giving the relationships:-

HCi = HAi(Rads) * half the frame length
Roti(Rads) = HCi/Si

The relationship of the ground flow at the two ends of the frame to the external reference is:-

Front = RA + Roti Rear = RA - Roti

Signs of the Angles

Strict attention must be paid to the signs of the various angles to ensure that their correct relationship is preserved for all conditions. These are:-

'RA' positive to the left, negative to the right
'HA' positive to the left, negative to the right
'Hw' positive when rotating anti-clockwise

'Roti' takes on the sign of HCi which in turn takes the sign of 'Hw' via 'HAi'. The other conventions adopted are:-

Flow Angles. Positive when that flow applied to the front of the frame would lead to a positive (anti-clockwise) rotation.

Forces ('F1,F2'). Positive when causing an anti-clockwise turn.

The resulting rule for maintaining the correct relationship at the rear wheel under all conditions is:-

$$L2 = HA - (RA - Roti)$$

Since the front wheel is free to steer under the influence of the road and bar forces its angle ('SA') must be measured in absolute terms. Once its resulting position for a time increment has been established then the relative angle ('L1') it makes with the ground flow can be found. The sign convention here is:-

Front wheel to frame ('RSA') positive when anti-clockwise.

Front wheel flow angle ('L1') positive when causing an anti-clockwise rotation.

The rule for finding 'L1' is:-

$$L1 = SA - (RA + Roti)$$

and the relative steering angle is:-

$$RSA = SA - HA$$

Order of calculating the variables

It is obvious that the exact place in the routine where values are updated will make a difference to the outcome and so their sequence must be chosen with care. Variables common to several equations, such as velocity, must be updated at the end of the period. It will be seen in the programs AUTO and DESTAB in appendix 1,(a) lines 6000,6999 that the sequence is:-

Forces (F1,F2,FF) from previous angles (L1,L2)

Accelerations New forces, old velocities, trail & bar force

Angle increments. New forces & accelerations, old velocity

New flow angles Roti,L1 & L2

New velocities

New trail distance and bar force.

Rotation in the Vertical Plane

Roll is influenced by two couples. First the weight acting over the horizontal distance from the support point of the wheels when there is an angle of lean, and second the side force acting through the tyre contact points acting over the vertical distance from the ground to the centre of mass. This latter couple is exactly the same as the centrifugal force acting over the same distance. The way the moments of intertia interact with these two couples in altering the roll is complicated. The weight rotates the rider/bike combination about the ground contact point but when the bicycle is turned to counter a fall the action of the wheels on the ground does not pull the centre of mass back up to a position above the contact points but moves them in under the weight as it were. The equations which express this relationship do not resolve into convenient values. For the program however the general situation can be simply expressed in this way. More lean means more acceleration into the fall and more ground/wheel angle means more acceleration out of it. The values for these couples are easy to find so the problem rests in finding suitable values for the inertias or viscosities of the response to them. As a simplification of the true situation the moment of inertia used for the weight acceleration, 'WIo', was taken about the ground contact point and that for the tyre-force, 'FIo', was taken about the centre of mass. In practice this solution works well and there was no need to trim the values.

The values used for working out the roll rate are:-

'VwDOT'	Angular acceleration in roll (R'' in figs)
'Vw'	Angular velocity in roll (R' in figs)
'VA'	Roll angle (R in figs)
'WIo'	Moment of inertia about ground contact point
'FIo'	Moment of inertia about centre of mass
'HG'	Frame height of CG above ground.
'FF'	Combined side force from tyre/ground points.

The acceleration in roll is found with the line:-

```
VwDOT=((WT * SIN(VA) * HG) / WIo)
          +((FF * COS(ABS(VA)) * HG * -1) / FIo)
```

'FF' is the value found in the previously described horizontal rotation section. Note the correcting couple takes the reversed sign of this value not the lean angle.

The increment, angle and roll velocity for Ti are found in the same way as the equivalent values in yaw:-

```
VAi = (Vw * Ti) + (VwDOT * 0.5 * Ti^2)
VA = VA(previous) + VAi
Vw  = Vw(previous val) + (VwDOT * Ti)
```

and the order of calculation must be adhered to.

Calculating the Effective Trail Distance

The effective trail distance is the distance from the ground/tyre contact point of the front wheel to the steering axis measured perpendicular to the axis,(see figure 4.3). As the steering angle increases so this distance reduces. For any steering angle the distance also reduces as the angle of lean increases.

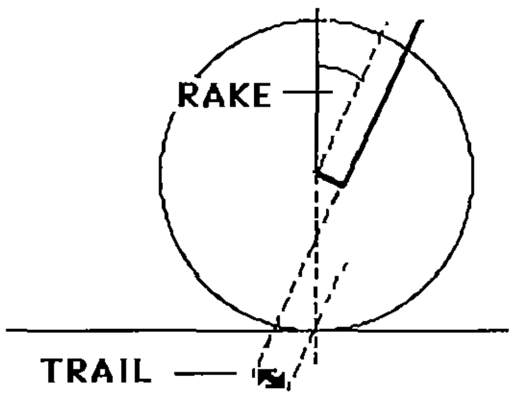


Figure 4.3 Showing the effective trail distance in relation to the front wheel and front forks.

At varying combinations of roll and steering angle the distance reduces to zero and then increases in the opposite direction. At small lean and steering angles when the distance is positive it provides part of the autostability of the bicycle and is therefore a vital ingredient of the model. There are three ways of finding this distance. (1) Make selected physical measurements on a real bicycle at different steering and lean angles. (2) Describe the front fork and frame in space coordinates and apply the appropriate transformations. (3) Apply spherical trigonometry. Of these three the last is the only one which will provide an accurate value for all combinations of angles without taking up either too much memory or too much computation time. The equations are complicated and would take up a great deal of space to explain in detail, thus the final solution only is given. The other two methods were used to provide a table of selected values as a check on the accuracy of the method used.

Variables External to the Subroutine

'RSA' Angle between the front wheel and the frame
'VA' Angle between the frame and the vertical
'RP' The front wheel radius
'HL' The rearward 'rake' of the steering axis
'R90' Rad of ninety degrees
'Ld' Zero angle trail distance

First the signs of the steering and roll angle are adjusted:-

```
SA = ABS(RSA)        VA = ABS(VA) * SGN(VA) * SGN(RSA)
SD = (ATN(TAN(SA)*SIN(HL))
```

Some abbreviations to simplify the layout:-

```
CD = COS(SD)         CH = COS(HL)         SW = ACS(CD * CH)
```

Then:-

```
b = RP * COS {ACS [(CH-(CD*COS(SW)))
                              /(SIN(SD) * SIN(SW))]}
theta = (R90 + (VA + SD))
GA = ATN {b / (RP * -1 * TAN (theta))}
trail = {(RP * SIN (GA - SW)) + Ld}
```

The Printed Graphs of the Simulation

With the exception of two graphs which show the output in the horizontal for direct comparison with the actual recordings, all the figures showing the performance of the computer simulation take the same form. With reference to figure 4.4, which is the first of these diagrams, it will be seen that a brief title identifies the model and the speed at which it is running. The output is displayed on five vertical axes with zero time at the bottom. Seconds are displayed in the left margin. At the top of each axis is a bar and above this a figure in brackets which shows the value along the X axis of half the bar. Above this is a letter which identifies the variable running on that axis. These are the same for all the diagrams and read, from left to right:-

R Angle of lean (roll) in degrees
S Steering angle relative to bike frame in degrees
R'' Roll angular acceleration in degrees/sec/sec
S'' Steering angular acceleration in degrees/sec/sec
R' Roll angular velocity in degrees/sec

Testing the Model

With the discrete time increment method employed in the model the changes are never absolutely accurate as there is no feed-back between functions during the interval. For example changes to the steering angle during time Ti would obviously affect the rate of frame rotation so that the predicted change in frame angle due to the previous wheel angles will never be quite correct.

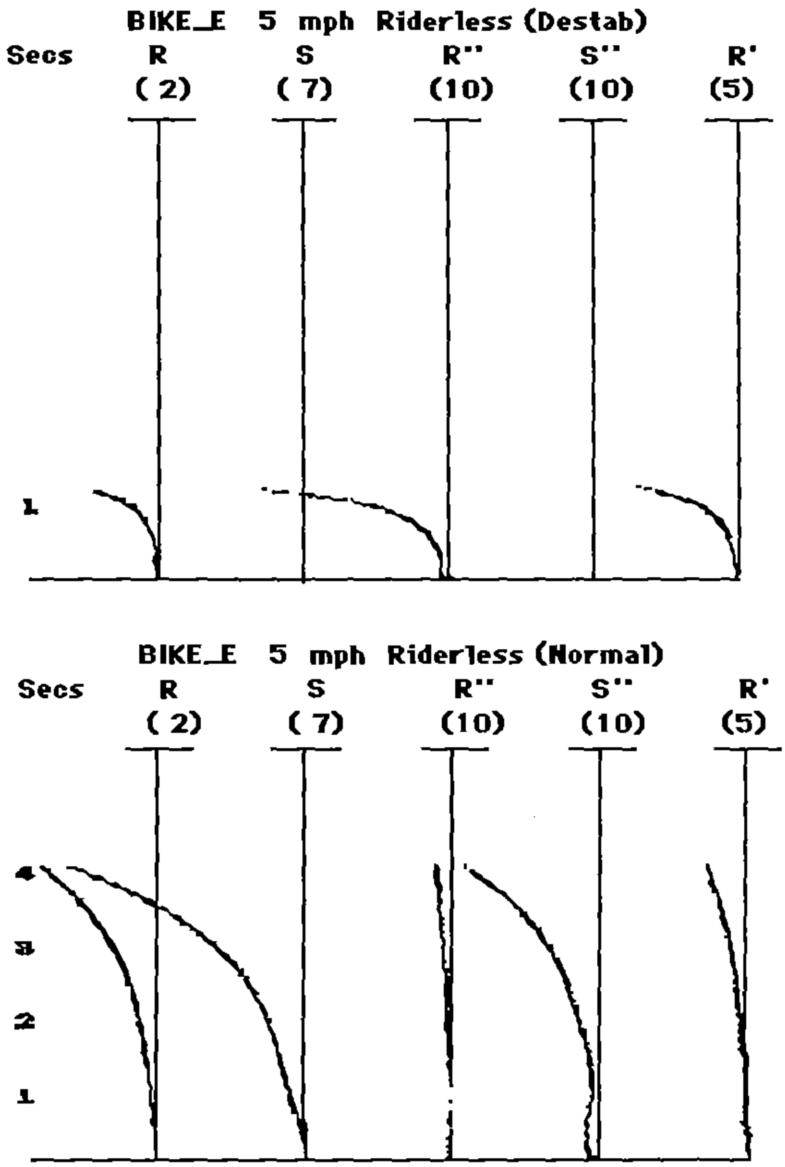


Figure 4.4 The behaviour of the simulated Triumph bicycle without a rider pushed off at a speed of 5 mph. Speed decay is not simulated. The top graph shows the destablized machine and the lower graph the normal bicycle. See text for details.

It is evident that greater accuracy could be obtained by operating some recursive procedure which ran through each set of calculations a number of times trimming the input variables on each run to get the best possible fit between the competing contributions. However it was decided to do without this if possible by using very small time increments and putting up with the long computing time. The nearer the time increments come to zero the nearer the procedure approaches a truly continuous relationship.

As will be seen in later chapters the model reproduces all the general characteristics of the real bicycle. If the bar is turned during upright running the bicycle rolls strongly out of the turn and if then left to its own devices the autocontrol will restore upright running. Increase in speed increases the autostable response. Trimming the tyre response coefficient will adjust the amount of front wheel movement required to produce a given lean/turn movement without altering the overall relationship. The physical dimensions of both the rider and the bicycle can be altered without changing the general performance. It is even possible to put some rather extreme bicycles into the model, such as a penny farthing or a circus 'tower' bicycle (in which the rider sits on the top of a six-foot tower with remote steering) without disturbing the behaviour.

An exact correspondence between the model and the particular bicycle chosen was not important as the requirement was to represent the general rider/machine situation. Any competent rider can ride any normal bicycle without practice, and it was assumed for the purposes of the initial model that all riders on any bicycle behave in roughly the same way. To serve its purpose the model had only to capture the characteristic behaviour within this general bracket. When the time interval is too large the system starts to overcontrol and eventually reaches a stage of diverging oscillation. A time interval of 10 msecs was established as the best compromise. At 20 msecs there was some sign of instability on hard manoeuvres and at 5 msecs, any difference was too small to show on the screen printouts.

Two specific tests illustrate the above points. Anticipating the findings of chapters 5 and 6, a delayed control system is a more demanding test of the simulation than the instant autocontrol of the normal bicycle. In the first test such a system, set at a delay of 120 msecs and the normal time interval of 10 msecs, will contain an initial disturbance of 5 degrees of lean within 10.5 degrees of roll. If the interval is changed to 5 msecs the performance is indistinguishable from that at 10 msecs. If the interval is increased by a factor of four to 40 msecs the fall is still checked at 10.5 degrees but the system is thrown into an unstable oscillation.

The second test simulates pushing the bicycle off at a smart trot without a rider. A normal bicycle treated in this way will fall, slowly at first, into a turn one way or the other. After about 4 seconds the angle becomes extreme and the bicycle falls rapidly to the ground. The destabilized bicycle pushed in this way falls to the ground in about 1 second in the direction of the first angle displacement.

The real bicycle will slow down during this manoeuvre whereas the simulation has no capacity for variable speed so is slightly slower to fall. Figure 4.4 shows the computer printout for the two conditions described using a launch speed of 5 mph and an initial displacement of 0.1 degrees to the left. In the first there is no autocontrol and the bicycle falls over in about 1 sec. In the second, with the autocontrol working, the gyroscopic and castor effects limit the rate of fall but cannot contain it and the bicycle eventually falls over in about 4 seconds. The time to fall for the real bicycle when launched at a fast trot was about 3.5 secs. The failure of the autocontrol to prevent the fall is mainly a function of the speed. It will be demonstrated in chapter 7 that when the speed is high enough the autostability will maintain straight running with a rider. If the simulated bicycle is launched without a rider at 20 mph it runs true and will recover from disturbing pushes to the handle bar. No test of the real bike was made at this speed although the author heard a first-hand account from an owner who, as a result of a bet, pushed his riderless bicycle down a steep hill and it ran upright to the bottom.

It might be thought that changes in weight would have a large effect on the performance but this is not so. Because the coefficient of tyre response depends on weight the increase in disturbing couple is matched by an increase in tyre effectiveness which keeps the performance more or less the same. A test of the model with different riders gave the following responses to a fairly strong initial disturbance of 5 degrees using the destabilized bicycle which is a more severe test of the system:-

Wt of Rider (stones)	**Init. disp.** (degs)	**Fall contained** (by. degs)
5	5	8
11.5	5	8.9
18	5	7.6

In each case the general characteristic was exactly the same, that is the bicycle recovered to stable running after two or three damping oscillations though there were of course small differences in the detail of how much bar was used to control the movement. The exact performance depends on how the coefficient actually alters with weight, but for the purposes of the study the performance resulting from the approximation was quite adequate.

Summary

This chapter has introduced the simulation which is used to test various control sequences. It has avoided the classical difficulty caused by the lack of tractable equations by using a discrete step technique which, although slow in operation, represents the mechanism of free riding sufficiently accurately to predict performance of a variety of possible control sequences. In the next three chapters a close study is made of roll and handle bar angles recorded during free riding. Control sequences suggested by this work are tested on the simulation to find their stability and whether they produce an output characteristic which matches that of the real machine and rider.

5. THE CALIBRATED BICYCLE

Introduction

The main requirement was to obtain a detailed record of the activity in the roll plane and at the steering head on a common time base during normal free riding. Before any recordings had been made it was not known exactly which information would be of the most value so provision was made for recording both roll and yaw rates. It became evident that the yaw information was not needed and since the number of recording points per unit time for any single channel depended on the total number of channels in use only the roll and handle bar channels were used for the main runs.

Angle Change Sensors - Roll and Yaw

Either an accelerometer or a roll-rate meter will provide the information required but the latter type of sensor was chosen as it was cheaper and more robust. Two Smiths Industries type 902 RGS/1 Rate Gyros, were mounted at ninety degrees to each other, one in the vertical rolling plane and the other in the horizontal yawing plane. No matter what the angle of lean, the roll sensor continues to give the correct rate of change but the yaw meter output is corrupted by any lean, giving a response that depends on the cosine of the angle. This was considered acceptable since the main interest was in the roll channel and for normal riding the angles of lean were not expected to exceed ten degrees which means the yaw output would be within 98% of its true value. The roll-rate meters are 'tied gyros'. A gyroscope is set in gimbals which allow movement in the measuring plane only. Any displacement of the gimbal from zero is detected by an optical sensor which then drives it back to the zero position via a precessing current applied to a coil winding. The current is proportional to the rate of angular movement and this is the detected signal. The maximum rate is 50 degrees per second which is more than adequate for the task and the sensitivity is 60 mVolts/degree/sec. The gyros are powered by a 6 volt accumulator carried on the bike in the instrument box.

Angle Sensor- The Handle Bar

The angle of the handle bar is read from the output of a sensitive potentiometer geared via a rubber belt drive to give 360 degrees of potentiometer movement for 106 degrees of bar movement. The potentiometer output varies from +2.5 volts to -2.5 volts giving a sensitivity of .0139 volts per degree of movement. The Zero position of the bar and potentiometer drive were etched with two marks that were aligned when the wheel was dead ahead. Some difficulties were experienced at first with zero drift due to the 'O' ring drive band losing its elasticity. This was overcome by fitting a thicker band. Zeros were measured with a special routine during testing but since the main interest focussed on the rate of angle change, that is the differential of the output, exact zeroing was not very critical.

Speed Sensor

A perforated disc driven by a road wheel with a light-sensitive cell counting the rate at which the perforations passed it, produced a voltage output proportional to the road speed. Since this device required its own transmitting channel it was not used in the main runs in order to improve the density of recording points for the roll and handle bar channels. Speed was not a critical factor and was calculated approximately from the length of the run and the time taken.

Transmitting the Output Voltages

Initially a radio relay link was built to transmit the output voltages from the sensors to the microcomputer for recording but the problems of interference between the gyroscopes and the transmitter were never satisfactorily overcome so a simple cable was used instead. A 5mm diameter multicore screened cable carried the four output voltages from the detector box on the bicycle to the micro-computer. Losses due to cable length were found to be negligible and the rider was unaware of the slight drag at the rear of the machine. An 80 ft cable gave about 25 seconds of recording time for a rider travelling very slowly in a straight line. Longer recordings were of course possible when turning. Most of the runs were in a more or less straight-line but no difficulties were experienced even when several turns were made back over the cable.

Recording the Output Voltages.

The positive and negative outputs from the gyroscopes and steering potentiometer were converted on board the bike to the 0-1.8 volts necessary for the Analogue to Digital Converter (ADC) in the BBC microcomputer. The electronics, the gyroscopes and the accumulator battery were housed in a box that was bolted to the rear carrier of the bicycle. The transmission wire trailed from the rear of the box clear of the back wheel. The corrected voltages were fed directly into the ADC port of the BBC which was housed in a mobile laboratory with a mains electricity supply. An assembly code routine running on the micro read the output from the ADC channels at their fastest conversion rate which is approximately 10 milliseconds per channel and put the raw data into a reserved memory block. The additional manipulations brought the time for recording one point to approximately 13 msecs plus a constant 4 msecs overhead regardless of the number of channels in use. At the end of the run this block was down-loaded onto disc, clearing the space for the next run. A short binary file was also stored for each run giving the run details associated with the raw data file. Another program measured and recorded the zero voltage output of the four channels as a check between runs.

CONTROL OF THE DESTABILIZED BICYCLE

The Experimental Bicycle

A Triumph 20 inch wheel model was used for the runs. This gave a large range of seat and handle bar adjustment, allowing any size of subject from large adult to ten years old child to ride with comfort. The recording box and handle-bar potentiometer could be easily removed and replaced. Only the rear brake was retained because of the bar potentiometer. The three speed gear could be altered between runs but was normally set on low gear.

Removing the Castor & Gyroscopic Effects

The front forks of a normal bicycle are designed to provide a measure of autostability. In order to ensure that only the rider's contribution to control was recorded this stability had to be removed. Figure 5.1 and the frontispiece show the alterations made to achieve this aim.

First the frame was altered to remove the rake from the front wheel steering axis, bringing it into the vertical. The forward throw of the axle was also removed by mounting it on a bracket. The distance between the ground contact points of the wheels was not altered but the front point now lay directly on the extended steering axis at all steering and lean angles. With this configuration, side forces generated during steering no longer produce a couple in the steering head. The handle-bar remained in its normal position driving the front wheel via a short drag link. Jones (1970) showed that the front wheel of a bicycle acts like a gyroscope during riding, precessing the steering into the fall and providing a degree of autostability. When he constructed a bicycle with a second front wheel alongside the first and rotated it in the opposite direction the bicycle was much less stable in roll. Jones' wheel was not driven but spun-up by hand before the run.

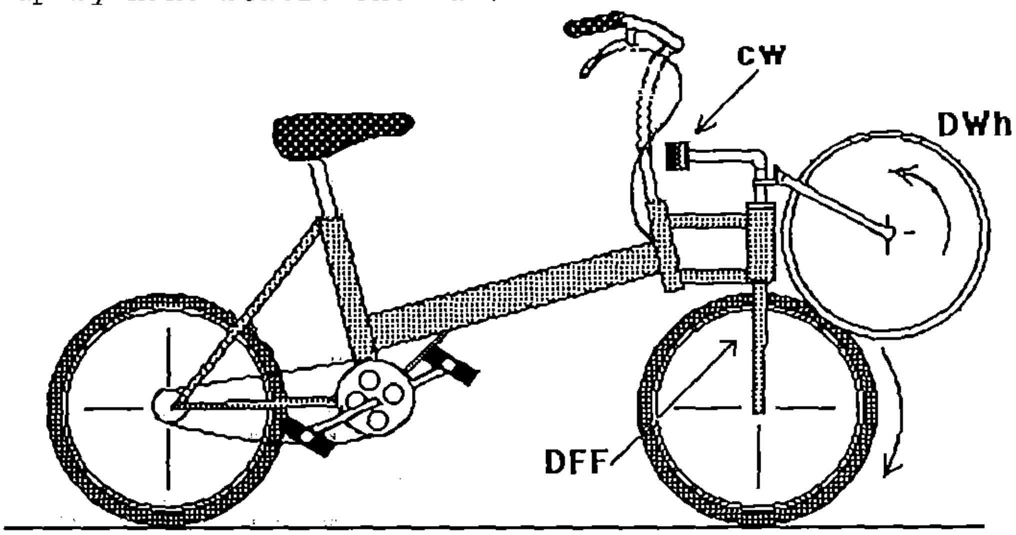


Figure 5.1 The destabilized bicycle, showing the front forks (DFF) without castor, trail distance nor headrake. The destabilizing wheel (DWh) is driven in the opposite direction to the front road wheel which cancels the gyroscopic effect during rolling movements. This wheel is mass balanced by a counter weight (CW).

To remove the gyroscopic effect from the experimental bicycle a second front wheel was mounted above the primary wheel in such a way as to be driven in the reverse direction but at the same speed. The tyre was removed so that the grooved surface of the rim ran on the top of the normal tyre and the rim was weighted to give it the same mass distribution as the original. This arrangement put the second wheel ahead of the centre of rotation so it was balanced with a counter weight.

The Performance of the Zero Stability Bicycle

Although the extra wheel and the counter weight obviously increased the inertia of the steering assembly and the indirect operation made for a little more play than normal, riding the Zero Stability Bicycle felt almost exactly the same as riding the unmodified machine. This was predictable since the autostability makes little contribution to control at low riding speeds. The steering felt light and well balanced, although the sight of the large assembly moving during turns was a little strange at first.

Two simple tests demonstrated that the autostability had indeed gone. Like Jones' destabilized machines this bike had no capacity to run on its own. If launched at a good running speed it fell rapidly towards the side of the first random displacement where the unmodified machine would run on its own for several seconds. A pedestrian pushing a normal bicycle can steer it by holding the saddle and rolling the frame towards the desired direction of turn. The destabilized bike could not be steered in this manner as the wheel just kept pointing dead ahead no matter what the operator did with the frame. It was not possible to ride this bicycle 'no-hands', and it was potentially dangerous as a road machine as there was no natural tendency for the front-end to iron out sudden directional disturbances caused by road bumps. Neither experienced nor inexperienced riders had any difficulty controlling this machine in ordinary manoeuvres at low speeds, even when blindfold.

Subjects

The runs to which this section refers were made by two subjects. Rider A was a male subject, age 52 years, weight 178 lbs. He was an experienced bicycle rider in good current practice. Rider B was also a male, age 34 years, weight 147 lbs. Rider B had been a regular rider in his youth but had not ridden a bicycle much during the five years preceding the experiments. The two riders' leg lengths were sufficiently similar for them to use the same seat pillar height. This put the riders' centre of mass some 150 mm above the seat and slightly in front of it. The scale drawing in appendix 1.(b) shows the calculation for the combined centre of mass for rider and bicycle. Despite the difference in weight between the two subjects the two centres of mass are very close together being just in front of the saddle peak.

Method of Operation

The runs were made on a calm dry day on a sand-surfaced hockey pitch. A mobile laboratory containing the microcomputer was positioned on the edge of the area near to a mains plug on an electric sub-station. The transmitter cable was pulled out to its full length to one side and the rider positioned at a marked start point heading on a course leading back down the wire. The runs passed fairly close to the recording station and were continued beyond it taking the wire out to the other side. The experimenter stood within reach of the microcomputer. When ready for the run to start he called for the subject to start and pressed the start key as soon as the rider was stable. The program shut down after recording 750 data points in each channel, which at 30 msecs per point is 22.5 secs. The end was signalled by a double beep and the experimenter called for the rider to stop.

If it looked as though the rider would come to the end of the wire before the automatic time was up the run could be successfully terminated by pressing the appropriate key. If the rider failed to stop then the cable pulled out of its mounting without damage. The near end of the wire was firmly anchored to prevent its damaging the computer. Each recording period lasted approximately 22 seconds, starting shortly after the rider set off. All runs were started from the same place and the approximate location where the recording terminated was noted. Since speed was not regarded as a critical value the approximate mean distance of the runs was measured as 90 feet which gave an estimate of speed of 4 ft/sec or just under 3 mph.

Blindfold Riding

At the start of the study it was evident that the detection of roll rates is critical to the operation of any control system. Since both the vestibular and visual systems are capable of giving this information it was decided to attempt blindfold riding during the recording runs in order to reduce the number of sensory channels being used. It turned out in practice that depriving the rider of vision seemed to make little or no subjective difference to the task, once the initial worry of riding out of the prepared area was overcome. So far six people have ridden blindfold. In each case the rider put on the blindfold and went straight off without any difficulty. In two cases, both children of ten, this first run was on the destabilized model making the task that much more exacting. Lack of time has prevented a more thorough investigation to date, but the sureness with which all six subjects tackled their first blindfold run argues for its generality. All the runs relevant to this section were made with the subjects blindfolded.

Instructions

The subjects were instructed to ride as slowly as possible without falling off until told to stop. There were two reasons for opting for the lowest possible speed. The first the restriction of the transmitting cable and the second was the need to get as much movement in the traces as possible. The response from the tyre when turned out of its true track, which provides the force for turning and therefore correcting lean, is a function of speed.

Thus at low speed more handle bar angle is needed for any given lean effect. The subjects were instructed to make no special attempt to maintain direction, the intention being to stop the run if the limit of the wire was reached or the run came too near to the recording van. The reason behind this instruction was that, combined with the lack of visual information, it was hoped that no navigational control would be added to basic stability control during the runs. However it transpired that, despite this instruction, subjects tended to check developing turns unintentionally so that the general direction of the start was maintained for the rest of the run.

Comparing the Channel Outputs

The raw data from both channels were digital records of the voltage output from the transducers. The roll channel was a record of rate of angular velocity at each sample and the bar channel was a record of angular displacement. The sample interval was 30 msecs between each channel point. The BBC handbook warns that although the ADC reads to 12 bits only 10 bit accuracy should be relied on.

Since all operations are carried out on the acceleration information which has been smoothed twice by taking the mean of seven local values each time it was not considered necessary to convert the raw data. However as a check the roll and bar values from a 600 point run were compared with an 8 bit version. There were 264 differences out of 1200 points none of which was greater than plus/minus 1. The bar channel lagged 15 msecs behind the roll channel, this representing the time the analogue digital converter takes to make a single conversion and the program takes to store the value. Therefore at zero LAG between the channels the bar channel is lagging the roll channel by 15 msecs. When, however, the handle bar data is differentiated the local rate has been obtained by taking the change between the target value and that value which immediately precedes it. Consequently the differential value is in effect the mean over the previous 30 msecs interval. The associated roll value, which is a direct reading of angular velocity, falls half way through this interval, with the result that for the velocity and acceleration data the two sets of readings are correctly synchronized and may be directly compared without adjustment. To compare like with like the following operations were performed.

The roll output was integrated to give roll angle. Since the interest lay in relative changes this integration was performed by summing the roll velocity data without applying the time increment. This gave an analogue of roll angle over time. During this operation the curve was graphed so that a check could be made of the zero position during the run. With straight runs the sum of the roll velocities was near to zero over the total time. Small adjustments of the DC constant value accumulate to big changes in the final values so the zero could be trimmed to a sufficiently accurate figure where there were any anomalies. This output was then paired with the angle data of the bar channel. In graphical studies the amplitudes were normalized to bring the curves together. The horizontal scale in the angle graphs has been adjusted to allow for the 15 msecs difference between the channel recording points.

To provide a comparison between the roll and bar velocities the bar output was differentiated by taking the change over the preceding interval and noise removed by taking the running average of seven local values. This was then paired with the roll data. Again the time interval factor was not applied and in graphical presentations the amplitudes were normalized to bring them together. These velocity values were differentiated once more and given a further smoothing to provide a comparison between the acceleration channels.

Although the main argument depends principally upon operations to the angular acceleration channels a further smoothing and differentiation was performed to produce the third differential of the angle, or jerk. Much of the detailed information is lost in this operation due to the extra smoothing which is necessary to remove noise. Peaks are truncated and some smaller waves are lost but the relationship between the general trends is much easier to see in this filtered form.

The Recorded Runs

Appendix 2.(a) shows the plots of the roll angles and handle bar angles for twelve blindfolded runs on the destabilized bicycle by the two subjects. Runs 25 to 30 were by rider A and runs 31 to 36 by rider M. Appendix 2.(b) shows a limited section of each run giving the angle, angular velocity, angular acceleration and jerk for the roll and bar (dark lines). The full runs are given as an indication that the selected portions are representative of the whole. A limited section, 12 secs of running time between point 100 and point 500, was chosen for display so that the detail of the waves could be more clearly seen. The start and finish of the runs were avoided as there were possibly untypical readings while the rider settled down to steady riding, or prepared to stop as the wire was pulled out near to the full length. The horizontal scale shows the recorded points which are at 30 msecs intervals, thus the marked hundred intervals are equivalent to 3 secs. The vertical scales throughout have been adjusted by multiplication during the graphing procedure to bring the peaks as near together as possible for comparison between the rates of the two channels.

RUN	ROLL		BAR	
	max	min	max	min
25	0.93	-1.98	31.14	-50.52
26	1.82	-1.21	38.11	-42.41
27	1.27	-1.10	31.06	-47.25
28	3.66	-1.28	73.11	-22.64
29	1.07	-1.92	33.63	-50.28
30	2.05	-0.86	58.24	-31.22
31	0.80	-1.61	11.35	-46.97
32	0.66	-1.95	14.59	-42.41
33	0.20	-1.06	18.21	-27.72
34	0.57	-0.79	27.88	-27.28
35	1.99	-0.68	35.98	-44.17
36	0.68	-1.40	26.55	-47.59

Table 5.1 Maximum and minimum angles of roll and bar in degrees for the destabilized runs 25 to 36.

The slow riding speed means that a large angle of handle bar is needed to get an adequate response from the tyres to control the roll and table 5.1 shows the maximum and minimum angles of roll and bar used in these run segments. It will be seen that none of the runs deviated very much from upright running although large amounts of handle bar were needed to achieve this. The roll angle was calculated from the roll rate by assuming that the velocities applied for the duration of the interval between samples (30 msecs) in which each was recorded, and the resulting angle increments summed for roll angle.

General Characteristics

The activity in the first three channels of a typical run out of the twelve under investigation is reproduced in figure 5.2 for easy reference. For exact details the appendix printouts should be studied as the reproduction process introduces a small degree of distortion. All the runs show the same general characteristic. In the angle channel, shown on the first horizontal axis, it is possible to make out an irregular slow wave from side to side, assuming the convention that above the zero line is left and below is right.

The run in figure 5.2 has about 7 reversals of direction between data point 100 and data point 500, a time of 12 seconds, giving a wave period of approximately 3.5 secs. Superimposed on this slow wave is a much shorter one which is more clearly seen in the velocity and acceleration channels. In the example there are something in the order of thirty reversals of direction giving a wave period of about 0.8 secs. It is not easy to arrive at a simple criterion which will allow a cut and dried decision as to what distinguishes a wave from noise but an approximate 'eyeball' count of the half-waves of both the long and short period movement in the twelve run is given in table 5.2. The slower wave is taken from the angle curves and the faster from the velocity curves. The mean number of slow half-waves for the 12 runs is 5.7, giving approximately 0.25 hertz and the mean for the fast waves is 23 giving 1 hertz.

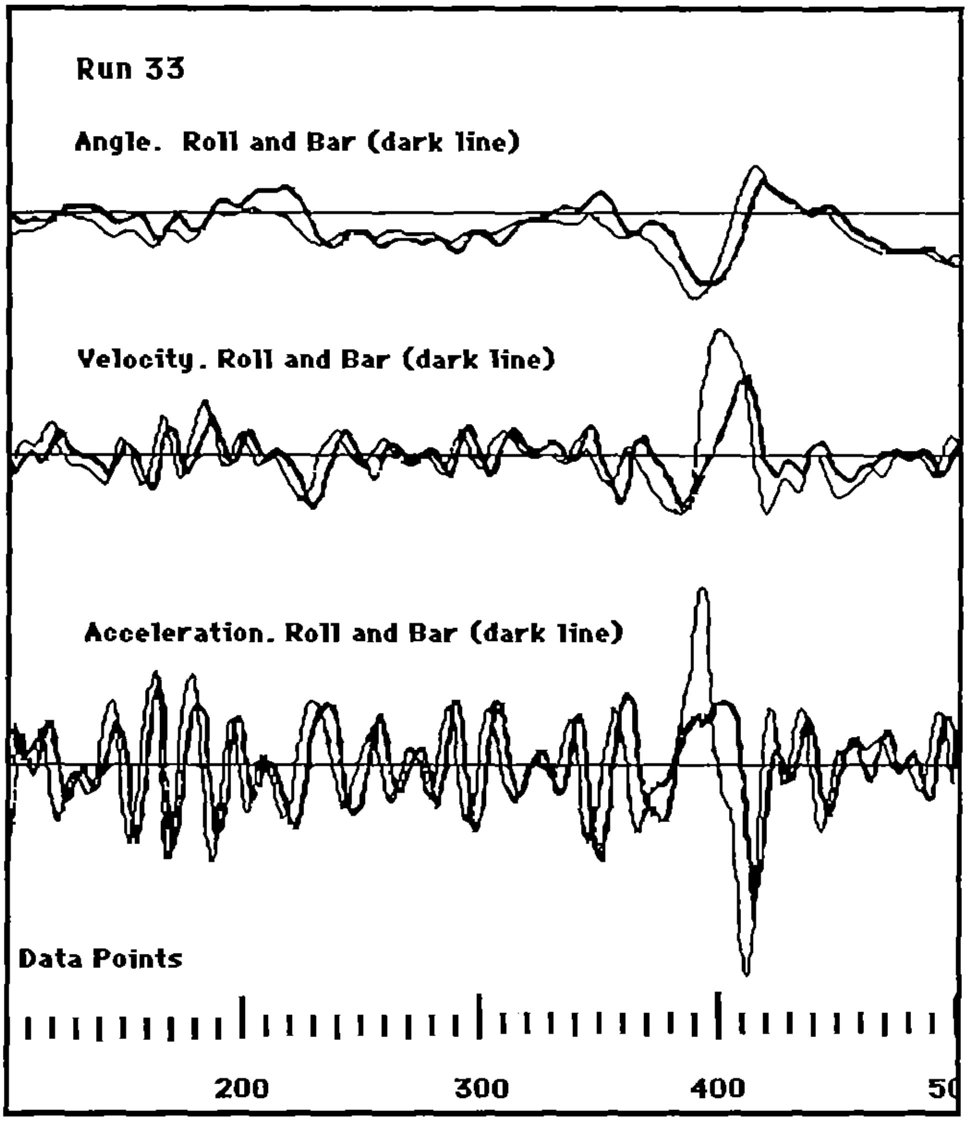


Figure 5.2 A typical section of slow straight line riding on the destabilized bicycle showing the activity in the first three channels. Reference should be made to the original computer printout in appendix 2,(b) for exact details as the copying process introduces a small amount of distortion.

The slow wave shows a tendency to a square shape with fairly fast changes alternating with several seconds of slow change while the differential waves have a triangular or 'saw tooth' shape which is maintained to the third derivative. This third derivative of angle or rate of change of acceleration usually referred to as the jerk, is shown on the fourth horizontal axis in the appendix records but has not been reproduced in figure 5.2 to save room. In the unsmoothed form the waves show the same triangular shape as the preceding curves but are very noisy. The smoothing process has flattened the peaks but it is easier to see the time relationship between the waves in this form.

Even before the relationship between the movement in the roll and bar channels is analysed statistically quite a lot about the nature of the control being used can be gleaned from a simple inspection of the traces. When 'open-loop', that is when there is no control input at all, the bicycle/rider unit will fall at an increasing rate of acceleration until it hits the ground.

RUN	big waves	small waves	small/big
25	5	20	0.250
26	4	20	0.200
27	4	22	0.182
28	4	21	0.190
29	3	22	0.091
30	5	19	0.263
31	7	32	0.219
32	7	26	0.269
33	6	30	0.200
34	5	26	0.192
35	9	21	0.429
36	10	22	0.455
Means	5.7	23.4	

Table 5.2 The approximate number of large and small half-waves counted between points 100 and 500 in the destabilized runs 25 to 36 with the ratio of small to big waves in the third column. See text for details.

This basic response is shown in the computer simulation record in the upper half of figure 4.4. Because the moment arm of the disturbing couple is constantly changing with the angle of lean this roll movement can only be bought to rest by a controlling response which is able to alter at exactly the same rate and exactly synchronized in time. If the control system cannot achieve this, then the next best thing is to alter at the same rate but at some phase delay. During the delay the control will be locally inappropriate, but providing the phase shift is short compared to the natural frequency of response, it will give stable control, although the nature of the movement will be oscillatory. If the system cannot continuously change at the same rate as the disturbing couple the only means of control left is to change in discrete steps. Here, at best, the controlling value will be correct once during a discrete interval as the disturbing couple passes through that value.

Continuous traces of the changes taking place in the disturbing and controlling couples will immediately reveal which class of control is being used. If a discrete steps are being used then one of the derivitive curves will show the handle bar trace moving in square steps while the associated roll trace moves in a non-linear curve. That is during the discrete interval the bar produces a fixed acceleration or a fixed velocity while the roll angle, in its response to the constantly changing moment arm, will be following a changing one.

It is evident from the traces that a discrete steps are not being used to control the roll angle and this is confirmed later in this chapter where it is shown that the movement in the bar has a very high correlation with the local movement in the roll, but not with its own previous movement which it obviously would have if it was using a 'ballistic' type of standard acceleration rate rather than following the changes in roll. It is also evident that a very short phase lag/follow system is not in use since the acceleration is not damped down to nothing. This leaves the continuous follow at some moderate delay and it can easily be seen that in all four derivitives a great deal of the bar change is a delayed repeat of the movement in the roll channel. The phase delay varies both between runs and within runs but a study of the zero crossing points shows that in run 33 in figure 5.2 the delay appears to vary between a quarter and a half of one of the ten data point intervals, that is between 75 and 150 msecs.

The Similarity Between the Roll and Bar Traces.

An inspection of the records for these runs shows that the rate of movement of the handle bar is following that of the roll at some fairly consistent time delay. The next task is to find out how closely they are matched and what exactly the delay is between them. It is useful to bear in mind at this point that, with the autostability removed from the bicycle, all movements in the handle bar are due entirely to movements of the rider. If the rider were to let go of the handle bar the steering would remain at its last angle. If, as is apparent, the handle bar is following the acceleration changes of the roll then the rider must be making it do so.

Cross Correlation Function (CCF)

The first test of similarity between the two curves also provides information about the delay between them. The CCF carries out a Pearson product-moment correlation on two columns of time series data. At each pass it varies the 'lag' between the two columns. So for instance if a range of lag values up to 10 was being examined, the first pass pairs the tenth value in the first column with the first value in the second column, then the eleventh with the second and so on. The second pass takes the ninth with the first and the eighth with the second and so on. This yields a series of correlation coefficients from lag values of -10 to +10. If there is a similarity in the rate of change in the two columns at some lag value the correlation will jump to a high figure at that lag with high correlations at the nearest lag values either side.

	section	Pr	lag	section	Pr	lag	R sqr
RUN	1	2	3	4	5	6	7
25	100-700	.89	4	200-400	.91	4	84.9
26	100-700	.88	4	"	.85	5	73.9
27	150-700	.83	4	"	.84	4	74.9
28	100-700	.83	4	"	.83	3	71.1
29	100-700	.82	3	"	.83	2	69.1
30	250-650	.80	4	300-500	.82	3	70.1
31	100-700	.88	2	100-300	.89	2	81.8
32	100-700	.90	2	"	.93	2	86.9
33	100-700	.84	2	"	.91	2	86.6
34	100-700	.90	3	"	.86	3	87.3
35	100-700	.82	3	"	.87	3	78.5
36	100-700	.87	3	"	.89	3	79.7

Table 5.3 Showing the correlations and lags between the roll and handle bar angular accelerations for the twelve destabilized runs (25-36) between the points indicated in column 1. See text for further details.

Short lengths of totally uncorrelated data or large changes in phase within an otherwise highly correlated set have a disruptive effect on the final correlation value. Column 1 in table 5.3 shows the section of the total run used to obtain the correlations in the following column. For all but two runs the central 600 points, representing 18 secs of running time, were used. The start and finish sections were discarded for the reasons already given. Run 27 and run 30 gave correlations below 0.7 for the 100-700 section and an exploration showed a sharp increase for the more limited sections indicated so these were used. The CCF is performed on the smoothed acceleration data of the roll and bar channels. Limited sections of these data are displayed in the graphs in appendix 2,(b). Column 2 of table 5.3 shows the Pearson product-moment correlation coefficient obtained for each run and col. 3 shows the lag value at which this high figure appeared. The critical value at 0.01 probability level even for the short set of 400 points at a lag of 50 is 0.14, so it can be seen that these correlations are all highly statistically significant.

The MICROTAB statistical package running on a BBC B. microcomputer was used for subsequent operations and limited memory forced a further reduction of the data sample to 200 points. Column 4 Table 5.3 shows the sections selected for each run. Run 30 again proved more choosey than its predecessors and the sample was shifted to get a slightly better correlation. The similarity between the correlations and lags obtained with CCFs in the short sections and those from the full run may be checked by comparing the values in columns 5 & 6 with those in 2 & 3. The correlations are of the same order but the differences in lag for rider A (runs 25 to 30) suggest that this value is not fixed but varies to some extent within a run. A closer look at this point will be taken later when an alternative method of measuring lag has been introduced.

Whether the peaks of high correlation are isolated or appear at regular lag intervals depends on the exact differences between the waves being considered. In the case of exactly similar waves with constant wave-lengths and peak amplitudes then groups of alternatively positive and negative high correlations will appear at half-wave periods. The lag values at which the maximum peaks appear give the phase difference between the waves. If there are differences in wave shape within similar wave lengths, such as a sine-wave versus a more triangular wave then the same regular peaks of high correlations will appear but the peak values will be lower, reflecting the differences in local amplitudes. In the case of exactly similar sets of values where the wave-length and/or amplitude varies throughout the length of the run, then the CCF gives a much more 'focussed' response. With regular wave-length but varying amplitude from wave to wave there is a sharp focus of peak correlation at the critical lag value. The positive and negative peaks still appear at half-wave intervals but their peak correlations are much lower than that at the correct lag value. When the wave-length varies then the secondary peaks tend to disappear and the peak of high correlations is confined to the critical lag value.

RUN	order	+	-	zero-wave	-	+	totals cols 3-7
1	2	3	4	5	6	7	8
25	1	.4	.6	.91	.5	.4	19
33	2	.4	.7	.91	.5	.3	19
32	3	.2	.6	.93	.4	.2	14
36	4	.2	.6	.89	.3	.3	14
27	5	.3	.5	.84	.4	.2	14
26	6	.3	.4	.85	.3	.3	13
34	7	.2	.6	.86	.4	0	12
28	8	.2	.5	.83	.3	.1	11
35	9	0	.6	.87	.2	0	8
31	10	0	.5	.89	.2	0	7
30	11	0	.5	.82	.1	0	6
29	12	.1	0	.83	.1	.1	3

Table 5.4 The peak correlation values either side of the absolute peak value from table 5.3, cols. 5 & 6 at half wave intervals. Thus cols. 3 & 4 are the correlations found at a full wave and one half wave preceding the peak wave respectively, and 6 & 7 are those following it. Col. 8 shows the total values of the subsidiary wave peaks (Cols. 3-7) on which the runs have been ordered. Col. 5 is correct to 2 significant figures the other columns are corrected to 1 place of decimals.

A CCF analysis was performed for the indicated sections of each run for a range of 24 lag values either side of zero. The results are summarized in table 5.4. The ZERO WAVE at column 5 shows the peak correlation obtained at the lag value given in column 6 of table 5.3. On either side of this are the peak values at the nearest half-wave positions. These are given simply to 1 place of decimals so that the eye can more easily pick out those runs which show little evidence of peaks either side of the critical value. The secondary peak values are summed in column 8. These have been used to list the runs in descending order of subsidiary peak strength. There are approximately 12 half-waves in each of the six-second run sections. From the appearance of the CCF output it is possible to deduce that about one third of the runs had fairly constant half-wave periods over the six seconds run with differences in amplitude accounting for the reduction in correlation; a third had a good deal of disruption in the wave period length which suppressed the secondary waves and the final third lay somewhere between.

It looks from table 5.4 as though there is a tendency for high correlations to be associated with high secondary peak values. Columns 5 and 8 show a 0.616 correlation which is significant to $P<.05$ (Critical value for 10 df 0.576). The critical variables which affect the correlation between two similar wave forms may be considered as having two components. The first is the rate of change of amplitude within a wave period, and the second the half-wave period length. Since the CCF printouts, summarized in table 5.4, show that half the runs have considerable differences in wavelength within the 12 secs run the question that arises is whether it is this factor which also causes the extra reduction in peak correlation or whether there is some unidentified factor which affects both the wave-length and the overall correlation at the same time. In order to answer this it is necessary to examine the effects of distortions in amplitude and wave-length upon correlations in some more detail

Effect of Amplitude and Wave-length

It is evident that two wave forms must be very similar to obtain correlations in the order of 0.8. It is also evident that the final figure is a consequence of the relationship between the two values at each time point. It would however by useful to have some general idea of how amplitude and wave-length, as defined in the previous paragraph, affect the final correlation.

1. Amplitude. If it assumed that there is a perfectly consistent wave-length throughout both sets of data then it is evident that the maximum distortion to amplitude that can occur within a half-wave is that one set of values is at zero and the other somewhere near the maximum. The following table shows the reduction in correlation between sets of data as a result of flattening part of one of them. The basic wave is a sine function with 100 max. amplitude, ten 360 degree waves with a sample rate of 18 degrees, giving 200 points. This gives approximately 10 points to each half-wave. The second wave is progressively flattened by setting the indicated points at zero. The R squared term from a regression prediction of one set of values from the other is a more sensitive measure of similarity than correlation so both measures are shown.

Degree of flattening	**Correln**	**Regress R sqrd**
1/2 wave (1 to 10 to zero)	0.975	95.1%
3/4 wave (1 to 15 to zero)	0.952	90.6%
1 wave (1 to 20 to zero)	0.945	89.4%

2	waves (1 to 36 to zero)	0.894	79.9%
3	waves (1 to 55 to zero)	0.836	69.9%

This is a straight line function and does not depend on the absolute number of waves present but the proportion which are 'flattened'. In general terms if three out of ten waves are at the maximum amplitude difference then a perfect correlation will be reduced to just over 0.800. In the case under examination the maximum correlation is 0.91 and this drops to a minimum of .83, which is the equivalent in the table above to the difference between 2 and 3 waves set to zero, that is a change of 1/10 of total waves. It is therefore evident that quite large differences in wave area would be needed to account for a reduction of this magnitude if the amplitude differences were the only factor affecting it. Actual differences in wave area will be dealt with shortly.

2. Wave-length. The reason that amplitude does not have a large effect on the overall correlation is that the disruption is confined to the locality of the associated wave. When there are differences in wave-length, the location of the disruption makes a big difference to the resulting correlation. To unpack this effect the same wave form used for the amplitude test was altered as follows; the values in the second set of data were phase delayed by an increasing number of degrees. For each delay value the consequence on the correlation for the number of waves so affected was measured. Thus if there is a phase change of 20 degrees in the fifth wave (out of a total of ten) then half the waves are phase shifted 20 degrees from the other half. If on the other hand only the last wave in the run is shifted 20 degrees the distortion is confined to this one position. A phase shift of 40 degrees (approximately a fifth of a half-wave) even if applied over the maximum of half the run only reduces the correlation to appx.

0.94. However a shift of 180 degrees when applied over half the run gives half at a correlation of 1.0 and half at -1.0, and therefore gives a correlation of 0. In effect the correlation process sets the whole run at 90 degree phase lag which gives a zero correlation. As the change is moved down the run the consequences are mitigated but are still strong. Just one wave 180 degrees (half a wave) out of phase at the end of a run of ten waves will reduce an otherwise perfect correlation to 0.8. Shortly these differences will be examined in detail but in the meantime a close examination of the acceleration curves for the runs in appendix 2,(b) show that there are frequent phase changes of about a quarter the mean wave-length, and occasional examples of half-wave length phase shifts. (Run 25, 450-460; run 29, 150-160; run 30, 345-355; run 35, 390-410). Of course just how much phase shift there is also depends on the mean lag taken for the section of run in question and the relationship between lag and wave-length will also be dealt with in a later section. It is however evident that a badly placed phase shift of this sort is sufficient to account for the lowering of correlations noted when selecting data runs for examination.

A more detailed discussion must be delayed until the method of extracting a measure of wave-length and area has been introduced. However the data summarized in table 5.4 suggests that the amplitude values are well coordinated over time, that is the areas under the curves are closely matched, giving a high correlation between the two wave forms at the appropriate lag value. When the wave lengths within the run are consistent then this leads to the high secondary peaks at half-wave intervals shown in rows 1 to 4 of the table. When there are differences in the wavelengths within the run the peak correlations are reduced and the secondary peaks are suppressed. Therefore the expectation is that areas should show a greater correlation between roll and bar than wave lengths and that where there are large reductions of correlation between roll and bar in a section of run this is due to differences between the wavelength rather than amplitude.

Regression Analysis

To examine more closely the relationship between the roll and bar movement a regression analysis was performed on the acceleration data to see to what degree the roll values predicted the bar values. For all subsequent regressions the sections of data from point 200 to 400 were used for each run. There was considerable variation in the lag values between runs and possibly within them as well. The lag value from the CCF analysis, shown in column 6 of table 5.3 was used to locate the regression analysis. This procedure uses the equation:-

Predicted Value =
Constant +(multiplier * Predictor value)

to predict a set of values from the roll data. It then compares the predictions with the bar values at the appropriate delay. In a series of reiterations it alters the two injected values until the best fit is obtained. Column 7 in Table 5.3 shows the R squared term, which being the square of the correlation coefficient times 100, is a measure of how well the final regression equation fits the overall data. The minimum F value for the run was 452. The degrees of freedom are 1 and 196 and the critical F value for 200 degrees of freedom at a significance of $p<.001$ is 11.17. All the 't' values for the acceleration term were in excess of 20 and the critical value for $p<.001$ for a df of 120 is 3.37. It can be seen that the observed level of association between the two sets of values at the given lag is very highly statistically significant.

Thus the analysis so far has shown that the basic form of the rider response on the destabilized bicycle was a close imitation of the roll rate at a mean delay between 120 to 60 msecs. The next phase in the analysis will be to focus on the local changes in wave-lengths, delay, and area under the curve for each wave within the runs to see if there are any further invariant relationships in the data.

WAVE PERIOD, AREA AND DELAY ANALYSIS

Introduction

The analysis so far has shown that the movement in the bar acceleration channel is closely related and dependent upon the movement in the associated roll channel. Although the CCF analysis gives a mean delay between the channels it is evident from an inspection of the graphs that there are considerable changes in both wave period and delay both between and within the runs. It is obvious from the high correlations obtained that the areas under each individual wave must be closely matched but here again there are obvious differences. In order to find out more about these differences a program was written which extracted wave periods, areas and delays for the runs.

Matching the Roll and Bar Waves

The following operations were carried out on the roll and bar acceleration waves between points 100 and 700. Throughout the discussion the word 'wave' is used to mean a half-wave in the convention of an alternating positive, negative wave form.

Wave Period. The roll and bar records were each treated as follows. The next zero crossing and direction was identified by its point number. A search was made for the next zero crossing and the interval in points constituted the wave period interval which for simplicity will now be termed the wave length.

Wave Area The values of the points within a wave were summed to give a value which is a direct analogue of the area under the curve.

Delay. Each roll wave was matched with the next bar wave of the same sign. Occasionally one of the waves fails to cross the zero line at its lowest point and is consequently missed by the search process. This leads to an artificially long delay period. Any delay greater than 10 data points was discarded. If the bar wave recrossed the zero line within the next roll wave then one reading was lost, and if the bar wave failed to recross the zero line at all then two were lost.

RUN	25	26	27	28	29	30	31	32	33	34	35	36
All	45	43	46	53	53	46	57	57	61	59	59	58
Match'd	42	40	37	42	42	38	49	52	55	53	40	50
Prop	.93	.93	.8	.79	.79	.82	.86	.9	.9	.89	.68	.86

Table 5.5 Showing the number of matched waves found in the destabilized runs (25-36, points 100-700). The last row shows the proportion of matched to total waves. See text for further details.

Table 5.5 shows the proportion of waves which were successfully matched using this criterion. There were slight discrepancies between roll and bar totals as an occasional wave will just fail to cross the zero line but these were not thought to be of importance and the total wave figure refers to roll waves only. From this it was concluded that the matched waves were representative of the activity in the two channels and the analysis proceeded on these waves.

Internal Consistency

The first question to be answered is how consistent are the measures within the runs. Table 5.6 shows the mean values for wave, area and lag for the 12 runs. (cols. 1,3,5,6,9).

	wave-period				wave-area				lag	
RUNS	roll		bar		roll		bar			
	1	2	3	4	5	6	7	8	9	10
25	14	48	12	48	122	77	115	80	4.5	48
26	14	42	13	48	120	67	98	80	4.0	62
27	15	37	13	49	146	63	138	75	4.1	51
28	13	35	12	40	112	58	109	63	4.0	52
29	13	44	12	42	96	70	86	74	3.6	57
30	14	38	13	46	106	70	101	64	4.3	53
31	14	53	10	46	115	72	79	67	2.9	54
32	11	42	10	40	105	65	86	66	2.9	41
33	11	44	10	44	103	92	90	77	2.9	45
34	10	38	10	36	105	66	104	66	3.6	38
35	13	39	12	56	141	73	132	81	4.1	48
36	11	42	11	43	117	72	100	71	3.9	48
means	13	42	11	45	116	70	103	72	3.7	50

Table 5.6 Showing the values and variability for the half-wave periods, wave areas and lags for the 12 destabilized runs 25-36 (points 100-500). The even columns show the coefficient of variation (stand. dev./mean * 100) for the value in the preceding (odd) column. Each value is the mean for the run. All but column 9 are corrected to the nearest whole number. Column 9 is corrected to 1 place of decimals.

The even numbered columns show the coefficients of variation. This is the standard deviation divided by the run mean and, being independent of the absolute values, may be used to compare the amount of variability for all measures. These values should be read in conjunction with the histograms of the actual scores given in appendix 2,(c).

	Waves roll/bar		Areas roll/bar		Autocorrelation		
	Corrn.	sig	Corrn.	sig.	Bar wave	Bar area	Roll area
RUN	1	2	3	4	5	6	7
25	.44	.01	.80	.01	ns	.62	.42
26	.37	.05	.85	"	"	.49	.37
27	.38	.05	.54	"	"	ns	.57
28	.56	.01	.63	"	"	.34	ns
29	.42	"	.80	"	"	ns	.46
30	.84	"	.69	"	"	.43	.37
31	.71	"	.80	"	"	ns	.31
32	.72	"	.80	"	"	ns	.36
33	.82	"	.90	"	.35	.53	.50
34	.51	"	.82	"	"	.55	.48
35	.44	"	.74	"	"	.46	.44
36	.48	"	.82	"	"	ns	ns
means	.56		.77				

Table 5.7 Showing the roll/bar correlations and autocorrelations for wave-period and area. Columns 2 & 4 show the significance level for the correlation in the preceding column. In columns 5-7 the coefficient is shown only if it is significant at better than the P<.05 level.

Because of the row limit in MTAB these have been shown separately for the two individual riders but they give a clear illustration of the point that the wavelengths are much closer to the means than the areas which have a square distribution. This is reflected in the coefficient of variance being nearly double for the latter. The lag shows a similar characteristic to the wavelength.

Relationship Between Roll and Bar

Since the correlations and regressions have shown that there is a close relationship between the roll and bar movement the next question is how the local changes in wavelength and area are correlated between the roll and bar.

Table 5.7 shows that there are significant correlations between both sets of values but that the area is the more closely correlated of the two. Thus a situation exists in which there is a tendency for the wavelength to vary to a lesser degree about a single value but when changes do occur they are only moderately correlated between the roll and bar channels,(col. 1).

The areas of successive waves on the other hand show almost twice as much variation as the wavelength and have a square shaped distribution showing that any one of the range of values is as likely to appear as another. As these changes take place they are highly correlated between the roll and bar. Column 3 shows that 8 out of the 12 runs have a correlation of over 0.8 with a mean for all runs of 0.77. Thus there are many small areas and many large areas and a small tends to be followed by a matching small and a large by a large. Wavelengths tend to vary about one size and where there are differences a small one is less frequently followed by another small one. The delay between the channels also shows a tendency to be distributed around a single value and the variation is of the same order as the wavelength. The mean values of lag extracted by the measuring process for each run can be checked against the lags resulting from the CCF analysis by comparing column 9, table 5.6 with column 3, table 5.3. In general the former are slightly higher than the latter but it should be borne in mind that they are measured exclusively at the zero crossing position whereas the CCF is taking the best interval for all parts of the curve. Because the minimum interval is 30 msecs this is in any case a rather coarse measure, giving discrete jumps to represent a process that must certainly be continuous.

The only dimension the rider can alter is the rate of bar movement. However the way in which it is altered can take several forms. First the length of the delay between the sensed roll rate and the bar rate output can alter. Rapid changes in the delay are bound to lead to local changes in wavelength. The amount of response, or gain, can be altered. If the rate is held at zero for example for a short time then there will be associated changes in the local wavelength which will lead to changes in delay measured at the zero crossing points. The same thing will happen if the gain is rapidly increased or decreased and very similar effects will follow the superimposition of bar rates that are independent of the basic follow rate. A more detailed analysis of whether these changes are noise caused by the system's inability to sustain a constant value for lag or gain and how they affect the characteristic follows in the next chapter. However one more question can be answered at this stage and that is whether there are any signs of these changes being ballistic in nature.

Evidence for Ballistic Control

The recorded roll and bar rates show that the system is operating continuously and not in discrete steps. However it might be asked whether it produces, for example, a standard wavelength or delay which achieves a partial solution to the immediate control problem and then gradually shifts this value on the basis of feedback of errors between the desired state and the state actually achieved. If any of the values showed this sort of change then there would be an autocorrelation with neighbouring values within the run.

The autocorrelation process performs a series of correlations between a time series and the same series shifted by a lag value. The first pass compares point 1 with point 2, point 2 with point 3 etc. The second pass compares 1 with point 3 and 2 with 4. If there is any tendency in the run for neighbouring values to be more like each other than more remote values the correlation will be high at a lag value of 1 and perhaps 2.

The delay value can be dismissed quickly as there were no significant correlations between one value and neighbouring values up to a lag of 8 for any of the 12 runs. Column 5 of table 5.7 shows that there was only one significant correlation at a lag of 1 for the bar wavelengths and none at a lag of 2. Thus it is clear that there is no 'ballistic' tendency in the wavelength. Column 6 shows that 7 of the 12 runs showed a moderate degree of correlation between immediate neighbouring values (lag of 1) of the bar areas. There were no significant correlations for the second lag position. Since the bar area is highly correlated with roll area (Col. 3) it would be expected that when for some external reason two adjacent roll areas are similar then the bar area would show the same tendency. Of the seven runs with a significant correlation at 1 lag, six show a significant correlation at 1 lag in the roll data. It can be concluded that any sort of ballistic control is very unlikely in the bar area since five runs showed no similarity in adjacent values but displayed general characteristics of control no different from the other seven runs. Since run 28 showed a significant correlation in the bar area at 1 lag without there being a similar correlation in the roll area the appearance of such a correlation cannot be due exclusively to the observed tendency for the bar area to copy the roll area. In general it appears that the dynamics of the system as a whole are such that there is a tendency for roll areas to show some degree of autocorrelation and that since the bar area is closely associated with the roll area this is reflected by a lesser degree of autocorrelation in the bar areas.

Summary of Basic Run Output

Two subjects rode the destabilized bicycle, blindfolded, for six runs each of just over 20 seconds. Although instructed not to correct for any turns they did in fact keep the bicycle oscillating about the upright, reversing incipient falls about once every two seconds. This was not achieved smoothly as there was a short wave oscillation of roll of about 1 hertz. Because of the low speed large amounts of bar movement were needed to control the roll but the analysis is concerned with the rates of change rather than absolute values. Because all autostability had been removed from the bicycle all the bar movement must have been due solely to rider response. The form of this response was a close imitation of the roll rate at a delay which varied from 4 to 2 data points (120 to 60 msecs), measured by the mean delay given in the CCF analysis. A regression analysis showed that from 70% to 86% of the bar movement was accounted for by the movement in the roll channel. The 1 hertz wave component was isolated in the acceleration waves at the zero crossing points and waves with same signs matched. Each pair of waves yielded measures of lag/delay, local half-wavelength period and area under the curve. Lag and wavelength showed a coefficient of variation of 40/50 about a mean value with the roll and bar channels correlating at about the 0.55 level. The areas on the other hand showed a coefficient of variation of 70 with a fairly even distribution between the maximum and minimum values. The matched wave areas showed a correlation at about the 0.77 level. It was evident that the system was detecting the roll changes continuously not at discrete intervals and there was no tendency for the bar responses to be 'ballistic'.

The first part of the analysis has shown that, although each run had a completely different sequence of values in the two channels, an invariant relationship between the activity in the roll and bar rates existed. The handle bar angle responded continuously to the changes in roll rate, which since the riders were blindfolded must have originated in the vestibular system. The delay between detection and response was considerably faster than that traditionally associated with central decision making and is therefore in the range associated with the functional stretch reflex. The next stage will be to find how such a response affects the performance of the rider/machine and whether that part of the bar activity which is not accounted for by the roll activity is noise or some additional means of control.

6. SIMULATING THE DESTABILIZED BICYCLE CONTROL

Testing the Implied Control System

In the previous chapter it was discovered that a large part of the activity in the handle bar acceleration channel during normal straight running on the bicycle was accounted for by the movement taking place in the roll acceleration channel some 100 msecs earlier. The next step in the analysis is to put this kind of control into the simulation to see what performance characteristic results. This output will be compared with that of the actual runs and modifications sought which will bring the two nearer together. The final aim will be to try to construct a control system for the model which gives an output with the same characteristic as that of a real rider over a comparative run time.

The General Response to Delay/Follow control

Moving the bar to the left forces a roll to the right so that a rising roll value is suppressed by the rising bar that follows it at the lag interval. It can thus be appreciated that the effect of the delay in the bar leads to a situation at every peak where the bar is still increasing even though the roll has already been forced to reverse. During this interval the bar, having checked the roll increase in the initial direction, is now driving it the opposite way. Thus when the bar follows the roll at a delay there are 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, first the length of the delay and second 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. The limit case in the opposite direction is when the delay is as long as the time taken for the bicycle to fall all the way to the ground, say 2 seconds. In this situation 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. Even if the delay is substantially less than that given above and the bar movement manages to contain the fall by virtue of a high multiplication factor, this same high factor will then force the roll in the opposite direction during the lag period. On the reverse it will be faced with a much worse condition as the bicycle will now be falling the other way at a speed that is the combination of both the gravity effect and the velocity it acquired during the reverse thrust.

Consequently it can be seen that with a lag/follow system the gain factor must be matched to the delay period so that with a long delay a high gain does not drive the system into diverging oscillations. There is also an absolute upper limit for lag where even a weak gain factor will fail to reverse a roll divergence. There must also be some minimum delay period that is dictated by the time taken for the physiological mechanism to extract the information, process it, transmit it to the operating muscles and for those muscles to respond. In the previous chapter the lag for the two riders, measured at the zero line, was seen to vary about a mean of approximately 100 msecs with occasional values near to zero or greater than 200 msecs. The first question to be answered is what is the general response characteristic of the simulated bicycle to variations in lag and gain in a delay/follow system.

Stability

The output of a system proposed for the rider/bicycle combination has two principal parts, one a steady state component directly related to the input and the other made up of transient terms which are either exponential or oscillatory with an envelope of exponential form.

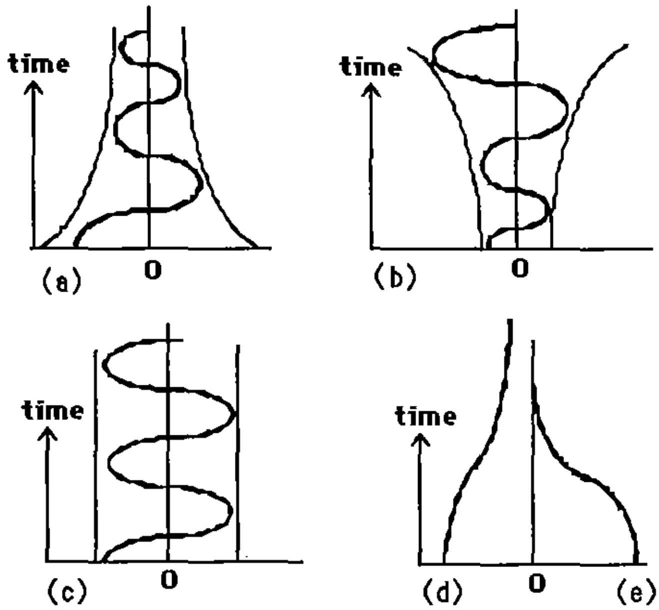


Figure 6.1 The five kinds of stability common to feedback control systems. The difference between the actual value and the desired value is used to drive the initial disturbance back to the zero line. The ratio of the control force to the damping dictates whether the system is stable or unstable.
(a) Under-damped; stable oscillatory.
(b) Under-damped; unstable oscillatory.
(c) Under-damped; 'just stable'.
(d) Over damped.
(e) Critical damping.

Damping in the system suppresses these transient effects and the way it behaves as a result is described as follows. If the exponentials decay to zero the system is said to be stable. If any exponential increases, the system is said to be unstable and a theoretically 'just stable' system shows a sinusoidal oscillation with a stable amplitude. Figures 6.1,(a),(b) & (c) show an example of each case. If these transients are too heavily damped the steady state component may fail to reach the controlling value in which case the system is said to be overdamped. When the damping is such that the new value is reached rapidly without oscillation the system is said to be critically damped. Figures 6.1,(d) & (e) show these last two conditions. Since the term 'critically damped' has a precise definition the term 'dead-beat' will be used to describe a condition which nearly approaches the critical state. Appendix 3,(a) shows the four main cases on the simulator using the destabilized Triumph with a 160lb rider at 4 mph using the delayed roll/follow control with a lag of 120 msecs. Although only the repeat of the roll acceleration has been discussed so far the latter part of this chapter has been anticipated in constructing these diagrams in that the bar channel is a repeat of a combination of both the acceleration and velocity roll channels for reasons which will shortly become evident.

It would be convenient at this stage to have some quantitative measure of stability with which to describe the effects of gain and lag. The normal engineering control procedure for describing the stability and the suitability of proposed control for a system is to work from the open-loop data to the closed-loop performance. The open-loop equation of the system in the Laplace form is graphed on a Nyquist diagram which plots the real terms on the X axis and the imaginary on the Y axis. From this diagram it is possible to predict what time and gain constants will produce a stable closed-loop system.

The quantitative measures of stability are the gain and phase margin which are defined as follows (Healey,1967,pages 102-117):-

Gain margin. That increase in open-loop gain which gives an overall gain at 180 degrees phase shift of unity.

At this point the system is on the verge of instability. A negative gain margin indicates an unstable system.

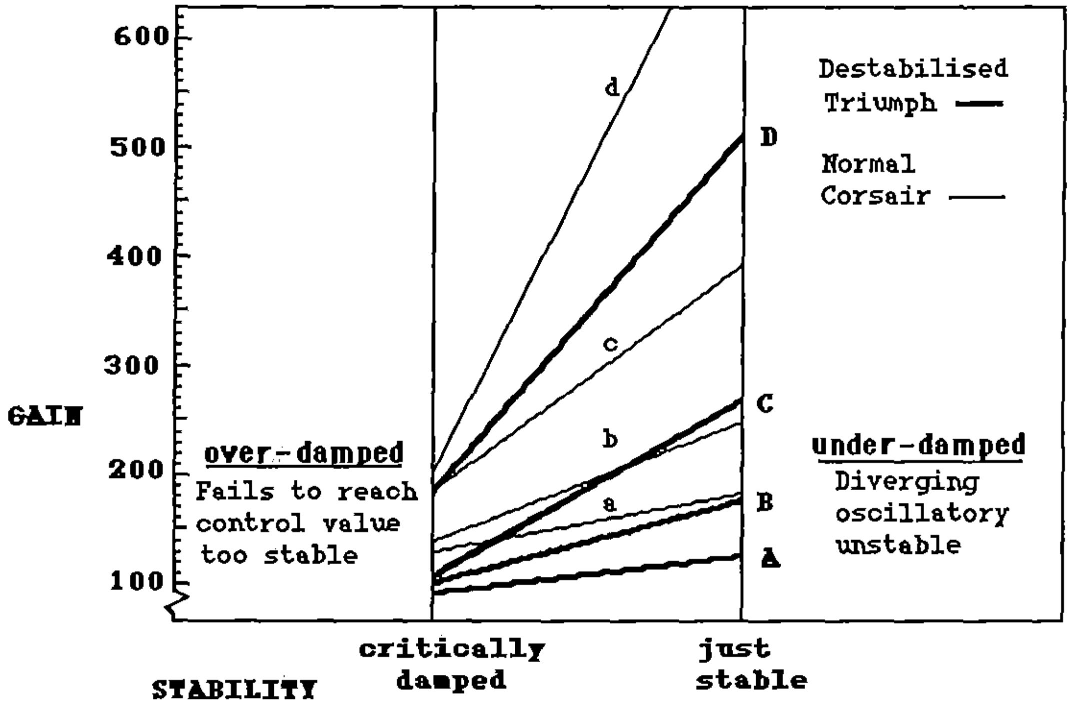


Figure 6.2 The upper and lower stability limits for two different 'bicycles' running on the simulator. The dark lines show the gain settings associated with these two points for the Triumph 20 destabilized machine at 200,150,100 and 50 msecs lag, identified by the dark lines A,B,C and D respectively. The same points for the Carlton Corsair tourer are shown by the light lines a,b,c and d. The speed is 4 mph and the rider dimensions 6ft and 5 slugs (161lbs).

Phase margin. That phase lag required to put the system on the verge of instability with the existing gain value. If the system is already unstable this value will be negative. In the absence of open-loop data no single quantitative measure for the stability can be given. However an idea of the stability performance of the total system running with the repeat/delay control can be obtained by identifying the two points where the system changes characteristic from underdamped to over-damped and from stable oscillatory to unstable oscillatory for a range of the critical variables gain and lag. Figure 6.2 shows in graphic form these two points for a range of gain and lag values.The function of the stability between these points is continuous and would appear on a Nyquist diagram as a spiral. Because no values for the stability are available here the two points are merely joined with a straight line to aid identification. The two boundary conditions were obtained by gradually increasing the gain setting until the trace showed the required characteristic. For the 'Critical damping' case (Appendix 3,(a), first figure) the gain setting was that which caused the velocity trace (R') to just reach the Y=0 axis but not cross it. For the 'Just stable' case (Appendix 3,(a), third figure) the gain setting was that which gave no change in amplitude (measured in the acceleration channel, R'') over time.

The two points enclose the range of useful stability. For any given lag when the gain is low the stability is good but the power to control disturbances is poor. As the gain is increased to give more power the system approaches the point of unstable diverging oscillation. When the lag is long only small gain values are possible, and as the lag gets shorter so more and more gain can be used without sending the system into the unstable range.

The lag and gain are the critical variables for any given system, other variables having little effect on the stability performance. Different bicycles constitute different systems with different stability characteristics. To illustrate this point the stability range for two machines is shown. The dark lines show the stability for the Triumph experimental bicycle and the light lines the stability of a large wheeled touring bicycle (Carlton Corsair). The bicycle speed and rider dimensions are the same in both cases. It is evident that the design of the tourer is superior to the small wheel utility machine allowing more gain to be used for the same lag.

Changes of non-critical values within a single system do not have much effect on the stability. To illustrate this point the effect of a range of rider dimensions (weight and height) and road speeds on the gain settings for the two stability points for the Triumph bicycle running at 100 msecs lag are shown:-

Speed 4 mph. Lag 100 msces.			
Wt stones	Ht ft	Stability	Gain
18	6	Critical	100
		Just stable	265
11	6	Critical	100
		Just stable	265
5	4	Critical	110
		Just stable	200

Table 6.1 The effect of rider weight and height on the upper and lower stability boundaries. Taken from runs on the simulated destabilized bicycle.

It can be seen from this table that large changes in rider weight and size have very little effect on the stability boundaries of the system. As already mentioned in chapter five the response from the tyres which provides the controlling couple is a frictional force which is dependent on the weight. The heavier the rider the more power per angle of drag is available for countering the weight disturbance so there is in fact not a great deal of difference in the amount of gain required between light and heavy riders. However, even if this were not so, it would not change the stability boundaries. It would merely mean that, for a given lag, a heavy rider would reach the diverging oscillatory condition sooner than a light rider, not that the threshold was different.

Rider 11 stone 6ft. Lag 100 msecs		
Speed mph	Stability	Gain
2	Critical	110
	Just stable	275
4	Critical	100
	Just stable	265
6	Critical	115
	Just stable	250
10	Critical	115
	Just stable	230

Table 6.2 The effect of speed on the upper and lower stability boundaries. Taken from runs on the simulated destabilized bicycle.

The response from the tyres is dependent on speed. Thus more tyre/road angle is needed to counter a given lean angle as the speed decreases which means that more gain is needed for a fixed lag when manoeuvring at low speed.

However the gain margins are not much changed by speed so that the system will be more oscillatory at low speed because it is forced to operate at a higher gain setting and thus nearer the 'just stable' boundary and not because the stability characteristic has altered.

Power for Control and Wavelength.

In general the greater the gain the greater is the instability and the lower the gain the lower is the power of response. All control systems are a compromise between these two opposing requirements. There are two unstable conditions, one when the gain is so low that the system cannot correct a disturbance and the other when the gain is so high that the system takes on a diverging oscillation. Regardless of where the stability margins lie the control needs the power to deal with disturbances and this is a function of absolute gain. As the angle of lean increases so does the disturbing couple and the rate of fall increases exponentially. The correcting couple must accelerate faster in order to contain it and the absolute value of the gain is the critical value which dictates its power to do so regardless of the ratio of gain to lag

Disturbance 5 deg. initial lean		
Gain	Lag	Angle where fall checks
100	(60,120,200)	Failed to check fall
140	60 120 200	11 degs. 11 degs. 13 degs.
Disturbance 15 deg. initial lean		
140	(60,120,200)	Failed to check fall
200	60 120 200	25 degs 26 degs 35 degs

Table 6.3 Showing how the power to check an initial disturbance depends principally on the gain. Figures taken from a run on the simulated destabilized bicycle with an 11 stone rider at 4 mph.

Table 6.3 shows the effect of different absolute gain settings on the ability to reverse an initial disturbance for a range of lag values. The the roll error, times the gain factor is applied to the handle bar at the phase shift indicated by the lag value. The angle where the fall checks is the roll angle at which the fall due to the initial lean angle was checked and reversed. It is apparent that the performance is not entirely independent of the lag value. The longer the lag the later the steering sets off in pursuit so even though it is growing at the same multiplication factor as the short lag case it has a more difficult task to start with. This accounts for the reduced performance in the 200 msecs lag case. All the recorded runs showed variations in the wave period.

Gain	Lag	Wave-period
	(msecs)	(secs)
100	100,120	2.5
120	"	1.9
130	"	1.6
140	"	1.5
200	"	1.0 (1.3)
280	"	0.7 (0.9)
400	"	0.5

Table 6.4 The effect of gain on wave-period during the recovery from the disturbance due to an initial lean angle of 5 degrees. Simulation of the destabilized bicycle with an 11 stone rider at 4 mph. See text for comments on lag effects and figures in brackets.

The time taken to reverse a disturbance is a function of the gain for any given lag. Consequently the wave period in a series of reversals is also a function of gain. Table 6.4 shows how the period of the oscillations during the recovery from an initial disturbance of 5 degrees lean varies with different gain values.The gain is the critical variable controlling the wave period but once again lag has a small effect. The periods for the above table were measured by counting the number of waves on the screen and then noting the time elapsed during their formation. However for short lags the lower gain settings produce an almost dead-beat performance and it was not really possible to do more than make a rough estimate of where the only wave terminated, thus the figures given are those for lags of 100 and 120 msecs. The figures for lags of 60 and 200 agreed where they could be measured with slight increases in the shorter wave periods for lag 200 as indicated in brackets.

Summary of Lag/Follow General Characteristics

A repeat of the roll activity in the bar acceleration channel at some delay is capable of containing disturbances introduced into the system. The success in containing these depends on two main factors. First the gain must be high enough for the bar response to catch and reverse the roll rate before the angle of lean gets too high and second the ratio of gain to lag must not get so high that the system becomes unstable. It has also been shown that changes in gain lead to substantial changes in wave period whereas changes in lag have only a marginal influence. Table 6.5 summarizes the various effects of lag and gain. The heavily outlined boxes show the range of gain values which give a stable performance for the three lag values, ranging from unstable due to too little power at one end to diverging oscillation at the other.

It is evident from the traces in appendix 2,(b) that, whatever the reasons, the control system in the 12 test runs is near the lag/gain ratio for the 'just stable' condition since there is more sign of incipient divergent instability than dead-beat critical damping. It should not be expected that the simulator model can make precise quantitative predictions about the detailed performance of the actual bicycle since a number of the variables are only approximately defined, particularly the way the tyre coefficient varies with speed and angle. However the observed mean wave period of 1 hertz and lag of 100 msecs with a high degree of oscillation ties in well with the computer predictions. The 120 msecs lag gives a 0.9 wave period when the gain is such as to put it on the 'just stable' limit. This setting gives plenty of power to deal with quite large disturbances.

Since the delay between sensing a change of roll and implementing a change of bar is a sum of various internal processes it is very unlikely that the value would be absolutely stable. However this noise alone will not account for the changes in wave period as we have seen that the influence of lag on its own is weak. There is a 0.45 correlation between the lag and the roll wave period for 11 of the 12 runs, indicating that changes in one are connected with changes in the other. It is obvious that whenever the wave period changes, there is a transient and quite strong effect on the local lag value as measured at the zero-crossing point. A sudden reduction in the wave period will also shorten one or two lag values at the site of change. It seems likely therefore that the changes observed in the lag value are caused by both noise due to instability and changes in the wave period, with the latter being the stronger effect.

It seems clear from the behaviour of the simulator so far is that there is no need for constant change in the gain when riding the bike in a straight line with low lean angles. Running as it is around 100 msecs lag with a gain setting high enough to put it in the stable oscillating condition it has more than enough power to deal with the disturbing couple of the weight.

Lag	Gain	Characteristic	Disturbance (degs) 2	5	15	Wave period (secs)
200	80	Overdamped	nc	nc	nc	-
	90	Stable dead-beat	12.8	nc	nc	2.5
	120	Stable Osc.	5.8	16.5	nc	1.9
	130	just stable	5.7	14.5	nc	1.6
	140	Unstable Osc.	5.3	13.4	nc	1.5
	200	Unstable Osc.	4.5	10.7	35.0	1.3
120	70	Overdamped	nc	nc	nc	-
	90	Stable dead-beat	12.0	nc	nc	2.6
	140	Stable Osc.	4.2	11.0	nc	1.5
	200	Stable Osc.	3.0	8.0	26	1.0
	240	just stable	3.0	7.4	23	0.9
	280	Unstable Osc.	2.8	7.0		0.7
60	100	Overdamped	nc	nc	nc	-
	140	Stable dead-beat	4.2	11.0	nc	-
	200	Stable dead-beat.	2.8	7.5	25	1.0
	280	Stable Osc.	2.6	6.5	20	0.6
	350	Stable Osc.	2.5	6.0	18	0.56
	470	just stable .	2.3	5.5	17	0.5
	500	Unstable Osc.	2.2	5.5	17	0.4

Table 6.5 The effect of gain and lag on stability. Lag in msecs, gain in nominal units and figs. in cols 1-3 in degrees. See text for details.

Control, however, has a problem in establishing just what that gain setting should be, as differences in speed affect the balance between the response from the tyre on the road, which is speed dependent, and the weight couple, which is not. The tyre response is a value which will also change considerably between different bicycles and on different road surfaces and it is not parsimonious to propose that the rider carries a variety of settings in memory from which the appropriate value is selected as a result of sensing the critical variables which affect it. 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 Smiley, Reid & Fraser, 1980) showed that operators adjusted the gain factor to allow for different system delays, thus demonstrating that humans are able to alter gain for control purposes. The simplest solution to the gain problem would be to try some default value and observe the response. If this is too low then the gain is turned up and if too high it is reduced. At the start of a run it is obvious that the setting will always be high to cope with the low speed and a large error in initial selection could be safely corrected by putting a foot back down on the ground. The result of such a procedure is bound to be considerable variation in the gain setting during a run especially since the system prefers to operate with a high gain putting it near the 'just stable' boundary. Thus, since wave period is dependent on gain, it can be argued that at least some of the wave period changes are due to this cause. Bar movements not connected with the roll/follow response will also change both period and lag but whether there is some as yet unidentified additional input producing this effect must wait until the characteristic has been analysed to a greater depth.

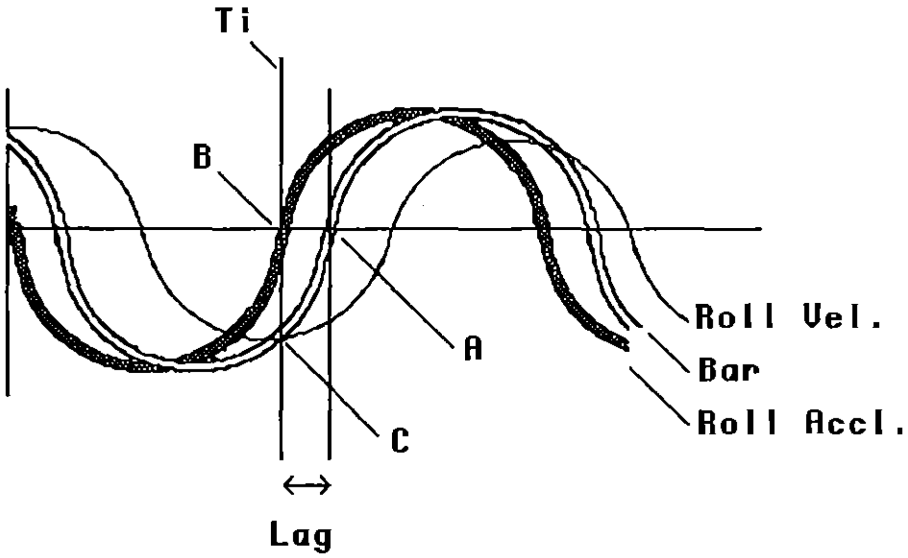


Figure 6.3 Illustrating how the values in the roll velocity channel vary compared with those in the acceleration channel at a sample point shown by the line Ti. The Bar channel is shown as a repeat of the roll acceleration at a delay marked as 'Lag'. See text for other details.

Acceleration and Velocity

When the regression analysis was performed on the roll and bar data in the previous chapter it was assumed that the roll acceleration information was the only ingredient being used by the system to modify the bar output. Control systems however may utilize various forms of the basic input to achieve different results. Figure 6.3 shows a formalized representation of the roll acceleration and velocity waves and the bar acceleration wave following the roll acceleration at a delay labelled LAG. If it is assumed that the bar value is a repetition of the roll acceleration then the relevant value associated with the bar value A is marked at B. At this point the associated roll velocity value is at C. Because the velocity curve runs 90 degrees behind the acceleration curve it shows a maximum value here as opposed to the acceleration value B, which is zero. Thus the control system could increase its response at low acceleration values by adding in the velocity as well. Obviously when the acceleration value was at a maximum the velocity would be making no contribution. In practice the velocity value could be obtained from the acceleration by integrating successive values which is the sort of operation a neural circuit is well able to perform. In the next section the effect of using either the acceleration or a combination of acceleration and velocity on the characteristic will be explored.

Assume first that the control is only responding to the acceleration value. When there is a disturbance either from road irregularities, side winds or a stray uncoordinated movement by the rider, an acceleration in roll will result. Since there is a delay in responding, velocity of roll will accumulate during the interval between the start of the disturbance and the response which checks the acceleration. Even when the acceleration has been removed the velocity will remain and the lean will continue to increase at a steady angular velocity.

In practice, since the increasing angle of lean will give an increase in disturbing couple, the acceleration will start again without any external encouragement and the process will be repeated with more velocity accumulating. Figure 6.4 illustrates this sequence on the computer model running at 4 mph with a lag of 120 msecs and a gain setting of 240. The bar acceleration is a repeat of the roll acceleration only.

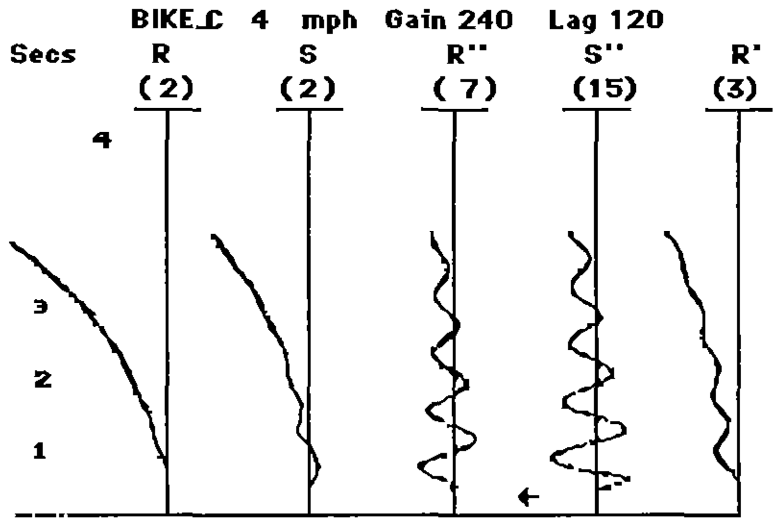


Figure 6.4 Delay control on roll acceleration only. In this and the following three figures the disturbance is a symmetrical on/off push of 600 msecs rising to a maximum by half-way. The start is marked by an arrow which shows the direction of the effect on the roll acceleration (R''). The figure at the top of the left axis (4) shows the nominal strength of this push.

From the exact upright position a small disturbing pulse is introduced. It can be seen that the roll acceleration (R'') is rapidly contained and oscillates about a mean value that is itself moving slowly left. This drift is quite clear in the velocity channel, R'. The velocity that was introduced during the disturbance remains, so the angle of lean, R, keeps increasing. The velocity itself increases as well because of the imbalance between the disturbing and correcting couples with increasing lean angle.

If the control is now altered to feed both roll acceleration, R'', and velocity, R', into the bar response the characteristic alters as shown in figure 6.5. Here the bar is responding to the accumulated velocity value as well as the acceleration and the former is gradually reduced to zero in three or four oscillations. However the angle which also accumulated during this operation is not removed as can be seen by the resulting lean, R. In general terms the velocity and acceleration introduced by the disturbance are removed by turning the bicycle into the lean until the centrifugal force balances the displaced weight couple.

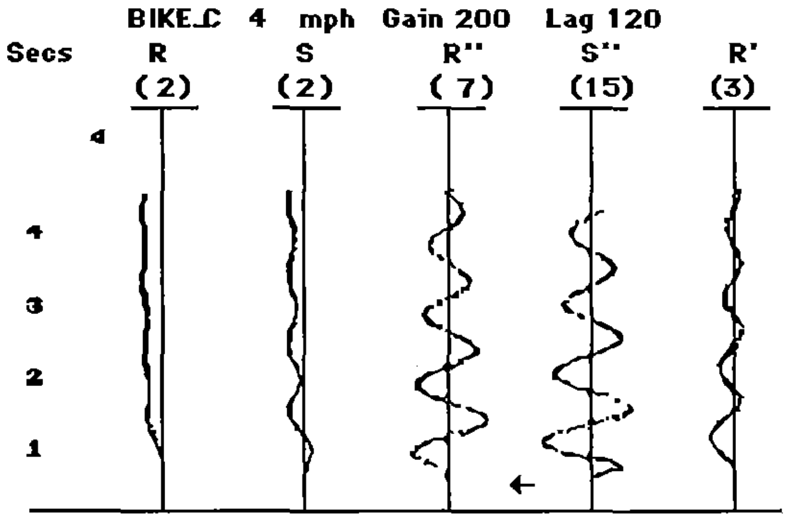


Figure 6.5 Delay control on roll acceleration (R'') and velocity (R'). The gain has been reduced to allow for the additional effect of velocity. All other values are the same as in figure 6.4.

Velocity Contributions in the Recorded Runs

Since the velocity curves (appendix 2,(b)) can be seen generally to return to the zero line from each wave excursion they seem to suggest that some velocity information is being fed back into the bar movement. In order to test this a multiple regression was run predicting the bar acceleration values from both roll acceleration and roll velocity values. Columns 1 and 2 in table 6.6 show a comparison between the R squared values for this regression and those from the previous regression using acceleration data alone. Column 3 shows the significance levels for the multiple regression. All the acceleration terms remain very highly significant and only one of the velocity terms falls below $p<.001$ to $p<.05$. (Run 28). Again the F numbers for the goodness of fit of the regression are all well over the critical value for $p<.001$. In every case the R squared value rises, the actual differences are shown in column 4 with a mean difference of 3. From this it may be concluded that the combination of roll acceleration and roll velocity provide a better prediction of the bar acceleration movement than the acceleration on its own. In this section of some of the runs, 32,33 and 34, the combination is accounting for 90% of the bar movement, which when allowance is made for noise and external disturbances is very high indeed.

This evidence supports the idea that the main influence on the bar movement is a continuous repeat of the activity in the roll channel sensed as both changes in acceleration and changes in velocity. The delay between the two channels is not absolutely constant but is sufficiently so to yield very high correlations when a mean value is used. There are differences between the run sections analysed here. The R squared values for these sections correlate at 0.74 with the original Pearson's product-moment coefficient values for the whole runs shown in column 2 of table 6.3. This is an indication that some runs have more extraneous movement in them than others but it will be shown shortly that there are also considerable differences of this sort within quite short sections of the runs. It will be argued later that this irregularity is a consequence of one of the essential control features. Attempts to control using velocity on its own are not successful because in effect it is the same as increasing the length of the delay by a quarter of a phase, which with a basic wave-period of about 1 secs means a minimum delay of 250 msecs plus any further transmission lag.

Section 200-400				Col 2-1	Section 200-370				Col 7-5
	accl	accl/vel			accl/vel		plus angle		
RUN	1	2	3	4	5	6	7	8	9
25	85	87	.001 .001	2	89	.001 .001	89	.001 .001 ns	0
26	74	76	.001 .001	2	76	.001 .001	77	.001 .001 ns	1
27	75	77	.001 .001	2	71	.001 .001	71	.001 .001 ns	0
28	71	73	.001 .05	2	70	.001 ns	71	.001 .05 ns	1
29	69	73	.001 .001	4	73	.001 .001	74	.001 .001 ns	1
30	70	74	.001 .001	4	67	.001 .001	67	.001 .001 ns	0
31	82	83	.001 .001	1	83	.001 .001	83	.001 .001 ns	0
32	87	91	.001 .001	4	91	.001 .001	91	.001 .001 ns	0
33	87	90	.001 .001	3	89	.001 .001	89	.001 .001 .01-	0
34	87	89	.001 .001	2	89	.001 .001	90	.001 .001 ns	1
35	78	84	.001 .001	6	84	.001 .001	84	.001 .001 ns	0
36	80	85	.001 .001	5	85	.001 .001	85	.001 .001 .01-	0
mean				3					0.3

Table 6.6 The R squared terms & significance of the predictors for a series of multiple regressions predicting bar from roll. See text for details.

An examination of the upper and lower stability limits using the same procedure as that applied to the model of the destabilized Triumph which provided the values for figure 6.2 using velocity information only shows that the system is inoperable with such a long delay. There is no critically stable point since a gain setting which is low enough to prevent oscillation provides so little power that the front wheel reaches a critical value before the fall is contained. If the gain is increased sufficiently to contain the fall by a reasonable lean angle the system is so underdamped that it goes out of control before the second reversal can take place.

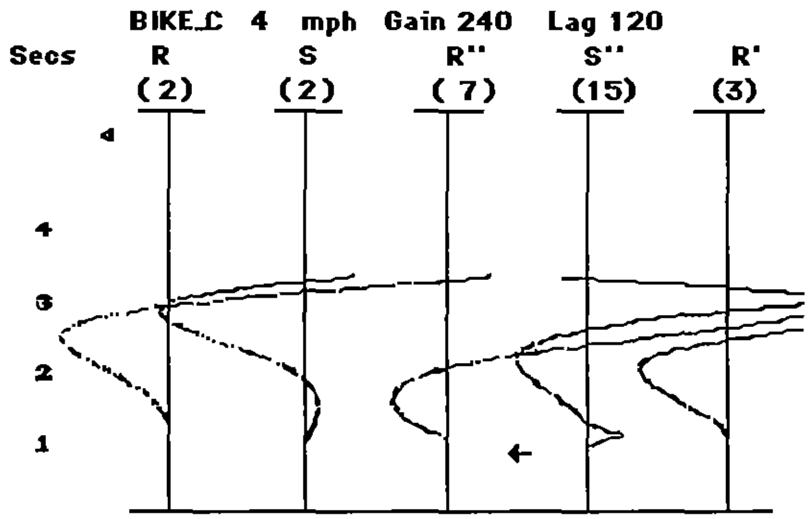


Figure 6.6 Delay control on roll velocity (R') only. The gain has been increased slightly to balance out the loss of the acceleration contribution, other values as in the previous three figures.

To provide a comparison with control using acceleration feedback this condition is illustrated in figure 6.6. Removing the acceleration contribution reduces the overall gain so this has been slightly increased to put the first reversal angle on the screen. The velocity growth runs a quarter phase behind that of the acceleration, consequently the gain drives the roll a long way after the reverse before the velocity value rises far enough to check it. The initial fall is reversed after about 6 degrees but the control is so slow in building up that the lean has reached 19 degrees to the right and the roll acceleration has only just reversed. Since there will be a further delay before the roll velocity reverses there is no chance of recovery before the lean angle becomes excessive.

Absolute Angle as an Input Variable

If the control is using only acceleration and velocity, as described above, the response to a disturbance would be a stable turn. However if the next disturbance happened to be on the same side then a further increase in lean and turn would result and there would be nothing to prevent excessive angles accumulating after a period of running. Thus otherwise undirected runs would be expected to show considerable changes of direction and occasionally loss of control. In order to keep a constant mean heading the control must respond to the angle as well. It is evident from the fact that the subjects kept an approximately straight course during the runs, even though they had been instructed not to bother, that the riders did react to the lean angle or to the rate of turn which will always accompany lean when under control. Therefore the next question that arises is whether to go a step further and include the lean angle R in the bar response so that the lean angle is also removed, returning the machine to upright running following a disturbance.

Figure 6.7 shows that the system is well able to accommodate such a modification. Here the roll angle R has also been added to the bar response. The increasing lean, R, acting through the bar rate, forces the velocity, R', further to the right than in the previous two runs which in turn brings the lean back gradually to zero in a series of gentle oscillations and the machine resumes straight upright running. A bicycle controlled in this way would maintain a straight upright course, gradually removing any lean angles that accumulated as a result of external disturbances, which is exactly what happens with motor-cycles and bicycles at speed.

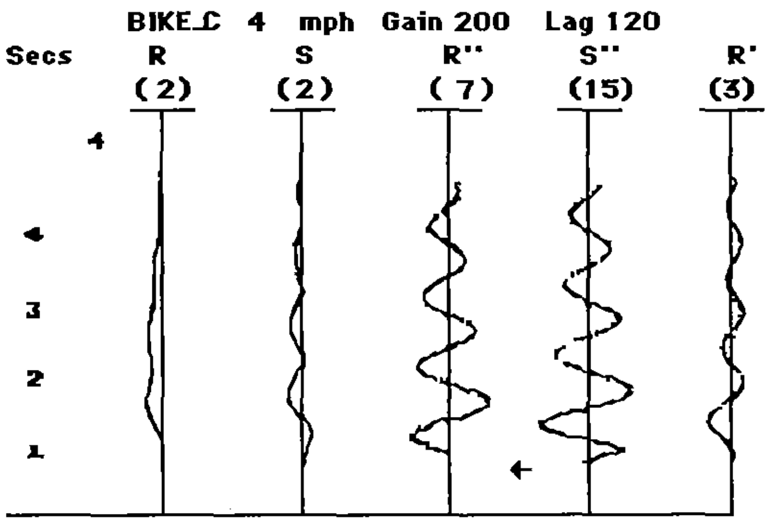


Figure 6.7 Delay control on roll acceleration (R''), velocity (R') and absolute roll angle (R). Other values as in the previous three figures.

Evidence Against Continuous Angle Control

The appearance of the roll angle traces in the destabilized runs does not seem consistent with the smooth removal of lean angle illustrated in the computer simulation of figure 6.7. Although all the runs maintain a mean of zero there are constant excursions either side forming the observed 0.25 hertz wave. In order to test whether angle was also being used by the delay/follow system a multiple regression was performed predicting bar response from acceleration, velocity and angle data. Due to lack of memory space in the statistical routine some of the run points had to be discarded. The regression is performed on the first 170 points of the 200 point run used for the previous regressions, that is points 200 to 370. Column 5 in table 6.6 shows the regression for the two predictors, acceleration and velocity, for the shorter sections so that it may be compared directly with column 7 which is the regression for the three predictors, acceleration, velocity and angle. It will be seen that removing the last thirty points has revealed some local differences within the runs but the significance of the predictors remains above the $p<.001$ level except for the velocity contribution to run 28 which has fallen below the significance level. The reliability of the R squared prediction remains well above the $p<.001$ level throughout. Although the reliability of the R squared prediction remains at the same high level for the three predictors, column 8 shows that only 4 of the angle contributions are significant, 3 at $p<.01$ and 1 at $p<.05$. Of these, two at the $p<.01$ level are negative sign which means that to obtain the overall fit on these runs the angle component was being subtracted not added. This of course is a bigger argument against its being a regular contributor than its being not significant. The other two predictors remain at a high level of significance with the same sign. Column 9 shows that the change in R squared brought about by adding the angle term is much less than the change produced by adding the velocity term shown in column 4 but where it exists it is always positive.

There is no evidence to support the proposition that the angle term is used continuously in establishing the bar movement. However, where the angle term is significant the correlation improves so it is possible that angle is being added discontinuously with its sign independent of the other two continuous contributors. That is there are irregular short pushes which may work either against the roll or with it.

The Discontinuous Application of Roll Angle

If the underlying control is a delayed repeat of the roll acceleration and velocity in the bar acceleration on which some form of angle control is intermittently superimposed then one would expect the prediction of bar from roll acceleration and velocity to show similar discontinuities. The regression analysis gives the residual values, which are the differences between the predicted value and the actual value at each data point. If those which exceed the 95% value (1.96 of the standard deviation from the mean) are plotted, short runs of disruption over several adjacent values are revealed. Two short sections of 50 data points each were selected from each run, one which included such an area of disruption and one which did not. The terms 'clear' and 'disrupted' will be used to distinguish between the two types of run. Table 6.7 shows the clear sections selected in column 1 and the disrupted sections in column 6. Two clear sections (Runs 32 and 33) were shorter than 50 to prevent the inclusion of a disrupted section. The other columns show the results of regression analyses first with acceleration and velocity as predictors and then with angle added. Columns 4 and 9 show the significance level and direction of the three predictors and columns 5 and 10 show the change in R squared value which resulted from the addition of the angle factor.

Throughout all runs the significance of the R squared term remained well clear of the $p<.001$ level. No F distribution term fell below 100 with a critical value of 11. Some runs showed no increase of R with the addition of the angle term, some showed a considerable increase and none showed a reduction. There was slightly more change, measured by the means, in the disrupted areas but the distribution of the contributions shows quite a marked

	Clear Section					Disrupted Section				
RUN	1	2	3	4	5	6	7	8	9	10
25	325/ 375	96	96	.001 .001 ns	0 0	265/ 315	89	89	.001 .001 ns	0
26	230/ 280	87	90	.001 ns .01-	3	260/ 310	62	64	.001 ns ns	2
27	250/ 300	58	68	.001 ns .001	10	290/ 340	83	94	.001 .001 .001-	11
28	300/ 350	68	79	.001 ns .001	11	230/ 280	81	89	.001 .001- .001	8
29	200/ 250	87	87	.001 .05 ns	0	250/ 300	87	87	.001 .001 ns	0
30	300/ 350	89	90	.001 .001 ns	1	210/ 260	76	83	.001 .001 .001-	7
31	230/ 280	97	97	.001 .001 ns	0	300/ 350	83	87	.001 .001 .001	4
32	250/ 290	97	99	.001 ns .001-	2	290/ 340	88	89	.001 .001 .05-	1
33	260/ 295	97	97	.001 ns ns	0	345/ 395	93	93	.001 .001 ns	0
34	260/ 310	96	96	.001 .001 .05-	0	200/ 250	85	88	.001 .01 .01	3
35	200/ 250	82	83	.001 ns ns	1	345/ 395	85	86	.001 .001 ns-	1
36	320/ 370	91	91	.001 ns ns	0	250/ 290	87	93	.001 .001 .001-	6
				mean	3.2					3.6

Table 6.7 Comparing the R squared term from regressions predicting bar acceleration from roll in two sections, one disrupted and one clear, from each of 12 runs. See text for details.

difference. Most of the change in the clear runs comes from two high values in runs 27 and 28. These two runs also show another difference in that their starting R values are much lower than the other ten. If these two runs are excluded then the mean changes become 0.6 for the clear runs against 2.49 for the disrupted runs which is consistent with the view that the angle term is having little effect in the clear sections but is contributing to the bar acceleration movement in the disrupted sections.

All the acceleration terms remained very highly significant and positive in sign. Although the velocity term was highly significant in all but one of the disrupted runs, five in the clear runs were not significant, though two of them were in the $p<.1$ bracket. All remained positive. The contribution of the velocity term to the regression equation is much smaller than that of the acceleration (means over 20 regressions: velocity factor 0.030, acceleration factor 0.834). A possible explanation of this difference between the clear sections and the disrupted sections is that there is very little velocity present in the short clear sections so the contribution locally falls below significance. An examination of the traces in appendix 2,(b) is not very encouraging to this view although it is difficult to make a clear judgement without some specific criterion.

If it is supposed that the acceleration output from the semi-circular canals is integrated by some neural process to obtain velocity then such a process is likely to take some time and may be partly discrete or have some threshold value below which is does not operate. This could lead to the more definite appearance of velocity in the disrupted sections if the disruptions are associated with more roll movement.

An interesting result is the effect on the significance levels and signs of the angle predictor. Table 6.8 shows a levels and signs of the angle predictor. Table 6.8 shows a summary:-

Significance	Clear	Disrupted
NS (p>.1)	7	4
NS (p<.1)		1
S (p<.05)	1(neg)	1(neg)
S (p<.01)	1(neg)	1
S (p<..001)	3(2 neg)	5(3 neg)

Table 6.8 Showing how well the roll angle predicted the rate of bar change in a clear section and a disrupted section of 12 runs (see text for definitions). Significance of the angle predictor term from the regression is in the left hand column and the number of incidences in either condition for each level is shown in the next two columns.

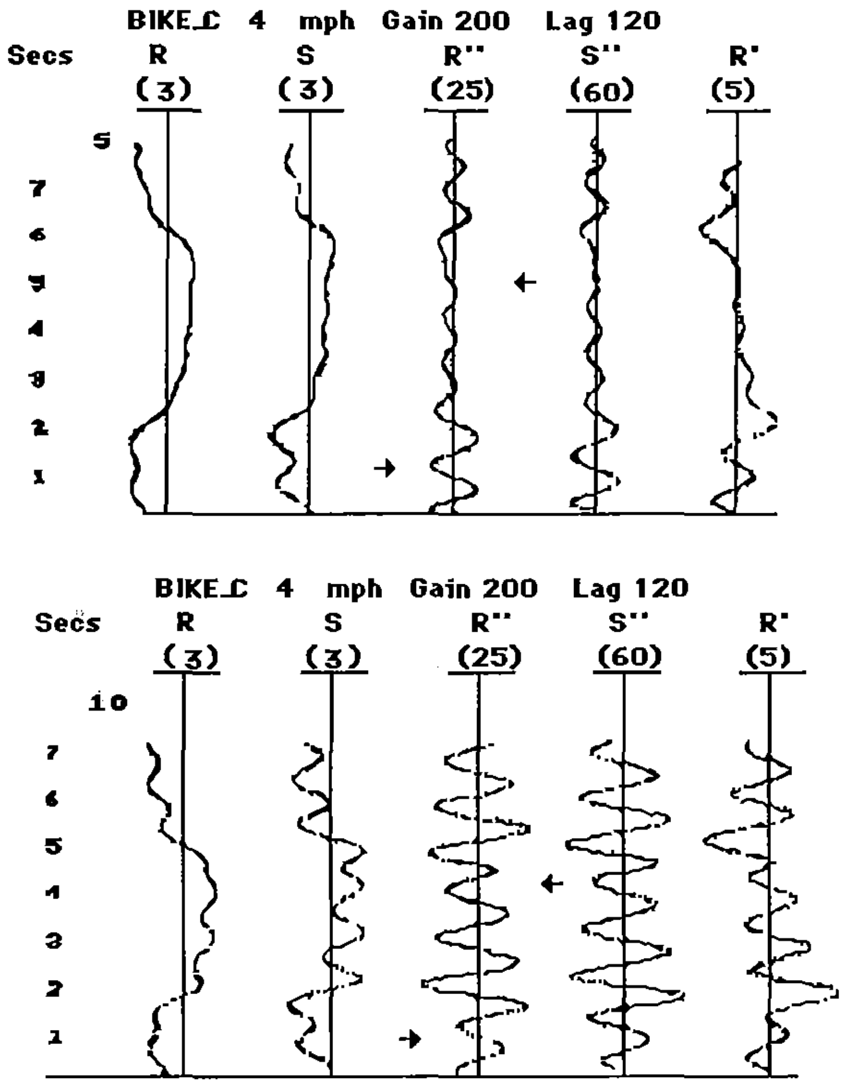
Since only one significant positive value for angle is found in the clear runs it is evident that this information was not making a continuous contribution to the bar acceleration values. Of the 7 significant contributions to the disrupted runs four are negative so it is clear that although there was a contribution from some source which correlated highly with the amount of lean angle present, it was not consistently applied in relation to the existing direction of lean. It should be borne in mind here that over 50 data points, about 1.5 secs, there is frequently very little change in the lean angle (appendix 2,(b)) so that the contribution to the regressions for this term is more in the form of a constant term rather than a variable.

Intermittent Control

It seems quite certain from what has been found so far that the roll acceleration continuously dictates the major part of the relationship between roll and bar, with a smaller addition from the roll velocity. Extra movement, which seems to be correlated with the absolute angle of lean, is superimposed on this base from time to time. The disrupted sections analysed in the previous section were chosen from the excessive regression residuals. To get a better picture of what these disruptions looked like for a complete run a routine was written which applied the multiplication factors for roll acceleration and velocity found in the regression performed on points 200-400 (Table 6.6, column 2) to the 100-500 sections of the runs shown in the graphs in appendix 2,(b). Those residuals which exceeded the 95% threshold were plotted to give the graphs in appendix 3,(b). A study of these plots shows that the same general characteristic is to be found for all runs. There are large sections with residuals below the threshold and occasional localized sections of 10 to 15 points where the values accelerate to a central peak value and then fall back again. Sometimes the peaks are isolated and sometimes they appear close together with the sign alternating.

The Simulation of Intermittent Peak Inputs

The next thing to discover was the effect on the characteristic when an intermittent peak input was superimposed on the continuous activity of the acceleration/velocity follow/delay system. To simulate this situation a routine was written which added a given force to the handle bar by increasing it in equal increments over a set period and then reducing it to zero in an equal number of steps. The peak value and period of application could be altered at will. The general response of the characteristic to these inputs was the same regardless of these two values.

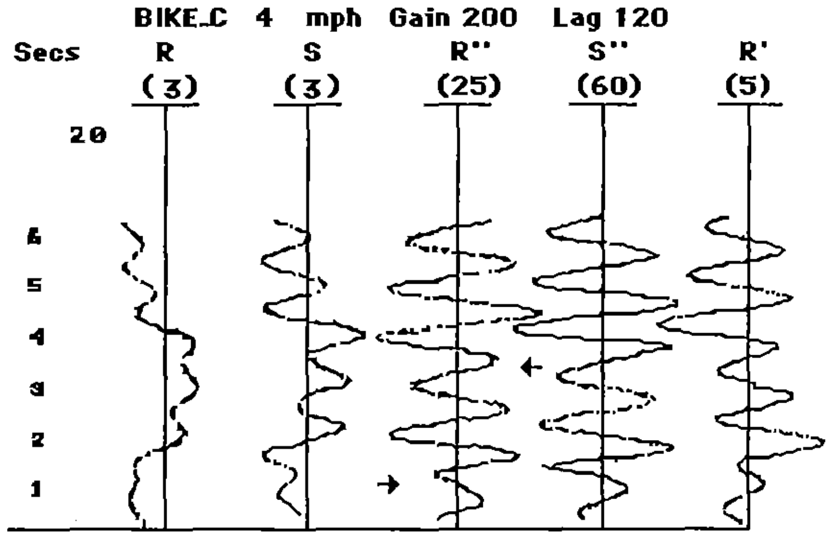


Figures 6.8 (a) (upper) & (b) (lower).The effect of pushes of various lengths applied to the simulated bicycle under roll/follow control. The initial disturbance is 2 degs. lean left. The push duration in (a) is 1200 msecs and in (b) is 600 msecs. The arrows show the start of each push.

A push produced a roll in the direction of application. When the push ceased the underlying roll/bar follow control removed the acceleration and velocity and left the machine in a stable condition with the accumulated lean angle remaining as already demonstrated. The amount of lean change that resulted was a function of the amount of power applied. That is, a long weak push equated to a short strong one, however as will now be shown the characteristic of response did alter with duration of push.

Figure 6.8 shows the effect on the characteristic of the simulated bicycle. The values used are the same as those used in the previous demonstrations. The lag was set at 120 msecs and the gain at 200 to put the system near the 'just stable' condition so that there would be plenty of movement. The machine starts off with a 2 degree lean to the left. Once the underlying roll/follow control has removed the disturbance and the bicycle is steady in a turn to the left a push is applied to force it to the right. The point at which the push is applied is shown in the figures by an arrow indicating the direction of effect on the acceleration trace (R''). Once the lean has reversed to the right another push is made to force it back to the left again. The strength of the push (shown in nominal units to the left of the R axis at the top) is adjusted with the length of the pulse to give the same amount of push in each case. Figure 6.8,(a) shows the effect of a 1200 msecs push of nominal value 5, (b) shows a 600 msecs push of 10 and (c) a 300 msecs push of 20.

One of the most interesting differences between the push effects is the behaviour of the velocity channel. Long pushes force the mean velocity curve away from the zero for several half-wave periods. One wave is well clear of the zero, that is it fails to make the zero crossing and the general displacement of the trace during the large angle movement is evident to the eye. The 1200 msecs period is equal to nearly three half-wave periods and the oscillations in the angle channel are suppressed during the change. As the period of application gets shorter the displacement of the velocity trace gets less as the main part of the movement takes place within one half-wave period (600 msecs is somewhere near the half-wave period and 300 msecs is well within it). With the shorter pushes the short wave movement is evident in the angle traces, R and S, which is also a feature of the real traces in appendix 2,(a) and appendix 2,(b).



Figures 6.8 (c). The push duration is 300 msecs; all other values as in previous two figures.

Evidence for the Push in the Traces

If it is proposed that part of the control system consists in imposing short pushes onto the underlying roll/follow control then it appears from the above that if the pushes were substantially longer than the half-wave period of 500 msecs then there would be a large number of incidents where the velocity wave failed to make the zero crossing and these would be associated with the pushes. Although it is difficult to define an exact criterion for a failure to make a zero crossing since the local wavelengths show variation, the following table shows an approximation of such occurrences.

Run	Detached waves	Location (data pt)	Excessive Residuals
25	1	330	7
26	0	-	10
27	1	275	3
28	2	280,350	5
29	3	260,320,440	6
30	1	460	15
31	3	310,325,460	4
32	3	200,280,460	7
33	1	425	10
34	4	200,295,370,415	7
35	2	270,380	8
36	7	165,250,310,345 etc.	5

Table 6.9 Showing the number of roll velocity waves which failed to make a zero crossing in the 12 runs and the number of pushes unassociated with roll movement in each run as indicated by the excessive residuals from the regression analysis. Whether the velocity trace crossed the zero line or not was judged by visual inspection and the location of each point is shown in column 2.

The final column shows the number of excessive residual peaks recorded in each run. There is obviously no reason for supposing that, if the excessive residual activity is a place where a directing push is applied, this leads to the velocity wave failing to cross the zero line. Thus it can be argued that if pushes are being applied at these locations they must be shorter than a half-wave. This view is further endorsed by the fact that none of the excessive residual runs are longer than 10 points, or 300 msecs.

Attention will now be concentrated on the section of run 33 from point 350 to 450. Figure 6.9 reproduces the roll and bar movement graphs from appendix 2,(b) and the regression residuals from appendix 3,(b) on the same page to assist in following the argument.

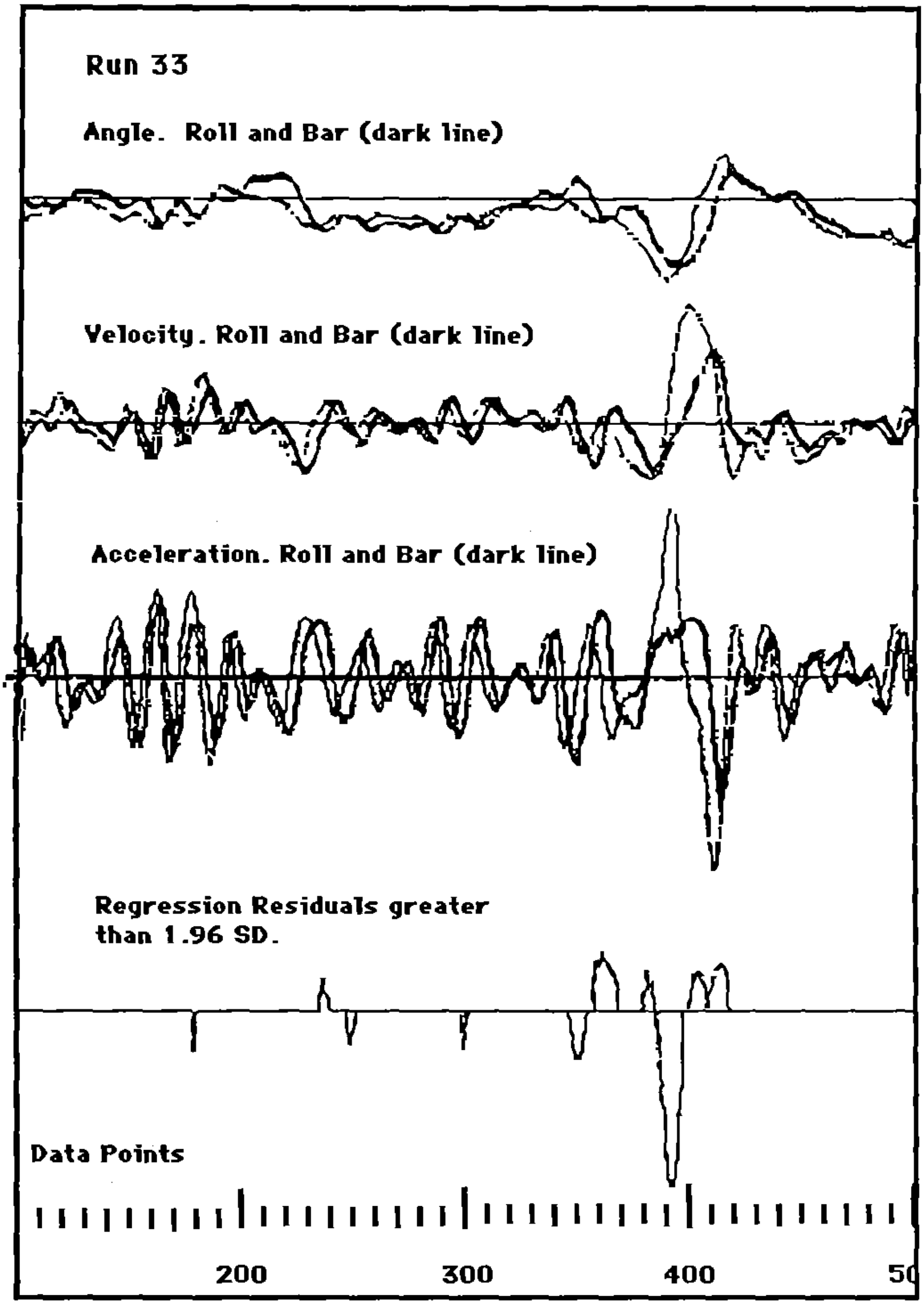


Figure 6.9 The first three channels from run 33 in appendix 2,(b) shown in relation to the excess regression residuals for this run from appendix 3,(b).

The convention applies that movement upwards is to the left and downwards is to the right. At point 360 the roll angle (faint line in the top graph) makes a rapid excursion to the right (down). This is reversed at 390 and there is a rapid movement to the left which is checked just after 410 from whence the movement becomes more gentle. Turning to the regression residuals at the foot of the page it will be seen that a left bar movement in excess of that predicted from the roll and velocity movement is located between 360 and 370.

At point 360 in the acceleration graph there is a bar response (dark line) to the left (up) well in excess of the roll acceleration. A glance to the earlier part of the acceleration trace will show that up to this point the bar peaks more or less match the roll peaks. (The immediately preceding lower wave which also has an excess peak with an associated residual peak is ignored at present to keep the argument simpler). The result of this extra acceleration in the bar drives the roll velocity response to the right (graph immediately above) so that it diverges from the bar velocity. The excess acceleration in the bar is reflected in the jerk trace by a steeper slope between 355 and 365 (from appendix 2,(b). The jerk trace has been left out of figure 6.9.) Despite the extra left bar input the underlying roll/follow mechanism eventually predominates as the push declines after its peak value at 365 and the bar acceleration pursues the roll acceleration to the right (down).

There is no excess push between 360 and 370 and the roll/follow movement of the bar succeeds in reversing the right going roll acceleration just before 370. Even though the roll has been reversed the bar continues to accelerate to the right for the delay period (about 100 msecs or a third of one of the marked intervals) thus driving the roll more strongly to the left back towards the zero line. However at 380 a further small left bar residual excess appears so this movement is somewhat inhibited giving the rounded curve in the reverse of the roll velocity at 380 to 385. At just under 385 a very strong right bar residual excess appears so that the bar acceleration which has just begun to pursue the rising roll acceleration is severely truncated between 385 and 400. This leads to an exaggerated roll velocity peak which is reflected in the large left roll angle movement back across the zero line in the upper graph.

By 400 the control, no doubt unwilling to leave the recovery entirely to the underlying roll/follow system, puts in two successive excess residual peaks at 405 and 410 to assist in containing the left roll. These have the effect of holding the bar acceleration on the left side between 400 and 410 thus driving the roll acceleration to a very exaggerated right peak at 415 which ties in with the reduction in the big roll velocity bulge between 390 and 415 and with the termination of the big left roll movement between the same points in the upper graph.

The above section was chosen for examination because it was the most exaggerated push in the sample. Equivalent corresponding movements in the angle, velocity, acceleration and jerk traces can be seen at the locations of the other larger excess residuals but are more difficult to follow as their size diminishes. The exact shape of the trace which results from such additions depends on where the push falls in relation to the existing wave.

Figure 6.10 shows how a small wave adds to a big one to produce a modification in shape that depends on their phase relationship. The section of run 33 analysed above gives good examples of both in-phase and out-of-phase additions. The downward peak at 350 coincides with the down going acceleration wave and exaggerates its movement without distorting its shape. The next upward peak does the same. The small upward push at 385 is in opposition to the existing wave and cuts its top off with some distortion. The large peak at 390 is also opposing the acceleration wave and also distorts its quite badly. Run 27 shows an in-phase addition at point 305 and there are other examples of both in and out-of-phase distortions elsewhere, though not always accompanied by excess residuals.

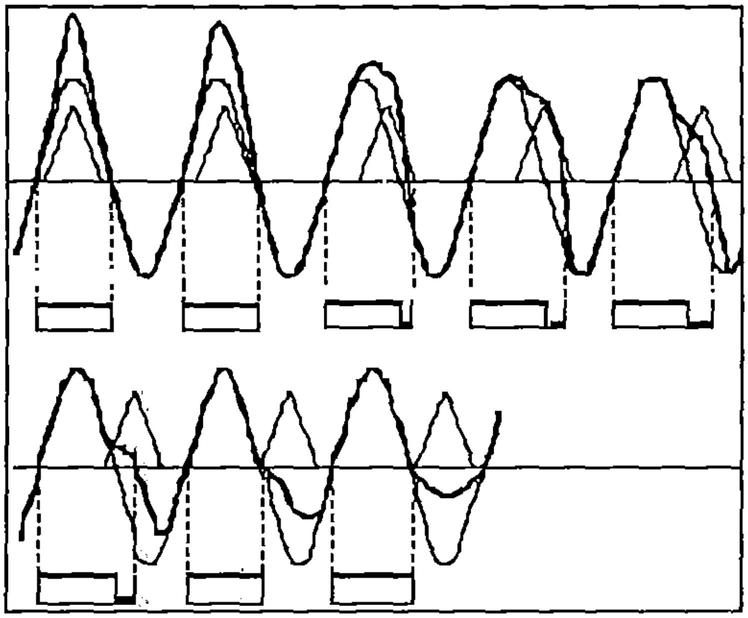


Figure 6.10 The effect of phase change on the appearance of a wave. The small triangular wave is added to the continuous saw-toothed sine-wave at an increasing phase interval to give the dark wave shape. The bars show the change in wave-length.

Control for Angle of Lean

There should be no surprise at the above findings as, providing that the main bar response is a delayed copy of the roll activity then excess values for the residuals must produce the observed effect. The question is whether the riders are using these pulses to control the machine or whether they are accidental inputs. No satisfactory method of analysis has been discovered by the author for examining this point conclusively. The runs on the simulator show that push inputs will produce changes in lean. The regression analysis shows that angle makes no continuous addition to the bar movement and the simulation has shown that with only acceleration and velocity controlling bar acceleration, any angle that accumulates will remain in the form of a steady turn into the lean. Since the riders all kept a more or less straight course during their runs they must have been controlling for angle in some way or other and the extra pushes represented by the excess residual peaks are the most likely source of this control.

The angle traces show that all the runs have a tendency for 3 or 4 seconds (100 points equals 3 secs) of a slow drift of the mean lean angle followed by a fairly sharp turn back towards the zero, executed within about 1 second. In order to get a clearer picture of how the excess residuals relate to the movement of the bicycle the location of the former were printed on the same time base as the angle of lean curves (light line) from the upper graphs in appendix 2,(b). These can be found in appendix 3,(c). The arrow direction shows the influence of the excess push on the existing trace. That is, a residual shown below the line in the previous graphs, such as that at point 395 in run 33 (appendix 3,(b)), is shown as an 'up' arrow indicating that extra bar to the right (down) gives a boost to the left (upwards) roll. Where an excess residual push is attached to the X=0 line it has been omitted because of difficulty in seeing whether it is the tail end of a wide pulse or a narrow one. Otherwise all the recorded pushes are shown and no distinction has been made between large and small ones. To establish whether the excess residual pushes were in fact associated with changes in lean angle the following analysis was performed. The following criteria are taken as dividing the roll angle response in the region of the pushes into one of 5 categories.

<u>Case 1</u>. The direction of roll is the same as the direction of the arrow.

<u>Case 2</u>. The slope changes direction in accordance with the direction of the arrow.

<u>Case 3</u>. There is no movement either way.

<u>Case 4</u>. The slope is against the direction of the arrow.

<u>Case 5</u>. The slope changes direction against the direction of the arrow.

Three 'windows' of 300, 450 and 600 msecs width were applied successively to each arrow so that the window exposed the next angle values starting at the arrow location. Each arrow was given three chances to obtain a successful rating (case 1 or 2) by successively increasing the width of the window. As soon as one of the two success criteria was met the window size was taken as the score for that arrow. If the arrow failed to meet one of the successful cases then it was recorded as whichever of the others was appropriate. The last two cases (4 & 5) were combined as a single unsuccessful class. The results from the 93 excessive residual points were as follows:

300 Msecs	66
450 Msecs	15
600 Msecs	5
Zero	0
Contra (4 & 5)	7

Although the criteria for judging the slope movement are somewhat subjective, a very large proportion fall into the 450/300 mesecs acceptance category. One of the five 600 msec points (run 27 push 3) is right at the peak of an appropriate reversal and only misses a 300 msecs category because the rule starts the window at the point. At least one of the contradictory points on closer examination can be seen to be working in the successful bracket when combined with the influences of neighbouring pushes. That is, the effect on the acceleration movement does not always lead to an observable movement in the angle. (This was point 7 in run 33, already dealt with in detail above.)

The above results suggest that the excess residual pushes do lead to changes in the roll angle. It can also be seen, especially in the first five runs, that the rapid changes in angle already noted frequently have associated residual arrows in appropriate locations. However it is also true that there are some large angle changes with no associated residual peaks. Run 25, point 240 provides one example, run 27 point 200 another. Presumably there could be a large peak just below the 1.96 threshold which got its power from time of application rather than amplitude and is therefore masked by the noise. The failure of an arrow to appear on the first reversal of a long rapid roll movement such as at run 26 (265), run 27 (215)(360)(390) & run 29 (390) is not surprising as the computer simulation shows that the roll/follow response to a large externally imposed movement reduces the rate of roll almost as quickly as the initiating movement. (figure 6.6 (a) Reversal at 2.5-3.0 secs). The pushes which follow the initial reversal in the examples quoted would be consistent with a rider putting in a push to counter the shallow oscillating drift that follows the initial strong reversal and force the bicycle back towards the upright.

Although it seems clear that the pushes identified by the excess residual peaks are causing the bicycle to change its roll angle it not so easy to establish what feature might be triggering these inputs. The absolute angle values for roll are unreliable as they are the result of integrating the recorded velocities and the constant term has been established only approximately. The bar trace, which records actual angle not velocity, has been used as a guide for 'zeroing' the angle data but the exact distance of the various excursions from the zero line are only approximate. It should also be borne in mind that the angles involved here are small, less than 2 degrees. There are a number of examples of quite sharp turns from apparently upright running (run 27,{320}, run 33,{370}), but in general there are no sudden turns away from the zero line when the lean angle is already substantial. That is, any drift in lean is always curbed not exaggerated. Thus the overall impression is that somehow the control detects lean angle rather approximately and, when this exceeds some threshold value, pushes are used to bring the angle back towards the zero.

In the last three runs several alternate left/right pushes have been introduced when the bicycle is running upright, which make no overall change to the angle but produce a comparatively large local wiggle. Feedback control systems depend upon the changes in the primary signal for their operation. When the signal gets too weak it becomes swamped by noise and the control 'dithers' about the zero waiting for something definite to appear. Hunting to and fro either side of zero is one way of improving the signal to noise ratio. Initially it was supposed that the rider might be injecting short ballistic pulses, timed to coincide with the zero crossings of the roll acceleration, to give an increased response. However a more parsimonious explanation is that riders increase the gain value to approach, or even temporarily exceed, the 'just stable' condition which results in large oscillations in the acceleration channel without associated changes in the mean roll angle. When, however, the bicycle is balanced near the upright there is little actuating signal so the gain has nothing to multiply and a high value will not produce a rapid change. It is therefore possible that the left/right pushes observed here serve the purpose of disturbing the upright balanced position in order to improve the actuating signal.

Since the blindfolded riders had no direct information about absolute angle they could only have recovered such information either by some sort of neural integration of the rolling and yawing acceleration or from sensory changes at the contact points with the bike due to the centrifugal forces during the turns. With the very small angles involved the latter changes would be very small indeed and the integrations would suffer from the same sort of inaccuracy due to lack of the constant term as is found in the data conversion. Both of these could account for the lack of any clear regularity in the application of pushes as revealed by the excess regression residuals.

Combined Intermittent and Continuous Control

A high correlation was found between the roll and bar activity throughout all the runs, rising to a peak in places where the roll acceleration and velocity activity accounted for over 95% of the movement in the bar acceleration (col.2, table 6.7) and was above 80% for every total run (col.2, table 5,3). Since the only movement to the handle bar is through the rider's arm movements it can be concluded that the basic control system used by the riders applied the rates of angle acceleration and velocity sensed in roll as rates of angle acceleration to the handle bar after a delay that varied about a mean of approximately 100 mesecs. The failure of the angle term to maintain significance and constant sign in a multiple regression over several seconds of run time (col.8, table 6.6) indicated that angle was not continuously applied in the same way. A computer simulation showed that, with only acceleration and velocity controlling the bar, the control failed to remove angles that accumulated, thus a bicycle using such a system would end up in a turn which would get tighter and tighter depending on which way random disturbances affected it. The fact that the riders did remove turns during the runs showed that angle must have been fed back into the control in some form. When the points where excess bar angle acceleration over that predicted by the roll angle acceleration and velocity were plotted on the same time base as the angle movement they were frequently (87%) associated with an appropriate roll movement within a half-wave length (mean 0.5 secs), but there were a number of containing movements which did not have accompanying excess residuals associated with them. Simulated runs showed that pushes imposed over periods greater than a half-wave length led to distortions in the velocity curves which were not observed in the run graphs. It was also noted that the maximum period for the excess residual peaks was 300 msecs.

Overall it is considered that the evidence suggests the riders were using a continuous delayed feedback control which removed acceleration and velocity in a series of 'just stable' oscillations. As angle accumulated some threshold was exceeded and a push or series of pushes were added to the continuous control to oppose the lean. The small lean angles involved and the lack of direct information about absolute angle led to a rather noisy operation of the intermittent part of the system but the general trend was a slow increase of lean during a series of short wave oscillations and a short sharp change of angle back towards the zero, which was then either checked again with further pushes or allowed to settle down into another slow change before the threshold for action was again exceeded. The intermittent pushes were of a ballistic nature, showing an exponential rise to a peak and a similar decay. These pushes did not replace the underlying movement but were added to it to produce a composite wave form which means they must have been angle independent, implying a muscle tension independent of length. They were not timed in relation to the underlying movement as they sometimes enhanced a wave and sometimes inhibited it.

Variations in Lag and Gain

Change in lag, wave period and area was a feature of all the runs. It is fairly certain that the phase lag and gain would show small random changes about some mean even if the control had no reason for altering them since they are the consequence of neural operations which are unlikely to be absolutely stable. Change in lag on its own merely alters the potential stability of the system and cannot be seen as an effective controlling variable, and once the lag is fixed then the gain is also fixed to give the best response without going into the unstable condition. Thus it is argued that lag and gain are reasonably stable values which remain fixed so that the bar/roll follow control can operate effectively. It can easily be seen that a push superimposed on an otherwise perfectly regular bar/roll follow wave form will cause large local disturbances to both the lag and wave-period. Over the 12 runs there was an average of one excess regression residual every 1.5 secs (12 runs of 400 points, ie 12 secs, 93 pushes) so it is evident that there would be a good deal of disruption from this source and since the pushes are not driven by the roll change the initial movement would not be highly correlated with that in the roll channel. As the roll follow responds to the disruption the phase error is removed and the two wave periods correlate more closely.

Thus it can be seen that it is a consequence of a control where uncoordinated short pushes are superimposed on continuous wave/follow activity that there will be disruptions to the lag and wave periods which are only partly correlated between the roll and bar channels. The wave areas on the other hand are a reflection of the power applied and will correlate more closely when the system is maintaining a controlled path near to the upright. A larger than normal bar push suddenly introduced does not lead automatically to a large area for that wave as can be clearly seen in run 33 (figure 6.9) around point 400, since the extension of wavelength allows the amount of power applied to balance. Referring back to table 5.4 in chapter 5, it was noted that when the overall correlation was high there was a more stable wave-period. This ties in with what has been learned about the disruptive effect of wavelength change on correlations and the conclusion is that the wavelength disruption comes from uncorrelated pushes added to the relatively stable underlying bar/roll follow control, rather than changes in the lag or gain per se.

Imitating Full Control on the Simulation

Figure 6.11 shows the simulated bicycle running under fully automatic control with the speed and response values trimmed to approximate those of the real runs. The bar acceleration is a repeat of the roll acceleration and velocity channels delayed 120 msecs. The gain has been set at 220 to put the system near to the 'just stable' condition to mimic the movement found in the real traces. The intermittent rule applies a push of nominal value 16 applied over 300 msecs whenever the angle exceeds a threshold of 1.6 degrees. To avoid applying a second push before the first has had time to produce a change in the lean angle, further pushes are locked out for one half-wave period. The points at which the intermittent control applies a push are shown by an arrow which relates to the acceleration traces using the same convention as before. The arrow points in the direction in which the angle is driven. Figure 6.12 shows the first part of the same run in a horizontal format similar to the one used for the real run records so a comparison between the general characteristics can be made more easily.

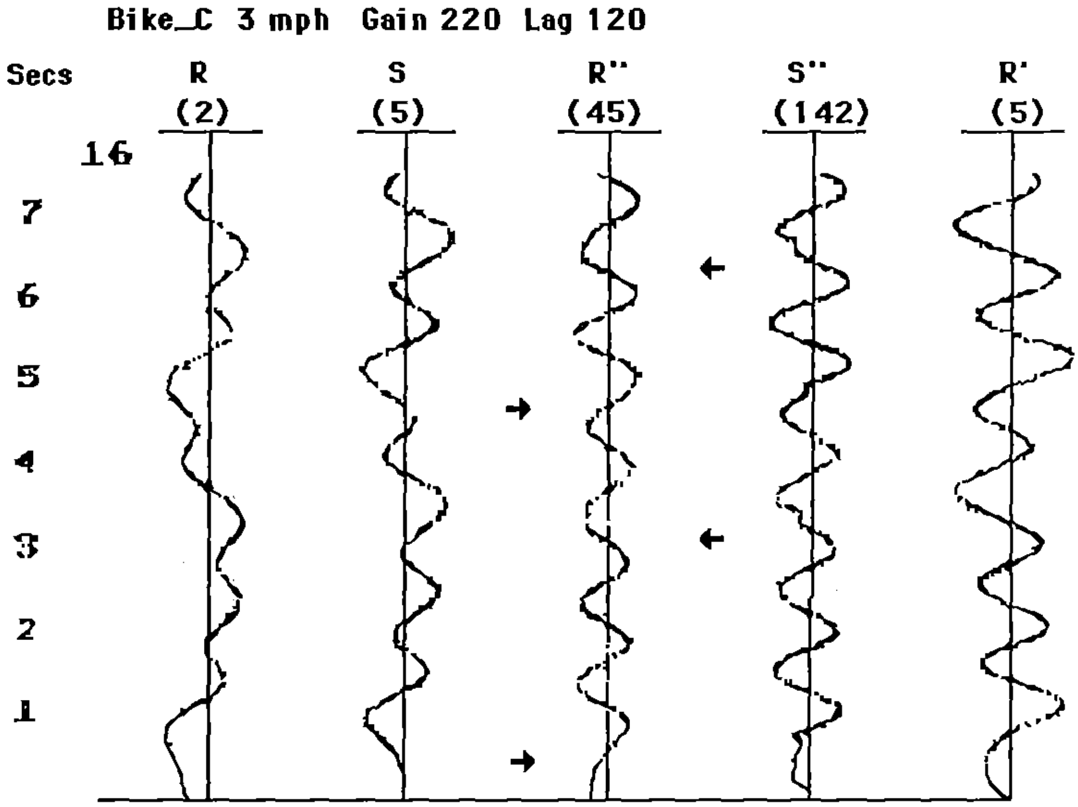


Figure 6.11 Simulated automatic control. Basic control is repeat of roll acceleration & velocity at a delay of 120 msecs with the gain set to give a 'just stable' response. When lean angle (R) exceeds 1.6 degs a 300 msecs push is added to the basic control to bring the lean back towards the vertical. Each push is shown by an arrow.

It can be seen that the intermittent threshold rule, superimposed on the continuous roll/copy/delay control, produces a trace that is very similar to those of the actual runs. The local distortions to the roll acceleration trace seen at 3.5, 5 and 7 secs, caused by the addition of the triangular short push to the underlying wave, may be compared with the distortions shown in figure 6.10 and similar shapes in the run traces.

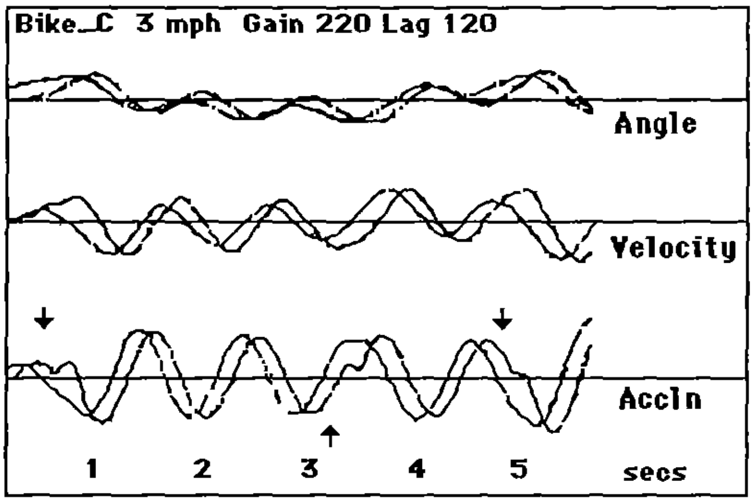


Figure 6.12 The initial 5 secs. of the run shown at 6.11 turned through 90 degrees to assist comparison with the record from the experimental bicycle under the same running conditions.

Nested Control Loops

Smiley et al. (1980) studied how the control technique of naive car drivers altered with learning. When subjects first started the task they tended to remove lateral displacement errors by altering heading until the displacement began to decrease and consequently over-controlled. Since they also made corrections to heading errors, independent of displacement errors, the solution to the first problem led to a contra-response from the second. In effect the two loops worked against each other instead of in unison. As they gained experience the subjects altered their technique so that the two control loops were nested. A displacement error was corrected by demanding an appropriate angle change in the heading loop which continued to operate about this new value until the displacement had reduced, at which point the heading demand was returned to the original zero.

In the proposed control for the destabilized bicycle no such nesting takes place. The underlying roll angle acceleration and velocity loop continues to operate autonomously. The push demand temporarily overpowers the continuous control and imposes a roll error upon it. In automatically removing the roll error the bicycle is turned into this lean error which is the solution required by the push. A similar performance is seen in bipedal balance when runners sprint from starting blocks. The initial instability is solved by accelerating the centre of mass as fast as possible in the direction of lean. In the bicycle the acceleration is provided by the turn rather than the linear acceleration of the sprinter, but it has the same characteristic in that it solves the toppling problem by altering the acceleration of the support point relative to the centre of mass.

Summary.

This chapter has explored the control technique used by the subjects riding the destabilized bicycle in a straight line, blindfold at very low speeds. In this condition a normal bicycle has very little natural stability and the experimental bicycle had none. The riders achieved basic balance by repeating the roll acceleration and velocity as steering angle accelerations. This allows absolute angle to accumulate. When some lean/turn threshold was exceeded the bicycle was forced back towards the upright with a short pulse lasting less than half a wave period. The next chapter considers how this control system might be applied to the conditions found in normal bicycle riding where the contribution of autostability becomes significant.

7. CONTROL OF THE AUTOSTABLE BICYCLE

Normal Control

The previous two chapters examined in detail the control used for riding a bicycle with all the autostability removed. This chapter will deal with the application of what has been learned to the problem of controlling a normal bicycle. Three qualifications affect the records taken from the normal bicycle. First the limited length of the recording wire prevented any fast runs. Second the records of bar movement contain contributions from two sources, the riders' arm movements and the autostability responses of the bicycle, and there is no way of discriminating between these. Also, because lateral body movements lead to autostability responses, some of the controlling movements may come from this source without there being any indication of this in the records. Third, all the normal runs were done on the Triumph bicycle before its conversion, consequently these records differ from the ones already presented not only in the presence of autostability but also in the extra weight of the conversion. This, together with the remote steering linkage, slightly altered the inertia and friction in the steering assembly.

Low Speed Control with Autostability

A short summary of the autostability effects will be given as a preparation for the discussion of normal control. Due to the front-fork design three couples act continuously on the front wheel. Whenever the frame is rolling there is a precessing force trying to turn the front wheel in the direction of the roll. Any increase in the angle between the front wheel and the direction of its local travel will produce a restraining couple, due to the castor effect, which inhibits the movement. Whenever there is an angle of lean the castor effect also gives a couple trying to turn the wheel in the direction of lean. The higher the speed the stronger the first two effects. The greater the angle of lean the smaller the last two become, because the geometry reduces the effective trail distance, 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.

Autostability depends for its effect on speed. When the speed falls below some limit there is insufficient response to prevent a fall without assistance from the rider. The next section discusses the differences between ten runs on the normal bicycle with those already discussed for the destabilized machine. The same subjects provided five runs each and the conditions were exactly the same in every respect as the destabilized runs except that the bicycle was the Triumph 20 before conversion.

The traces of these runs are not presented but to a casual inspection they are indistinguishable from the destabilized runs reproduced at appendices 2,(b) and (c). In order to compare the two sets of runs the values of the matched waves, the extraction of which was described in detail in the previous chapters, will be used.

Table 7.1, columns 1 and 2, shows a comparison between nine characteristics of the two types of run. Column 3 shows the significance of a t-test between the two sets of means. The justification for using the t-test is based on the following argument. It is evident that during a run the value of some variable such as lag or wave-length is very definitely influenced by preceding values and therefore violates the assumption of sampling independence required for the t-test. However, if it is assumed that the mean value for lag delay or wave-length or wave area during a single run is a characteristic of the system representing the combination of the bicycle and the rider then it is reasonable to argue that there exists a population of such mean scores which will be normally distributed about some mean value over a large number of similar runs. When some single value is changed, in this case the change from the normal to the destabilized bicycle, then this distribution either changes or remains the same. Although the values for several successive runs are still not truly random samples from this population the t-test used has some validity in indicating whether there are differences or not.

Variables	**Col.**	**Norm.**	**Destab**	**Sig.**
CCF roll/bar full run	1	0.86	0.85	ns
Lag. Mean counted vals	2	3.6	3.7	ns
Roll half-wave period	3	13	12	ns
Bar half-wave period	4	10	11	ns
Roll wave area	5	88	115	.01
Bar wave area	6	44	103	.001
Stand.dev. bar/roll	7	0.36	0.67	.001
Corrln. roll/bar waves	8	0.32	0.56	ns
Corrln. roll/bar areas	9	0.64	0.77	.001

Table 7.1 Comparison between the normal and destabilized runs for nine variables. Lags and wave-periods are in data-point intervals (30 msecs) and areas in nominal units. Values in rows 1 and 7- 8 are corrected to 2 places decimals, those in row 2 to 1 place decimals and in rows 3-6 to the nearest whole number. See text for details of t-test to which the last column refers.

Since the samples were not of the same size and nothing was known of their variances a t-test of two unrelated samples was used, (MICROTAB twosample). As will be seen the correlations between the roll and bar angular accelerations for the full run show no difference. Although there were some differences between the two individuals in the distribution of their lag values during a run it can be seen that the combined mean values over a run for either bicycle remain the same. Also the mean half-wave period for the matched waves show no significant differences. However the areas of the matched waves in the destabilized system were significantly larger than those for the normal bicycle, with a greater difference in the bar than the roll.

The above results seem consistent with a combination of autocontrol and human roll/follow control at low speed. The autostability, which works almost instantly compared with the rider's control action, reduces the roll angle movements arising from both external disturbances and the overcontrol due to the slower corrections of the delayed human responses, but the speed is too slow for all the movement to be removed. The wave period, which is a consequence of the lag/gain ratio and the dynamic properties of the system, remains the same in either case but the areas which represent the power applied are less than the roll areas because the automatic control is limiting the roll departures earlier and therefore less bar is needed to contain them. The bar area is also proportionally less in the normal bicycle output. Row 6 shows a comparison between ratio of bar angle standard deviations from the mean divided by roll angle standard deviations. This is a measure of how much bar movement is needed to contain the roll movement and confirms that the autostable control requires less. At least two factors can be identified which would promote such a difference. First the greater the absolute lean angle the greater the disturbing couple due to weight displacement so more bar is needed to check a larger angle of lean, and, since the autostability is checking the roll more quickly than before, the angles will be smaller. However the angles of lean in all cases were very small (see table 5.1) and it is hard to see how a difference of 1 degree could cause such a difference since the sine value hardly changes in this regime. A second possibility is that the greater inertia and less positive action in the modified front fork design of the destabilized bicycle leads to greater overcontrolling. The castor effect in the normal bicycle, which works against all movements that try to push the front wheel out of alignment with the direction of travel, would also tend to damp out any overcontrolling due to steering assembly inertia.

As expected row 7 shows that the correlations between the roll and bar half-wave period are not significantly different, although those of the normal bicycle are slightly less correlated. However the areas do show a difference although it is not clear why this is so. It appears that for some reason when riding the normal bicycle, although the subjects made proportionally less bar movement per roll movement, more of this movement was unrelated to associated movements in the roll. There is the possibility that this was a learning effect since the normal runs were done near the beginning of the experimental period whereas the destabilized runs were done after both riders had acquired considerable experience of slow blindfold riding. That is, the extra uncorrelated bar movements could be noise due either to unstable gain values or accidental or exploratory pushes.

In summary the comparison between runs on a normal bicycle and runs on the destabilized machine at very low speed shows few differences, which is consistent with the idea that the autostability of the front forks is only providing a marginal assistance to the human roll-follow-at-a-delay control explored in the previous two chapters.

Controlling the Normal Bicycle at Speed

The next question to be discussed is what control movements the rider uses to direct an unmodified bicycle at normal riding speeds. It has already been mentioned that recordings of rider activity with a normal bicycle are contaminated by the autocontrol. However with the assistance of the simulation and some general observations at fast riding speeds a fairly clear picture of the necessary control system can be constructed.

General Observations on Fast Riding

The following experimental runs were made to obtain the general response of a normal bicycle to some simple control inputs at a speed where the autostability control had enough power to remove any accidental roll errors. The rider was a male weighing 178 lbs in good current practice riding a Carlton ten-speed sports tourer in good condition. Five runs were made in each configuration on a normal road surface down a hill which was sufficiently steep to maintain the speed without pedalling. The speed did not need to be known accurately but at the start of the each run the pedalling speed was approximately 2 to 3 half-cycles of the pedals per second in top gear (14/52 pedal/wheel ratio. 26 inch wheel). This equated to between 17 and 23 mph at which speed there was a high degree of autostability. Throughout the test runs the rider made every effort to prevent any movement between body and bicycle.

1. Inherent stability. The rider aimed to negotiate a 200 yard section of road without touching the handle bars and without moving his body. The bicycle was extremely stable with quite high forces in the steering due to the

autostability factors. On four out of the five runs the bicycle ran straight and upright down the middle of the road. On one run a single adjustment was made to heading.

2. Response to a disturbance. Once established in the hands-off running configuration described in 1. above, the rider pushed forward briefly with one finger on one handle bar. The immediate response was a sharp lean towards the side of the push. This was followed by a very rapid return to upright running with one or two decaying oscillations in roll either side of the vertical as the effect of the disturbance damped out. A small change in direction accompanied the correction.

3. Response to a steady push. From the hands-off running configuration the rider applied a gentle push with one finger to the end of one handle bar. The tip of the finger was used so that only a push could be applied. The push was held as constant as could be judged. The response to this input was a rapid lean in the direction of the push but this time there was no recovery. If the push was applied rapidly there were a number of damping oscillations about some mean angle of lean in the direction of push. If the push was applied slowly the angle gradually increased without oscillations. In both cases the lean stabilized at an angle that depended on the strength of the push and the bike went into a steady turn in the direction of lean. Although the push was maintained the handle bar reversed rapidly in the direction of the lean under the autostability forces during the start of the lean and during the turn the front wheel was turned slightly in the direction of lean/turn.

4. Recovery from a turn. Once established in the turn described in 3. above the rider rapidly removed the pushing hand so that both hands were well clear of the handle bar. The response was a rapid roll back to the upright. This continued over the vertical so that there

was a fairly large excursion of lean to the opposite side. Depending on the steepness of the original turn there were two or three damping oscillations in roll either side of the upright and the bicycle returned to straight steady running.

5. Modified recovery. In this configuration the push in the turn was removed smoothly and gradually rather than suddenly. The response was a smooth gradual recovery to upright running.

It was not possible to say for certain that there were no associated body movements modifying the autostability forces during these manoeuvres but the rider made every effort to ensure that none was made and if there were any unconscious movements they must have been very small. The effects observed were exactly what would be expected from an understanding of the autostability design of the bicycle. Left to its own devices the autostability resisted any tendency of the front wheel to leave the dead ahead position. Any roll was removed by the gyroscopic effect. Any lean was removed by the castor effect.

When the steering was displaced during upright running with a short push a turn resulted in the direction of the steering displacement, that is towards the side opposite to the push. This turn led to a roll 'out of the turn', that is towards the side of the push. This roll caused the front wheel gyroscopic effect to produce a precessing movement of the bar in the direction of fall. This movement of the steering started a turn in the opposite direction and thus balanced the fall.

When the bicycle was leaning over in the turn the weight of the rider and the machine acted via the castor effect to produce a couple with the trail distance, turning the wheel further in the direction of lean. This gave a greater centrifugal rolling effect than the displaced weight couple and the bicycle was rolled back towards the upright. These effects worked in unison to remove any lean angle in a series of oscillations either side of the upright.

When the autostability was modified by holding a steady push to one side (out of the turn) the extra angle due to the castor effect was opposed and the bicycle stabilized in a turn. The gyroscopic force at this speed overpowered the steering push and the resulting movement against the push was an addition of the two couples. It should be remembered however that at some steering/roll angle combination depending on the design of the bicyle the effective trail distance is reduced to zero and actually becomes negative if the angle of lean increases any further. (For example with the Carlton Corsair a steering angle of 10 degs maintains a positive trail distance to over 35 degrees of lean but an increase to 15 degs steering reverses the trail effect at about 25 degs lean.) Thus at very steep angles of lean the rider must modify his technique in this respect. At some point the machine becomes neutrally stable in roll and will keep turning without any bar pressure. Beyond this angle it will become increasingly unstable and will need into-the-turn pressure to prevent its going out of control. This almost certainly accounts for the 'uneasy feeling' encountered in fast steep turns typically when negotiating a roundabout.

The above effects could only be seen in this clear form when the speed was high. At low speed the autostability forces were low compared with the disturbing effect of the couple caused by the displacement of the centre of mass to one side of the support point so that greater angles of lean and rates of roll velocity were reached during the corrections. Below some low speed the autostability forces on their own were not enough to contain the disturbing couple and had to be supplemented by movements from the rider. It was noted that these movements tended to include extra roll induced by upper body movements either as well as or instead of additional arm movements. The latter could not be subjectively experienced. The fact that they must have existed was deduced from the fact that when the hands were removed from the bar at low speed control was lost.

The Effect of Pushes on Control

It can be seen that the basic method of controlling the normal bike for changes in direction is similar to that seen in the destabilized bicycle. That is a push is added to the continuous movement of the autostability control. There is, however, an essential difference between the two underlying systems. The destabilized control responded to roll velocity and acceleration whereas the autostability of the front forks in the normal bicycle will respond to lean angle as well. When the speed is high, angle as well as roll rate is removed and the bicycle will return to upright running under autocontrol. A single on/off push causes the destabilized system to take up a turn whereas it merely causes a temporary disturbance in the normal bike which returns to upright running as soon as the push is removed. In order to keep the bicycle turning in the latter case the push has to be maintained.

This difference is illustrated on the simulated model. Figure 7.1 shows the effect of a single on/off push on each in turn. The time of application of the disturbing push is the same in both cases but the force has been adjusted to give exactly the same initial excursion of the handle bar acceleration (S''). Because the castor effect produces a strong damping effect on any steering movement out of true the force needed to produce a similar effect on the bar is higher by a factor of 5. In the upper diagram the simulation responds in the same way as the bicycle in the high speed tests in that the initial disturbance is damped out after two decreasing oscillations and upright running is rapidly resumed.

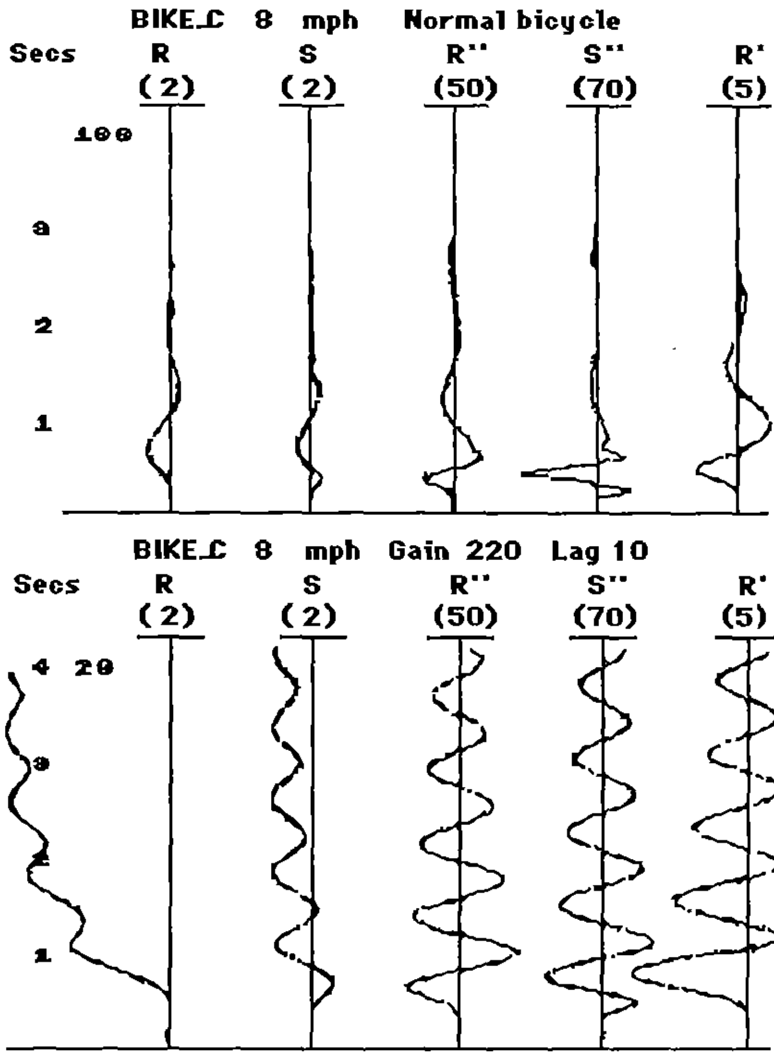


Figure 7.1 The effect of a single on/off push on the autocontrol. (upper graph) and destabilized system (lower graph). The push is applied over the same time interval with the strength trimmed to give the same initial response from the steering acceleration (S'').

In the lower diagram the roll acceleration (R'') is damped out with the trace showing a mean of zero. The velocity (R') is initially displaced to the left by the push but returns to a mean of zero after about 3 seconds.

The angle incurred during this operation is not removed and the destabilized bicycle continues to lean and therefore turn in the direction of the disturbance (R). The scale in the roll channel has been left large deliberately so that a direct comparison may be made between the two figures. The gain and lag in the destabilized control has been chosen to give a lightly damped converging oscillation.

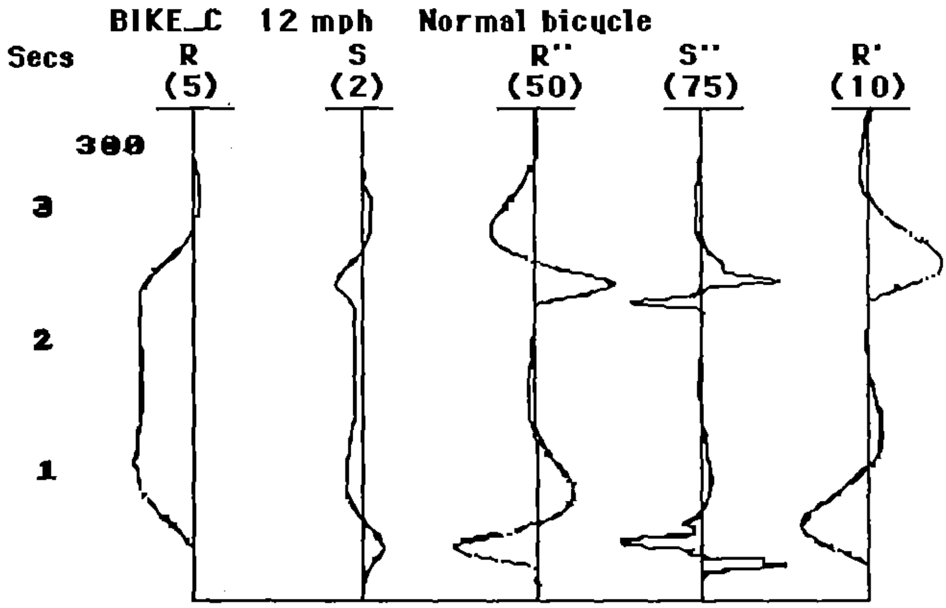


Figure 7.2 Simulation of push control of the autostable bicycle at 12 mph. A single 'on' push turning the bar to the right (right peak in channel S'' at 0.3 secs) gives a smooth roll to the left. The autostability forces immediately respond and check the lean at 7.5 degrees giving a steady turn left until the push is removed (left peak in S'' at 2.25 secs) when it returns to upright running without further attention.

Controlling the Normal Bicycle in a Turn

It was seen in the high speed tests that a push held on the bar led to a balanced turn in the direction of push at a rate that depended on the strength of the push. It was also seen that gently removing the push once in the turn led to a smooth recovery to the upright. Figure 7.2 shows this operation simulated on the model at 12 mph. The push to the right causes an excursion of the bar in that direction (S).The autostability forces rapidly oppose this and under the combined effect the bar moves to the left to follow and contain the fall by 7.5 degs. The result is a steady lean and therefore turn to the left. When the push force is removed at just over 2 secs (note the sudden left excursion in the steering acceleration channel S'') the unrestrained castor effect moves the bar further left causing the centrifugal couple to dominate the falling couple and the bicycle returns to the upright with one gentle oscillation. Thus the technique for turning a bicycle at a speed where the autostability is high is to apply a gentle push in the desired direction of turn, maintain the push until it is time to recover and then remove it upon which the bicycle automatically resumes upright running.

The faster the speed, and therefore the higher the autostability forces, the smoother the response to a given strength of push. When the speed falls and the autostability forces begin to reduce, the push must also be reduced to keep the control smooth. Steep turns at low speeds are therefore likely to be more oscillatory. Unfortunately no systematic recordings were made of manoeuvres but some rather casual recordings were made early on of the entry to and recovery from a turn with the normal bicycle at about 7 mph. Unfortunately two of the subjects were unable to carry out this manoeuvre without going out of control and their productions are of little use except as an interesting example of overcontrolling. However one subject produced a good trace of a smooth entry to and recovery from a turn and this is shown in figure 7.3.

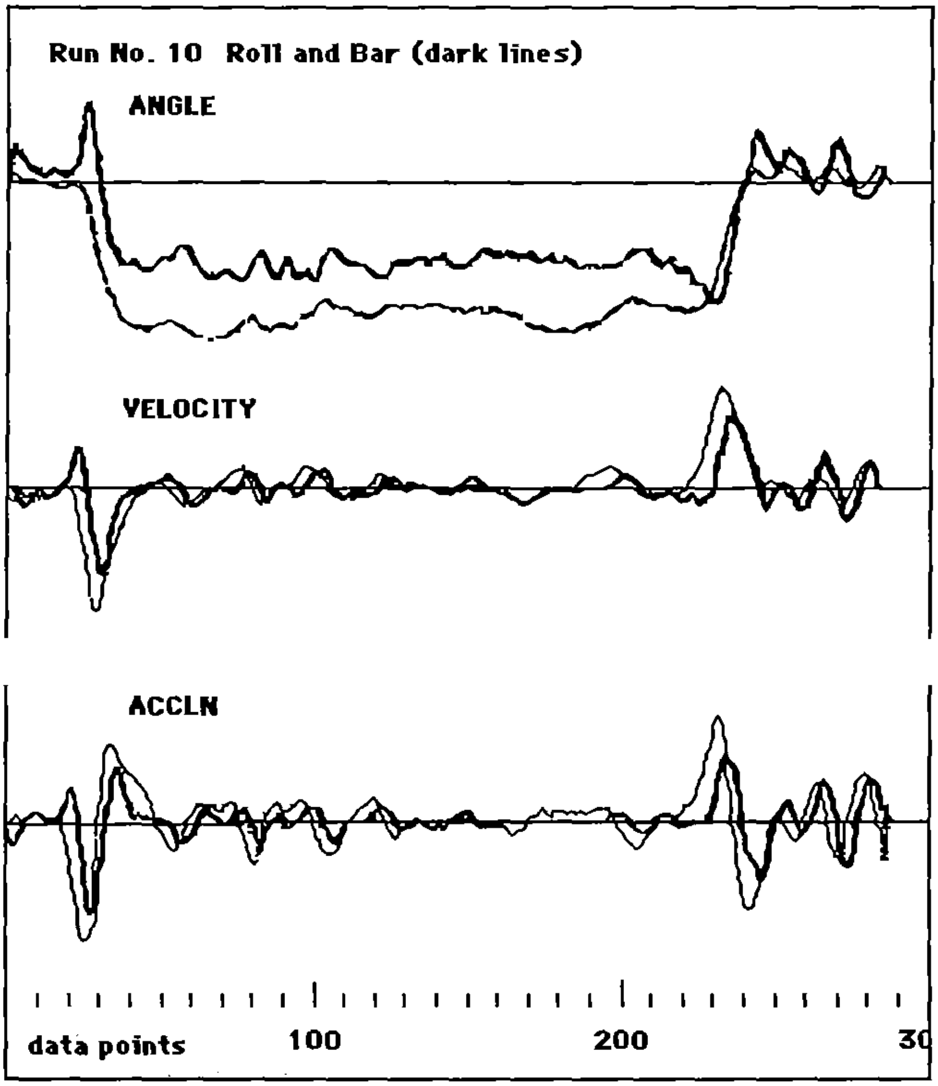


Figure 7.3 Showing the angle, velocity & acceleration for roll and bar (darker lines) for a 360 degree turn (Run 10) on the unmodified bicycle with a sighted rider. See text for details.

Single Recording of a Successful Turn

This run was made on the normal Triumph 20 bicycle before modification. The recording was made at an early stage of the experiments when the recorder was using four channels instead of two which gives an interval of 56 msecs between recorded points. The rider was the same subject who produced the high speed observations and for this run he was not blindfolded. The instructions for the run were as follows. The rider accelerated to a comfortable riding speed on a course which took him back along the wire and across the front of the recording station. The recorder was started as soon as run speed was achieved. At some point approximately opposite the recording station the experimenter called 'now' and the subject initiated a turn to the right as quickly and as steeply as possible consistent with smooth control. The turn was continued for 360 degrees holding as steady an angle of lean as possible at which point a smooth recovery was made. The run was terminated once straight running had been resumed.The actual mean angles during the turn were 9 degrees of lean and 5 degrees of bar. The radius of the turn was measured as approximately 15 ft so the speed can be calculated from the equation:-

Force = Mass x Speed^2 / Radius

where the force is that needed to produce a couple to balance the weight couple at 9 degrees lean with a weight of 200 lbs and a lever arm of 3 feet. This gives a speed of 6 mph. This also cross checks with the time for the turn recovered from the graph of the run. A 15 ft radius turn has a diameter of 94 ft which takes 11 secs at 6 mph. There are 200 points of 56 msecs each between the initiating spike and the recovery, ie 11.2 secs.

It is not possible to discriminate between arm induced bar movements and secondary effects due to body lean in the traces from the normal bicycle. Whichever method is used, and there is a likelihood that a combination of both methods is the normal technique, the only way a rider can initiate a large roll rate is by moving the bar to give a turn in the opposite direction to the desired roll. Figure 7.3 clearly shows this initiating movement of the bar at the start of the turn in all three graphs and the corresponding rapid increase in roll angle. For about 80 points after the initiation there is some 1 hertz oscillation which damps out. Between points 160 and 210 the record shows very little movement in the rate traces which is due to the inability of the recording system to capture the reduced movement when the bicycle is under autocontrol alone. The extra filtering in the jerk trace removes all the bar movement and most of the roll between the initiating spike and the recovery so this channel was not included in the figure. After the recovery there is a resumption of the 1 hertz oscillation. This record shows that the rider was able to hold a steady push on the bar between point 160 and 210 which just balanced out the castor effect and left the bicycle turning steadily under the gyroscopic effect.

Table 7.2 shows the statistics for this run. Because of the difference in channel interval, results have been converted to milliseconds so that a direct comparison can be made with the results for the previous runs. These have been taken from tables 5.3, 5.6 & 6.3 and show only the results for runs 25 to 30, since these were the contributions by the same rider. The full run correlation for the roll and bar acceleration at 0.87 is comparable to that for the destabilised bicycle at 0.84. This was achieved at a lag of 112 msecs as opposed to 115 msecs on the destabilized system. There are only about a dozen distinct waves in this run and these were measured by eye.

Consequently the measurement of the matched waves is rather approximate. However the mean lag measured at 117 msecs compares with a mean lag for this rider in the destabilized runs of 122 msecs. The half-wave periods in the oscillatory parts of the run are somewhat longer but show the same sort of relationship to each other as indicated in the bar/roll ratios. No attempt has been made to make a meaningful conversion of the wave areas between the two systems so these have been omitted.

The regressions for the first 170 points predicting bar from acceleration, velocity and angle show a similar pattern to those for the destabilized runs. The acceleration and velocity account for 81.5% of the bar movement which rises to 85.7% when the angle term is included but this is unreliable as the latter does not give a significant contribution. The significance of the velocity and acceleration terms remain above the $p<.01$ level in both regressions.

Variable	**Run 10**	**Destab**
CCF roll/bar whole run.	0.87	0.84
Lag for best correlation. (msecs)	112	115
Lag, mean at zero-crossings. (msecs)	117	122
Roll half-wave period.(msecs)	587	416
Bar half-wave period.(msecs)	424	367
Ratio of bar/roll half-wave.	0.72	0.88

Table 7.2 Comparison between a medium speed manoeuvre on a normal bicycle (Run 10, fig. 7.3) and the mean of 6 straight slow runs on the destabilized bicycle (runs 25-30, rider A) using 8 variables. Lag and wave-periods have been converted to msecs. Correlations and ratios are corrected to 2 places of decimals. Msecs are corrected to the nearest whole number.

The overall picture shows that at this speed the autostability is not powerful enough to cope with the high rate of roll-in imposed by the initial push and during the entry to the turn the rider is supplementing this with the sort of control seen in the destabilized runs giving the 1 hertz wave in these portions. For the second half of the turn the rider achieves a stable solution and the bicycle turns under autostability control alone although the recording is too coarse to pick up the much reduced movements. The release of the holding-in push can be seen in the angle bar trace between 215 and 240 and this is seen as a suppression of the appropriate response to the rising roll at 230 in the acceleration trace. Despite this fairly gradual initiation the autostability cannot deal satisfactorily with the check at the upright and the rider again brings in supplementary control between here and the end of the record. The evidence from the simulation runs and the high speed runs indicates that had the speed been higher the autostability could have dealt with this problem on its own. Similarly had the rider in this run rolled in and out more gently then the indications are that the same would have applied even at this lower speed.

It must also be borne in mind that during this run the rider could see and therefore had immediate information about lean angle available. However, the oscillations just after entry and particularly after recovery suggest that this did not lead to a more sophisticated application of angle, but that the rider was still using the technique observed in both the destabilized and normal very slow runs. That is, he was using short pushes to obtain changes in lean angle.

The rider would also have been able to enhance the autostability effect by making rolling movements of the upper body which would not be detected by the recording system. On the recovery, for example, he could have allowed the frame to rotate over the upright while keeping his upper body in the vertical (a local upper body roll to the right) which would give both a gyroscopic precession and a castor effect to the left, providing a force opposed to the combined mass movement. The recorder, being fitted to the frame, would pick up this movement as a roll past the vertical whereas to an observer it might seem as though the rider had stopped in the vertical. That is, the recording device only shows the movement of the combined mass when there is no relative body/machine movement. Such body movements do seem to be made at intermediate speeds and although the precessional response of the front wheel is very quick the body movements themselves are fairly slow due to the inertias involved.

Imitating the Turn on the Simulation

The above run can only be imitated on the model approximately because of the low speed and high roll-in rate. The model cannot be seen as an exact representation in detail of the real events so its performance at an equivalent speed is not necessarily exactly the same, nor is the added ingredient of body movement modelled. If a push strong enough to give the initial roll-in rate of 10 degs per second is applied and the autostability is left to its own devices the result is a large oscillation with a mean of about 7 degrees (R in Figure 7.4,(a)). Similarly if this push is removed rapidly at the end of the turn then the initial rate of roll-out is the same as the real trace but there are large oscillations about the zero lean position. However by a little juggling of the input a fair representation can be achieved.

The difference needed on the entry is to check the roll angle at the desired angle of lean without reducing the high rate of entry. This must be achieved by removing the pressure that is driving the roll at some critical point.

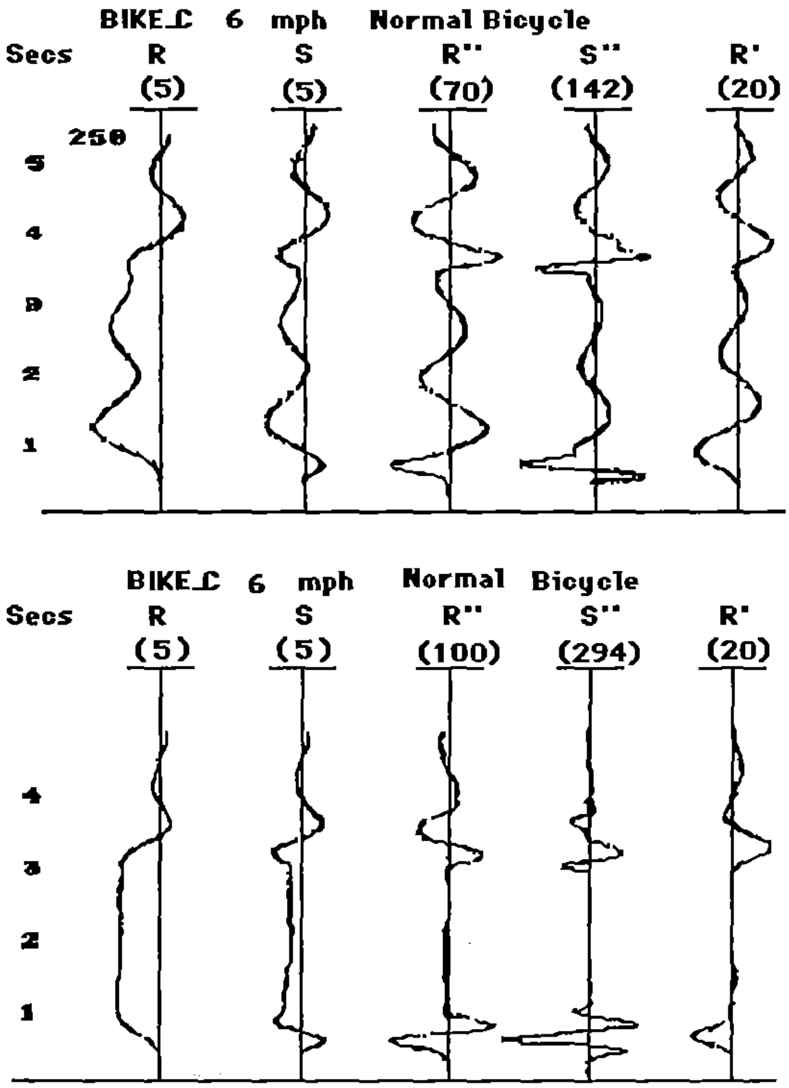


Figure 7.4 Imitating the real trace of a turn and recovery. If a push strong enough to give the same roll-rate as the real trace is applied and held (upper figure (a)) the resulting turn is oscillatory. When the technique is slightly modified (see text) the characteristic is nearer the performance of the real bicycle and rider. (Lower figure (b)).

The two outputs can be made to match by reducing the initial push back to zero in the standard push period immediately following the rise. Thus the input takes the form of a pulse, rising to a maximum and falling back to zero at the same rate. This allows the bar to move further in response to the autostability couple, thus checking the fall earlier. If the tension were left at zero then there would be a strong roll back towards the upright after the fall was checked, so it is obvious that tension must be reapplied to keep the machine in the turn.Reapplying the original push here produced too strong an effect but by experiment a push of half the original value was found to check the fall more or less dead beat as in the original.

The recovery can be imitated in the same way. Since it can be seen from the unmodified control used for figure 7.4,(a) that merely removing the bar push leads to over control, then some extra step must be taken to prevent this happening. Removing the pressure at a very low rate, over several seconds, smoothly returns the lean angle to zero without over-control but this is not what the rider in this run has done. A strong recovery is initiated when the pressure holding the bike in the turn is released. Since this does not lead to a large overrun then pressure must have been reapplied at some subsequent point to damp this out. A range of matched amplitudes and timings may be used to produce very similar traces in the computer output. The trace shown was achieved by setting the pressure to zero within the standard time increment thus starting a strong recovery. Half the original value held during the turn is reapplied after the recovery has got under way 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 of zero lean without making much difference to the behaviour. Once again it is emphasized that the above modifications could be equally well achieved by upper body movements which recruit extra autostability responses, but since the simulation does not include body movements they must be shown in terms of extra arm forces.

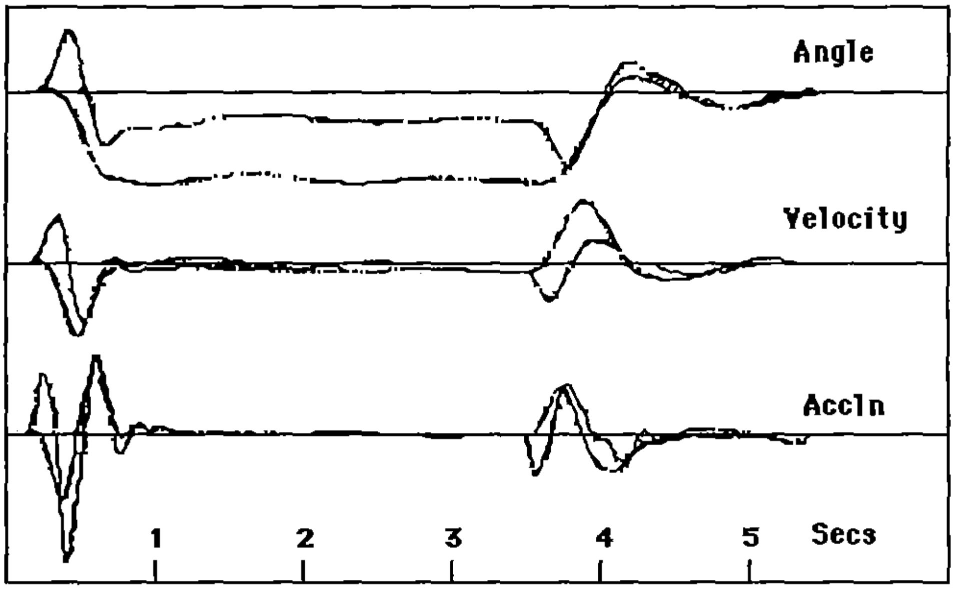


Figure 7.5 The simulated run shown in figure 7.4 (b) transposed to the same axes as the actual run shown in figure 7.3 to assist a direct comparison of the characteristics.

The output giving rise to the traces in figure 7.4,(b) has been transferred to horizontal axes in figure 7.5 to make a visual comparison between the computer simulation and the original run traces in figure 7.3 easier. Since the modifying pushes described above are fed in from the keyboard, the run in 7.5, although the same in principle as that in 7.4,(b), is not exactly the same in detail.

It can be seen that although the details of the simulated run and the real run are different the general characteristics are very much the same. It is the imbalance between the rate of roll-in and the riding speed that has caused the difficulty here since figure 7.2 shows that at a higher speed just a straightforward push and release achieves almost exactly the same characteristic as the actual run.It is interesting to note that two other less experienced riders who attempted to make a similar manoeuvre were unable to do so, both going out of control after the entry point. They initiated a strong roll-in on the 'now' call but were unable to control the check at the required lean angle. Consequently, although the difference between the simulation and the real trace may be due to the model failing to reproduce the correct response at this low speed, it is equally possible that forcing the bicycle to perform smoothly in this way at low a speed requires a higher degree of skill than that possessed by the two riders who failed and that the successful run was achieved by the more experienced rider supplementing the basic push control with either more complex arm movements or appropriate body movements.

Directional Control of the Normal Bicycle

Thus it can be seen that control of the machine at normal speeds is achieved in the following manner. The design automatically ensures that roll disturbances are damped out and the bicycle will return to upright running from low angles of lean. Allowing for a certain amount of low frequency oscillation, lean and turn are always equated. An angle independent tension on the handle bar, added to the autocontrol couples, will cause the bicycle to roll in the direction of push and then to turn in that direction, despite the rather confusing fact that the push appears to be in opposition to the required turn. Releasing the push causes the bike to recover to the upright. It is now evident that the rider's contribution is exactly the opposite to that used for a car or a tricycle. A push with the right hand in fact turns the handle-bar to the left. The reason the bar then turns back into the fall is due to the autocontrol couple not the rider's push which is actually opposing it. If the rider were to ignore this and turn the bar in the desired direction of turn the result would be a violent uncontrolled fall out of the turn. The informal survey, mentioned in chapter 3, suggests that riders generally believe that they themselves turn the handle bar into the initial roll and are unaware that in fact they are holding an angle independent push in the opposite direction throughout the turn. In reality reversing the push forces a very rapid recovery from the turn.

Mixing the Two Systems.

So far two somewhat different directional control systems have been proposed. Both systems achieve a turn by applying a push which turns the handle bar initially in the opposite direction to the desired turn. When the speed is low a short on/off push produces a fairly sharp roll followed by an oscillatory turn and when the speed is high such a push will only produce a wobble so the push must be maintained to achieve a turn. The question arises how does the rider know which method to employ and do they interfere with each other? Because the bicycle autostability has, by comparison with the human control, virtually no delay before responding and because the castor effect needs a high force to overcome its damping effect, the forces associated with the former anticipate in time and completely dominate in degree those of the latter. The faster the speed the greater this discrepancy as the castor damping effect keeps rising with increased speed whereas the bar forces in the undamped manual control must be reduced to compensate for the increasing force-per-wheel-angle response.

In practice the general sensitivity to response rate of human control mentioned in the previous paragraph is sufficient to allow a smooth change over of control as the speed drops below autostability levels. When there is good autostability then the small forces involved in the manual system fail to make any appreciable contribution but because autostability is working this contribution is in any case redundant. As the speed falls the autostability forces reduce until, at the point where they begin to fail to get a grip on the errors the weaker manual forces become significant and either supplement or take over the task.

Individual Differences.

This study was primarily intended to discover the general technique of bicycle riding. The skill is so common and yet so constrained that it was one of the initial hypotheses that there would be few large individual differences in the characteristic of responses. It was also realized that only when the details of the control being used was known would it be possible to design experiments which highlighted the differences between different riders. The study has not proceeded beyond the first stage and all the data comes from only two riders. These data, representing some 7 mins of control, are adequate for establishing the general principles involved but do not form a basis for a proper comparison between individuals' performance. However, some comparisons between these two riders are tentatively presented and the MICROTAB twosample t-test for two unrelated samples with different variance is used to test the differences following the same logic as before. That is a mean of such a value as lag or wave period for a run is regarded as one of a population of such values for this individual on this machine doing this task. Table 7.3 shows a comparison of the same values used for the normal/destabilized comparisons. The data are those from five normal runs and six destabilized runs for each rider.

Variable	**A**	**M**	**Sig.P<**
Lag measured at zero-cross	4.2	3.1	.001
Roll half-wave period	14	11	.001
Bar half-wave period	12	10	.001
Bar wave area	112	95	ns
Roll wave area	87	66	ns
CCF whole run	0.85	0.86	ns
Corrln. bar/roll wave	0.41	0.48	ns
Corrln. bar/roll area	0.67	0.74	ns
SD ratio bar/roll	0.52	0.53	ns

Table 7.3 Comparison between the two riders (A & M) using nine variables. Lags and wave-periods are in data-point intervals (30 msecs), wave areas in nominal units. Correlations and ratios corrected to 2 decimal places, lags to 1 decimal place and the other values to the nearest whole number.

Row 1 shows that there was quite a difference between the lag values over these runs and the t-test shows this to be highly significant. The histograms in appendix 2,(c) show that there is a considerable difference in the distributions, rider A having a wider spread of values about the mean. Rows 2 and 3 show that rider A had a significantly longer wave period that rider M. The simulated runs showed that with shorter lag a higher gain could be used for the same stability and that higher gain gave a shorter wave-length. It can be seen from the angle traces in appendix 2,(b) that both riders used a combination of lag and gain that put the system somewhere near the 'just stable' condition, thus, assuming that lag is a basic value for the rider, the wave-period should show a difference in the same direction. The t tests show that the differences in mean roll and bar areas were not significant, which implies that despite differences in lag and gain the two riders moved the bicycle either side of the mean path about the same amount and used approximately the same amount of power to do so.

The whole-run correlations between roll and bar acceleration were almost exactly the same (row 6) as were the correlations between the matched roll and bar waves both for period length and area or power. The ratio of bar to roll standard deviation, the measure of how much bar was needed to achieve control (row 9) are almost identical. These last results are an indication that the system is so unstable that it leaves very little room for alternative solutions to these relationships.

The overall picture is one in which both riders produced very similar performances on either machine. There are some indications that the lag value is different for each rider and since the lag value for rider A was the same when riding sighted at higher speed during the turn manoeuvre it looks as though this might be an individual characteristic. No rider could have a mean lag much in excess of 150 msecs and still generate enough power to control a bicycle in normal riding without going into the unstable diverging oscillatory regime. There must also be some lower limit for lag due to the time taken for the sensory mechanism to react to changes and transmit these to the operating muscles. There is not a great deal of leeway in this value and it would be expected that measures taken for a large number of riders would show a distribution of differences with a mean of somewhere about 100 msecs and accompanying adjustments of gain (and consequently wave period) to keep the system somewhere near the 'just stable' condition. Presumably this latter feature is a method of keeping a good signal to noise ratio for the control response to work on.

Summary of Bicycle Control

Because the bicycle is so unstable there is little freedom of choice when postulating control systems. When the autostability of the normal bicycle is removed the rider supplies a very similar, though less efficient, control. The acceleration and velocity movement in roll detected by the rider are applied continuously via a suitable gain factor to the muscle tension in the controlling arms. Because the human is appreciably slower than the autostability to apply this correction there is a delay of about 100 msecs between the roll curve and the bar curve. This produces a torque in the steering head which damps out the roll movement in a series of oscillations, taking the form of a 1 hertz wave. This torque is supplemented by short pulses of additional tension which produce a temporary shift in the balance of the left and right velocity oscillations giving an initial sharp change in lean angle followed by a series of damping oscillations giving a slower 0.2 hertz wave superimposed on the shorter wave.

The human roll stability does not conflict with the mechanical autostability control because it is much slower and uses much lower push values. When autostability is present it dominates the human contribution but gives way to it smoothly when at very low speed it fails to produce sufficient controlling effect.

In normal operation riders may be observed to roll the upper body out of turns at low speed presumably in order to increase the autostability effect. However, since none of the riders had any difficulty riding the destabilized machine without extra training it appears that beginners learn the roll-follow technique to start with and do not forget it even though it is not often needed for normal riding. This seems reasonable since children's first bicycles tend to have poor autostability and learning is obviously done at a very slow speed.

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. The 'roll-follow at a delay' control, 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. When higher order mental operations require a turn in one direction or another this must be converted into the instruction 'push left to go left' or vice versa. Presumably, at some higher level of organization, the rider would be aware whether the speed was high or low and would modify the instruction accordingly. Selecting 'high speed' in error would lead to a severe wobble and possibly loss of control whereas mistakenly selecting 'low speed' would merely lead to an absence of response.

Of course the story does not end there. It was seen in chapter 4 that as the angles of lean and steering increase so the trail distance reduces until at some angle which depends on the geometry of the bicycle it actually reverses. Steep turns, particularly at low speeds where the steering angle will be large, approach this reversal point and as they do so less and less push will be required to sustain the turn. If the critical point is passed then the castor will work in reverse and the rider will have to provide a push in the opposite direction to prevent an unrestrained increase in lean. The rather uncertain feeling engendered by very steep turns is no doubt due to the decreasing castor stability. It is evident from Jones' (1970) experience with the exaggeratedly reversed castor bicycle, URB IV, that providing such a push is within the scope of normal riding skills, although he reported that it felt 'very dodgy'. This is understandable for, unlike the destabilized bicycle which produced no mechanical torque on the steering, a reversed castor effect is actually trying to turn it the wrong way so the customary gain setting would be much too weak to oppose it. Jones' underlying control worked in the correct sense but would have needed considerable trimming to deal with the new problem. Despite the discomfort produced by the reversal of the trail distance the general control technique remains 'push on the side towards which you want to roll'. The consequences of pushing the wrong way are so rapid, dramatic and final that it may be seen that in general the problem of control is not so much finding which way to push to get the desired roll but adjusting the gain and keeping the push angle-independent to prevent overcontrol.

8. BIOLOGICAL CORRELATES OF THE CONTROL SYSTEM

The Requirements

This chapter considers what structures might support the proposed control system. No claims are made about exclusive neural pathways, simply that the requirements of the model do not contradict existing physiological knowledge. The model requires two things. First that accelerations in roll lead to matched accelerations in bar movement within a period of approximately 100 msecs. Second it requires that an angle independent tension can be applied to the handle bar for the duration of an intended turn.

Lee (1975) argues convincingly that the most sensitive and efficient proprioceptive organ for sensing roll movement is the visual system. He showed that it is superior to the vestibular system and in circumstances of conflict will dominate it. He also demonstrated that it can exercise direct control of the postural muscles without the subject being aware that any change is taking place. As soon as it was discovered that if a person could ride a bicycle sighted they could also ride it blindfolded without any retraining it was decided to run the experiments in the latter mode for two major reasons. First the riders having no obvious path to adhere to would be more likely to obey the instruction not to remove any turns which occurred and second the performance without vision was likely to be less accurate so there would be more movement in the traces which was important since the sample rate was rather marginal. The mechanoreceptors in the muscles, joints and skin are also used for small postural adjustments but as Lee points out their efficiency varies with the posture and the nature of the surface of contact. None of these sensors are appropriate to the basic bicycle balance task because pure roll does not produce any change at rider bicycle contact points. However during a balanced turn there will be a slight increase in pressure similar to the sensations encountered when a lift stops. This is a possible source of information in judging the threshold at which to initiate a recovery but the lift analogy should warn us that the system has a rather high threshold in this respect since very smooth lifts succeed in stopping without transmitting any sensation. Thus it can be seen that for these experiments the roll detection requirement will be satisfied if it can be shown that an output from the vestibular system, proportional to short-period roll accelerations, is fed via a reasonably short neural pathway to the gamma and alpha motoneurones of the arm muscles in such a way as to create in them a proportional tension without interference from antagonistic muscles and synergistic stretch reflexes.

The Vestibular System

The vestibular apparatus is a mechanism shared by many species. Its structure and operation have been extensively explored and the details are described in introductory text books.(e.g. Davson & Segal, 1978). In order to give a quick response to out-of-balance movements the neural connections take a characteristically short path to the relevant motor structures. The organs are situated in the inner ear, one on either side of the head. Each has three semicircular canals which respond to the relative movements between them and the fluid they contain. These lie in three mutually orthogonal planes so that any pair can be excited maximally by a rotation of the head about one of the three axes. The responses are fed via the vestibular neurones to the vestibular nuclei where they give an integrated output defining the movement of the head.

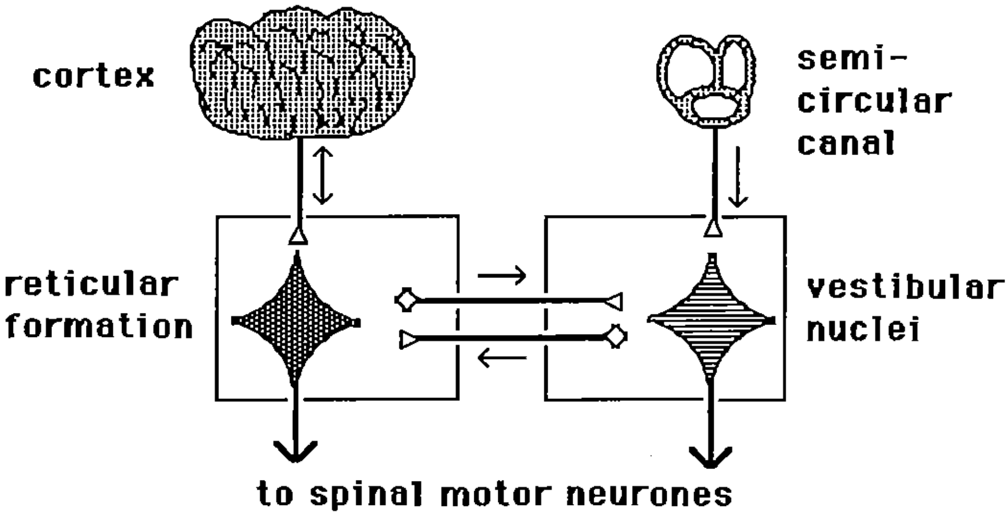


Figure 8.1 Pathways from the vestibular system to the limb muscles. Output can go either direct or via the reticular formation which is open to modification from the cortex. (Adapted from Davson & Segal, 1978)

Figure 8.1 shows a formal representation of the way in which information about the internal arrangement of the parts of the body is integrated with information from the vestibular system via the reticular formation. This is a region of the brainstem exerting a powerful influence on the skeletal musculature and consequently an important control-centre for the organization of movement.

There have been a number of experiments addressing the question of direct pathways from the vestibular system to motor control neurons. For example Eldred (1953) showed that a powerful influence was exerted on gamma fusimotor neurons by the vestibular system and this was confirmed in subsequent studies by Grillner et al.(1969), while Lund and Pompeiano (1968) showed that the extrafusal alpha motoneurones also received monosynaptic activation from the same regions. Lund and Pompeiano concluded that only extensor motor neurones were activated but Grillner et al. considered that those of the flexors were also activated via the reticular formation which has close connections with the vestibular output.

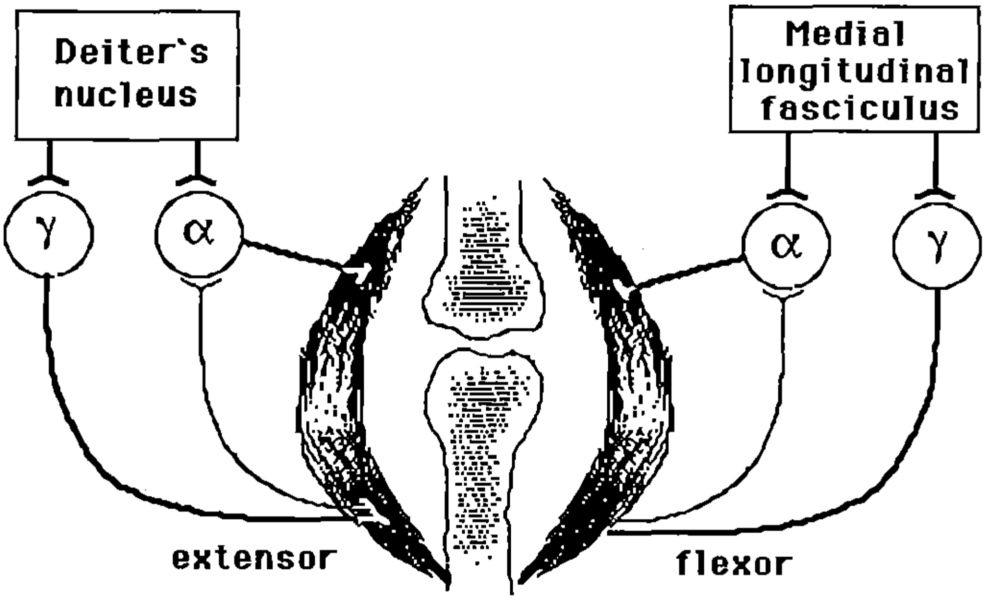


Figure 8.2 Schematic representation of descending monosynaptic effects via fast conducting fibres from Deiter's nucleus and the medial longitudinal fasciculus on the alpha and static gamma neurones to flexors and extensors acting at the knee-joint. All synapses are excitatory. (Adapted from Grillner, 1969)

They proposed the connections illustrated in figure 8.2 for the knee joint showing influences of both intra and extrafusal efferents from Deiters nucleus, which is a vestibular nucleus, and the medial longitudinal fasciculus, which is the main pathway taken by the reticulospinal fibres to the motor neurones.

The vestibular mechanism has two sorts of transducer, the otolith organ in the utricle and saccule, and the ampulla in the semicircular canals. Figure 8.3 shows the general arrangement of these structures in the inner ear. Detailed research into the output performance of the otolith organ has not been as extensive as for the ampulla. The exact role of the saccule is uncertain. Ablation seems to have no adverse effect on balance though there is some evidence that visual acquisition may be affected. The utricle responds principally to changes in the rolling and pitching plane.

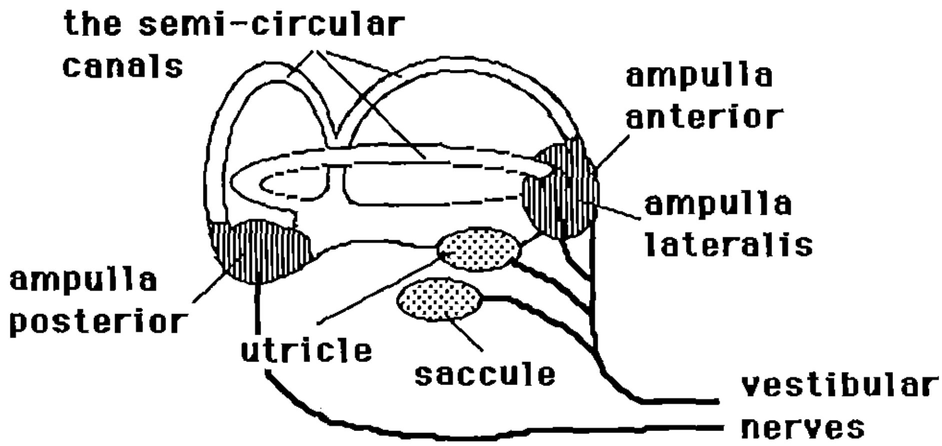


Figure 8.3 The general arrangement of the semicircular canals and the sensory transducers in the inner ear.

The general form of the discharge rate is a linear function of the effective force acting upon the organ (Fernandez et al 1972). It should be borne in mind that the way in which the total system integrates all the outputs from the various transducers at the vestibular nuclei during head and body movements is not known in detail. However, it seems fairly certain that the main function of the otolith organ in balance is to give a response to the static relationship between the head and the pull of gravity.

The operation of the ampulla, which responds to the relative movement between the semicircular canals and the endolymph they contain, has been the subject of a good deal of research. Steinhausen, following direct observations of the cupular of the carp in 1931, formulated the proposition that the movement under acceleration acted as a heavily damped torsion pendulum. (Summary in Hallpike and Hood,1953). Unfortunately such a model predicts that the output will fall to zero for the very short-period excitation which is the more normal type of stimulus encountered in everyday movements. Despite this the model was adhered to for many years leading to a dearth of experiments exploring this particular range of values. Some light, however, is shed on this subject by Fernandez and Goldberg (1971). They studied the output of selected neurons associated with the semicircular canals of the squirrel monkey when the animal was subjected to controlled rotations in a cage-like apparatus. When sine-wave inputs controlled the movement of the monkey's carrier it was seen that the response no longer followed the predictions of the damped torsion pendulum model. The information obtained from these experiments was used to modify the equations, by altering the time constants, until the predictions followed the observed output. Using the new values they predicted the responses to three rising half sinewave accelerations in the range of interest. These predictions are shown in figure 8.4. The upper graph shows the predicted response to the three stimuli. The lower graph shows the change of velocity for these on the same time scale to emphasise that the vestibular system discriminates between them with different spike rates even though they all peak at the same maximum velocity. Although this is a prediction, not an experimental result, it is a reasonable extension of the findings of the paper and gives a clear indication that the vestibular system is capable of producing a response that is proportional to the rate of angular acceleration. This is the sort of performance needed to drive the projected bicycle control model.

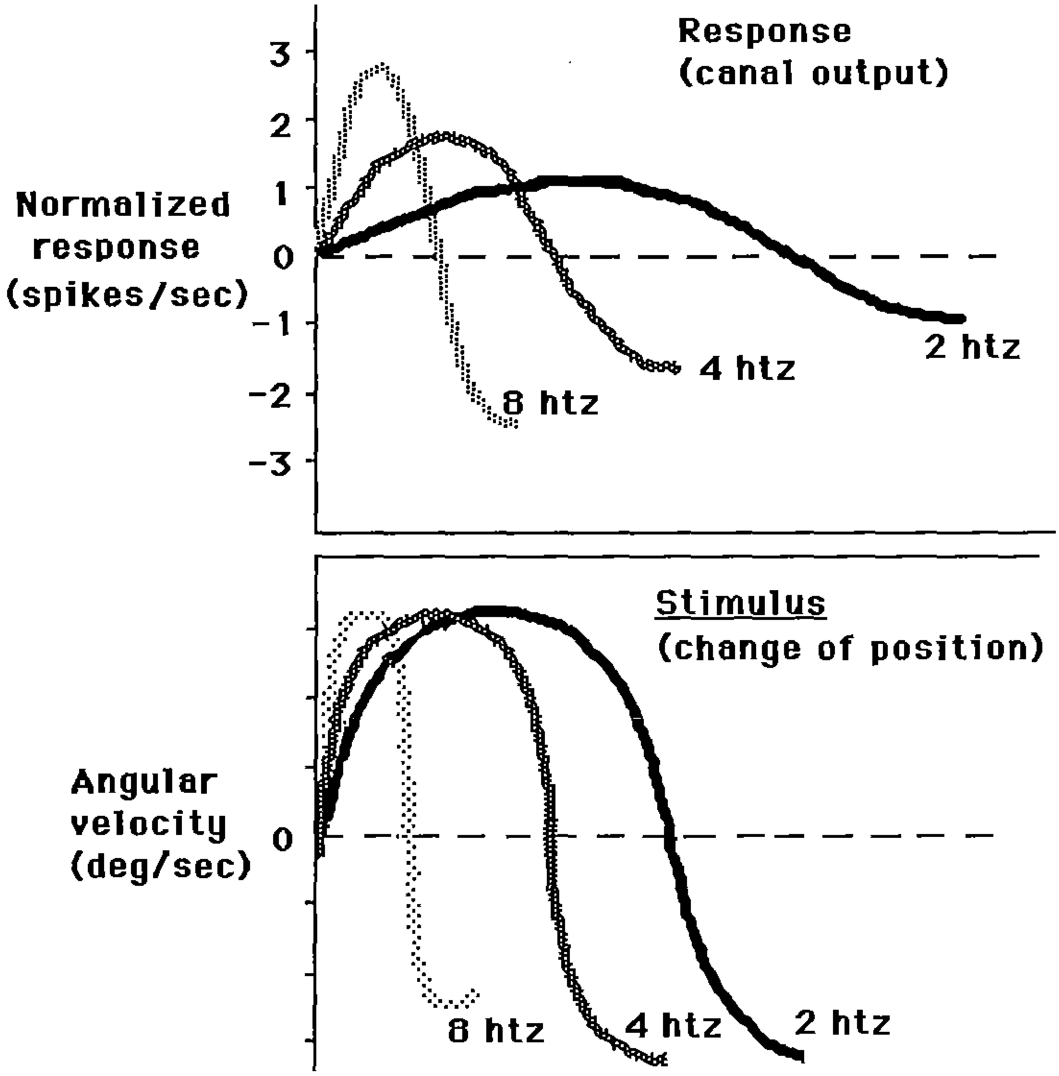


Figure 8.4 Showing how the response of the semicircular canal to short period rotations discriminates between different rates of acceleration (spike response, upper graph) even though the final angular velocity is the same in each case (lower graph). (Adapted from Fernandez & Goldberg, 1971, page 673)

The Motor System

The fine details of motor control are extremely complex, especially in the higher animals where there is an increasing contribution from central rather than local sources. Every limb has a number of independent muscle groups acting both as extensors and flexors and each muscle consists of a very large number of separate muscle spindles which themselves consist of a number of separate muscle fibres. Each fibre can be influenced by electrical, chemical and mechanical means and the nerves that take information from and to these fibres branch in many different ways, so that even within a spindle various groups of fibres share some nerve paths but not others. (de Vries, 1967; Thompson, 1975; Granit, 1970).

Many findings have been obtained from *in vitro* investigations of animal preparations. Sufficient important differences of detail between animals have been observed to make the direct extension of these to humans problematical. In the lower animals, such as amphibians, the intrafusal spindles are innervated by branches from the extrafusal musculature whereas in mammals there is an increasing independence of the intrafusal and extrafusal systems (Granit, 1970). In the former case it is possible to account for such behaviour as posture in terms of a spinal reflex response to stretch imposed by altering loads. In mammalian muscles, however, there are reflex-like movements which in fact depend on intrafusal activity and which can be maintained in the absence of extrafusal (alpha) output (Granit, 1970). The emerging picture is one of an extremely elaborate automatic control which is able to make constant adjustments to the multitude of individual muscle fibres. The balance of flexors and extensors by alternating the recruitment of various semi-independent muscle groups is an essential feature of smooth continuous operation.

Automatic and Volitional Control

The degree to which such systems are automatic, that is they depend on changes due to direct interaction with the environment, rather than volitional control by the higher centres of the brain, is still an open question.

The greater complexity of the mammalian system with its nerve tracts from the intrafusal spindles extending into the lower brain stem and beyond makes single cell recordings extremely difficult to interpret and these difficulties are multiplied by the fact that all natural movements are polyneuronal. In some systems, it is possible to build up a fairly clear picture of the contributions from the various parts of the nervous system. Euler has proposed a circuit for the action of the intercostal muscles during breathing that accounts for *in vivo* performance when the air passage is restricted. Control is shared between the spine, respiratory centres and the cerebellum and it is evident that since single inhalations and exhalations can be voluntarily imposed there must also be indirect links with the higher parts of the brain (Granit, 1970).

In an experiment by Basmajian et al (1965) a subject learned to regulate the level of excitation from an electrode placed in the abductor pollicis brevis of the thumb. This was achieved by attending to visual and audio feed-back. It is clear that volitional control of very small muscular units is possible whatever the functional implications might be. In general it seems most probable that for well established actions such as breathing and walking there is a '*proprioceptive elaboration of a relatively simple central command alternating between flexors and extensors.*' (Granit, 1970) and that during the learning process the higher brain functions interrupt and redirect these established sub-systems to create new 'automatic' links which allow the new skill to become part of the repertoire.

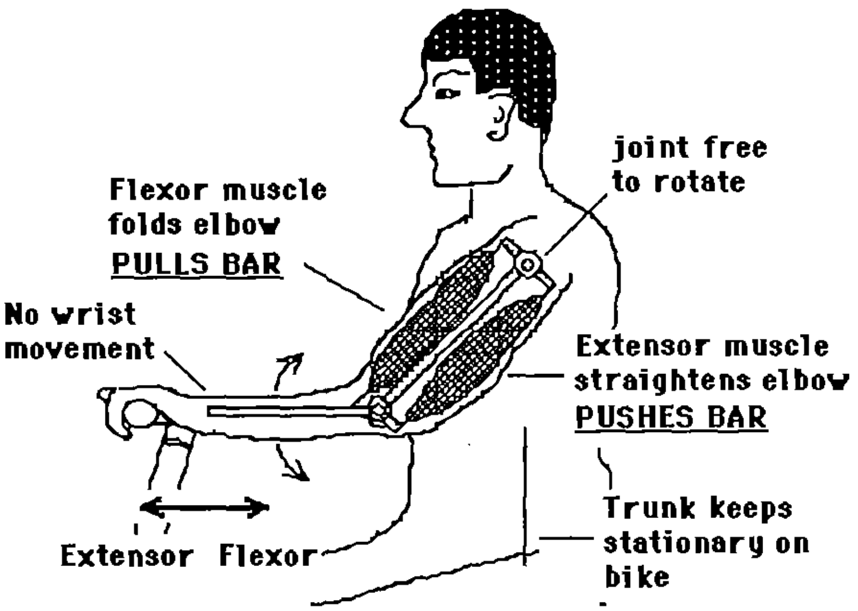


Figure 8.5 Showing the simple model for single arm control of the handle bar.

A Possible Control Mechanism

Typical control movements are used with steering wheels, boat tillers, aircraft joysticks etc., and take the form of a tension in the appropriate muscle group and inhibition of the antagonistic groups so that the control mechanism moves to that position where the muscle tension balances the mechanical torque. It is highly likely that, in common with most human activities, individuals will have a large repertoire of effective alternatives for achieving appropriate control movements but in order to compare the known capabilities of the motor-system with the control demands some simplified model is needed. Figure 8.5 shows a schematic layout for the proposed operation of the steering mechanism. An informal riding experiment was carried out in which the bar was held in every strange way that could be devised. Clenched fists, palms flat, back of the hands, finger-tips, wrists, lower forearms etc. The only problem encountered was when pushing or pulling very lightly with fingertips only. In this position the body was deliberately held back to avoid contributions from movements of the upper trunk. With sudden turns it felt as though one of the hands was coming off the bar which lead to a momentary wobble. When the load on the bar was increased by leaning backward or foreward depending on whether pushing of pulling the effect disappeared.

Thus it seemed that since the hands themselves were playing no part in the operation either as sensors or actuators it was reasonable treat them here as a single unit together with the wrist and forearm. In order to turn the front wheel the rider must alter the relative distances from the tips of the handle bars to the saddle and since it assumed that the lower trunk and legs do not normally move for steering purposes this is the same as altering the distances between the forearm extremities and the hips. This movement could be achieved in several ways. The arms could be kept the same length and the upper trunk swivelled, or the trunk could be kept still and the arm lengths altered by changing the angles at the shoulder and elbow.

Although either arrangement is possible from the purely mechanical aspect a simple experiment suggests that the postural reflexes give a more restricted choice. If one sits in a chair in front of a table and grasps the edge with the arms slightly bent at the elbow in an approximate imitation of the bicycle riding position (figure 8.6), an attempt to rotate the upper trunk by consciously changing the length of the arms produces only a change in arm tension. In order to alter the trunk position it is necessary to intentionally 'twist the body' in which case the arms just follow the movement.

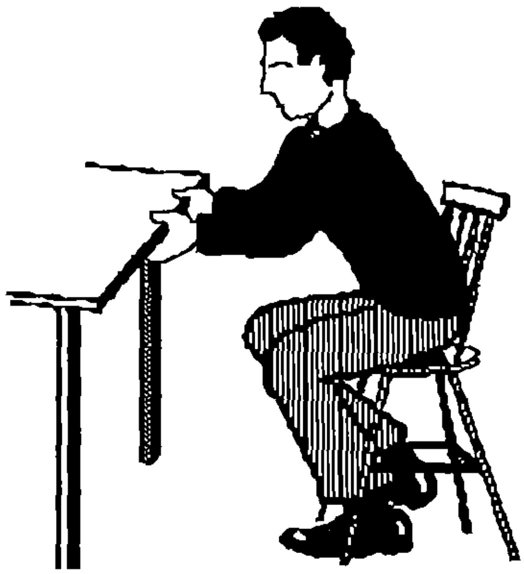


Figure 8.6 The simulated riding position.

If the chair is moved a little further back so that the weight of the upper trunk is partly carried by the table, as in the drop-handle bar position, the shoulders can still be twisted voluntarily and, despite the extra load they are now carrying, the arms move to accommodate this change. Allowing one hand to slip suddenly from the table edge leads to virtually no alteration in the trunk position, the full weight being taken by changes in the supporting muscles. This sudden shift of weight from both shoulders to one must produce a twisting couple on the upper trunk but no appreciable movement is noticed. This implies that there is a well established reflex that controls both the fore and aft and twisting movement of the trunk to oppose externally applied forces. It will therefore be assumed, in the interest of establishing a simple model for discussion, that control of the bar is effected by altering the tension in the elbow joint muscles and that the forces generated are transmitted entirely to the steering bar.

Also in the interests of simplicity it will be assumed that control is exercised by pushing and pulling on the bar with one arm only, leaving it open as to whether the other arm passively follows or makes a similar shared contribution. It may be noted in passing that, although one-handed riding is quite normal, most riders prefer to have two hands on the bar for difficult manoeuvres, suggesting that there may be some operational difference between one and two handed riding.

Resting Tension.

In the simplest of terms what is required for steady dead-ahead riding at speed is a situation where the muscles operating around the elbow joint are fully relaxed, allowing the handle bar to follow the movements of the autocontrol. However, it is necessary to propose some slight resting tension in order that the muscles will be in an 'alert' state to respond to control demands. This stable tension is the 'tonus' of the muscle defined by Basmajian (1962 p41) as '*..determined by both the passive elasticity or turgor of the muscular (and fibrous) tissues and by the active (though not continuous) contraction of muscle in response to the reaction of the nervous system to stimuli.*' Thus the flexor and extensor muscles will be set at some steady low value which holds the elbow joint at a particular angle in the absence of an external load but which will allow movement under such a load without the relative tensions changing. This slight resistance to movement due to tonus will act as a high-frequency damper in the steering system.

Muscle Control

The motor system has to fulfil three requirements. First it must provide a stable platform from which precise control movements can be made. Second it must apply an angle-independent torque force to the handle bar to produce a turn. Third, in the low autostability case, it must move the handle bar so that its angular acceleration continuously follows the acceleration in roll.

In animals with no independent neural circuitry to the intrafusal spindles the 'stretch reflex' provides a crude 'constant length' device. The role of the mammalian spindles in the control of muscle length is by no means fully understood, but there is no doubt that the stretch reflex to prevent changes in length is one of the available functions. Without going into any greater detail it can be seen that the requirement outlined here for stabilizing the trunk is consistent with what is currently known about the system.

When there is appreciable torque in the steering head from the bicycle's autocontrol the requirement is for the rider to allow this to operate and at the same time add a further torque force for additional control. When the elbow joint moves to accommodate the movement of the bar under the resolved rider/machine couple the muscle lengths will change. The length/tension ratio of the flexor and extensor muscles must be set to constant values so that their difference remains the same despite these changes in length. That is there must be no stretch reflex.

All the early work on muscles encouraged the idea that they achieved their postural tonus via a stretch reflex mechanism. This meant that when a muscle had achieved a set length due to alpha excitation any increase in length caused by some outside force such as change in body loading would automatically lead to the recruiting of extra fibres to increase the resistance and hold the position. Obviously such a system will not answer for the purposes of bicycle control. Later research has shown that in mammals at least the intimate control of the excitation values in the main alpha neurons of the muscles is subject to influences from both the intrafusal spindles and the golgi tendon organs. The afferent output of the intrafusals can be made selectively sensitive to length and rate of stretch or inhibited by changing the values in the static and dynamic efferents to these units. This output can be directed to excite or inhibit synergistic and antagonistic muscle groups remote from the detection site. The input and output connections to the intrafusal spindles have branches up to the brain and consequently the motor muscles are no longer tied to a simple stretch reflex. Response for various combinations of afferent and efferent excitation can produce a great variety of control responses.

As long ago as 1909 Sherrington reported a condition in a decerebrate cat where the extensor (vastocrureus) of the leg could be moved to various positions by the experimenter. Previously it had been thought that limbs would be either completely relaxed, in which case they would fall back under gravity if displaced, or rigidly held in some position against gravity, in which case attempts to move them would lead to a stretch reflex opposing the change. The condition observed by Sherrington, which he termed 'plasticity' has still to be fully explained but it is now apparent that the independent control of the intrafusal spindles and golgi tendon organs in muscles allows a large combination of autogenetic and antagonistic activity which could account for a condition where the reflex due to external stretching was inhibited (Matthews 1972, pp 443-445). The 'alert' no-signal condition proposed in the paragraph on resting tension above is similar to the plastic condition observed in the cat preparation, although since the arm is supported at handle-bar and shoulder the resting tonus need be nothing like so great as that required to hold the weight of the limb against gravity. Figure 8.7 illustrates an experiment by Buller and Lewis on the length-tension curves of the soleus muscle in the cat. The curve shows the change in tension (ordinate) against length (abscissae) when the muscle was subjected to a full 'tetanus' excitation (described in Granit, 1970).

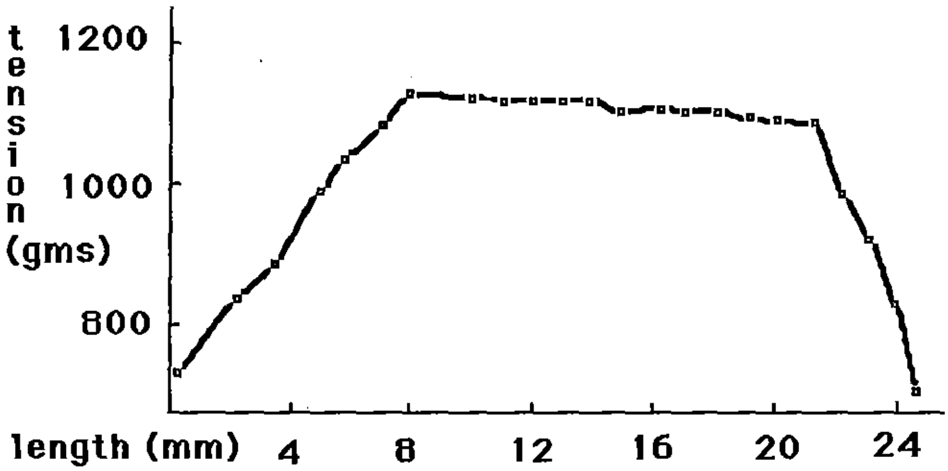


Figure 8.7 The relationship between length (abscissa) and tension (ordinate) of the soleus muscle in a cat when subjected to full tetanus excitation. (Adapted from Granit, 1970, fig. 10, page 23)

The implication here is that if this muscle, holding a load of say 1000 grams at a length of approximately 4mm, was then shortened by some external force to 3mm then the force generated would fall to 900grams and in the absence of any other input would continue to collapse since it could no longer support the initial load. If however the same test was applied on the flat part of the curve between 7mm and 20mm the tension would not alter and the new position would be held. Of course this experiment takes no account of what the antagonistic muscles are doing at the same time, nor of the effects of altered instructions from higher levels of organization as a result of the changes in excitation of the fibre afferents, but it does illustrate that the internal organization of this muscle can exhibit the quality of constant tension for changed length. Marsden et al.(1971) describe an experiment in which an unexpected opposition to the voluntary movement of a subject's thumb was suddenly introduced. In the normal state this resistance led to an automatic increase in the tension of the driving muscle to maintain the intended rate. When however the thumb was anaesthetised by local injection there was a reduction in the rate of response, indicating that the tension had not altered. This finding is usually quoted as an instance of the contribution of the joint and cutaneous sensors to this sort of 'reflex' since the muscle that does the driving is in the arm not the anaesthetised thumb. However the point here is that the subject is producing the kind of movement required by the control model for the operation of the handle-bar. In the case quoted the feedback seems to have been blocked by the anaesthetic. In the case of the bicycle it would have to be as a result of some sort of organized inhibition of the spindles and/or golgi tendon organs.

Thus it can be seen that the human neuromuscular system is capable of producing a constant tension in a muscle independent of changes in length and that volitional control over small isolated muscle units has been demonstrated. This is sufficient evidence to justify the claim that holding an angle-independent tension to produce turns is consistent with what is known about the motor control system.

The Roll Induced Movement

The final requirement is to produce a continuous angular movement of the handle bar in response to the vestibular output. There are many functions in mammals that show a fine control of position which can only be explained by independent spindle action. A good example being provided by the demonstrations by Euler that the desired 'tidal volume' of the lungs is controlled by the length to which the intercostal intrafusal muscles are stretched in breathing (in Granit, 1970). Thus the essential neural connection to adapt the existing system for roll-follow control is to take the rate of change of excitation in the vestibular system caused by rates of roll and apply it via some multiplier to the tension values in the arm muscles. It is not intended to imply that the implementation of such a link is in any way simple. The extremely complex polyneuronal nature of any limb movement is such that comparatively simple movements in the large muscle groups must be translated into a vast array of 'messages' to each of the individual muscle spindles involved.

An experiment by Partridge and Kim (1969) provides an interesting observation of a very similar system actually operating in the cat. They recorded the isometric tension in the triceps surae muscle of a cat during the sinusoidal excitation of the ampullary nerve bundles of the vestibular system. Between a wide range of frequencies the tension in the limb moved in sympathy with the oscillation of the stimulus, with a conduction delay of 15 msecs which is several times faster than that observed in the human rider. This is exactly the sort of arrangement required to operate the control model.

Comparison with Postural Control

There is a literature on postural control as distinct from motor movement because to some degree posture is seen as being controlled by local reflexes rather than a centrally controlled organization. The problem is that studies of posture in man show evidence of central contributions and complex responses for simple bipedal balancing tasks at latencies below the minimum recorded for voluntary movement. Recording exactly what every limb is doing during natural movements is extremely difficult and it is all too easy to misinterpret local motion because the whole action has not been captured. Consequently it is usually very difficult to be quite sure what role muscles are actually playing in a complex movement. There is evidence that sequences of postural actions are anything but 'dumb' local reflex responses, but at the same time their speed of action at the lowest level of the hierarchy argues that reflex like processes are being recruited in the responses. Since learning to ride a bicycle necessitates recruiting fast responses for lateral balance it is very likely that there is a link between standing postural control and bicycle control. The proposal that pushes superimposed upon and temporarily disrupting the underlying continuous balance induce desired changes in lean angle also speaks to bipedal balance during motion. The sprinter on his starting blocks represents an extreme example. The centre of mass is so far displaced from the support point that only a very high rate of acceleration will prevent a fall. By disturbing the autonomous balance system the higher centre of control forces a response which achieves its requirement without further contributions. Two sets of experiments exploring the sequencing of responses in maintaining standing balance will be used to illustrate some of the common points between the bicycle task and posture control.

Nashner's Platform Tasks

Nashner (1976) conducted a series of experiments in which subjects stood on a platform which could be translated in the antero-posterior (A-P) direction and rotated to give a 'toes up' (dorsiflex) or 'toes down' (plantarflex) movement of the ankle joint either independently or simultaneously. Changes in body sway and the torsional forces applied by ankle musculature were measured during platform movements. Nashner's interest was in the possible role of reflex responses in the ankle for posture control. Seven of the twelve subjects made no rapid compensation for the mildly disturbing changes induced but brought in appropriate ankle movements after about 200 msecs. These responses were considered to be of visual or vestibular origin so the focus was on the five who made fast reflex-like responses.

It was clearly shown that changes in ankle angle induced muscle responses in the smaller group, even when they were inappropriate and caused unwanted sway. When the platform was moved backwards the subjects made a toes down movement after a latency of approximately 120 msecs to oppose the induced foreward sway. When the platform was rotated in the dorsiflex direction without any translation the subjects responded with a plantarflex movement which was inappropriate and gave a self-induced sway backwards. After three or four trials this reaction was adapted out and then resumed when the conditions were altered to make it appropriate again. This sort of reflex movement is termed a Functional Stretch Reflex (FSR) as opposed to the faster myotatic response, which has a latency of 45-50 msecs. No myotatic responses were recorded in any of the experiments.

In his discussion the author proposes that both the fast reflex action of the smaller group and the delayed visual or vestibular response of the larger, fit into an hierarchical model of postural control in which the cerebellum exercises control over the gain of reflex responses to achieve the desired effect. He quotes two different models for the organization this control. Welford (1974) suggested that the central process adapts an internal 'model' of appropriate responses to cope with unexpected changes whereas Pew (1974) suggested that when faced with an inappropriate response the system suppresses the existing action to give more time to assess what was happening before producing a new response. Nashner suggests that these two models offer possible explanations of the difference between the fast responding and the slow responding subjects with the slow subjects using the latter strategy and the fast ones the former. Even when one of the slow subjects was told exactly what was happening he was unable to override the inappropriate fast response, but it is of course quite possible that a longer period of training might have allowed a conversion eventually to the more flexible system. Several subjects with deficits of the cerebellum were tested on the same task and showed little ability to adapt their fast responses in the inappropriate task.

These two models can be directly related to the problem of learning to ride a bicycle. The point about the bicycle task is that it appears on the surface to be a navigational problem, like riding a tricycle, but it carries with it a postural-like balancing element which is intimately tied in with the former. When the rider first tries to steer for direction only there is a strong out of balance effect. It can be assumed that the initial response will be that already established for postural balance, in the same way that Nashner's 'fast' subjects moved their ankles inappropriately. That is, the body will be rotated away from the direction of fall in an attempt to keep the weight within the support platform. In many cases the outside foot will in fact be moved from the pedal to the ground to ensure stability. The first thing the rider must learn is to suppress this inappropriate response and replace it with a handle-bar movement into the fall. Once this has been established the cerebellum can exercise its gain control of the arm action to achieve an acceptable balance between stability and power. The fact that Nashners' 'fast' subjects suppressed the inappropriate ankle response in typically three or four trials shows that such adaptation is part of normal balance and goes a long way to explaining why children can learn to ride a bicycle so quickly.

The difference between the myotatic and FSR response, (70-75 msecs) presumably reflects the extra time needed for the sensory pulse to ascend to the brain and the instruction to return. The difference in the latency between the slow and fast subjects, 200 msecs as opposed to 120 msecs, seems to be a function of different basic strategies and it is not necessary to assume that the slow subjects would be irrevocably committed to such a latency in different circumstances. That is once the connection between the vestibular or the visual system has been well established there is no reason why the latency should not reflect the time taken for the one way journey from the detecting site in the head to the arms. In bicycle riding the information for driving the response comes from the inner-ear or the eye which, unlike the ankles in the platform task, are sources very near to the cerebellum. Consequently there is no need to allow time for returning information. Partridge and Kim's cats, mentioned above, had a system delay of 15 msecs, so there seems to be no objection to the 60-120 msecs phase delay observed in the runs. It is also possible that the difference in delay between the two riders was due to a predisposition to 'fast' or 'slow' styles of response. Certainly the slow responder was the more skilled rider of the two and had a wide experience of other balance skills such as skiing and surfsailing.

A later paper Cordo and Nashner (1982) provide further evidence of activation of controlling muscles in both the leg and the arm at latencies below that elicited by purely voluntary movement. They also show that the postural balance system is anything but an unadaptable local reflex, and that the site of action can be switched without practise when this is appropriate to maintaining balance.

In a series of experiments subjects made arm movements or reacted to arm pulls which on their own would have upset the postural balance. By recording muscle activity in the arms and legs on a common time base it was shown that potentially disturbing arm movements were either preceded by appropriate leg movements or were held at a low level until the leg movement had been initiated. It was evident from their findings that the instruction to pull or push with the arm was interpreted in such a way that activity in the legs was first recruited to 'set up' the situation so that when the arm movement came it applied the mass of the body to the point of application rather than swaying the body out of balance. It was also shown that when movement of the arm was more appropriate to keeping balance the leg response was suppressed and the arm moved instead.

Of particular interest to the proposed bicycle control was an experiment where the subject stood on a platform which oscillated 10 degs 'toes up' and 'toes down' in a continuous 0.1 Hz cycle forcing the subject to make compensating movements of the postural muscles to keep balanced. At a signal the subjects had to pull or push a handle mounted at waist level. Cordo and Nashner's interest was the slight increase in reaction time of both the biceps and gastrocnemius muscles compared to the same task when the platform was stationary. Although the continuous movement to maintain balance was in the leg the superimposition of an additional burst of activity at a mean latency of 127 +- 38 msecs is exactly the sort of activity required of the arm in control of the destabilized bicycle with comparable delay.

Another interesting finding was the way that balance control was immediately transferred to the arm from the leg when this was the most appropriate movement. Such instant transfer of activity to a different site is exactly what is envisaged during the initial learning task. Cordo and Nashner's subjects already possessed the necessary organization to select the arm as the appropriate site of action. The naive bicycle rider apparently does not and must learn it in the same way that the experimental subjects had originally to learn theirs.

The voluntary response time from the biceps was measured as 155 +- 37 msecs, but during the pull and push trials this fell to 66 +- 12 msecs and 73 +- 24 msecs respectively. This supports the earlier claim that when acting as a coordinated system the response time of muscles can be much faster than the latencies which are elicited by voluntary movement, and consequently it is argued that the 60-120 msecs phase delay discovered in the continuous roll/bar control of the destabilized bicycle is quite in line with this class of movement delay.

Lee's Swinging Room

The final reference to the postural literature concerns a set of experiments by Lee and Aronson (1974) and Lee and Lishman (1975). In the first experiments the authors induced inappropriate postural responses in standing infants and later in adults. When a 'swinging room' produced the sort of visual information usually associated with body sway, even though no change in posture was present, subjects tended to make compensatory movements which led to loss of balance. This effect was stronger in the infants but was also present in the adults to a lesser degree.

In the second paper the authors concluded, again using their swinging room apparatus, that vision was the primary source of postural information for standing balance.

Subjects were induced to respond to room movements as though their balance had been upset. In one experiment the room was moved back and forth over a distance of 6 mm in a regular sinusoid with a period of 4 secs. The subjects were briefed to ignore any room sway but a record of body movements showed that they were swaying with the room even though they reported that they had not moved. The paper shows a reproduction of the room and subject trunk velocities over a period of about 50 secs. These measurements were made from analogue pen traces and no digitized version was recorded, however the phase relationship between the two traces on the page is correct. (Lee, D.N., personal communication).

It is obvious that the visual stimulus must have been the relative movement between the room and the subject and that the subject's movement as shown by the trunk trace must be subtracted from the room movement to obtain this relative motion. The events interact in a loop. The room sways and causes the subject to induce a trunk sway to match it as though there had been a postural change. This at once effects the relative movement between the subject and the room and leads to further changes. A casual examination cannot tell us how much the vestibular system contributes to the observed motion but the authors showed that movement with the eyes shut was greater than the movements induced by the room implying that the visual information gives a greater accuracy in maintaining balance.

There are close links between this balancing task and the bicycle riding task. In both cases the underlying action seems to be outside the conscious control or knowledge of the subject. In the destabilized bicycle task the vestibular activity appeared to be controlling the handle-bar responses and in the postural task the room movements appeared to control the body movements. In both cases the control seemed to be almost direct. In an attempt to learn more about the detail of the form of control in the room swaying task the curves published in the paper were used to obtain the relative velocity and acceleration movement between the body and the room on the same time base.

The Trace Differentials.

Simple measurements on the traces given show that the trunk velocity has a mean phase lag behind the room velocity of 0.75 secs with a maximum of 1.45 secs. However it is the relationship between the trunk movement and the relative movement of the room which is the more important so the traces were enlarged to double the size on a photocopier and then digitized using a PMS Graphbar sonic bit-pad. Approximately 300 sample points were taken of each trace giving a density of about 6 points per second, or about 25 points per wave. The two records were registered by interpolating between points to give values at equal step intervals. The trunk velocity was then subtracted from the room velocity to give the relative velocity between them and this curve was differentiated by taking the local slope between the values immediately before and after each point. These three curves are shown on the same time base in figure 8.8. The X axis has been expanded so only half the run is shown. We can see that the relative velocity is a regular wave with the same period as the trunk velocity with a phase difference of about 90 degrees or 1 second. Since this is the information driving the response it is, as expected, in advance. The relative acceleration is much noisier and it is not possible to know how much of this comes from the rather coarse level of recording and transformation.

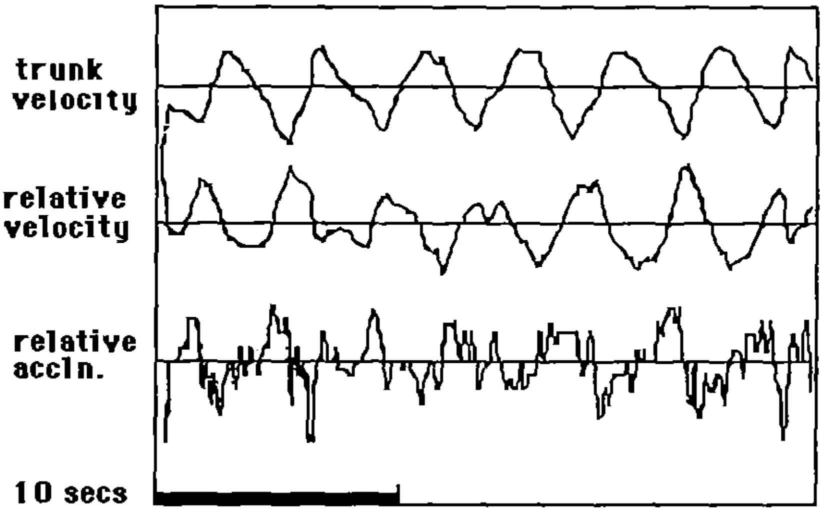


Figure 8.8 Actual trace of the trunk movement caused by a gently oscillating visual stimulus. (Adapted from Lee & Lishman, 1975, page 87).

Possible Control Systems.

A closer look at what sort of systems might control standing balance and be disturbed in the manner shown in the Lee and Lishman experiments shows that the problem is complex and leads to the caution sounded above about drawing simple conclusions from the traces of trunk and room motion. In order to explore possible control systems the bicycle simulation was modified to reproduce a much simplified version of the standing task. The following dimensions were used to represent a typical person: weight 160 lbs with a rigid body 6 feet tall having the mass evenly distributed along its length with the centre of mass half way at 3 feet. The eye level was 5.5 feet and all movement was assumed to be around the ankle joint. It is quite obvious that in real life people have a much wider choice of movements with which to respond to vertical imbalance. With the ankle joint locked the foot gives quite a large support base in the fore and aft direction and any disturbing push would lift the toe or heel and give a strong correcting couple. Movements of the big toe provide a powerful couple very fast and it is known that loss of the great toes in an accident does give balance problems. It is very likely that the ankles, knees and waist joints all act together in a synergistic response which would have important effects on the way the centre of mass moved in relation to the support point. However the fact remains that very small movements of the swinging room produced body sway responses so it is evident that the subjects in the experiment were primed to make active responses to disturbances and not just relying on the passive stability conferred by a locked ankle joint.

The problem for the standing person is this: any displacement of the centre of mass from directly above the support point leads to an increasing rate of acceleration into a fall. The subjects in the swinging room experiment only deviated 5mms either side of the upright so if the height of the measuring device on their backs was about 4 feet they were only swaying through an included angle of less than 0.5 degrees. Thus we can see that very small changes are significant and the performance of the simulation shows that it needs to be, if it is to keep control. Any active control must first sense a fall and then oppose it. The longer it leaves the correction the more effort it needs. If it produces a much bigger correction than is needed it will cause an acceleration back over the zero position and then will be faced with a worse situation on the other side. This will be repeated in increasing oscillations until one fails to reverse. Thus we can see that the problem is the same as that encountered in the bicycle control. Discrete corrections are far too unstable to be realistic, so the sensed rates of movement must be fed back with a gain which is big enough to contain any expected disturbance but not so great as to produce a diverging oscillation. Any long delay between sensing and implementation will increase instability and therefore limit the amount of gain which can be used. If only acceleration is fed back the velocity will not be removed, if both the velocity and acceleration are fed back then any angle which accumulates during the operation will remain and this will lead to a further increase in the falling couple. Stability is typically achieved by actively oscillating about the zero point.

Control of limb joints must take place via changes in length of muscles. Extensor and flexor muscles must work in sympathy and movement is possibly specified by giving a common set point at which the tensions are equal. However, as far as the joint movement is concerned this is received as a torque couple and that is how such changes were modelled in the simulation. The movement around the ankle was obtained by working out the weight couple from the displacement of the centre of mass from the support point and adding to it any muscle torque specified by the control system. The room movement was modelled so that relative movement between it and the person could be found.

First the simulation was given a feed-back control system which fed the velocity and acceleration of the trunk into the ankle joint opposing any fall. The gain was trimmed so that it could restrain the natural fall to somewhere the same as that seen in the experimental traces, ie. about 0.25 degrees in one second. The unrestrained fall rate will give about four times this dispersion in the same time period over the same angle range. Now the Lee and Lishman demonstration shows that when the room moved the person responded as though he had swayed so the control was changed to feed in relative movement between the room and the eye position rather than the actual body movement. The result was that initially the control torque worked in the same direction as the weight couple and an acceleration much greater than the free fall case was the result. With the gain available this system was unable to contain the initial fall and went out of control at the first dispersion. If the gain was increased so that the fall could be checked the system became unstable going into an ever increasing divergent oscillation. In real life it is evident that dangerously excessive accelerations invoke a different level of response, such as putting out a foot or raising an arm. In any case the experimental subjects did not behave in this way but contained the fall within 0.25 degrees.

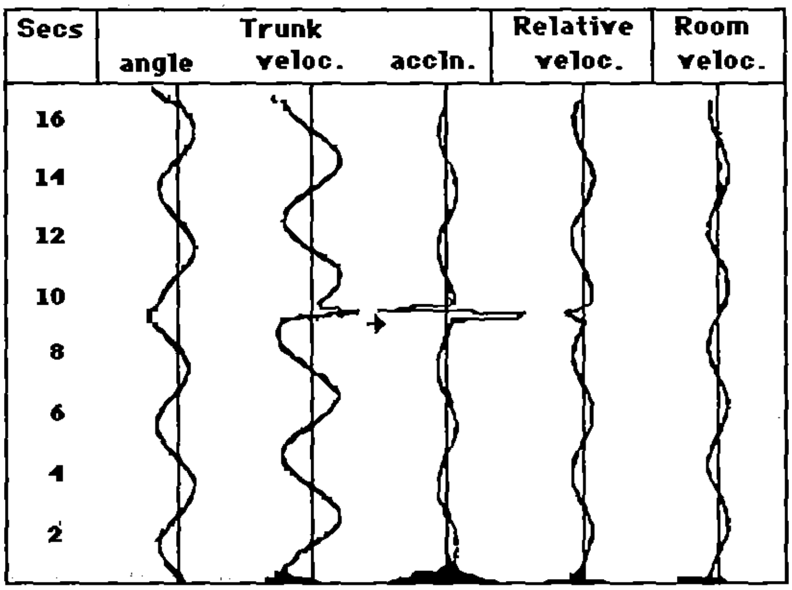


Figure 8.9 Simulation of standing balance with trunk acceleration being driven by feedback of both vestibular and visual motion from the swinging room. A short pulse of 0.44 secs duration has been put in to the right at 9.0 secs.

Evidently what is needed is some sort of restraint on the rate of actual fall induced by the false room information. The vestibular system would not be subject to the deceptive movements of the swinging room but would be measuring the actual fall and thus could be a suitable source of information for such a restraint. The question then is, what happens if the control is fed both the visual and the vestibular changes? This is where the model comes into its own as it is certainly impossible to visualize what the effect of mixing the two inputs would be on the control output without one.

Figure 8.9 shows the output when the true velocity and acceleration in fall is fed into the control together with the relative velocity and acceleration due to the deceptive room movement. The result is a controlled trunk velocity with the same period as the room velocity which is exactly what we see in the real traces. The delay between these two in the simulation is about 0.5 secs as opposed to the actual mean lag of 0.7 secs but this can be increased to the same value in the simulation by introducing a delay into the control routine.In both this and the bicycle simulation it was demonstrated that putting velocity and acceleration information into the control leaves any accumulated angle untouched. In the bicycle case this left a residual turn, which is stable, but in the standing balance case it leaves and angle of lean which produces a disturbing weight couple. Since the simulation is controlling on velocity and acceleration only, the angle gradually accumulates as can be seen by the way the mean of the vertical angle trace in figure 8.9 is moving gradually left.

The human can easily alter the relative position of its parts to achieve a change in the relationship between the total centre of mass and the support point, something the simulation has no power to do. However another method of dealing with residual angles is to do what the bicycle riders did and put in a short push pulse to oppose them. Just to emphasize that a short push, such as might be administered by a rapid movement of the toes, will have the same effect as it did on the zero-stable bicycle, a single pulse lasting just under half a second has been put in at the nine second mark, and is shown by the arrow. This added pulse pushes the mean of the vertical angle oscillations back towards the zero line but leaves the basic characteristic unaltered.

In the actual trace the trunk velocity has a definite tendency towards a triangular shape. It could be argued from this that the underlying control is putting in a fairly steady rate of acceleration between peaks and changing sign rapidly at each of them. If this was the form of the control then the focus of interest would be what unique events occur in the stimulus immediately prior to the sign changes to cause them. Candidates here might be the rising relative velocity which triggers the change when it exceeds some threshold value or possibly the rise in the relative acceleration although this trace is much messier and therefore less unique.

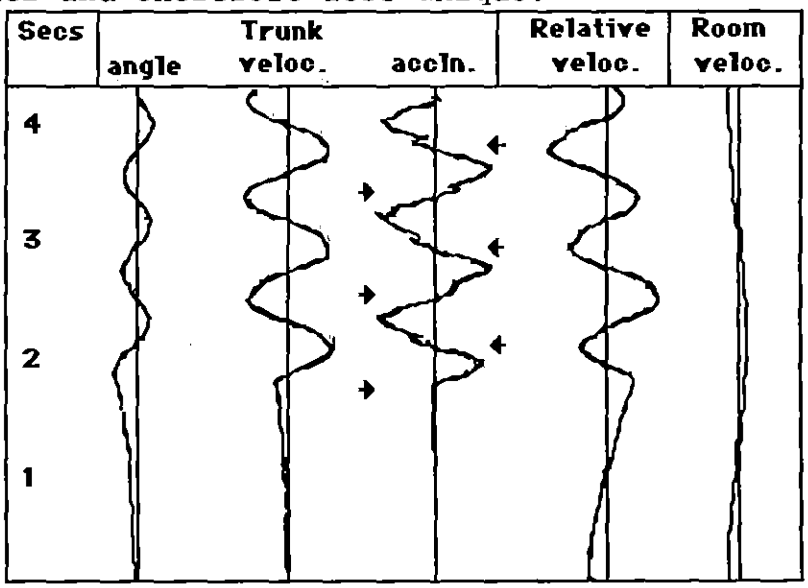


Figure 8.10 Simulation of push control for standing balance as described in the text. Trunk angle varies between plus and minus 0.3 degrees. The original room velocity has been put in for reference.

However there are a number of difficulties which appear when such a system is run on the simulation. Attempts to control by pulse inputs alone lead to diverging oscillatory instability. It is certainly possible to keep control by imposing short pulses on an underlying continuous feed-back whenever some angle threshold is exceeded. Figure 8.10 shows this working with pulses of a nominal value of 4.5 applied over a period of 0.36 seconds whenever the vertical angle exceeds a set threshold value. The difficulty is that the period of oscillation cannot be much increased without losing control. The period of the real trace is 4 seconds with an angle dispersion of about 0.3 degs. In figure 8.10 the initial fall to the left under the restraint of the continuous feed back is at about the same rate and reaches about the same angle. At this point a push which is strong enough to make the angle cross the centre line immediately reduces the period to about 1 second as shown in the figure. If it is reduced until the initial rate of reversal is nearer to the recorded 4 secs period then the centre line is never reached.If the length of the pulse is increased in an attempt to keep the reversal going there is an interaction between the continuous feed back and the long pulse and the trace starts oscillating about a mean angle which again does not cross the centre line. Only short pulses can be used to influence the continuous system without altering its basic characteristic. The inability to increase the wave period is due to the natural frequency of the oscillation of the trunk about the ankles assumed in the model. As has already been mentioned it is possible that a correlated movement of the body sections might make large changes to the effective radius of gyration and thus alter the natural frequency. It is evident that more data would be needed before a model which might produce a solution could be constructed and at present the triangular shape of the trunk velocity remains unexplained.

Although the model is a very simple one it does help us to understand several interesting properties possessed by such a system. If the natural control achieves this sort of stability by locking the ankle joint and relying on the passive stability of the foot it would not have responded to the swinging room. Active balancing of a standing body around such small angles as half a degree displacement involves almost inevitably some sort of continuous feed back about the rate of sway. If there is too much power the characteristic will be a diverging oscillation. If, in the swinging room experiment, it is supposed that the subject is under the control of visual information only then a gain appropriate to normal conditions would be unable to contain the sway induced by the false movement of the room. It further shows that if the conflicting information of both the vestibular and visual channels is added together so that both are making equal contributions then the behaviour of the model in the presence of the swinging room is in many respects the same as that of the actual recording. A much more detailed record of such movements would be necessary before a similar analysis to that done on the bicycle could be carried out but in the interim it can be stated with some confidence that standing balance control seems to face the same class of problem as that for riding the destabilized bicycle and that as far as can be judged from the rather sparse information given in this paper humans set about solving this problem in much the same way using the same basic neural equipment.

The aim of the bicycle study was to find out the minimum conditions necessary for control and because of this the trials were carried out with the subjects blindfolded. Unfortunately lack of time prevented any trials with sighted subjects so no comparison is possible as a series of calibrated runs would be needed to determine whether there was any difference in the angle control when visual information was available. However the general performance of the riders seemed exactly the same under blindfolded or sighted control and a study of wheel tracks showed the same short and long period oscillations were present under both conditions so it looks as though a continuous input for angle is not used when sighted. It would however be very interesting to be able to ride a bicycle within a large swinging room to see if the resulting performance was consistant with the visual information replacing or combining with the vestibular input. All that can be said for sure from the bicycle experiments is that loss of vision caused a minimum of disruption to the established sequence of responses and surprisingly did not 'feel' subjectively any more difficult than normal riding. On balance this finding together with the analysis on the Lee and Lishman data suggests that the vestibular and visual information are both available and under normal circumstances will both give the same input. The complete loss of one leads to the other taking over but the distortion of one in a 'deceptive' manner leads to an output which is consistent with an addition of the two inputs.

Summary

The model proposed for control of the bicycle requires that the upper trunk of the rider is held in a constant relation to the lower trunk and consequently the machine, during control movements. The arms must produce either steady angle-independent tension loads on the handle bar for turns with full bicycle autostability or short period on/off pushes when this is weak or absent. They must also supply a continuous movement following the roll acceleration when machine autostability is below some threshold value on which the directional pushes are superimposed. Although none of these functions has been demonstrated specifically for the bicycle, it is argued that the system as understood at present clearly has the capacity for all three and that the sensory and motor performances revealed in other balance tasks is of the same general type as that required for the successful performance of the proposed bicycle control.

9. THE ORGANIZATION OF CONTROL

Introduction

The enquiry so far has shown in some detail how the handle bar of a bicycle is moved to achieve control. This knowledge will now be related to the existing theories of motor skill, already discussed in chapter one, to consider how the rider might achieve control in terms of internal organization.

The Essential Ingredients of Control

Because the bicycle is so unstable only a very limited number of systems will satisfy the control requirements. The autostability built into the machine by virtue of its design removes the need for any additional inputs to achieve basic roll stability when travelling over some critical speed. In this condition an angle-independent pressure on the handle bar produces a stable lean proportional and in the opposite direction to the push. This results in a turn in the direction of the lean and proportional to it. Upright running is restored by removing the pressure. Transient disturbances, such as surface irregularities, will lead to changes in the direction of running but roll divergence will be automatically removed. Steady disturbances, such as side winds, will lead to corresponding turns which can be countered by a continuous pressure on the appropriate handle bar. Anything which interferes with free rotation of the steering head under the influence of the autostability torque will cause loss of roll stability.

As the speed falls below the critical value the autostability forces will fail to contain roll divergence and unless prevented the bicycle will fall into a turn to one side or the other from which it will not recover. There is a transient range of speeds within which the autostability response can be enhanced by rolling the frame in the direction of fall. Frame rotation is induced when the upper part of the rider's body is rotated in the opposite direction, that is against the fall.

At very low speed the autostability fails to make a significant contribution and in the absence of any other inputs the bicycle will fall rapidly in the direction of the first roll departure. In this speed range riders are observed to move the handle bar angle at a rate which is a multiple of the roll angle, with a short phase-delay. The essential difference between this and the machine stability control is that it does not respond to absolute angle as well as roll rate. The consequence is that, in the absence of any further control inputs, lean angle errors will accumulate causing the bicycle to go gradually into a turn from upright running.

The absence of continuous absolute angle control and a longer delay in the human system, also leads to a difference in the effect of directional control movements. An attempt to use the steady steering pressures described above will give a rapid increase in roll rather than a steady turn. Directional control is now achieved by single short-period pushes, timed to allow the rather slow response to take effect. A single push produces an oscillatory rate of roll away from the side of application. A moderate push will reverse this and send the mean of the oscillations back towards the upright from where it will gradually oscillate either back down in the same direction or over on the other side. Straight running consists of a series of gentle oscillations about the upright at the natural frequency of the system, with a restoring push whenever the lean angle exceeds some threshold value.

Navigational control, that is steering the bicycle in relation to the environment, must always entail movements via the control systems described above. In normal conditions a turn will be demanded by a continuous push on the side opposite to the desired turn. In the low speed case this must be modified to separate start and stop pushes. In the abnormal case of 'no-hands' riding, which is effective only on bicycles with good autostability characteristics, a turn is achieved by a strong roll of the upper body away from the desired direction of turn. Even when riding normally such body leans will enhance any existing autostability forces. Apart from these limitations, navigational control poses the same problem as that found with other vehicles and is not part of this study.

The Applicability of Existing Theories

The relationship between existing theories of motor performance and what has been discovered about bicycle riding will now be considered. There seems to be no objection to applying a stimulus-response interpretation to the basic zero-stability control loop. The continuous change in the controlling muscles follows the vestibular output without interference from any higher level. The steering pushes do not replace it but are added to it. A stimulus-response view might also be applied to the apparently automatic removal of lean during straight running on the destabilized machine. Whenever the angle of lean reaches a particular threshold a recovery push is initiated, one state leading automatically to the next. This theory is not very helpful when the initial acquisition of the skill is considered nor is it any use when considering why a steering push is introduced for navigational purposes.

Motor Programs

An open-loop motor program approach cannot deal with the intimate relationship between roll acceleration and bar response in the destabilized control loop. The bar rate follows the roll rate in detail and the continuous feedback of roll rate is essential. Both the continuous and short-period steering pushes superimposed on the underlying system for turn control appear to be stereotyped open-loop events but the automatic removal of lean during straight running with the destabilized machine must depend upon feedback.

Schema Theories

The difficulty with fitting schema theories to specific functional models is, as already mentioned in chapter 2, that they are descriptions of how information is behaving and do not produce as their output variables which can be directly interfaced with the physical system. Schema theories are really aimed at explaining motor learning but since this must include descriptions of the behaviour which is learned they must be capable of reconciliation with the observed details of such events. The ability of schema theories to explain learning depends on a high degree of central control for both open-loop and closed-loop systems. There are however several versions, some more extreme than others, and interpretation depends on the specific details.

Schmidt (1976, p.46) originally committed himself to a minimum limit of 200 msecs for centrally controlled closed-loop events which will not do for the destabilized bicycle control. However he more recently (1980) accepted the mass-spring view of muscle activity in joint movement. This holds that the position of the joint is controlled by the specification of the length/tension ratio between the agonist and antagonist muscles and as such rejects the idea of intimate central control at the level of individual muscle groups which certainly eases the position.

Adams (1976, pp 96-97) rejects the proposed kinaesthetic response time of 119 msecs for closed-loop control and quotes studies which show cortical responses to peripheral stimulation of 4 msecs in monkeys. Given this sort of speed there might well be time for some sort of central contribution during the observed 60 msecs delay in the basic loop. The degree of contribution is of course open to speculation but this timely warning is sounded by Fernandez and Goldberg (1971, p.672): *Can it be argued that the central nervous system plays* (only) *a minor role in the dynamic properties of all vestibular reflexes? One need only consider the vestibulo-oculomotor system to be disabused of this notion. The fast phase of nystagmus is unquestionably of central origin. Even the dynamics of the slow phase cannot be explained on the basis solely of peripheral mechanisms.* Thus it can be seen that even when dealing with highly constrained peripheral activity it is not possible to make a simple central/peripheral division of control.

The central contribution referred to by Fernandez and Goldberg is rather different from that envisaged by Adams. The former intend that, since the purely mechanical properties of the vestibular system as a transducer cannot completely account for the observed neural output, there must be some additional transformation, possibly at a central location. Adams sees the sensory outflow as giving the central control a knowledge of results, or ongoing report on the success of the overall action, which is not appropriate to the destabilized control loop. There is a confusion here between two separate feedback control loops.

The inner loop has roll rate as its controlled variable with a desired value of zero. The manipulated variable is the angular rate of the handle bar. The measured variable is the rate of roll with a reference value of zero. The actuating signal is the difference between the reference and the measured variable, that is, the activity in the vestibular output. Although this is often called the error signal, this terminology is discouraged by control engineers as the error in the system is the difference between its present state and the desired value of the controlled variable (Healey, 1975). Thus it can be seen that the inner loop controls the roll rate about the desired value of zero by applying some function of the vestibular output to the handle bar. Because of inefficiencies the roll rate is never held exactly at zero and consequently there is always an actuating signal present. This is not however a measure of error for the system as a whole. The system is in error when the controlled variable (roll rate) is no longer averaging around zero. That is, when it departs and the bicycle falls over. It is this latter information that is appropriate to Adams' 'error feedback' value. The central control is only concerned with failures to achieve a mean balance. It is not concerned with the local variations in the actuating signal which are just an essential aspect of its correct functioning.

The next outward loop can be analysed in the same way. Here the controlled variable is direction of travel, the manipulated variable is still the bar, and the measured variable will be the optic flow, sensed centrifugal pressure or an integrated form of the horizontal yaw. The reference, depending on intention, will be *turn left* or *right*, *hard* or *gentle* etc. Control will be monitoring the actuating signal, that is the measured variable minus the reference. The central system, again in the terms of Adams' model, is concerned with the error between the desired direction of travel called for and the one actually achieved. This time it is the turn which is the by-product of the system's functioning.

When put like this it will immediately be appreciated that it is much easier to specify the structural correlates of the feedback for local control than that for the central process. Hardly any modification of the direct vestibular output is needed to account for the follow-up action of the arm muscles controlling the handle bar. How the activity in the afferent pathways from the various sensory neurons that are stimulated during riding is interpreted by the brain as constituting a failure to achieve the intended goal is a very different matter. Nothing that has been done yet in psychology or neurophysiology comes anywhere near hinting what such an activity might mean in structural terms. We return to the lack of a theory to handle the interface between information and structure.

Mass-spring Theory

The mass-spring theory states that the position of two adjacent skeletal units about a joint is completely specified by the ratio of the length/tensions of the opposing muscles which control them. The great advantage of this representation is that a controller wishing to move a limb to a position in space does not need to specify what trajectory is taken to get there. By dramatically reducing the possible degrees of freedom in this removes, at a blow, at least one of the nightmare areas of potential combinatorial explosion that haunt central control theories. A number of studies have shown limb movements which closely follow the predictions of this model (Kelso et al., 1980; Bizzi, 1980 and Schmidt, 1980).

Applying the mass-spring idea to the two levels of motor movement in the bicycle rider seems to present no problem. The theory envisages control by two variables. The length/tension ratio for opposing muscle groups and a stiffness value (Cooke, 1980). Bizzi (1980) presented evidence that the start position of the limb in relation to the body was needed for accuracy. If relative limb position is normally known then setting a length/tension ratio appropriate to the existing position of the arms with a low stiffness value would give the required readiness condition for riding the autostable bicycle discussed in the previous chapter. Controlling the length/tension variable with the vestibular output would produce the muscle length accelerations implied by the destabilized bicycle observations. In other words this gives the same effect as the simpler arrangement proposed in chapter 8 where the agonist muscle is excited and the antagonist inhibited.

A high stiffness setting does not alter the length/tension ratio which dictates final position, but it increases the amount of force involved in any movement. It has already been shown in chapter 6 that the longer the delay in the destabilized follow-up control the lower the gain in the response must be to prevent instability. In the opposed spring model gain equates to stiffness. That is a change in the stiffness variable will give accompanying changes in power of response for the same vestibular output.

The single control pushes in the zero-stable system would be achieved by adding to or subtracting from the existing length/tension value. The angle-independent pushes held for the duration of a turn in the autostable system are not quite so easily accounted for. If control must be exercised through only the two given variables then an approximately angle-independent tension over a restricted arc of movement could be achieved as follows. The length/tension (limb position) ratio is set appropriate to an angle well clear of the existing one. That is one that will never be approached in practice because of the response from the autostable torque. Now the stiffness value will dictate the tension and since there will be little change in length over the range of angular movement this will be approximately angle-independent. That is for any turn the length/tension variable is set at the same value with the stiffness variable controlling the amount of push.

Coordinative Dissipative Structures

Kelso *et al.* (1980) address the specific problem of relating the dissipative structure theory to the mass-spring concept of limb musculature. The most important change from the mechanical model is the implied difference in neural organization. The mass-spring analogy treats opposing muscle groups as single springs whose tension-to-length properties can be used as a control variable, together with stiffness and possibly viscosity. (Note:- Stiffness is the force required to change the length of the spring. Viscosity is the resistance depending upon the rate of movement). A mathematical or electrical analogue will give a performance that is very similar to the dynamic performances observed in animal limb movements. Although it is not explicitly proposed that the similarity extends to the details of structure, mechanical models encourage the idea that the complex neural system is organised in such a way that all the fibres associated with one muscle unit act together under the control of a single efferent. Individual muscles are then seen as being coordinated in the same way as the springs in the model.

A coordinative structure view is quite different. Here the primitive units are the individual muscle fibres. These are interconnected via a neural system which is no longer considered in terms of afferent/efferent function but takes the form of a complex interactive network. The changes at a sensory ending are fed to motor plates on neighbouring fibres to produce an unspecified general interaction which gives the whole limb the properties of a conditionally stable thermodynamic engine. Control inputs change the non-dimensional 'essential variable' (see chapter 2), modelled in the mechanical version by the length/tension value, which leads to stable states which equate to final limb position. A non-essential variable, modelled by stiffness, controls the force available during the movement.

The above concept seems to fit bicycle control rather well. The study by Partridge and Kim (1969) demonstrated that a regular wave form in the vestibular output led to a similar response in the forelimb of a cat. This capability is all that is necessary for the stability loop of the bicycle control model. In chapter 8 a mechanical model was used for the purpose of discussion but a dissipative structure model will do just as well. No one has yet shown how the fine detail of innervation in the muscles does actually produce the observed results, so both mechanical and coordinative structure models are equally possible.

One advantage of the dissipative structure is that it constrains the degrees of freedom at the local level making the control problem for the next hierarchic level that much easier. This feature does not have such a large impact on explanations of the mature control system since bicycle riding was specifically chosen because it dramatically limits the degrees of freedom of the rider. But the autonomous nature of the dissipative structure has considerable significance when considering the problem of skill acquisition. The *ab initio* rider is faced with the problem of how to move the bar to achieve control. The mechanical model allows considerable freedom of bar movement. It can be accelerated, moved at a steady velocity, moved continuously or discontinuously in jerks. Learning implies selecting just the right sort of movement out of all these and there is the temptation here to resort to prior knowledge at a higher level of organisation to assist this choice. The dissipative structure model requires control to be exercised only via the essential variable, thus constraining the possible responses. In this view the rather limited response possibilities of the biological structure happens to include one which allows bicycle control. Encouraged by the experience of others that he too possesses this ability the beginner runs through the limited repertoire of responses in a trial and error fashion until some degree of control results.

Internal Organisation for Bicycle Control

The bicycle was chosen because it is a very constrained system. Once the exact way in which the machine behaves during free riding is known it is possible to say a good deal about the behaviour of the rider. It makes sense to divide riding skill into two levels which though similar are distinct. The skill of riding a machine with high autostability is confined to producing torques on the steering bar proportional to the amount of lean and therefore turn. In addition to the above a rolling motion of the upper body will cause the autostability to produce a turn against the lean. Motorcycle riding is of this sort at normal speeds. The skill of riding a machine with either very low or zero autostability has two components. First the handle bar must be oscillated at a rate that follows very closely the oscillations in the lateral roll sensors. Second short pushes on the steering bar produce, after a short delay, oscillatory rolling velocities away from the push.

It will be seen that this system divides into several levels of control arranged in an hierarchy. At the lowest level is the autonomous loop which keeps the movement of the handle bar following the roll rate. Although, as has already been discussed, it is possible that the transformation of the vestibular output may require some function that is contained in the central nervous system this is not meant to imply that an external variable is introduced from that direction. The loop is completely self-contained and continuous and other control inputs must be added to it without interrupting its operation.

Above this level lies the push-control. Its method of application is to add a short ballistic pulse to the handle-bar. The evidence in chapter 6 shows that this control is applied automatically in straight running when the lean angle exceeds some threshold value. Unlike the roll response from the vestibular system the recovery from unwanted lean is complex, particularly when there is no direct information of absolute lean angle from the visual system. Since subjects reported being unaware of making this correction and had been instructed not to bother, it seems reasonable to postulate a semi-autonomous loop which monitors lean and then applies a correcting pulse when a limit value is exceeded. This loop must also allow for the slow response to avoid unstable overcontrol. It must be open to higher control when an intentional turn is to be made.

Lean angle must be judged from activity in various sensory channels but how this is integrated is not known. There are no theories at present which offer structural correlates for such functions. Thus the descriptive level has already moved away from the structural mechanical to the informational. The loop for the lowest level, described in the previous paragraph, is seen as electro-mechanical energy flowing from the vestibular system, down a motor neuron and into the upper arm muscles. The loop described here is a notion to show how activity at one site must inform activity at another. The bicycle model does at least show how the informational level is interfaced with the structural level. 'Give a pulse, left' is a typical output of the information loop and a down-flow of electromagnetic energy in the motor axon appropriate to a sudden push is the input for the muscle structure.

The control when autostability is operating requires no lower level loop. Because the machine loop is much faster and more powerful than the human loop, this need not necessarily be 'switched-off'. It could remain 'on-line' but dormant through lack of an actuating signal. The control pushes for lean must be added to the autostability torques by being angle-independent over the range of movement. Schemes for either the mechanical or mass-spring system have been indicated. These are not short pushes but are held on for the duration of the turn and the question arises whether they are open-loop or closed-loop. If the pressure is applied very slowly the machine response is almost dead-beat and therefore it would be possible to use the feedback rate of entry roll to central control to time when the push should be checked. Assuming a minimum decision-time of 200 msecs would not cause a problem at the slow rate but might with fast entry rates. However such a scheme puts extra loads on central activity and since rate of turn equates with tension there can be an open-loop demand directly for the required rate of turn.

Because the autostability removes absolute lean angles there is no need for the second control level postulated for the zero-stability condition. Since it must be switched off for navigation purposes in the latter situation then it seems to add no further burden if it is also switched off when autostability is present.

Both systems require some sort of interface between the purely navigational level and the levels of operation described above. This has to change the navigation output instructions of 'go left', 'go right', 'turn hard', 'turn soft' into steady pushes for the autostable case and pulse pushes for low stability conditions.

Learning and Development

Learning to ride a bicycle almost always entails attempts to ride at very low speed, often with poorly designed machines, and frequently on bad surfaces. Under these conditions autostability is at best very weak. It is therefore evident that most people need to learn the zero-stability skill first and this seems consistent with the observation that most bicycle riders can control their machines at very low speeds. Before any attempt to ride is made it is evident that the candidate already has the essential ingredients of success. Control of muscle groups via vestibular and ocular responses to short period angular accelerations is a vital part of bipedal balance, so the general class of event required by the bicycle control model will already be in existence. Accurate rate movements of the arms will also be a part of the normal repertoire. The candidate will have watched others riding and formed some idea that control is associated with movements of the handle-bar. On the negative side, most children have considerable experience with tricycles and outrigger bicycles before attempting single-track riding. This teaches them a use of the handle bar which is quite inappropriate and presumably makes acquiring the new control response more difficult.

Anyone who has watched a child learning to ride a bicycle will be aware that in the initial stages they induce large roll rates with bar movements which lead to loss of control. These are almost certainly the result of trying to control direction in the same way as they would a tricycle. The next stage which follows quite quickly is overcontrolling, where incipient falls are checked with correct bar movement but so strongly that an even greater fall results on the other side. After several diverging wobbles control is lost. At this stage it seems that the rolling effect of the bar is taking priority but the rate of application is gross. In effect the emerging balance loop is there but the relationship between lag and gain is wrong.

It is usual at this stage for the instructor to hold the back of the saddle and run with the machine. This constraint can correct the effect of over vigorous bar movement and the increased speed improves the response. Typically, short runs of several seconds are observed where the wobbles die down and quite smooth control is achieved. The trick is to let go during one of these smooth patches without letting the child know! As soon as he realizes he is no longer supported he starts overcontrolling. At some point along the way the roll rate sensed by the vestibular and/or ocular system has started to exercise direct control over the arm muscles in the short delay stability loop. Like many movement skills it appears suddenly, sprite like, out of the blue only to vanish as soon as it is attended to. Practice lures it out again and eventually leads to its permanent capture.

A slow verbal stage of learning does not seem appropriate for bicycle riding. For a start the basic control loop will not tolerate slow operation. If the phase slips much more than 100 msecs it gets out of synchronization with the natural frequency of the system and starts to enhance error, not reduce it. Secondly in general very few bicycle riders realize how they operate the bar for control. In the survey of ten riders referred to in chapter 3, none of them had a correct understanding of the necessary control movements so either they have all changed their minds since learning or their verbalization would have contradicted the actions necessary for success.

When one compares the time to acquire the basic skill with the enormous amount of practice required to perform some of the more exotic BMX tricks, one is encouraged to believe that the essential event which discriminates between not having and having riding skill, is something quite simple. Cordo and Nashner's (1982) subjects transferred postural control movements from leg to arm instantly when it was appropriate showing that a facility for rapidly connecting oscillatory activity at one neural site to another already exists. Here is another possibility for reducing the degrees of freedom. Say for instance that the body was internally aware of which sites were receiving some sort of regular wave stimulation. In this case the arm muscles controlling the bar are already the focus of interest so the attempt to succeed consists in feeding the activity from each prospective sensory site in turn to the site controlling arm movement. In the bicycle learning case we can see that there will not be many sites so stimulated. Providing we see the lower level of arm organisation as something like the mass-spring system then application of the correct wave form, that is the activity in the rolling plane, will produce approximations to the correct control movement. This is then trimmed by altering the stiffness variable in a direction that gives improved control.

Control of direction grows out of the realization that every time the machine leans over it turns as well.

Control movements which lead to leaning also lead to turns. Sudden pulse inputs to the bar cause a departure in lean.Trial and error will lead to the discovery that a short push causes a wobble away from it and that in wobbling the machine turns as well. It is interesting to note that the whole system, bicycle and rider, can be described as a single conditionally stable thermodynamic engine 'down-wind' of the control instruction set 'turn-left, turn-right, go straight'. All the individual events react with each other to produce the three end states which are selected from the centre via the essential variable, whatever that might be. Fascinating though this idea is, it does not in itself help in explaining what is happening. However, it sounds a warning that insufficient is known about the details of the structure to be able to indicate which dynamic model best applies.

Future Developments.

It is not easy to see how the bicycle experiments might be developed to provide any immediate short term useful function. The discussions in chapter 8 showed that it is almost certain that at the lower level fast reflexes are being recruited by the central organization to produce the angle/follow response in much the same way that Nashner and Lee showed fast unconscious ankle responses to maintain, or in the latter case disrupt, a standing position. Whether these are more thoroughly exposed in the bicycle riding task from the clinical view or not is open to question, and, since it involves the problem of relaying information during extensive movement it is unlikely that it offers any advantage as a means of diagnosing defects in this class of function. However useful or otherwise recorded bicycle riding might prove as a clinical tool, there are still a number of questions surrounding the control problem which would certainly be very interesting to clarify from a theoretical point of view. First a repeat of the destabilized runs without a blindfold would clear up the question whether riders take advantage of the absolute angle of lean available through the visual system to modify the push control observed when they were blindfolded. Then a set of runs with a manoeuvring task on both the destablized and the normal bicycle, sighted and blindfold would further unpack the higher level of the control hierarchy. Standard runs with a large number of subjects would allow an informative comparison of the derived values such as lag, wave-period and wave area, and highlight any personal idiosyncrasies in control strategies.

Probably the most interesting single discovery is the way the riders exercised control of the lowest balance loop by disturbing it rather than changing the zero set point which would certainly be the choice in a man-made system. The example of the sprinter on starting blocks was quoted as an indication that this sort of control exists at some level in running balance control, and it is also a fact that horse-riders, at the show jumping level at least, force the horse to turn by shifting their weight to one side to upset lateral balance.

During learning a self-contained bottom level loop is set up by some form of central control similar to that which allowed Nashner's subjects to select the arm as the most profitable site of action rather than the leg when this dynamics of the experiment were altered. This runs continuously with fast reflex-like responses, more or less under the direct control of some relevant analogue output. The next level above superimposes disturbances which disrupt the equilibrium at a lower level but by doing so provoke the required response as the autonomous loop works to restore the balance. More immediately profitable perhaps than extending the inquiry further into specific bicycle riding skills would be to extend the recording technique to a number of other balance movement skills, such as roller-skating, grass-skiing and wind-surfing to find if a similar autonomous roll response loop lies at the bottom of their control hierarchies. Such knowledge would certainly be of interest to sports scientists and coaches and indeed anyone whose task it is to teach people movement skills. Being unconscious, such movements cannot be taught directly by briefing and self-monitoring. Somehow they are learned quite suddenly under the stress of the demand and once established their presence seems to be quickly forgotten. It is also possible that this method of organizing the control hierarchy might extend to skills not immediately connected with the sport applications mentioned above such as manipulative tasks. Where skilled movements have this form of control then it should be fairly easy to isolate responses at the two distinct levels and thus diagnose whether a patient was experiencing difficulties at the reflex level, the next higher level or in the synchronization of the two together.

Conclusion

An interesting by-product of the bicycle study is further confirmation that there are body actions which are totally inaccessible to the consciousness. Both Lee and Nashner in the experiments previously quoted found this effect and it occurs as an aside in much of the postural literature. None of the ten riders in the survey quoted in chapter 3, nor any of the many other riders questioned by the author have been able to describe correctly how they exercised control, although almost all of them offered explanations. The author, more aware than any of them of the true direction of push during a turn, has never been able to 'feel' that he was applying a torque *against* the turn. The conviction that it is the rider who is causing the rotation of the handle bars into the lean as the turn develops, persists. In some strange contradictory way this remains true even when the push is applied with a single finger, which precludes the possibility of a pull. Similarly no amount of mental effort has enabled him to detect the operation of the basic balance loop on the destabilized machine. These observations are a serious warning against the reliability of introspective accounts about how a skill is performed and goes some way to explaining why many movement skills are taught so badly.

It is something of a paradox that riding a bicycle, although very complicated, is comparatively easy to investigate because the system is so constrained that it allows only a limited range of possible control solutions. It is likely that most of the other sports skills mentioned in the previous section would be more difficult both to record and simulate. However, since these skills and many others, including skilled hand movements, are likely to contain 'inaccessible sub-conscious' components only a detailed record of the physical movements during performance will reveal the secret of how the skill is controlled.

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APPENDIX 1(a)

The Simulator Programs

BIKE1 The controlling program for the following two routines. This sets up the parameters of the run and initials the screen graphics.

AUTOSF The 'normal' bicycle control. This supplies the basic front wheel stability and allows controlling pushes to be introduced from the keyboard.

DESTAB The destablized control system. This feeds the roll acceleration and velocity to the handlebar acceleration at the set lag and gain. It allows pushes to be superimposed either through the key board or automatically at a selected threshold of lean angle.

MOMENTS This program works out the moments of inertia for a new bicycle and stores them in the data files, BIKE_A, BIKE_B etc.

APPENDIX 1(b)

The Destabilized Bicycle
A scale drawing of the Triumph 20 bicycle used in the experiments. The original front forks are shown with a dotted line. The following features are shown:-

el & eh Effective length and height. To allow for the low density of the wheels the total length used for the moments of inertia is shorter than the overall length. The point 'el' lies approximately half-way between the 0.5 radius of gyration for a solid wheel and the 0.7 radius for a wheel with all its mass at the periphery. Slightly less has been subtracted from the vertical dimension.

mg The centre of mass (c of m) for the rider, assumed constant. (Rider A 175 lbs, rider M 147 lbs).

bg1 The c of m for the bicycle without the modification to the front forks, (33 lbs).

bg2 The c of m for the bicycle with the modification, (44 lbs).

dg The c of m for the front fork additions (11 lbs).

cg The c of m for the combined system. The four crosses show that the difference in rider weight and addition of the front fork modification made very little change in the location of the combined centre of mass.

APPENDIX 2(a)

Angle Traces of the Destabilized Runs.

The roll and handlebar angle traces for twelve blindfolded runs on the destabilized bicycle by two subjects. Runs 25 to 30 were by rider A and runs 31 to 36 by rider M. The plots show the full run of 750 points. The horizontal divisions show the recorded points which are at 30 msecs intervals, thus the marked hundred intervals are equivalent to 3 secs. The vertical scales have been adjusted by multiplication during the graphing procedure to bring the peaks as near together as possible to assist a comparison between the rates of the two channels. This conceals the large difference between their absolute values and Table 5.1 on page 96 shows the maximum and minimum lean and handle bar angles for each run taken from the raw data files before conversion.

APPENDIX 2(b)

Rates of Change of Angles for Destabilized Runs. Limited sections (points 100-500) of the 12 destabilized runs (25-36) are shown giving the roll and bar relationship for angle, velocity acceleration and jerk. See the text for full details. The bar channel throughout is shown with a darker line than the roll channel. One point in the horizontal scale is equal to 30 msecs. The vertical scales have been adjusted to bring the peaks together for easier comparison.

APPENDIX 2(c)

Lag and Wave Dimensions for Destabilized Runs.
Histograms of lag, half-wave period and area measured on the acceleration channel of the 12 destabilized runs 25-36. The two riders are shown separately. See text for the method of extracting the matched waves. The letter code at the start of each histogram identifies it as follows:-

A or M Rider Identity.

D or N Destabilized or normal bicycle.

R or B Roll or Handlebar channel.

LAG Delay between roll & bar in data points (30 msecs).

WAV Half-wave period length in data points (30 msecs).

ARA Half-wave area in nominal units.

Thus **ADRARA** is rider A on the destab. bike roll areas.

APPENDIX 3(a)

Effect of Gain on Stability.

The following four printouts from the computer simulation of the destabilized bicycle under delayed roll/follow control show the effect of changing gain on the stability response. The intial disturbance is 2 degrees lean left with a speed of 4 mph.

Channel headings

R	Lean angle (roll)	(degs)
S	Relative steering angle	(degs)
R''	Roll acceleration	(degs/sec/sec)
S''	Steering acceleration	(degs/sec/sec)
R'	Roll velocity	(degs/sec)

The figures in brackets show the value of half the bar at the top of each vertical axis.

<u>CRITICAL DAMPING</u> The first graph shows a dead-beat response which is very nearly at the critical damping value for gain. Because the gain is low the response is slow and the lean angle is not contained till 10 degs.

<u>STABLE OSCILLATORY</u> The second graph shows the effect of increasing the gain from 90 to 200. The characteristic becomes oscillatory but the tendency is to converge and thus stable. The initial disturbance is contained by just over 3 degs in less than a second.

<u>JUST STABLE</u> The third graph shows that a further small increase of gain to 220 puts the system into the 'just stable' condition where the oscillations neither converge nor diverge.

<u>UNSTABLE OSCILLATORY</u> The fourth graph shows that increasing the gain beyond 220 puts the system into an unstable state where the oscillations diverge. Both the last two runs contain the initial disturbance by just over three degrees in less than a second.

APPENDIX 3(b)

Regression Residuals for the Destabilized Runs.

The following graphs show the plots of those regression residuals predicting bar acceleration from roll acceleration and velocity which exceeded 1.96 of the standard deviation. The horizontal scale shows data points related to the original total run. The vertical scale has be adjusted to give a clear indication of location and the rate of change of value with time. Only the section 100 to 500 of the original run was used in each case. Each page contains two plots.

APPENDIX 3(c)

Excess residuals related to the roll plots.

The following graphs show the location and direction of the pushes implied by the excess regression residuals on the plots of the roll angle for the runs 25-36, points 100-500. The arrows are located at the maximum value of the excess residuals shown in the previous appendix and show the direction in which the push tends to drive the roll angle.

```
  10 REM**************************
  20 REM BICYCLE CONTROL BIKE1
  25 REM**************************
  30  REM This controls destabilised bike GOTIT1 (Put in Temp for run)
  40   REM or autostab bike AUTOSF (Put in O.TEMP) Check line 240
  60   graph=FALSE:@%=&00302
  70   IF T%<1 THEN PROCchoose ELSE T%=0:REM prevents calling itself
  80   DT$="":F1=OPENIN"IDENT":INPUT£F1,DT$:CLOSE£F1
 110   Ti=.01:NR=0:mm=304.8:CD=0
 120   DIM CH(5,3):DIM D(5):NN=31:DIM NB(NN)
 130   F2=OPENIN"DIMS":INPUT£F2,start,int:CLOSE£F2:CH(1,1)=start
 140   CH(2,1)=CH(1,1)+int:CH(3,1)=CH(2,1)+int:CH(4,1)=CH(3,1)+int
 150   CH(5,1)=CH(4,1)+int
 200   WB=0:Wrad1=0:rake=0:trl=0:Mass=0:WT=0:HG=0:bar=0
 210   WIo=0:FIo=0:HIo=0:LIo=0:FwIo=0
 220   mph=0:VV%=0:Sbase=0:Vbase=0:S1=0:S2=0
 230    H1=0:H2=0:H3=0:H4=0:H5=0
 240    PF$="O.":FO$=PF$+"SIDE":REM Select auto (O.) or destab (N.)
 999 REM*********************************************
1000 REM Main
1010   mph=V%/10:PROCspeed(mph):NR=R%/100
1020   PROCnumbs_in(DT$):PROCallocate
1040   PROCsend_vals
1080   PROCtitle(mph)
1090   CHAIN FO$
1500 END
1599 REM*****************************
2000 DEF PROCsend_vals
2010   F3=OPENOUT"VALS"
2020   PRINT£F3,Ti,S1,S2,NR,CD,VV%,Mass,WB,HG,WT,WIo,FIo
2030   PRINT£F3,HIo,LIo,FwIo,trl,Wrad1,bar,rake
2050   CLOSE£F3
2090 ENDPROC
3000 DEF PROCchoose:LOCAL DT$,FC,NR,mph:FC=50:CLS
3010   REM Horizontal graph mult. facs. Width = 50/fac.
3020   H1=70:H2=170:H3=10:H4=25:H5=2
3025   L%=(50/H1)*100:M%=(50/H2)*100:N%=(50/H3)*100
3026   O%=(50/H4)*100:P%=(50/H5)*100
3030   REM
3040   REM Vert. graph mult. fac. 100 gives appx. 8 secs full screen
3050   Q%=150
3060   PROCshow_facs(H1,H2,H3,H4,H5,Q%)
3070   REM
3075   REM Names for channels. Refer to PROCnames for code.
3080   A%=3:B%=2:C%=13:D%=15:E%=12
3090   PROCshow_name(A%,B%,C%,D%,E%)
3100   REM
```

```
3105   REM Source file for bike type
3110   DT$="BIKE_C"
3130   REM
3135   REM Graph or Tables display. Tables = -1, graph = 0
3140   G%=0
3160   REM
3170   REM Bike speed mph
3180   mph=6
3190   REM
3195   Z%=10:REM Lag in hundredths sec
3196   REM
3200   REM Initial lean error in degrees (positive left)
3210   NR=0
3250   PROCbike_type(DT$,mph,NR)
3300   PRINT TAB(6,20);"If satis. hit RETURN."
3310   PRINT TAB(6,22);"Changes in lines 3000,3999"
3320   INPUT A
3330   CLS:REM CHAIN"SCALES"
3399   ENDPROC
6600 DEF PROCnumbs_in(DT$):LOCAL M
6620   F4=OPENIN DT$:INPUT£F4,FT$
6630                FOR M=1 TO NN:INPUT£F4,NB(M):NEXT M:CLOSE£F4
6650 ENDPROC
7000 DEF PROCallocate
7010   Mass=NB(21):WB=NB(1):HG=NB(23):WT=NB(22):trl=NB(7)
7020   Wradi=NB(2):bar=NB(25)/2:rake=NB(6)
7030   WIo=NB(27):FIo=NB(28):HIo=NB(29):LIo=NB(30):FwIo=NB(31)
7040   CD=0.001417*WT
7090 ENDPROC
8000 DEF PROCshow_facs(L,M,N,O,P,Q)
8010   PRINT TAB(6,2);"Sizes of bars on graph axes"
8020   PRINT TAB(8,4);L;"  ";M;"  ";N;"  ";O;"  ";P
8090 ENDPROC
8100 DEF PROCbike_type(N$,mph,NR):LOCAL CH$,DR$
8110   F5=OPENOUT"IDENT":PRINT£F5,DT$:CLOSE£F5
8130   PRINT TAB(6,10);"Bike Type "DT$
8140   IF G%=0 THEN CH$="Graph" ELSE CH$="Tables"
8150   PRINT TAB(6,12);"Display type "CH$
8160   PRINT TAB(6,14);"Speed "mph" mph"
8170   IF SGN(NR)=0 THEN DR$="right" ELSE DR$="left"
8175   PRINT TAB(6,16);"Initial error "NR" degrees "DR$
8180   PRINT TAB(6,18);"Gain  ";J%;" Lag ";Z%
8185   V%=mph*10:R%=NR*100
8190 ENDPROC
8300 DEF PROCshow_name(A,B,C,D,E):PROCnames
8310   PRINT TAB(6,6);"Channels selected"
8320   PRINT TAB(8,8);
8330   PRINT name$(A);" ";name$(B);" ";name$(C);" ";name$(D);" ";name$(E)
```

```
8390 ENDPROC
8400 DEF PROCspeed(mph)
8420   VV%=INT(FNspeed(mph)+.5)
8425   REM Next applies speed to gain factor.
8430   Sbase=220:Vbase=5:S1=Sbase*Vbase/(VV%*1000):S2=S1*1.43
8440   J%=Sbase
8490 ENDPROC
8500 DEF PROCtitle(mph)
8510     PRINT:PRINT;TAB(3);DT$;" "mph" mph";
8520     IF DT$ <> "BIKE_E" AND PF$ <> "O." THEN PRINT;" Gain "J%" Lag "Z%
8530     IF DT$ ="BIKE_E" THEN PRINT;" Riderless (Destab.)"
8550 ENDPROC
8600 DEF PROCnames:LOCAL L%:DIM name$(20)
8605 REM    1       2  3    4  5  6  7  8  9 10 11   12    13  14    15  16  17 18  19
8610 DATA Secs,HA,RSA,VA,RA,L1,L2,F1,F2,FF,Hw,HwDOT,Vw,VwDOT,Sw,SDOT,Rw,SF,FFA
8620  FOR L%=1 TO 19
8630   READ name$(L%)
8640  NEXT
8690 ENDPROC
8700 DEF FNspeed(mph):=(INT(((mph*88)/60)*10)/10)
```

```
   10 REM***************************
   20 REM BICYCLE CONTROL AUTOSF
   25 REM***************************
   30  TF=0
   35 VDU 23,240,24,48,96,255,255,96,48,24
   36 VDU 23,241,24,12,6,255,255,6,12,24
   40 DIM togg%(2):DIM op%(2):DIM BU%(2):DIM Inc(2):DIM SF(2):DIM bias(2)
   50 DIM CH(5,3):DIM D(5):DIM I(25):GF2%=Q%:mm=304.8:VV=0:lag%=Z%
   60 DIM F(5):F(1)=L%/100:F(2)=M%/100:F(3)=N%/100:F(4)=O%/100:F(5)=P%/100
  100 F1=OPENIN"DIMS":INPUT£F1,start,int:CLOSE£F1:CH(1,1)=start
  110 CH(2,1)=CH(1,1)+int:CH(3,1)=CH(2,1)+int:CH(4,1)=CH(3,1)+int:CH(5,1)=CH(4,1
)+int
  120 Bu=0:AL=0:RSA=0
  130 TS=0:g=32:R90=RAD(90)
  140 Ld=0:RP%=0:HL=0
  150 F2=OPENIN"VALS":INPUT£F2,Ti,S1,S2,NR,CD,VV%,Mass,WB,HG,WT,WIo,FIo,HIo,LIo,
FwIo,trl,Wrad1,bar,rake:CLOSE£F2
  160  Ld=trl*mm:RP%=Wrad1*mm:HL=RAD(rake)
  190  PrecIo=FwIo*2:Wldiam=Wrad1*2:PC=PrecIo*VV%*PI*2/(PI*Wldiam)
  200 B1=0:B2=0:B3=0:B4=0:C1=0:C2=0:C3=0:C4=0:C5=0:C6=0
  210 HA=0:SA=0:VA=0:RA=0:L1=0:L2=0:F1=0:F2=0:FF=0:Hw=0:HwDOT=0:Vw=0:VwDOT=0
  230 Rw=0:SRw=0:WTg=0:FTg=0:SF=0:Trl=0:Sw=0:SPY1=0:SPY2=0:SPY3=0
  310 MOM=Mass*VV%:Si=VV%*Ti::REM FIo=WIo:REM Both big
  500 Ffac=(VV%^1.8)*CD:T2=0.5*(Ti^2):FIg=HG/FIo:WIg=HG/WIo
  510  LFIo=LIo+FIo:WBF=WB*FIo:HGL=HG*LIo:WGL=WBF/HGL
  520  WT1=WT/2:WB1=WB/2:WB2=(WB1^2):CAC=Mass*(VV%^2):HIb=WB1/HIo
  600 oprate%=FALSE:BU2%=0:cheq%=TRUE:NN%=0:prvRw=0
  610 bias=0:drn%=0::dely%=16:afac=.25:Inc=0::amp=0:Tm=0
  999 REM*********************************************
 1000 REM Main
 1010    graph=TRUE:TT=0
 1030    VA=RAD(NR)
 1500    REPEAT PROCrun
 1530      NN%=INKEY(1)
 1540    UNTIL NN%=90 OR NN%=83
 1550    IF NN%=83 THEN *PRINT
 1590 END
 2499 REM****************************
 2500 DEF PROCcontrol(accl)
 2590    SF=bias
 2600    IF cheq% THEN IF NN%>0 THEN PROCcheck
 2620    IF oprate% THEN PROCoprate(Inc,dely%)
 2790 ENDPROC
 2959 REM******************************
 3000 DEF PROCcheck
 3010    IF NN%<65 THEN amp=FNamp(NN%) ELSE PROCturn(NN%,amp,dely%)
 3030    NN%=0
 3050 ENDPROC
 3100 DEF PROCoprate(Inc,dely%)
```

```
3120    cheq%=FALSE
3130    bias=bias+Inc:SF=bias
3140    BU2%=BU2%+1
3150    IF BU2%=dely% THEN BU2%=0:VDU5:MOVE 100,750:VDU 9,127:VDU4:oprate%=FALS
E:cheq%=TRUE
3190 ENDPROC
3300 DEF FNamp(val%):LOCAL amp:amp=(val%-48)*afac:PROCshowit(amp):=amp
3400 DEF PROCturn(val%,amp,dely):LOCAL Nbias
3410   drn%=0
3420   IF val%=76 THEN drn%=-1 ELSE IF val%=82 THEN drn%=1
3430   Nbias=amp*drn%:Inc=FNinc(Nbias,bias,dely%)
3440   check%=FALSE:NN%=0:oprate%=TRUE:PROCarrer
3490 ENDPROC
3500 DEF PROCshowit(val)
3520   VDU5:MOVE 100,800:VDU 9,9,9,9,127,127,127,127:PRINT val:VDU4
3550 ENDPROC
3555 DEF PROCarrer
3560   VDU5:MOVE 100,750:PRINT"*":VDU 4
3570   YY%=INT(TT*GF2%)
3575   IF val%=76 THEN XX%=800:arr%=240 ELSE XX%=580:arr%=241
3580   VDU5:MOVE XX%,YY%:PRINT CHR$(arr%):VDU4
3590 ENDPROC
3600 DEF FNinc(Nbias,bias,dely%):=(Nbias-bias)/dely%
3610   inc=(Nbias-bias)/dely%:PRINT inc*100:PRINT Nbias:PRINT bias:PRINT
4000 DEF FNforce(angle):LOCAL LL,sgn,val:sgn=SGN(angle):val=ABS(angle)
4010 IF angle=0 THEN LL=0 ELSE LL=(val*Ffac)*sgn
4020 =LL
4100 DEF FNhozdot(force):LOCAL I
4110   I=(HIo*COS(VA))+(FIo*SIN(ABS(VA))):=force*WB1/I
4200 DEF FNdl(vel,accl):=(vel*Ti)+(accl*T2)
4300 DEF FNvel(vel,accl):=vel+(accl*Ti)
4400 DEF FNweight(VA):=WT*SIN(VA)*WIg
4500 DEF FNpetal(VA,FF):=FF*COS(ABS(VA))*FIg*-1
4600 DEF FNfwdot(SF,F1,VA,T1,w,Sw)
4610   =((PC*w)+(SF*bar)+(F1*T1)+(WT1*SIN(VA)*T1*-1))/FwIo
4700 DEF FNturni(force):=ATN((force*Ti)/MOM)
4800 DEF FNhcirc(angle):=angle*WB1
4900 DEF FNturnw(angle):=angle/Ti
4999 REM**************************************
6000 DEF PROCrun:LOCAL HwDOT,VwDOT,Sdot,RAi,HAi,VAi,SAi,Roti,VSDOT,SSdot
6020   F1=FNforce(DEG(L1)):F2=FNforce(DEG(L2)):FF=F1+F2
6030   HwDOT=FNhozdot(F1-F2):VwDOT=FNweight(VA)+FNpetal(VA,FF)
6035   Sdot=FNfwdot(SF,F1,VA,Trl,Vw,Sw)
6060   RAi=FNturni(FF):HAi=FNdl(Hw,HwDOT):VAi=FNdl(Vw,VwDOT):SAi=FNdl(Sw,Sdot)
6070   RA=RA+RAi:HA=HA+HAi:VA=VA+VAi:SA=SA+SAi
6080   Roti=(FNhcirc(HAi)/Si):L2=HA-(RA-Roti):L1=SA-(RA+Roti)
6090   Rw=FNturnw(RAi):Hw=FNvel(Hw,HwDOT):Vw=FNvel(Vw,VwDOT):Sw=FNvel(Sw,Sdot)
6100   Trl=FNtrail(RSA,VA):TT=TT+Ti
6120   B4=B3:B3=B2:B2=B1:B1=VwDOT
```

```
6125   C6=C5:C5=C4:C4=C3:C3=C2:C2=C1:C1=Sdot
6130   VSDOT=(B1+B2+B3+B4)/4:PROCcontrol(VSDOT)
6135   SSdot=(C1+C2+C3+C4)/4
6140   RSA=SA-HA:SPY1=VwDOT:SPY2=VSDOT:SPY3=Sdot
6190   PROCdraft(DEG(VA),DEG(RSA),DEG(VSDOT),DEG(SSdot),DEG(Vw),TT)
6200 ENDPROC
6999 REM*******************
7500 DEF PROCdraft(D(1),D(2),D(3),D(4),D(5),TT):LOCAL XX%,YY%:YY%=INT(TT*GF2%)
7510   FOR M=1 TO 5
7515   XX%=(CH(M,1)-(D(M)*F(M)))
7520   MOVE CH(M,2),CH(M,3):DRAW XX%,YY%:CH(M,2)=XX%:CH(M,3)=YY%:NEXT
7530   IF INT(TT)>TS THEN VDU 5:MOVE 0,YY%:PRINT INT(TT):VDU 4:TS=TT
7590 ENDPROC
7999 REM*************************
8200 DEF FNtrail(SA,VA):LOCAL b,SD,SW,CD,CH,Theta,GA,CA:SN%=0
8205   SN%=SGN(VA)*SGN(SA):SA=ABS(SA):VA=ABS(VA)*SN%
8206   IF SA=0 THEN SA=.00001
8210   SD=ATN(TAN(SA)*SIN(HL)):CD=COS(SD):CH=COS(HL):SW=ACS(CD*CH)
8230   b=RP%*COS(ACS((CH-(CD*COS(SW)))/(SIN(SD)*SIN(SW))))
8240   Theta=(R90+(VA+SD)):GA=ATN( b/(RP%*-1*TAN(Theta)))
8260   CA=GA-SW:=((RP%*SIN(CA))+Ld)/mm
```

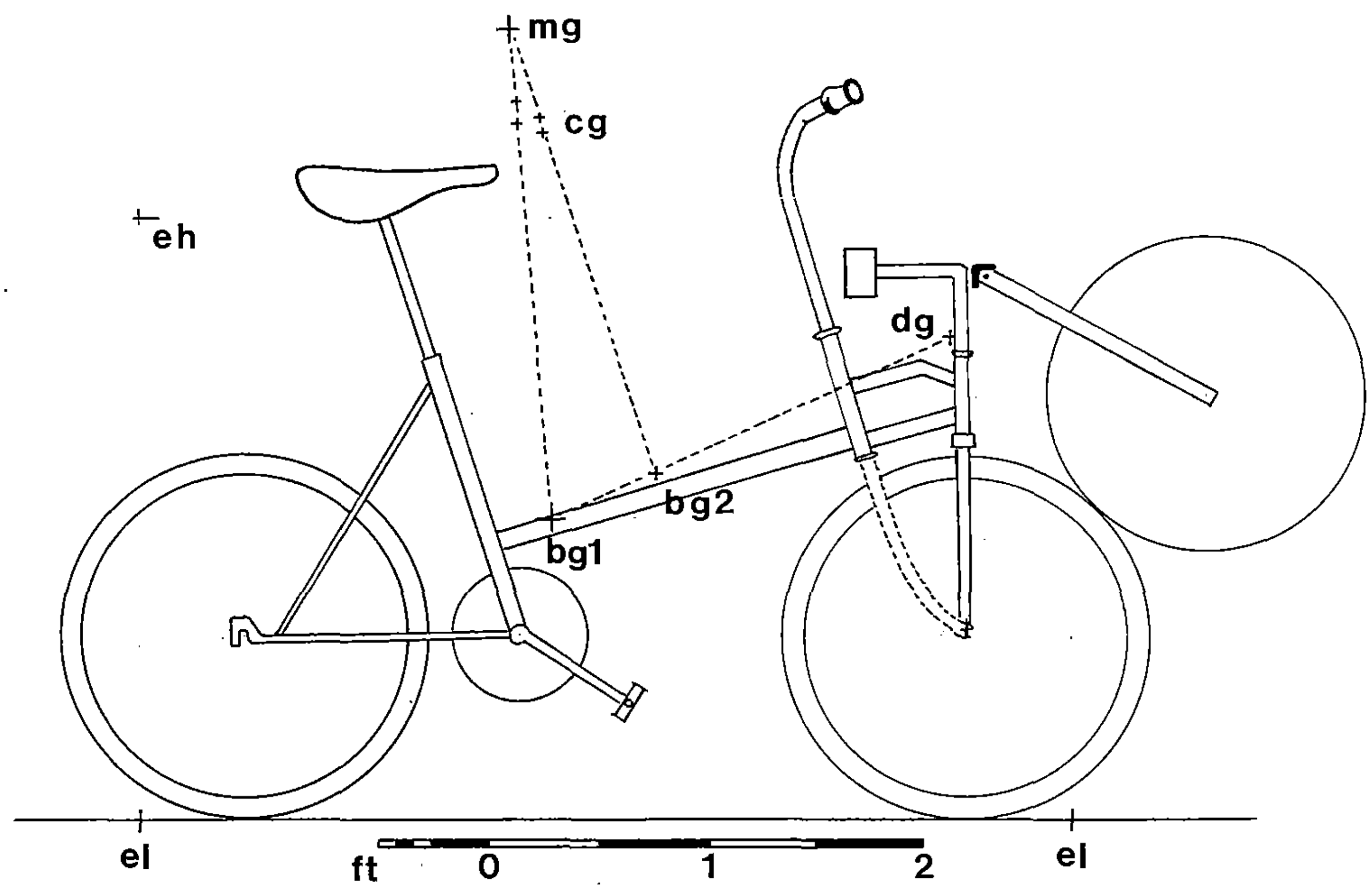
```
   10 REM************************
   20 REM BICYCLE CONTROL DESTAB
   25 REM************************
   30  TF=0
   35 VDU 23,240,24,48,96,255,255,96,48,24
   36 VDU 23,241,24,12,6,255,255,6,12,24
   40 DIM togg%(2):DIM op%(2):DIM BU%(2):DIM Inc(2):DIM SF(2):DIM bias(2)
   50 DIM CH(5,3):DIM D(5):DIM I(25):GF2%=Q%:mm=304.8:VV=0:lag%=Z%
   60 DIM F(5):F(1)=L%/100:F(2)=M%/100:F(3)=N%/100:F(4)=O%/100:F(5)=P%/100
   70
  100 F1=OPENIN"DIMS":INPUT£F1,start,int:CLOSE£F1:CH(1,1)=start
  110 CH(2,1)=CH(1,1)+int:CH(3,1)=CH(2,1)+int:CH(4,1)=CH(3,1)+int:CH(5,1)=CH(4,1
)+int
  120 Bu=0:AL=0:RSA=0:gate=FALSE
  130 Droll=0:Oroll=0:Dturn=0:roll=0:TS=0:g=32:R90=RAD(90)
  140 Ld=0:RP%=0:HL=0
  150 F2=OPENIN"VALS":INPUT£F2,Ti,S1,S2,NR,CD,VV%,Mass,WB,HG,WT,WIo,FIo,HIo,LIo,
FwIo,trl,Wradi,bar,rake:CLOSE£F2
  160  Ld=trl*mm:RP%=Wradi*mm:HL=RAD(rake)
  190  PrecIo=FwIo*2:Wldiam=Wradi*2:PC=PrecIo*VV%*PI*2/(PI*Wldiam)
  200 B1=0:B2=0:B3=0:B4=0:C1=0:C2=0:C3=0:C4=0:C5=0:C6=0
  210 HA=0:SA=0:VA=0:RA=0:L1=0:L2=0:F1=0:F2=0:FF=0:Hw=0:HwDOT=0:Vw=0:VwDOT=0
  230 Rw=0:SRw=0:WTg=0:FTg=0:SF=0:Trl=0:Sw=0:SPY1=0:SPY2=0:SPY3=0
  310 MOM=Mass*VV%:Si=VV%*Ti::REM FIo=WIo:REM Both big
  500 Ffac=(VV%^1.8)*CD:T2=0.5*(Ti^2):FIg=HG/FIo:WIg=HG/WIo
  510  LFIo=LIo+FIo:WBF=WB*FIo:HGL=HG*LIo:WGL=WBF/HGL
  520  WT1=WT/2:WB1=WB/2:WB2=(WB1^2):CAC=Mass*(VV%^2):HIb=WB1/HIo
  600 oprate%=FALSE:togg%(1)=TRUE:togg%(2)=TRUE:NN%=0:prvRw=0
  610 drn%=0:Odrn%=0:dely%=30:amp=0:afac=.005:way%=0:Tm=0
  999 REM******************************************
 1000 REM Main
 1010   graph=TRUE:TT=0
 1030 VA=RAD(NR)
 1500  REPEAT PROCrun
 1530     NN%=INKEY(1)
 1540     UNTIL NN%=90 OR NN%=83
 1550   IF NN%=83 THEN *PRINT
 1590 END
 2499 REM*************************
 2500 DEF PROCcontrol(accl,velo):LOCAL acfac,velfac
 2550 acfac=(accl*S1):velfac=(velo*S2)
 2560  I(25)=I(24):I(24)=I(23):I(23)=I(22):I(22)=I(21):I(21)=I(20):I(20)=I(19)
 2565  I(19)=I(18):I(18)=I(17):I(17)=I(16):I(16)=I(15):I(15)=I(14):I(14)=I(13)
 2570  I(13)=I(12):I(12)=I(11):I(11)=I(10):I(10)=I(9):I(9)=I(8):I(8)=I(7)
 2575  I(7)=I(6):I(6)=I(5):I(5)=I(4):I(4)=I(3)
 2580  I(3)=I(2):I(2)=I(1):I(1)=acfac+velfac:REM +(VA/10)
 2590  REM  GOTO 2620
 2610   IF Tm>0 THEN Tm=Tm-1 ELSE PROCthresh
 2620   IF togg%(1) THEN IF NN%>0 THEN PROCcheck
```

```
2640   IF op%(1) THEN PROCoprate(dely%,1)
2680 REM  IF op%(1) THEN SF=SF(1) ELSE SF=I(lag%)
2700     SF=I(lag%)+SF(1)
2790 ENDPROC
2959 REM*****************************
3000 DEF PROCcheck
3010   IF NN%<76 THEN amp=FNamp(NN%) ELSE PROCturn(NN%,amp,dely%,1)
3030   NN%=0
3050 ENDPROC
3100 DEF PROCoprate(dely%,tp%)
3120    togg%(tp%)=FALSE
3130    bias(tp%)=bias(tp%)+Inc(tp%):SF(tp%)=bias(tp%)
3140    BU%(tp%)=BU%(tp%)+1
3145    IF BU%(tp%)=(dely%/2) THEN Inc(tp%)=Inc(tp%)*-1
3150    IF BU%(tp%)=dely% THEN PROCbucket
3190 ENDPROC
3200 DEF PROCbucket
3210   BU%(tp%)=0:op%(tp%)=FALSE:togg%(tp%)=TRUE
3220   VDU5:MOVE 100,750:VDU 9,127:VDU4
3250 ENDPROC
3300 DEF FNamp(val%):LOCAL amp:amp=(val%-48)
3310 PROCshowit(amp)
3320 =amp*afac
3400 DEF PROCturn(val%,amp,dely%,tp%):LOCAL Nbias,way%,arr%
3420   IF val%=76 THEN way%=-1 ELSE IF val%=82 THEN way%=1
3430   Nbias=amp*way%:Inc(1)=FNinc(Nbias,dely%)
3440   togg%(tp%)=FALSE:NN%=0:op%(1)=TRUE
3450   VDU5:MOVE 100,750:PRINT"*":VDU 4
3460   YY%=INT(TT*GF2%)
3465   IF val%=76 THEN XX%=800:arr%=240 ELSE XX%=580:arr%=241
3470   VDU5:MOVE XX%,YY%:PRINT CHR$(arr%):VDU4
3490 ENDPROC
3500 DEF PROCthresh:LOCAL roll,poke%:poke%=16
3510     roll=DEG(VA):IF ABS(roll)>1.6 THEN PROCpulse(poke%,SGN(roll))
3590 ENDPROC
3600 DEF PROCpulse(val,drn%)
3610   IF drn%=-1 THEN NN%=76 ELSE IF drn%=1 THEN NN%=82
3620   amp=FNamp(val+48):Tm=100
3690 ENDPROC
3850 DEF FNinc(Nbias,dely%):=(Nbias)/(dely%/2)
4000 DEF FNforce(angle):LOCAL LL,sgn,val:sgn=SGN(angle):val=ABS(angle)
4010  IF angle=0 THEN LL=0 ELSE LL=(val*Ffac)*sgn
4020 =LL
4100 DEF FNhozdot(force):LOCAL I
4110   I=(HIo*COS(VA))+(FIo*SIN(ABS(VA))):=force*WB1/I
4200 DEF FNdl(vel,accl):=(vel*Ti)+(accl*T2)
4300 DEF FNvel(vel,accl):=vel+(accl*Ti)
4400 DEF FNweight(VA):=WT*SIN(VA)*WIg
```

```
4500 DEF FNpetal(VA,FF):=FF*COS(ABS(VA))*FIg*-1
4600 DEF FNfwdot(SF)
4610  =((SF*bar))/FwIo
4700 DEF FNturni(force):=ATN((force*Ti)/MOM)
4800 DEF FNhcirc(angle):=angle*WB1
4900 DEF FNturnw(angle):=angle/Ti
4999 REM*************************************
6000 DEF PROCrun:LOCAL HwDOT,VwDOT,Sdot,RAi,HAi,VAi,SAi,Roti,VSDOT,SSdot
6020   F1=FNforce(DEG(L1)):F2=FNforce(DEG(L2)):FF=F1+F2
6030   HwDOT=FNhozdot(F1-F2):VwDOT=FNweight(VA)+FNpetal(VA,FF)
6035   Sdot=FNfwdot(SF)
6060   RAi=FNturni(FF):HAi=FNdl(Hw,HwDOT):VAi=FNdl(Vw,VwDOT):SAi=FNdl(Sw,Sdot)
6070   RA=RA+RAi:HA=HA+HAi:VA=VA+VAi:SA=SA+SAi
6080   Roti=(FNhcirc(HAi)/Si):L2=HA-(RA-Roti):L1=SA-(RA+Roti)
6090   Rw=FNturnw(RAi):Hw=FNvel(Hw,HwDOT):Vw=FNvel(Vw,VwDOT):Sw=FNvel(Sw,Sdot)
6100   TT=TT+Ti:REMTrl=FNtrail(RSA,VA)
6120   B4=B3:B3=B2:B2=B1:B1=VwDOT
6125   C6=C5:C5=C4:C4=C3:C3=C2:C2=C1:C1=Sdot
6130   VSDOT=(B1+B2+B3+B4)/4:PROCcontrol(VwDOT,Vw)
6135   SSdot=(C1+C2+C3+C4)/4
6140   RSA=SA-HA:SPY1=VwDOT:SPY2=VSDOT:SPY3=Sdot
6190   PROCdraft(DEG(VA),DEG(RSA),DEG(VSDOT),DEG(SSdot),DEG(Vw),TT)
6200 ENDPROC
6999 REM******************
7500 DEF PROCdraft(D(1),D(2),D(3),D(4),D(5),TT):LOCAL XX%,YY%:YY%=INT(TT*GF2%)
7510   FOR M=1 TO 5
7515   XX%=(CH(M,1)-(D(M)*F(M)))
7520   MOVE CH(M,2),CH(M,3):DRAW XX%,YY%:CH(M,2)=XX%:CH(M,3)=YY%:NEXT
7530   IF INT(TT)>TS THEN VDU 5:MOVE 0,YY%:PRINT INT(TT):VDU 4:TS=TT
7590 ENDPROC
7999 REM************************
8500 DEF PROCtitle
8520 PRINT;TAB(3);DT$;"Speed= "FNmph(VV%)" mph .S1 "S1" S2 "S2
8590 ENDPROC
8600 DEF FNmph(fps):=(fps/88)*60
8700 DEF PROCshowit(val)
8710   VDU5:MOVE 100,800:VDU 9,9,127,127:PRINT val:VDU4
8720 ENDPROC
```

```
   10 REM****************************************
   20 REM  FINDING MOMENTS OF INERTIA
   30 REM****************************************
   50 NN=26:N2=5:DIM NM$(NN):DIM NB(NN):DIM DM$(NN):DIM DT$(N2):DIM DT(N2)
   90 @%=&20309:satis=0:DT$=""
  100 WB=0:Wrad1=0:Wrad2=0:bikea=0:bikeb=0:rake=0:trl=0:Bmas=0:FWmas=0
  110 Bgrav1=0:Bgrav3=0:Bgrav2=0:Bgrav4=0:Mht=0:Mrad=0:Mmas=0:Mgrav1=0
  120 Mgrav3=0:Mgrav2=0:Mgrav4=0:mass=0:WT=0:HG=0:LG=0:bar=0:barmas=0
  136 Fwfac=1.4144:REM Convert to solid disc equivalent
  150 WIo=0:REM Vert moments about Ground contact point
  160 FIo=0:REM Vert moments about C of G
  170 HIo=0:REM Hoz moments about C of G
  180 LIo=0:REM Hoz moments about rear wheel
  190 g=32:REM Gravity
  199 REM*********************************************
  200 REM Main
  210 CLS
  220 PROCnames:PROCnumbs_in:PROCallocate
  600 PROCmoments:DT(5)=FNfwheel(Wrad1,Fwfac,FWmas,bar,barmas):REM FwIo
  800 PROCfinal:PROCshow:IF satis THEN PROCfile
  900 MODE 3:END
  999 REM*********************************************:::
 1000 DEF PROCmoments
 1010 LOCAL Mmom,Bmom
 1040 REM Vert ---------------------
 1050 Mmom=Mmas*(((Mrad^2)/4)+((Mht^2)/12)):Bmom=Bmas*(bikea^2)/12
 1055 REM about road contact pt.
 1070 DT(1)=FNmoms(Mgrav1,Bgrav1):REM WIo
 1080 REM Vert about CG
 1090 DT(2)=FNmoms(Mgrav2,Bgrav2):REM FIo
 1100 REM Hoz ---------------------
 1110 Mmom=Mmas*(Mrad^2)/2:Bmom=Bmas*(bikeb^2)/12
 1115 REM about CG
 1120 DT(3)=FNmoms(Mgrav4,Bgrav4):REM HIo
 1125 REM about rear wheel
 1130 DT(4)=FNmoms(Mgrav3,Bgrav3):REM LIo
 1140 ENDPROC
 1150 DEF FNmoms(man,bike):=(Mmom+(Mmas*(man^2)))+(Bmom+(Bmas*(bike^2)))
 1200 DEF FNfwheel(rad,fac,Wmas,bar,barmas):LOCAL Qrad,Wmom,Bmom
 1210     Bmom=barmas*(bar^2)/12
 1220     Qrad=rad*fac:Wmom=(Wmas*(Qrad^2)/4)
 1230     =Wmom+Bmom
 2000 DEF PROCnames
 2010 DATA "Wheel Base","Front Wheel Rad","Rear Wheel Rad","Effect. Ht"
 2020 DATA "Effect. Lgth","rake","trl","Bike mass","FWmass","Bgrav1","Bgrav3","B
grav2","Bgrav4"
 2030 DATA "Man Ht","Man Rad","Man Mass","Mgrav1","Mgrav3","Mgrav2","Mgrav4"
 2040 DATA "Comb Mass","Comb WT","Comb Grav Ht","Comb Grav Lgth","Bar eff.lngth"
,"Bar mass"
 2050 DATA "ft","ft","ft","ft","ft","degs","ft","slugs","slugs","ft","ft","ft"
```

```
2060 DATA "ft","ft","ft","slugs","ft","ft","ft","ft"
2070 DATA "slugs","lbs","ft","ft","ft","slugs"
2090 DATA "Vert about road. WIo","Vert about CG. FIo","Hoz. about CG. HIo"
2095 DATA "Hoz. about rear wheel. LIo","Front wheel Assy. FwIo"
2100 PROCnames_in:PROCdims_in:PROCans_in
2150 ENDPROC
3000 DEF PROCfinal:LOCAL M
3010   PRINT TAB(0,5):FOR M=1 TO N2:PRINT TAB(40); DT$(M);TAB(70);DT(M):NEXT
3090 ENDPROC
3500 DEF PROCfile:LOCAL M
3510   F2=OPENOUT "NEWBIK":PRINT£F2,DT$
3520                 FOR M=1 TO NN:PRINT£F2,NB(M):NEXT M
3530                 FOR M=1 TO N2:PRINT£F2,DT(M):NEXT M:CLOSE£F2
3590 ENDPROC
6100 DEF PROCnames_in:FOR M=1 TO NN:READ NM$(M):NEXT M:ENDPROC
6200 DEF PROCdims_in:FOR M=1 TO NN:READ DM$(M):NEXT M:ENDPROC
6300 DEF PROCans_in:FOR M=1 TO N2:READ DT$(M):NEXT M:ENDPROC
6500 DEF PROCshow
6510   PRINT TAB(43,1);"Moments of Inertia for "DT$
6520   PRINT TAB(43,2);"----------------------------":PRINT TAB( 0,0)
6530   FOR M=1 TO NN:PRINT NM$(M);TAB(17);NB(M);TAB(27);DM$(M):NEXT
6540   PRINT TAB(40,15);"Is this OK to file? y/n  ";:Y$=GET$
6560   IF Y$="Y" OR Y$="y" THEN satis=1 ELSE satis=0
6590 ENDPROC
6600 DEF PROCnumbs_in:LOCAL M
6620   F1=OPENIN "TRANS":INPUT£F1,DT$
6630                FOR M=1 TO NN:INPUT£F1,NB(M):NEXT M:CLOSE£F1
6690 ENDPROC
7000 DEF PROCallocate: WB=NB(1):Wrad1=NB(2):Wrad2=NB(3)
7010   bikea=NB(4):bikeb=NB(5):rake=RAD(NB(6)):trl=NB(7):Bmas=NB(8)
7020   FWmas=NB(9):Bgrav1=NB(10):Bgrav3=NB(11):Bgrav2=NB(12):Bgrav4=NB(13)
7030   Mht=NB(14):Mrad=NB(15):Mmas=NB(16):Mgrav1=NB(17):Mgrav3=NB(18)
7040   Mgrav2=NB(19):Mgrav4=NB(20):mass=NB(21):WT=NB(22):HG=NB(23):LG=NB(24)
7050   bar=NB(25):barmas=NB(26)
7090 ENDPROC
```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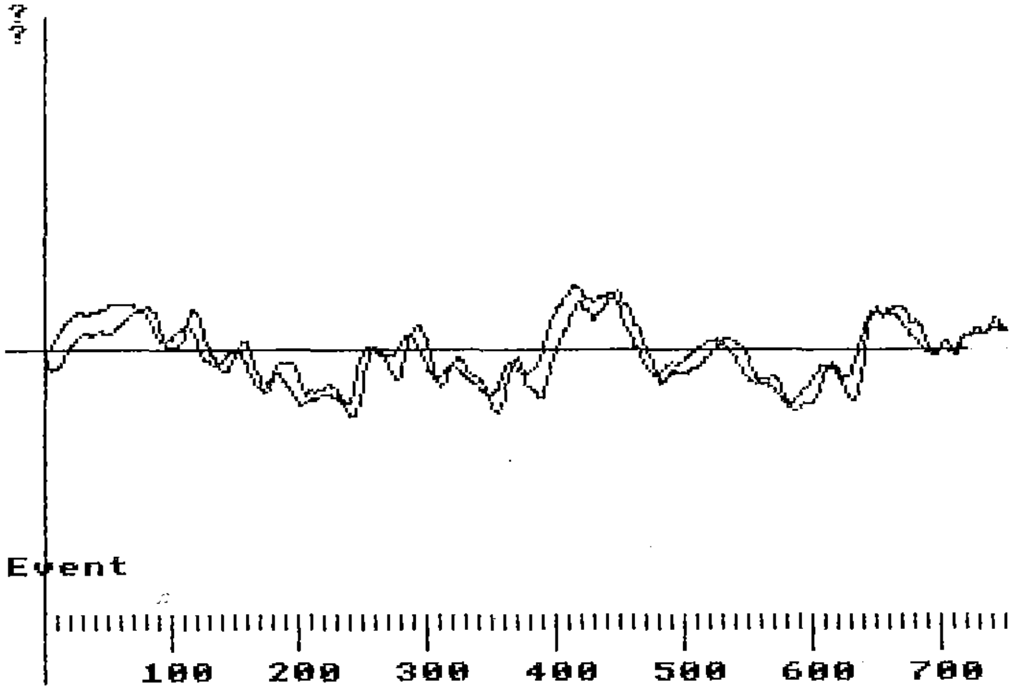
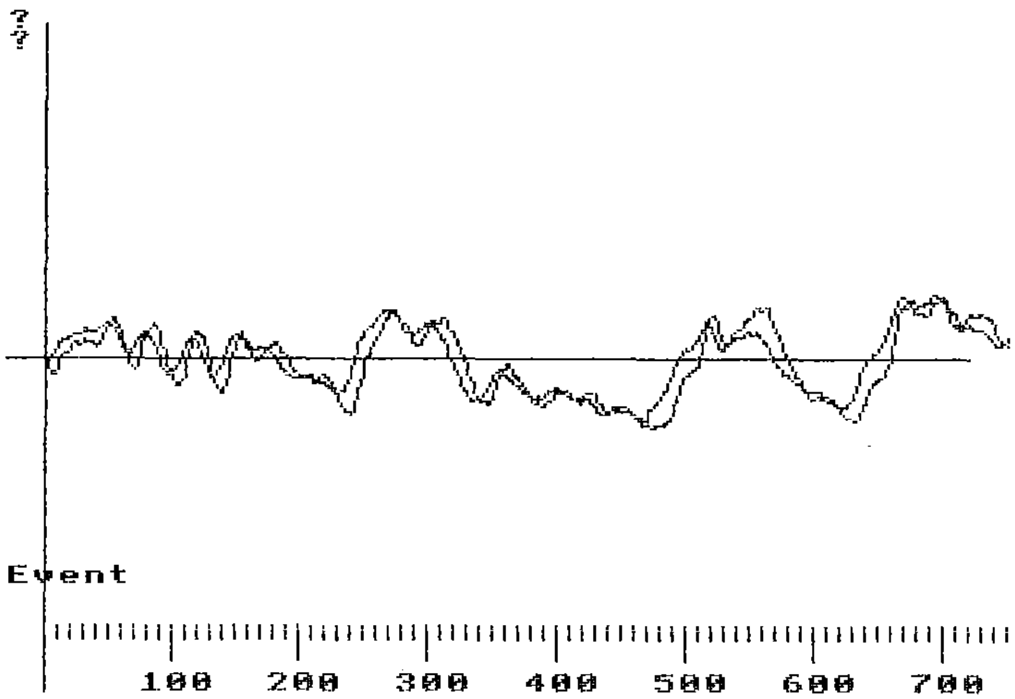
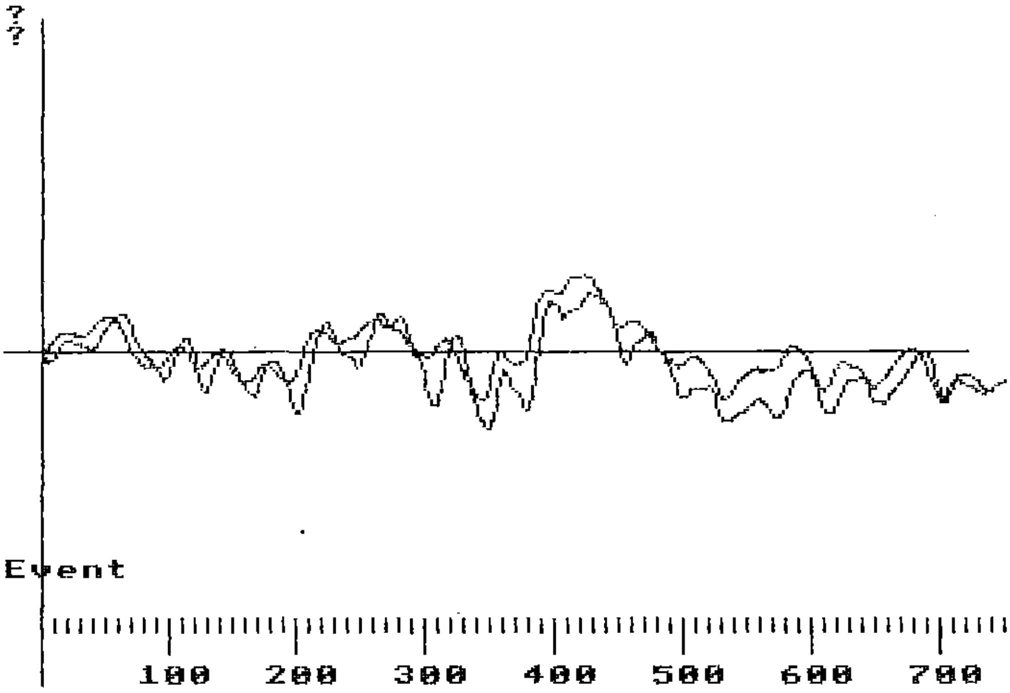


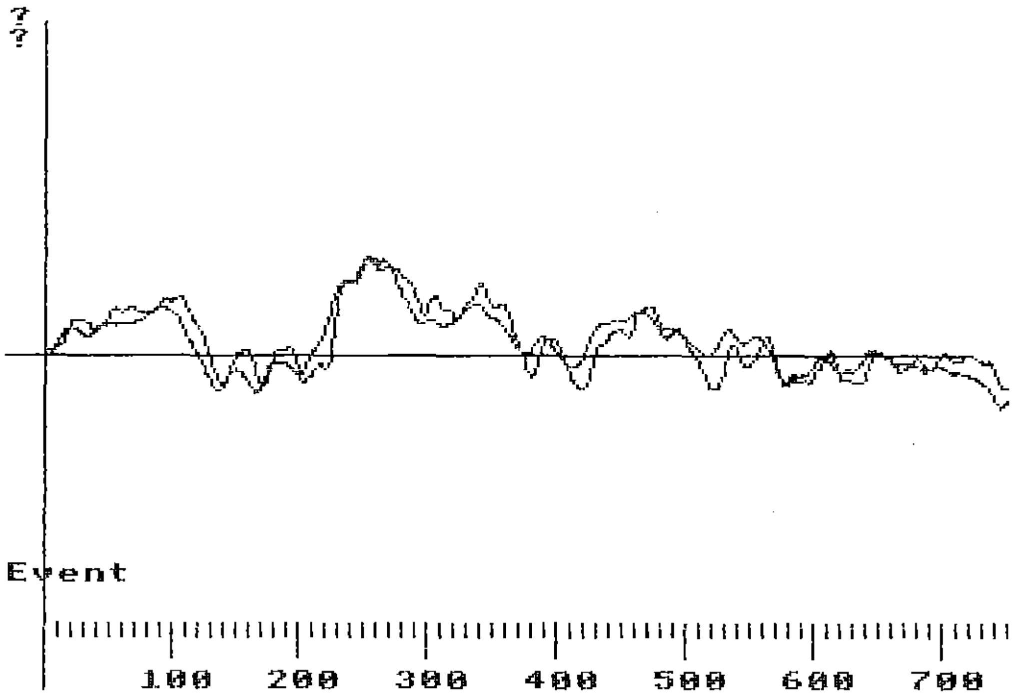
Run 25. Roll and Bar angles



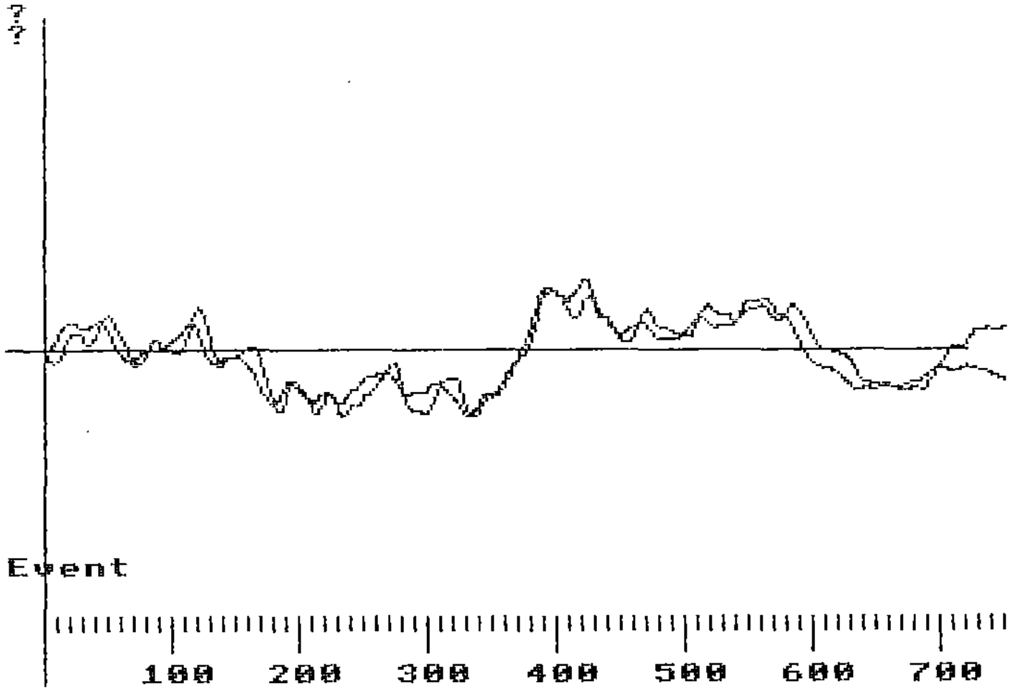
Run 26. Roll and Bar angles



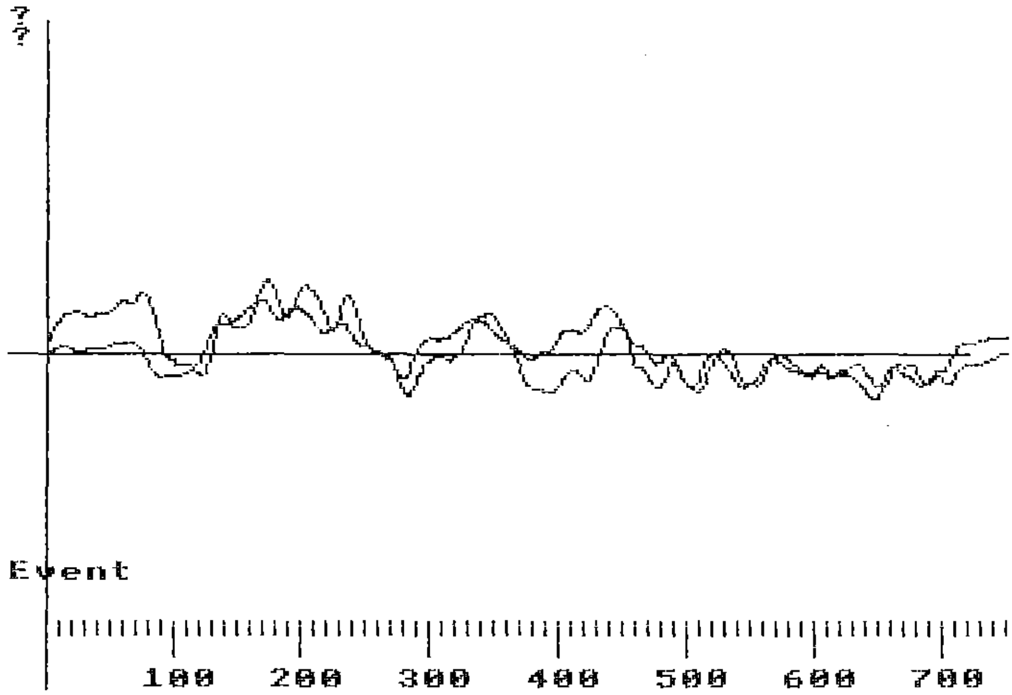
Run 27. Roll and Bar angles



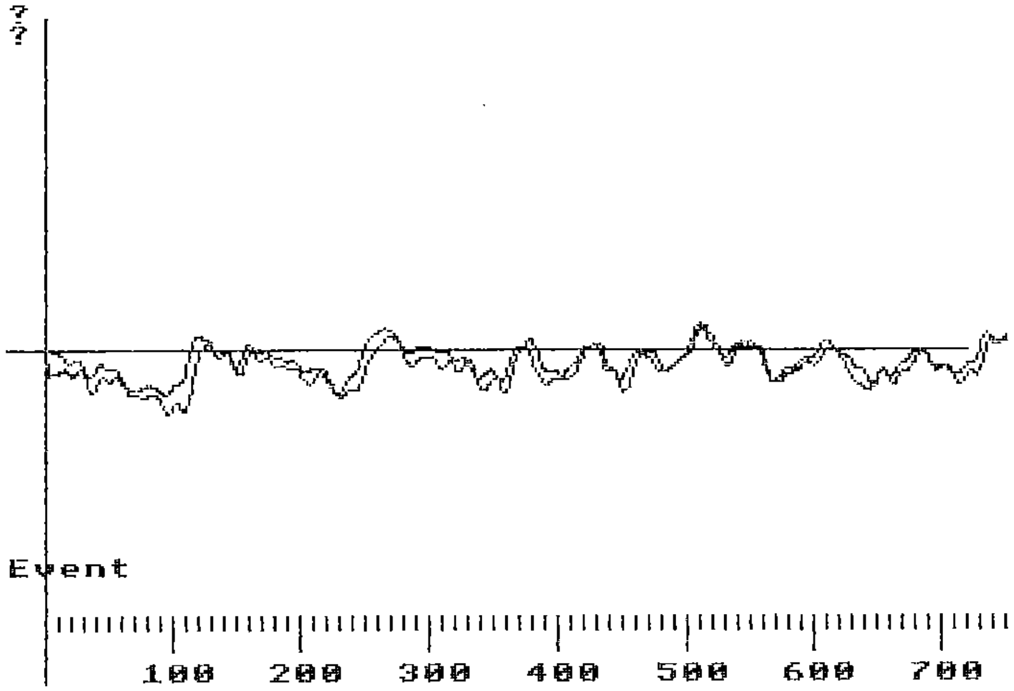
Run 28. Roll and Bar angles



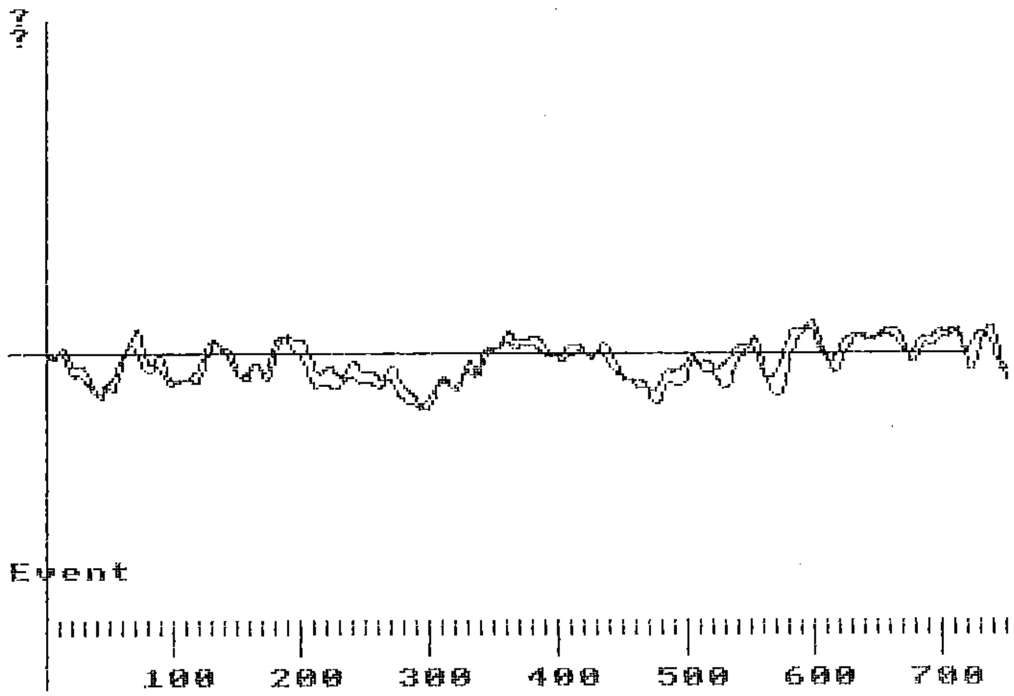
Run 29. Roll and Bar angles



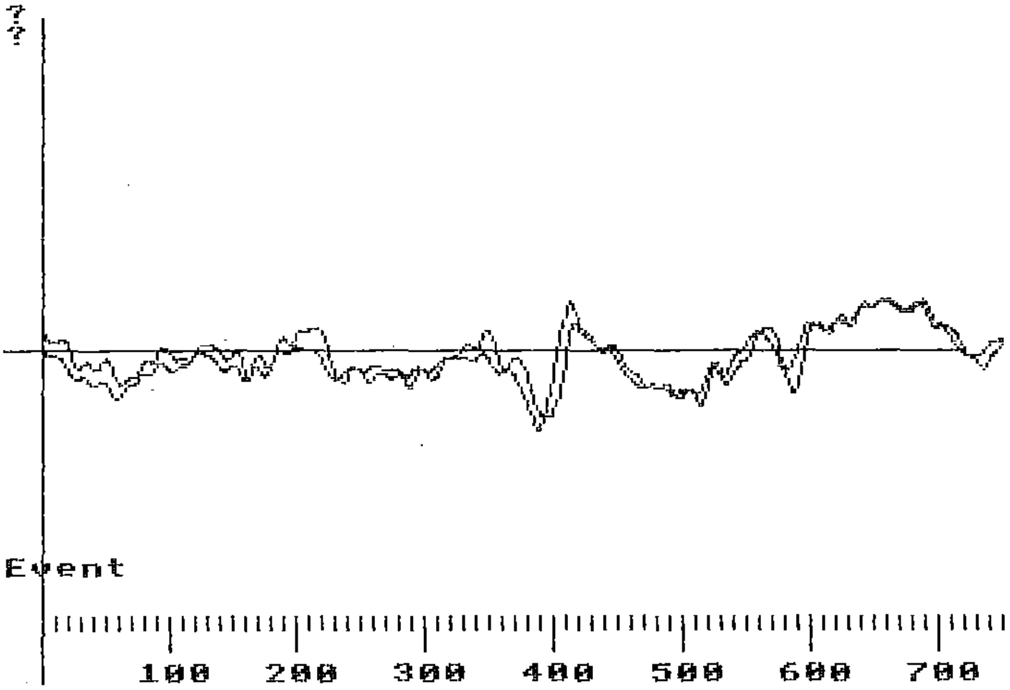
Run 30. Roll and Bar angles



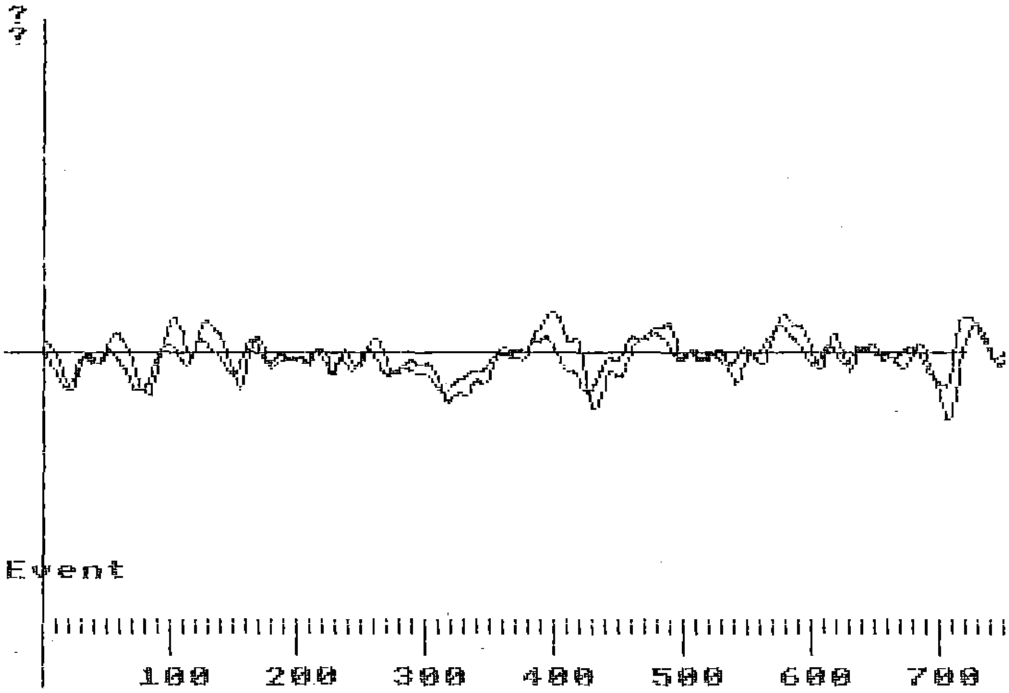
Run 31. Roll and Bar angles



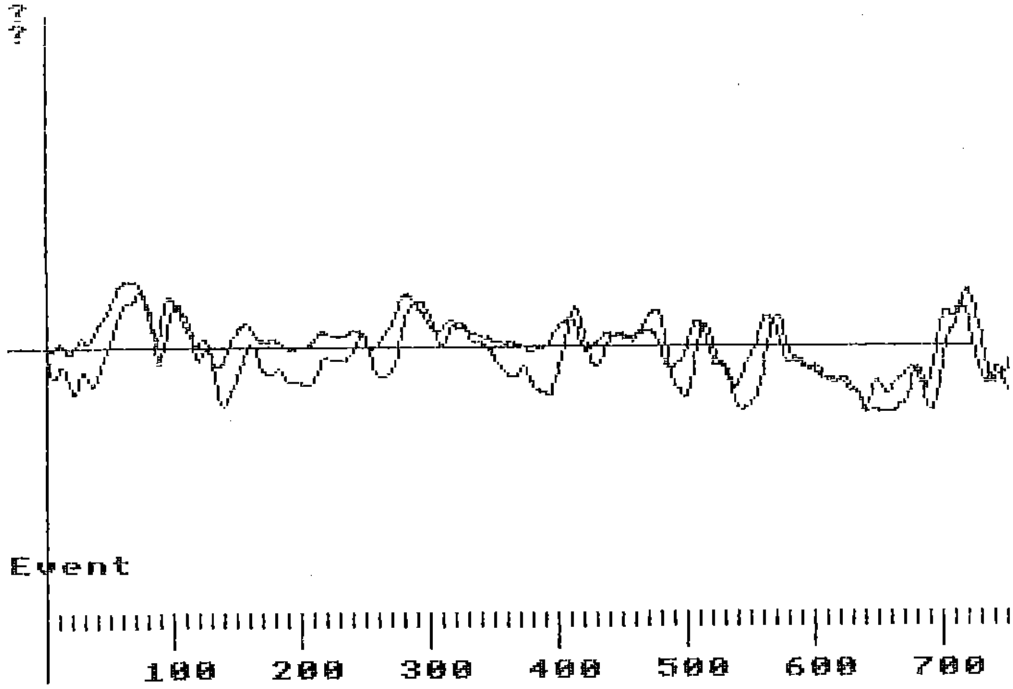
Run 32. Roll and Bar angles



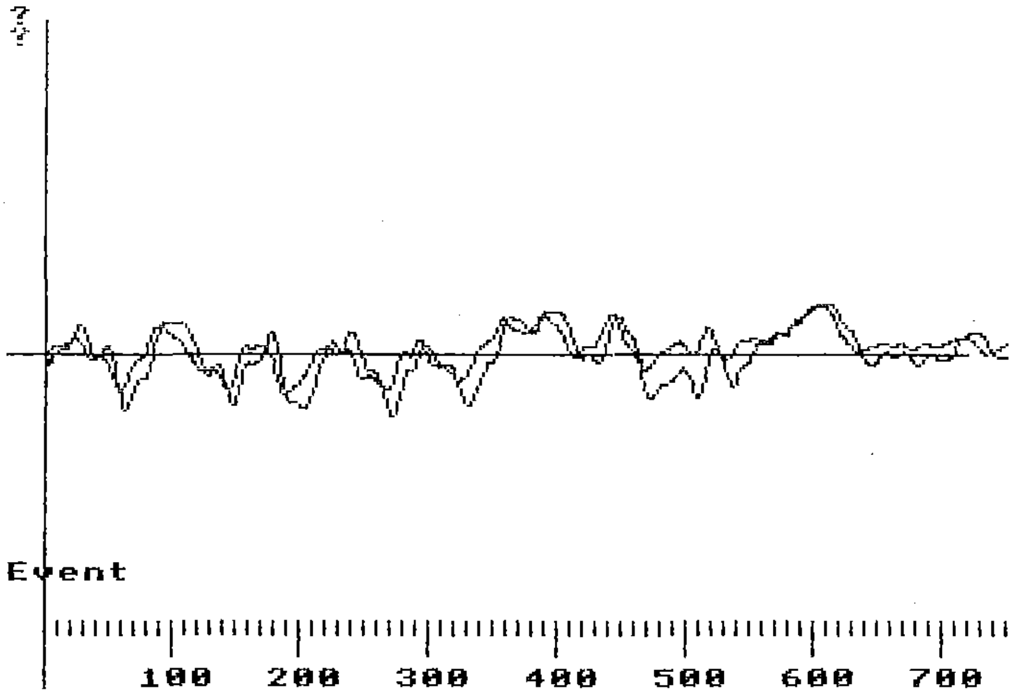
Run 33. Roll and Bar angles



Run 34. Roll and Bar angles

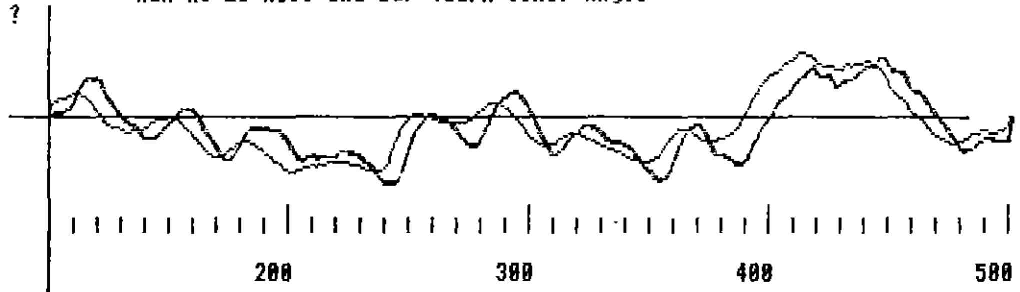


Run 35. Roll and Bar angles

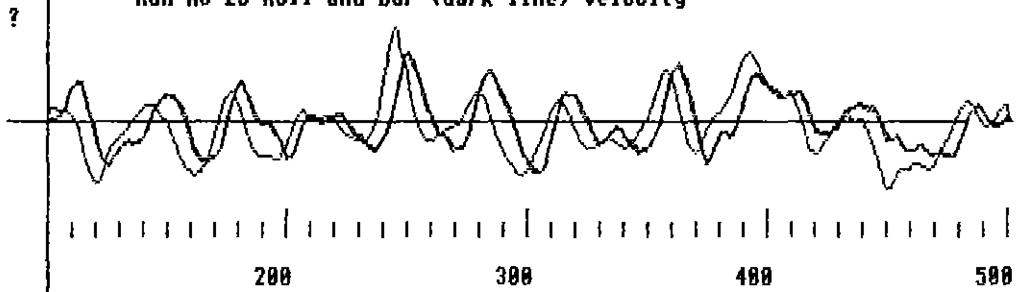


Run 36. Roll and Bar angles

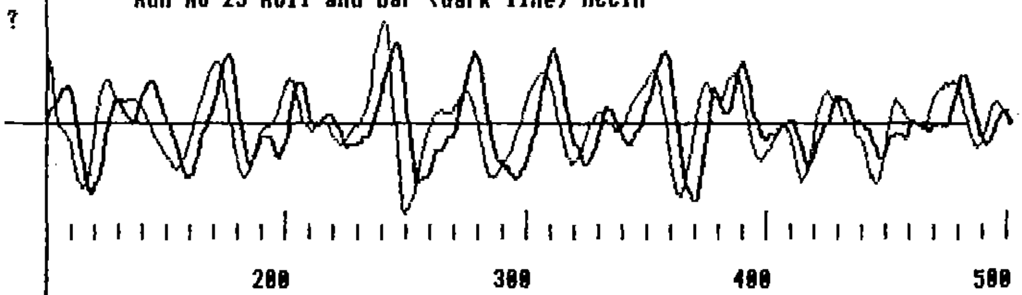
Run No 25 Roll and Bar (dark line) Angle



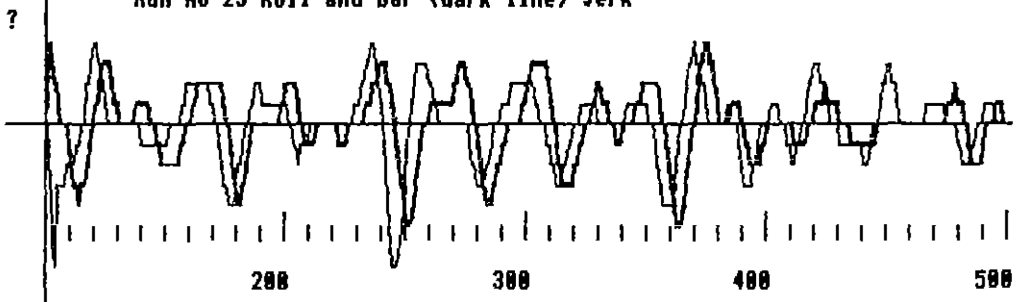
Run No 25 Roll and Bar (dark line) Velocity



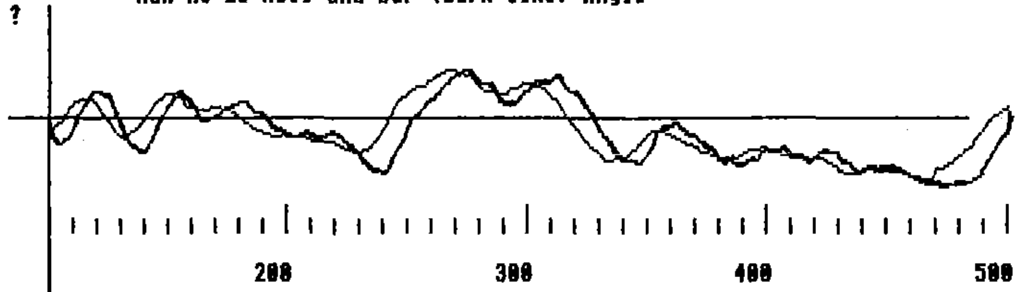
Run No 25 Roll and Bar (dark line) Accln



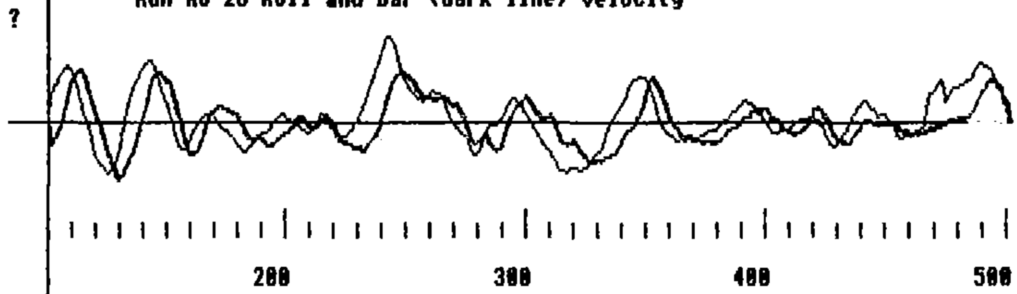
Run No 25 Roll and Bar (dark line) Jerk



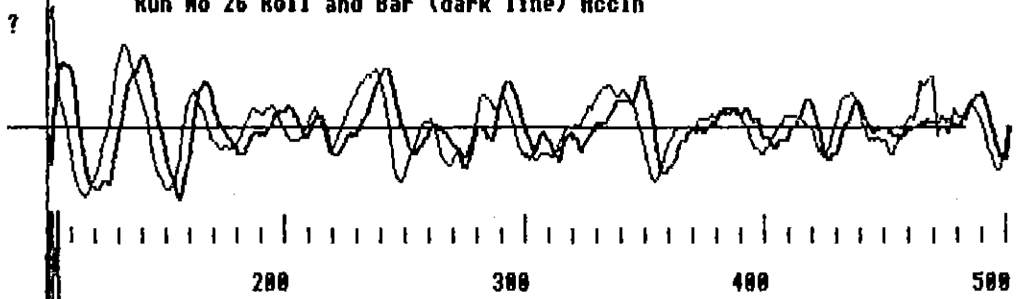
Run No 26 Roll and Bar (dark line) Angle



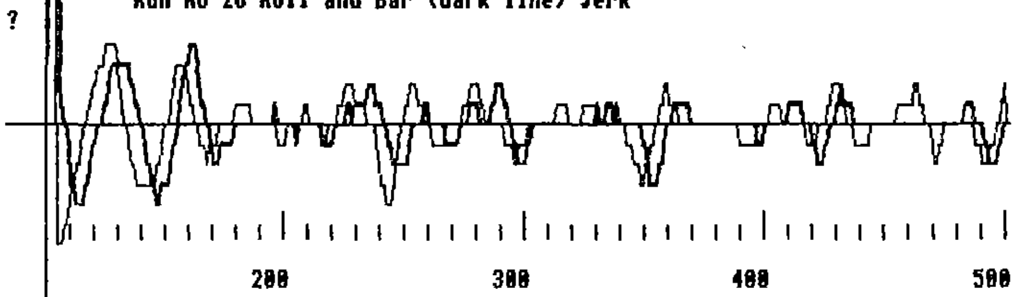
Run No 26 Roll and Bar (dark line) Velocity



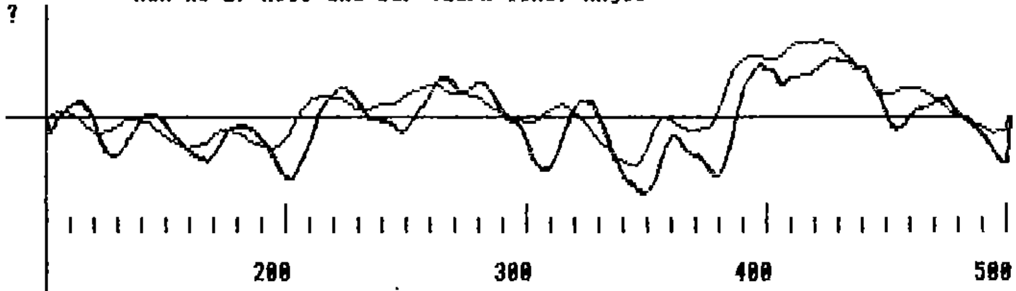
Run No 26 Roll and Bar (dark line) Accln



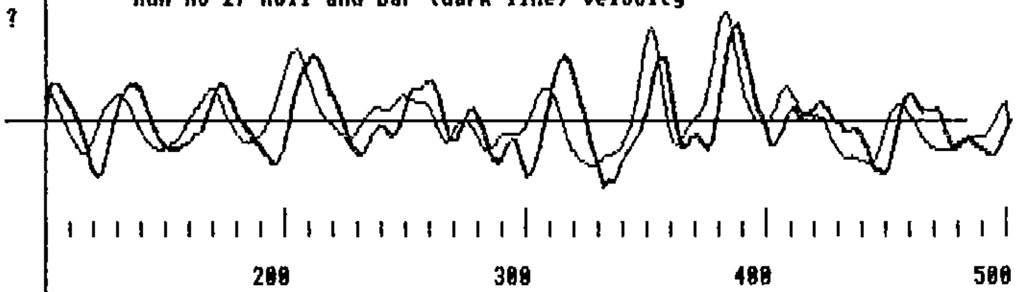
Run No 26 Roll and Bar (dark line) Jerk



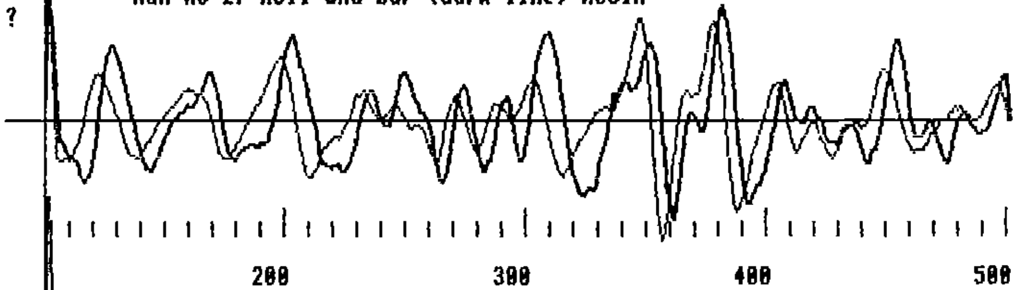
Run No 27 Roll and Bar (dark line) Angle



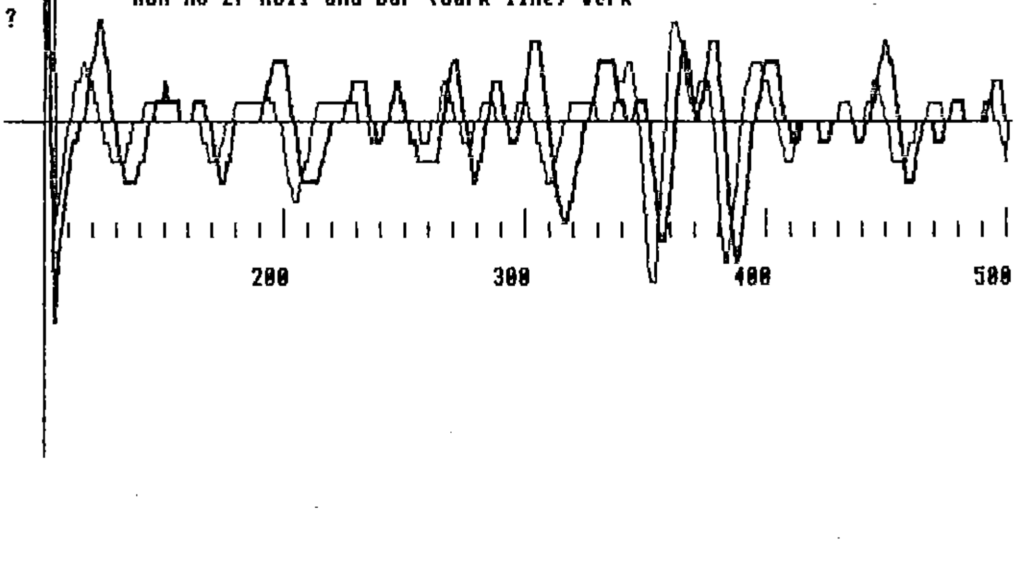
Run No 27 Roll and Bar (dark line) Velocity



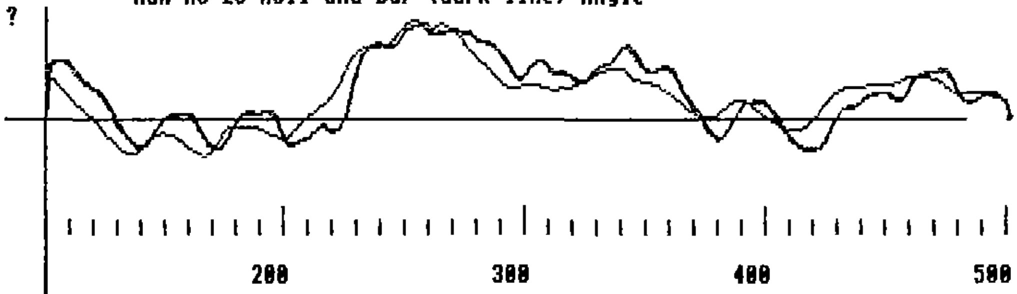
Run No 27 Roll and Bar (dark line) Accln



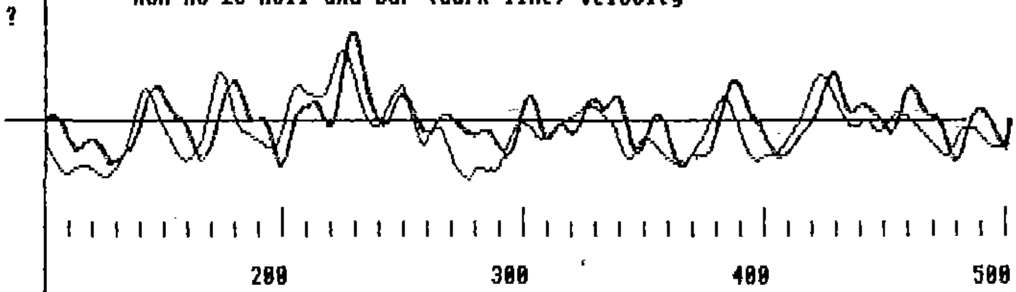
Run No 27 Roll and Bar (dark line) Jerk



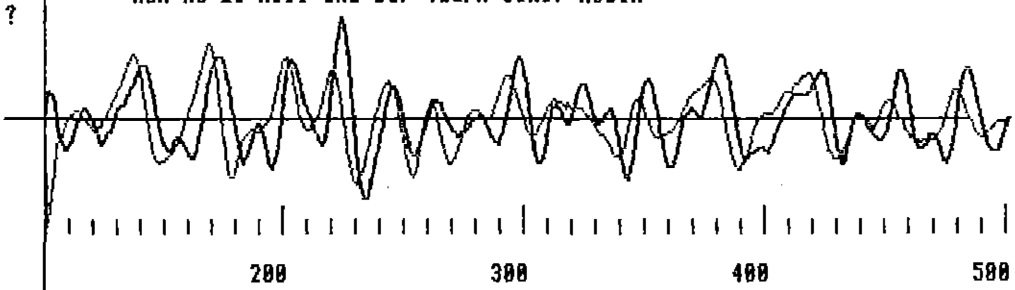
Run No 28 Roll and Bar (dark line) Angle



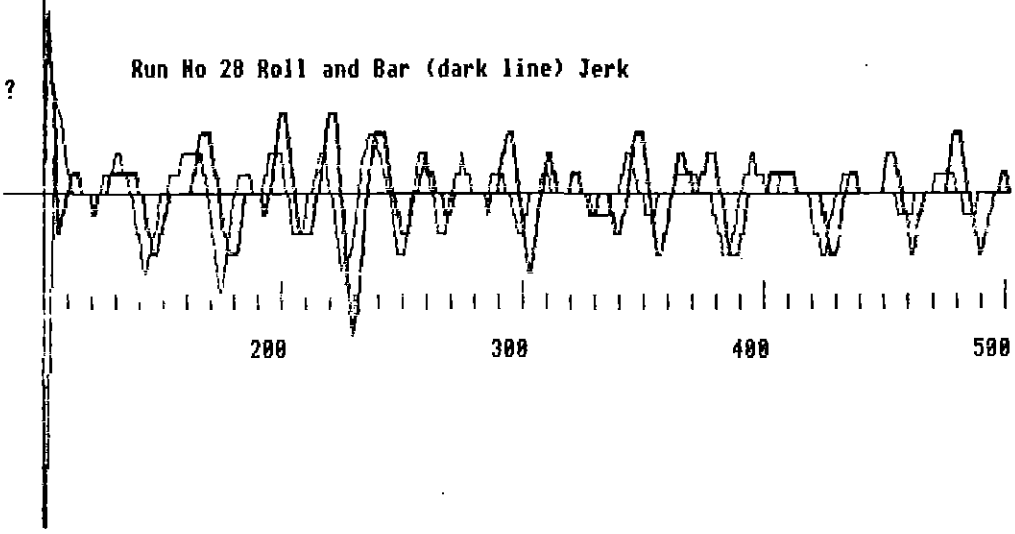
Run No 28 Roll and Bar (dark line) Velocity



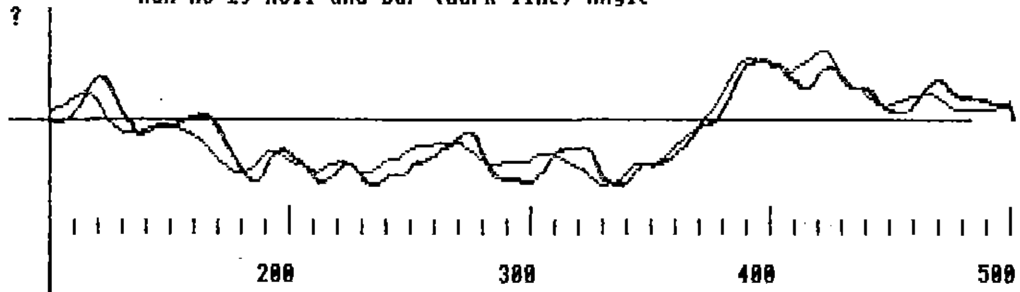
Run No 28 Roll and Bar (dark line) Accln



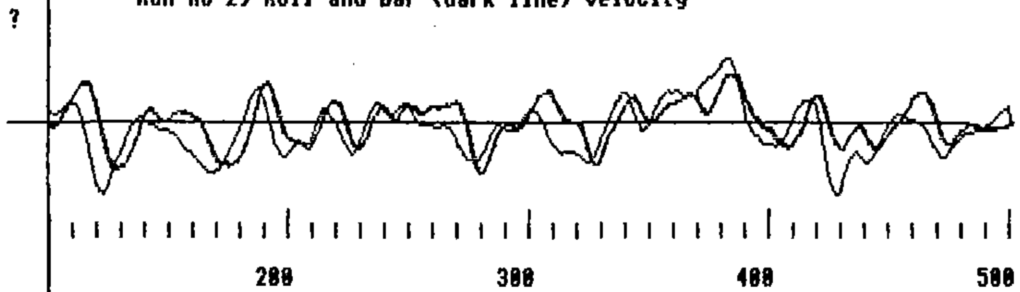
Run No 28 Roll and Bar (dark line) Jerk



Run No 29 Roll and Bar (dark line) Angle



Run No 29 Roll and Bar (dark line) Velocity



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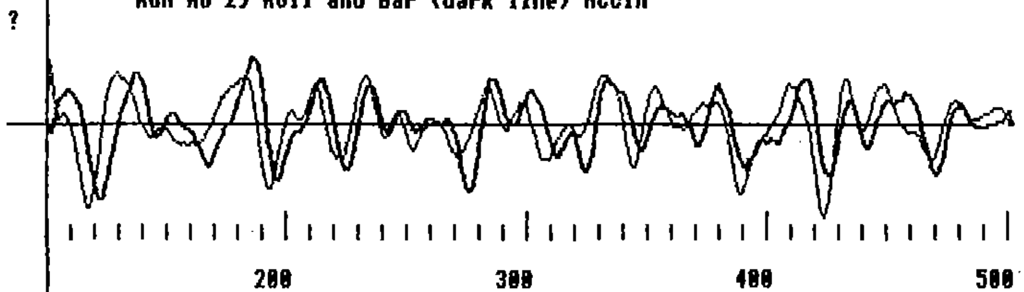
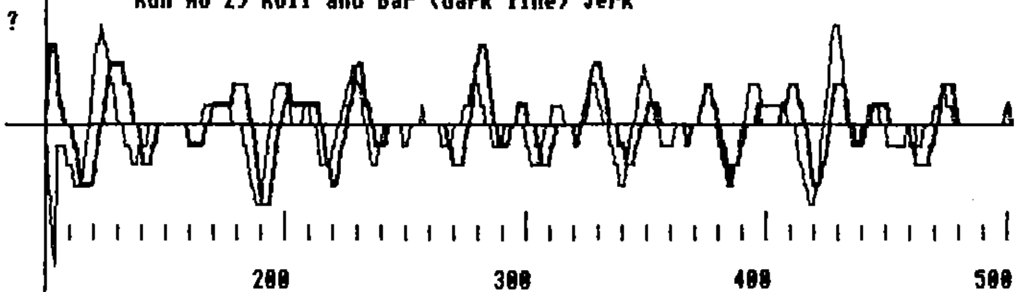
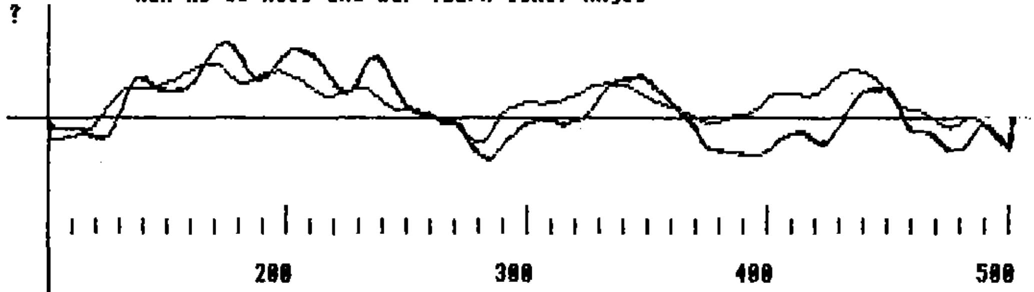


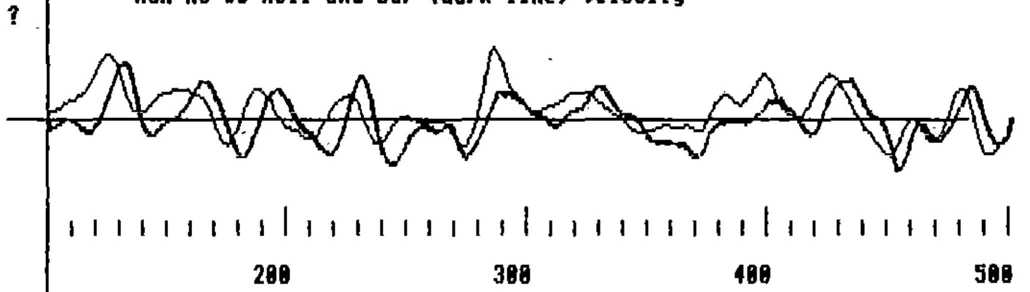
Run No 29 Roll and Bar (dark line) Jerk



Run No 30 Roll and Bar (dark line) Angle



Run No 30 Roll and Bar (dark line) Velocity



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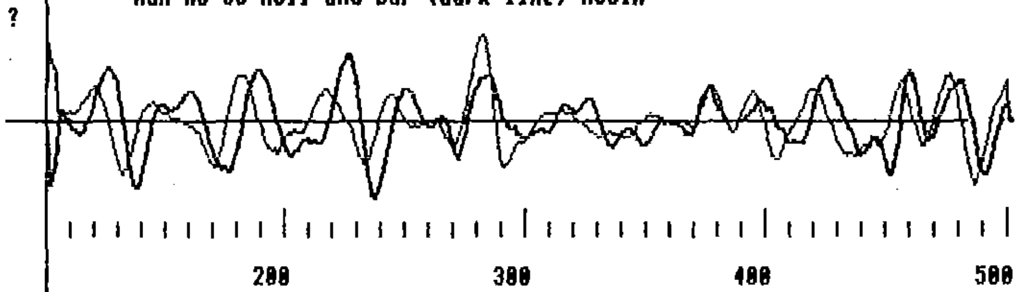

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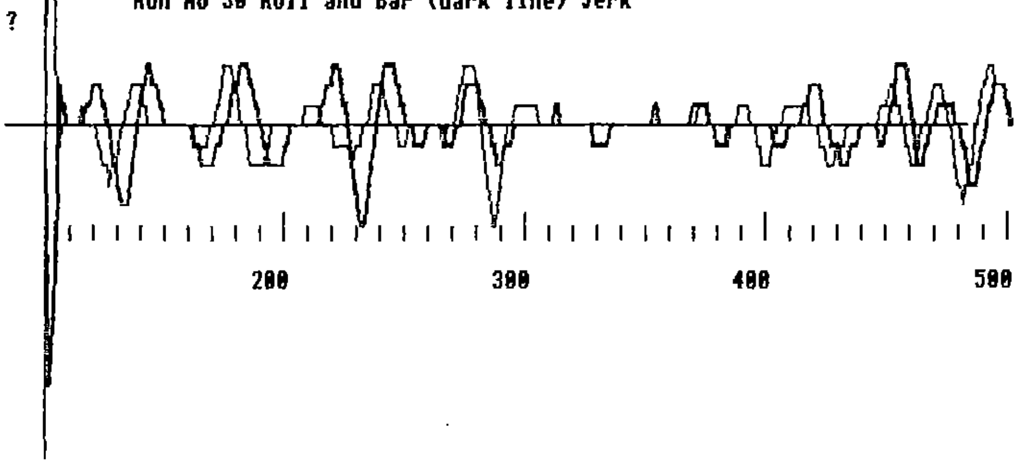
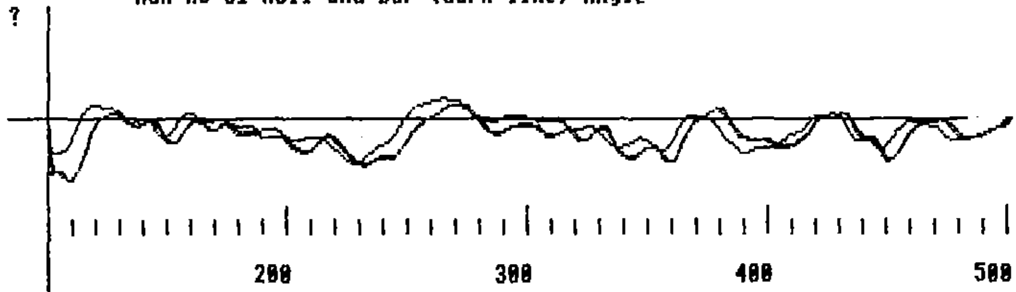
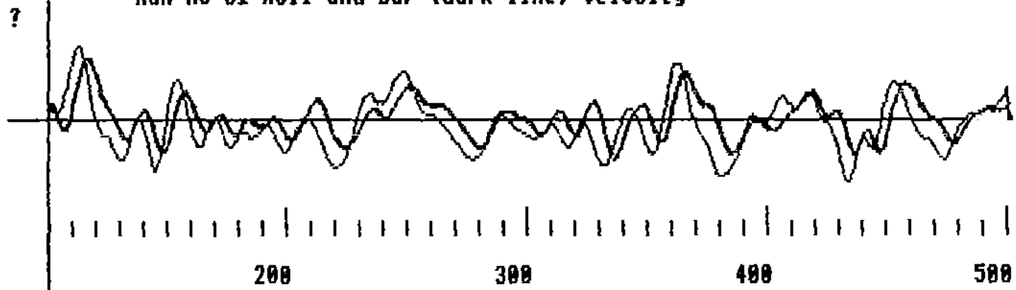


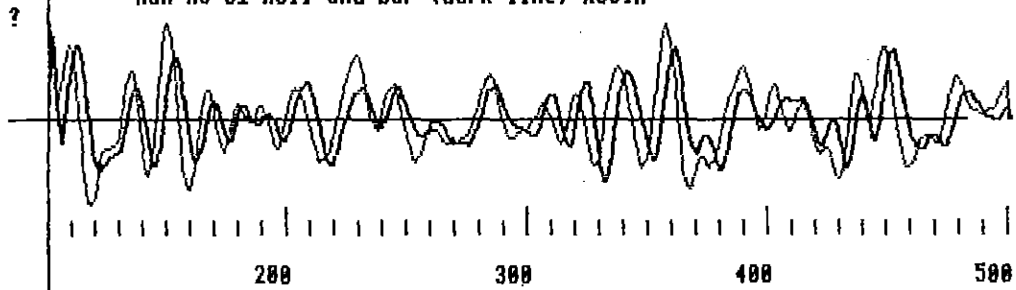
Run No 31 Roll and Bar (dark line) Angle



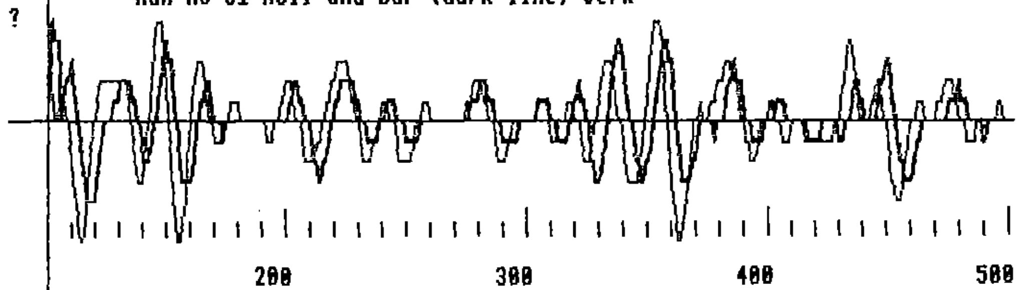
Run No 31 Roll and Bar (dark line) Velocity



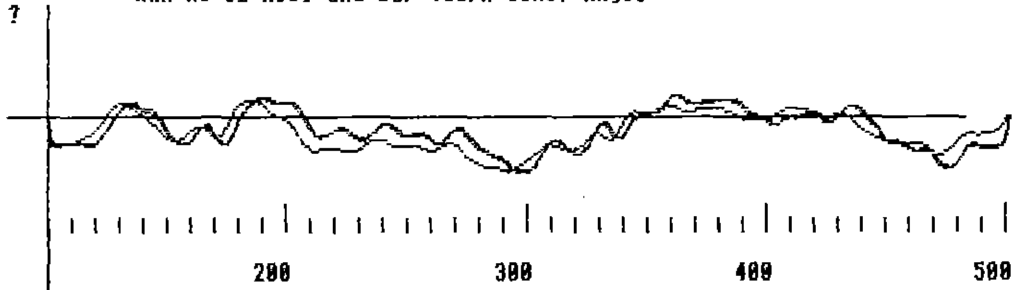
Run No 31 Roll and Bar (dark line) Accln



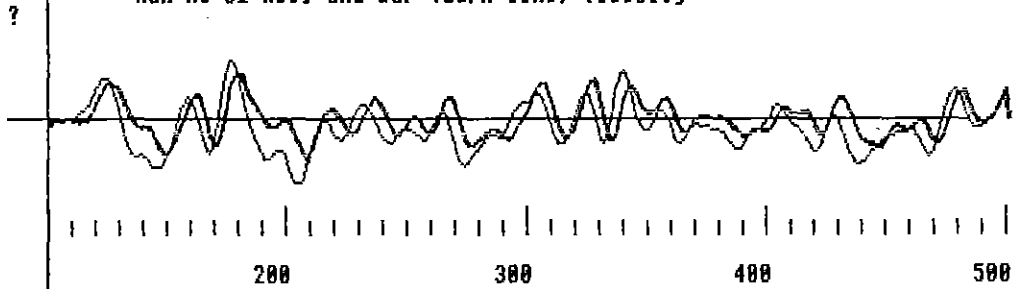
Run No 31 Roll and Bar (dark line) Jerk



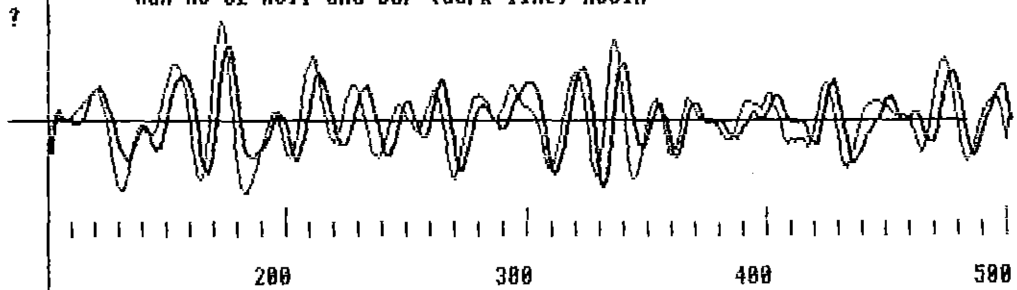
Run No 32 Roll and Bar (dark line) Angle



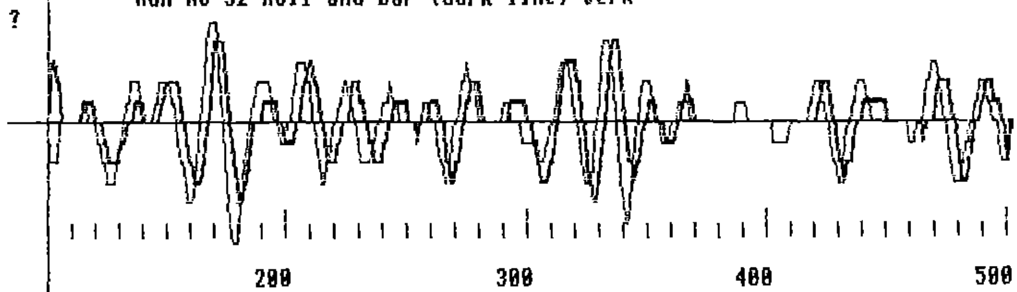
Run No 32 Roll and Bar (dark line) Velocity



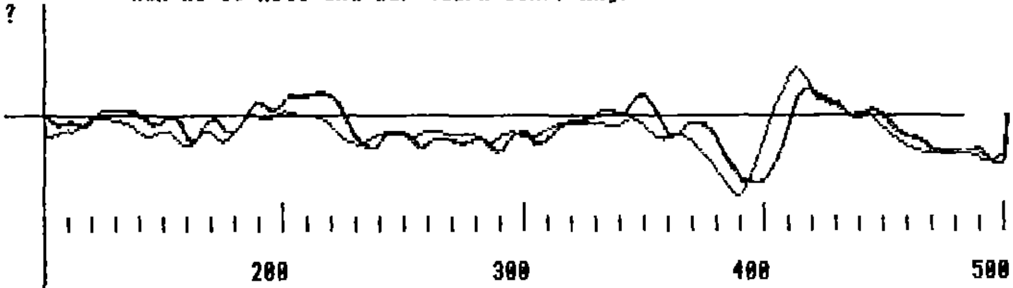
Run No 32 Roll and Bar (dark line) Accln



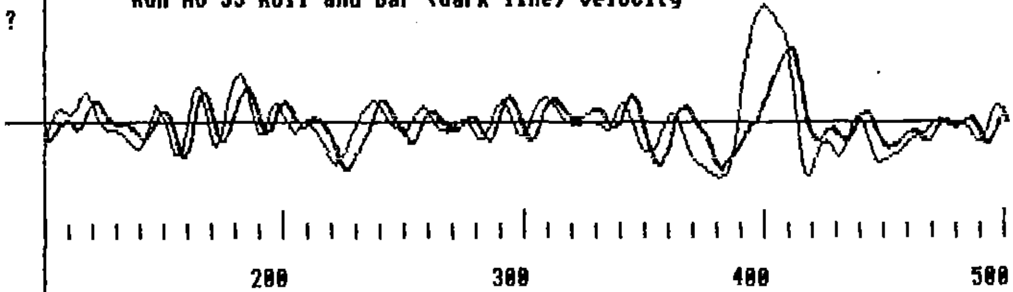
Run No 32 Roll and Bar (dark line) Jerk



Run No 33 Roll and Bar (dark line) Angle



Run No 33 Roll and Bar (dark line) Velocity



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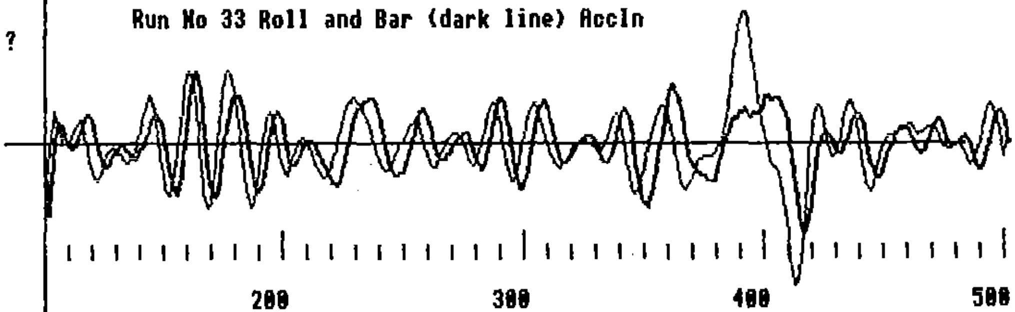
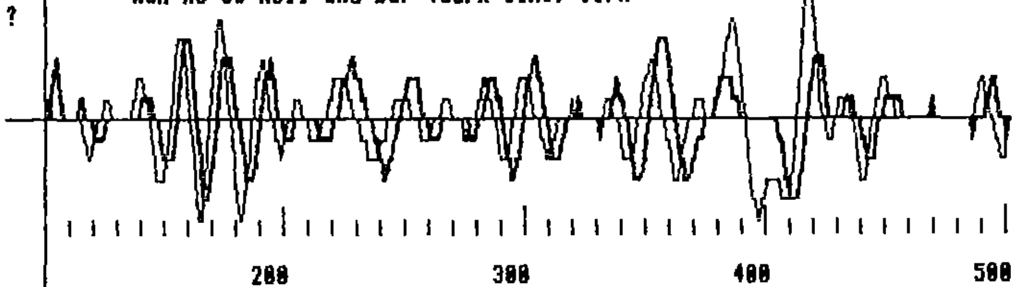
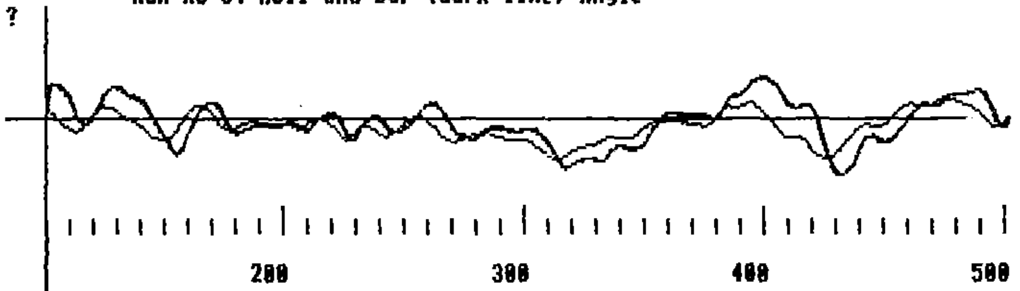


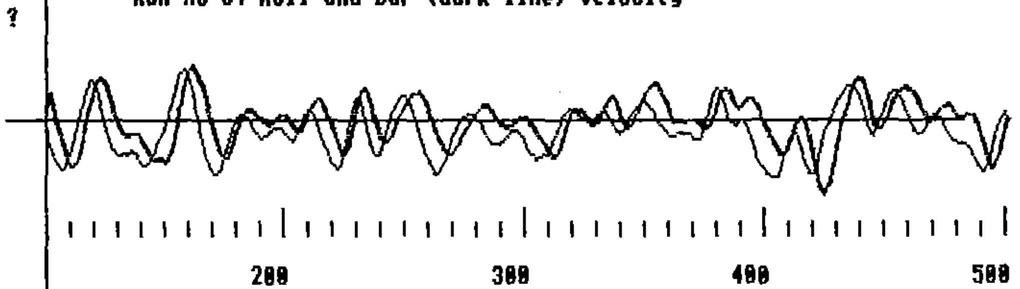
Run No 33 Roll and Bar (dark line) Jerk



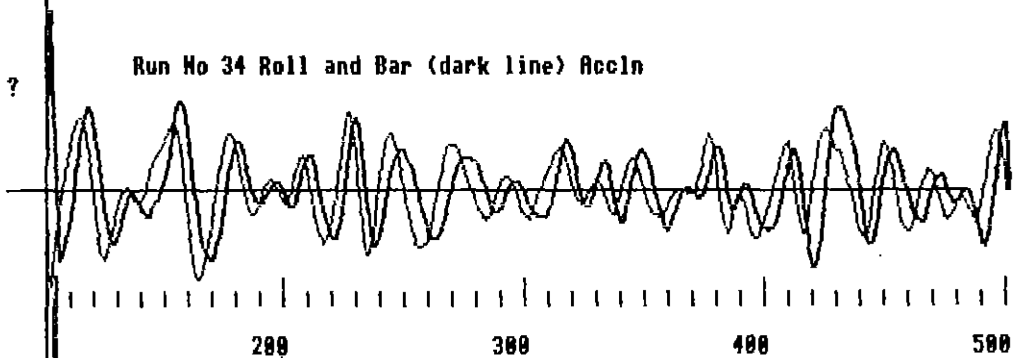
Run No 34 Roll and Bar (dark line) Angle



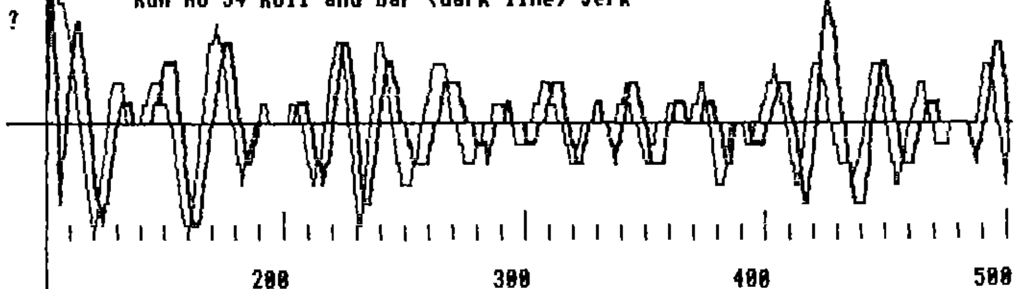
Run No 34 Roll and Bar (dark line) Velocity



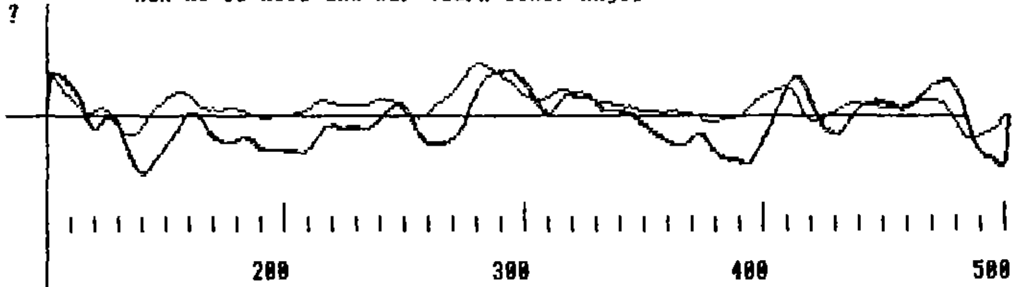
Run No 34 Roll and Bar (dark line) Accln



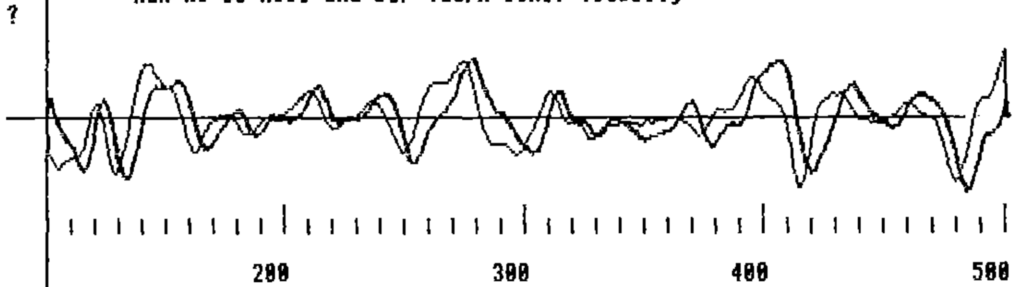
Run No 34 Roll and Bar (dark line) Jerk



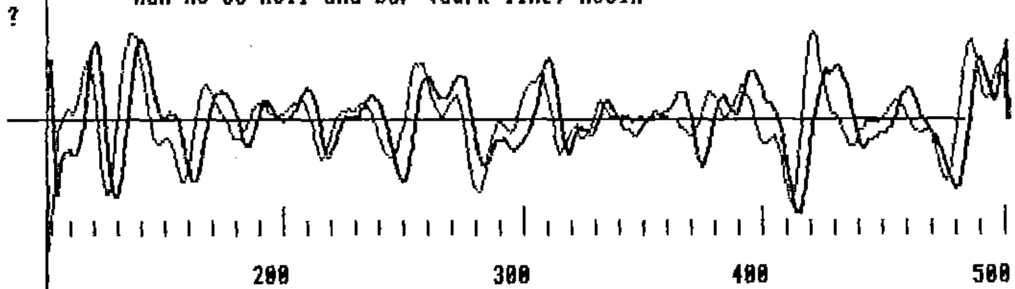
Run No 35 Roll and Bar (dark line) Angle



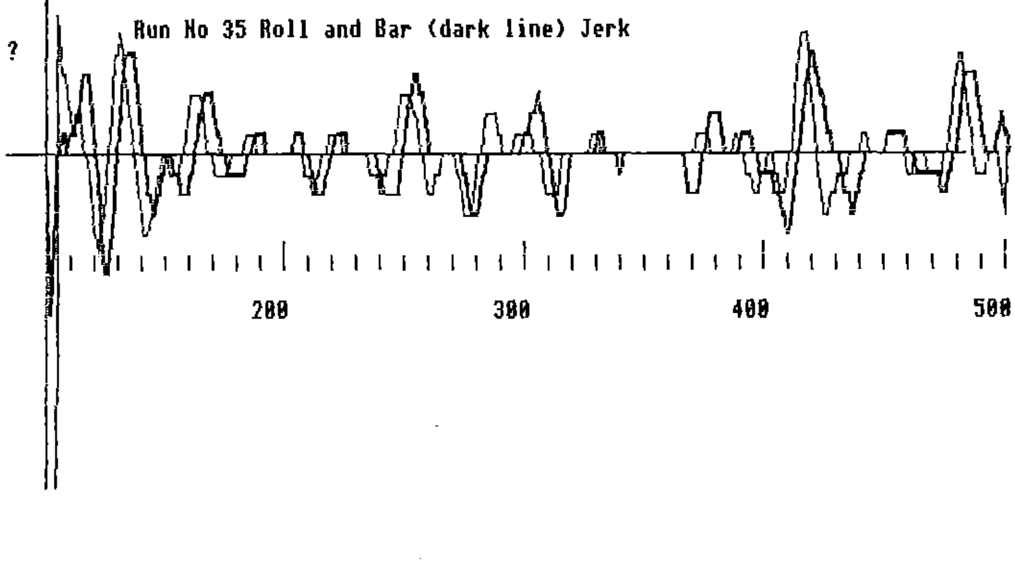
Run No 35 Roll and Bar (dark line) Velocity



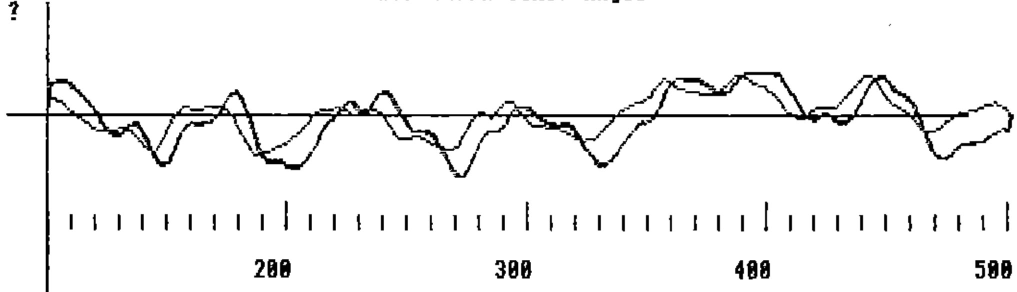
Run No 35 Roll and Bar (dark line) Accln



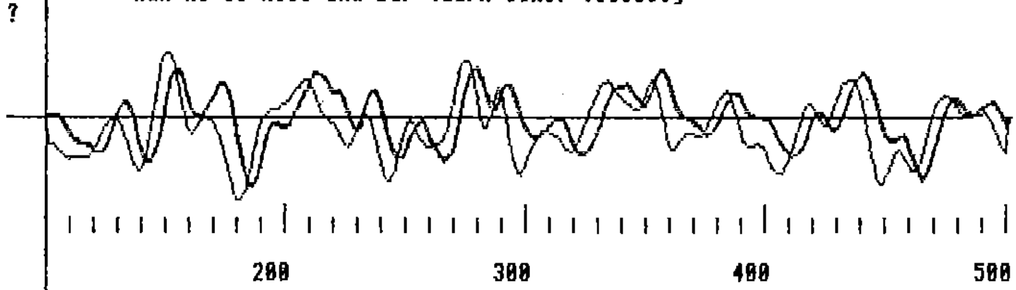
Run No 35 Roll and Bar (dark line) Jerk



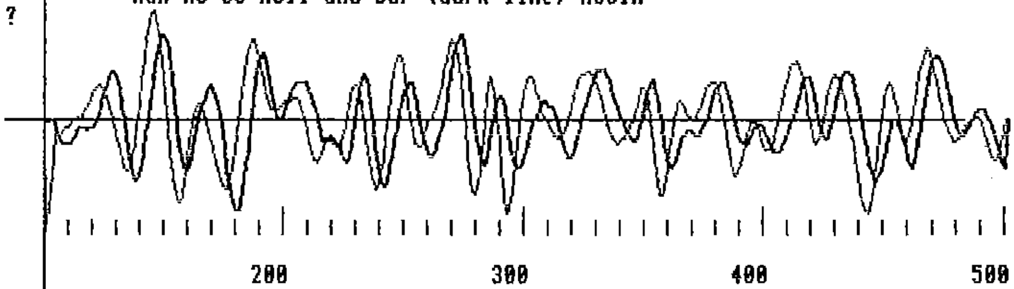
Run No 36 Roll and Bar (dark line) Angle



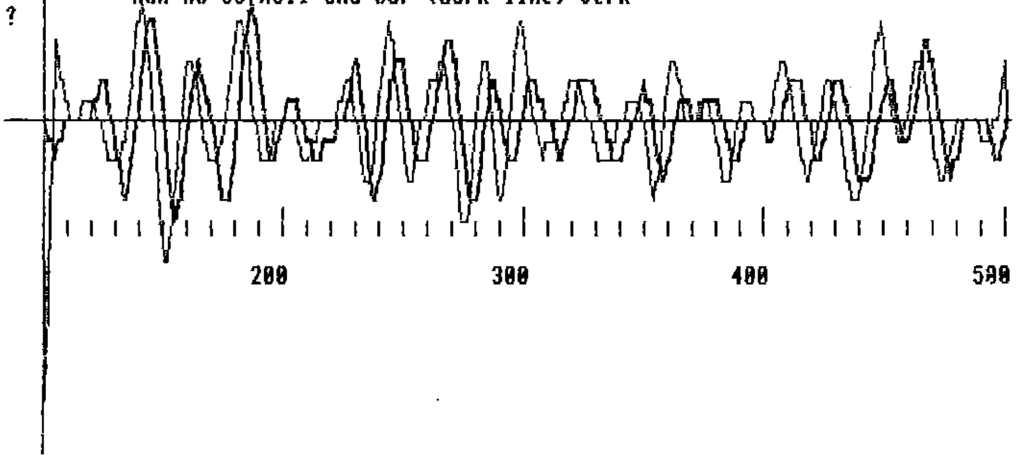
Run No 36 Roll and Bar (dark line) Velocity



Run No 36 Roll and Bar (dark line) Accln



Run No 36 Roll and Bar (dark line) Jerk



MDRARA all runs

```
Mid-pt Freq

5       13     *************
15      10     **********
25      20     ********************
35      16     ****************
45      18     ******************
55      14     **************
65      20     ********************
75      10     **********
85      18     ******************
95      13     *************
105     16     ****************
115     12     ************,
125     8      ********
135     9      *********
145     10     **********
155     14     **************
165     9      *********
175     6      ******
185     6      ******
195     9      *********

     * = (1)         Mean = 114.114094   Std. Dev.= 83.7320775
```

MDBARA all runs

```
Mid-pt Freq

5       17     *****************
15      13     *************
25      24     ************************
35      17     *****************
45      18     ******************
55      15     ***************
65      16     ****************
75      17     *****************
85      18     ******************
95      24     ************************
105     9      *********
115     13     *************
125     18     ******************
135     6      ******
145     11     ***********
155     8      ********
165     8      ********
175     10     **********
185     3      ***
195     0

     * = (1)         Mean = 100.422819   Std. Dev.= 81.6115518
```

ADRARA all runs

Mid-pt	Freq	
5	19	*******************
15	12	************
25	5	*****
35	14	**************
45	12	************
55	8	********
65	12	************
75	7	*******
85	11	***********
95	12	************
105	12	************
115	8	********
125	15	***************
135	12	************
145	6	******
155	7	*******
165	9	*********
175	7	*******
185	7	*******
195	7	*******

* = (1)   Mean = 115.298755   Std. Dev.= 79.2304923

ADBARA all runs

Mid-pt	Freq	
5	28	****************************
15	16	****************
25	5	*****
35	8	********
45	9	*********
55	12	************
65	12	************
75	14	**************
85	12	************
95	11	***********
105	5	*****
115	7	*******
125	15	***************
135	7	*******
145	7	*******
155	3	***
165	5	*****
175	7	*******
185	8	********
195	10	**********

* = (1)   Mean = 116.091286   Std. Dev.= 104.80264

```
MDRWAV all runs

Mid-pt Freq

1       0
3       5       **
5       13      ******
7       46      ***********************
9       68      **********************************
11      61      ******************************
13      33      ****************
15      21      **********
17      15      *******
19      14      *******
21      8       ****
23      8       ****
25      2       *
27      2       *
29      2       *
31      0
33      0
35      0
37      0
39      0

     * = (2)        Mean = 11.2013423    Std. Dev.= 4.83760419
```

```
MDBWAV all runs

Mid-pt Freq

1       3       *
3       5       **
5       10      *****
7       48      ************************
9       85      ******************************************
11      58      *****************************
13      33      ****************
15      23      ***********
17      11      *****
19      6       ***
21      6       ***
23      3       *
25      2       *
27      4       **
29      1       *
31      0
33      0
35      0
37      0
39      0

     * = (2)        Mean = 10.4261745    Std. Dev.= 4.52690534
```

ADRWAV all runs

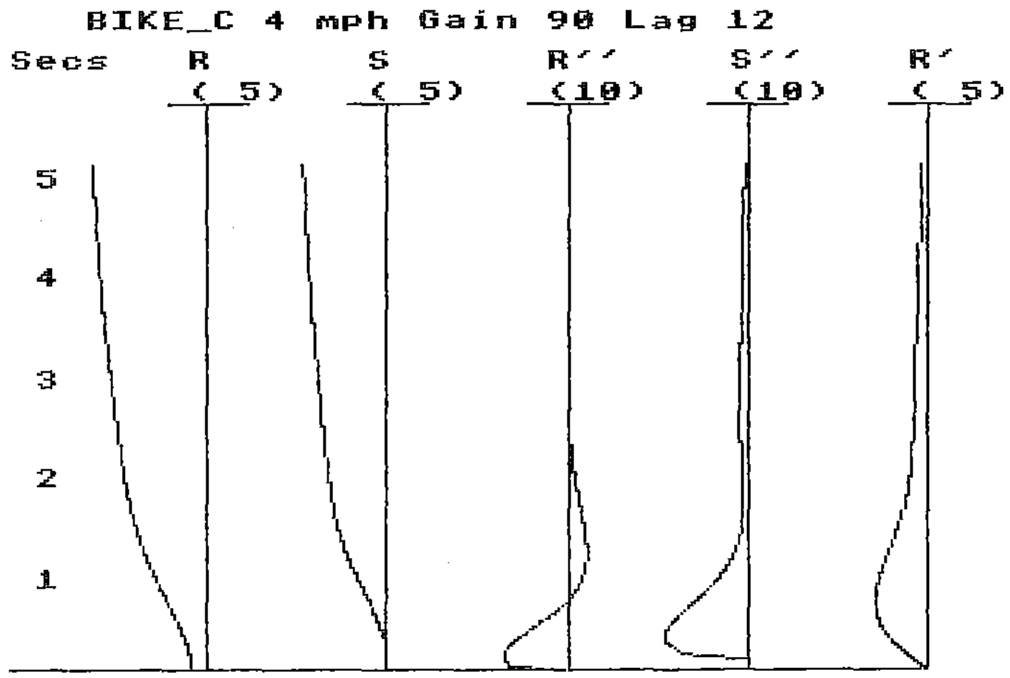
```
Mid-pt Freq

1       0
3       2       **
5       14      **************
7       16      ****************
9       21      *********************
11      29      *****************************
13      44      ********************************************
15      30      ******************************
17      33      *********************************
19      24      ************************
21      6       ******
23      6       ******
25      6       ******
27      2       **
29      3       ***
31      4       ****
33      1       *
35      0
37      0
39      0

     * = (1)         Mean = 13.8381743   Std. Dev.= 5.72201427
```

ADBWAV all runs

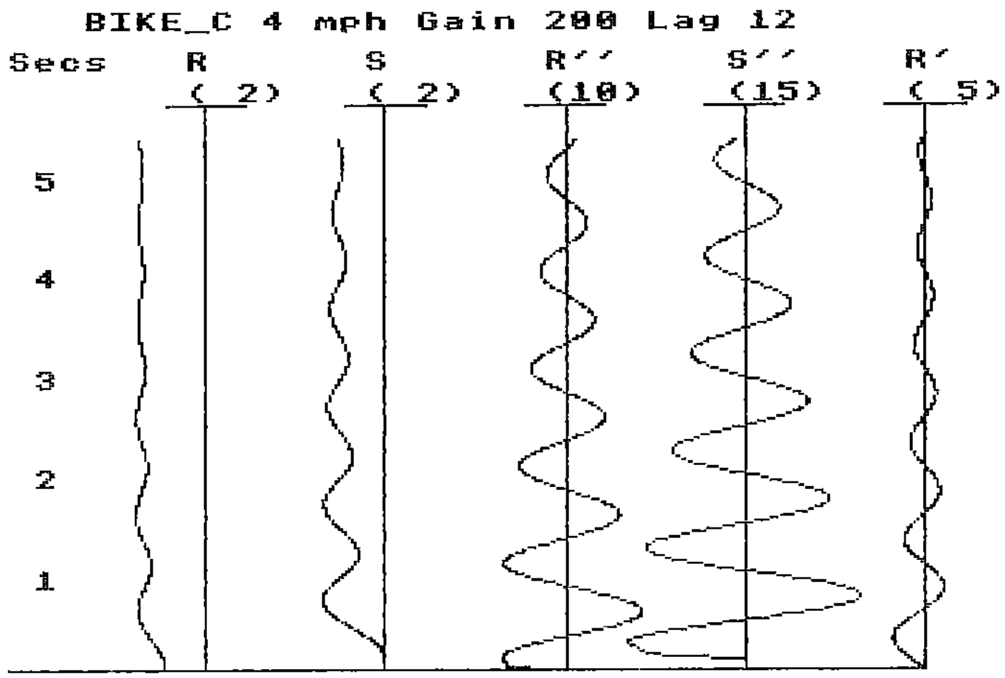
```
Mid-pt Freq

1       4       ****
3       8       ********
5       21      *********************
7       20      ********************
9       26      **************************
11      35      ***********************************
13      41      *****************************************
15      29      *****************************
17      15      ***************
19      19      *******************
21      12      ************
23      6       ******
25      4       ****
27      0
29      0
31      1       *
33      0
35      0
37      0
39      0

     * = (1)         Mean = 11.9917012   Std. Dev.= 5.47570394
```

```
ADLAG all runs

Mid-pt Freq

0       0
1       28     **************
2       27     *************
3       49     ***********************
4       43     *********************
5       37     ******************
6       16     ********
7       18     *********
8       12     ******
9       6      ***
10      2      *
11      1      *
12      2      *
13      0
14      0
15      0
16      0
17      0
18      0
19      0

     * = (2)          Mean = 4.2033195     Std. Dev.= 2.28020286
```

```
MDLAG all runs

Mid-pt Freq

0       0
1       19     *********
2       75     *************************************
3       88     ********************************************
4       62     *******************************
5       35     *****************
6       7      ***
7       1      *
8       4      **
9       4      **
10      2      *
11      1      *
12      0
13      0
14      0
15      0
16      0
17      0
18      0
19      0

     * = (2)          Mean = 3.36912752    Std. Dev.= 1.63579504
```

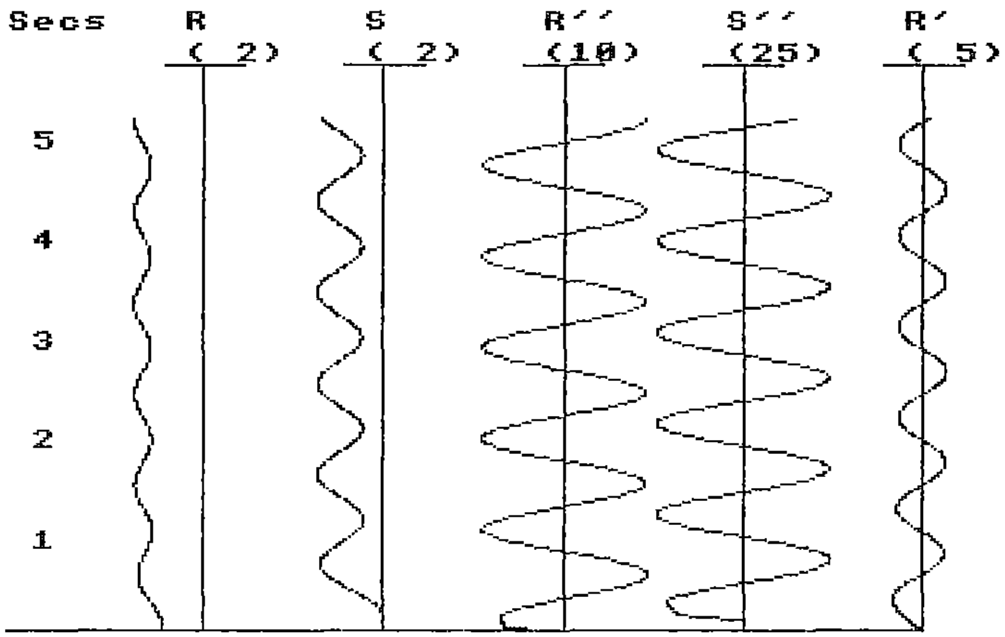


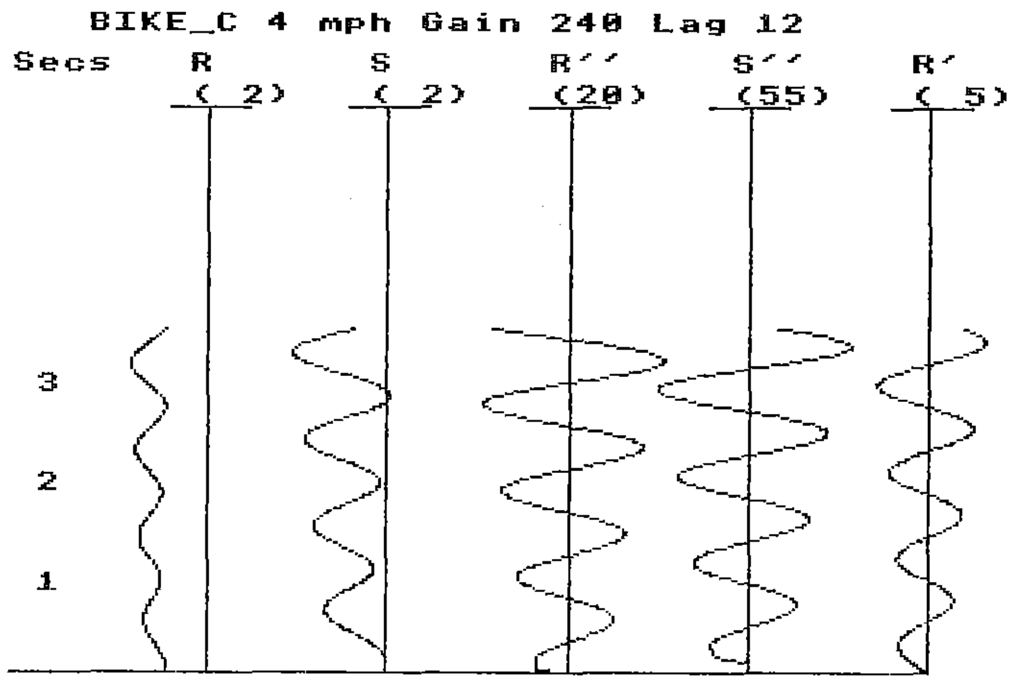
BIKE_C 4 mph Gain 90 Lag 12
Secs
R
(5)
S
(5)
R''
(10)
S''
(10)
R'
(5)
5
4
3
2
1



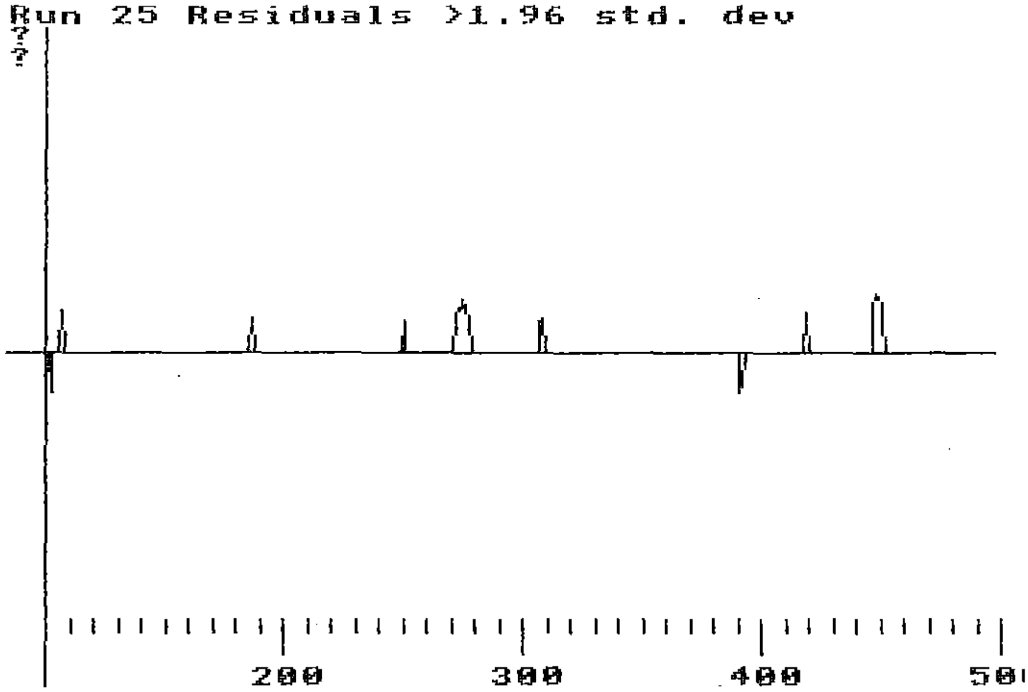
BIKE_C 4 mph Gain 200 Lag 12
Secs
R
(2)
S
(2)
R''
(10)
S''
(15)
R'
(5)
5
4
3
2
1

BIKE_C 4 mph Gain 220 Lag 12

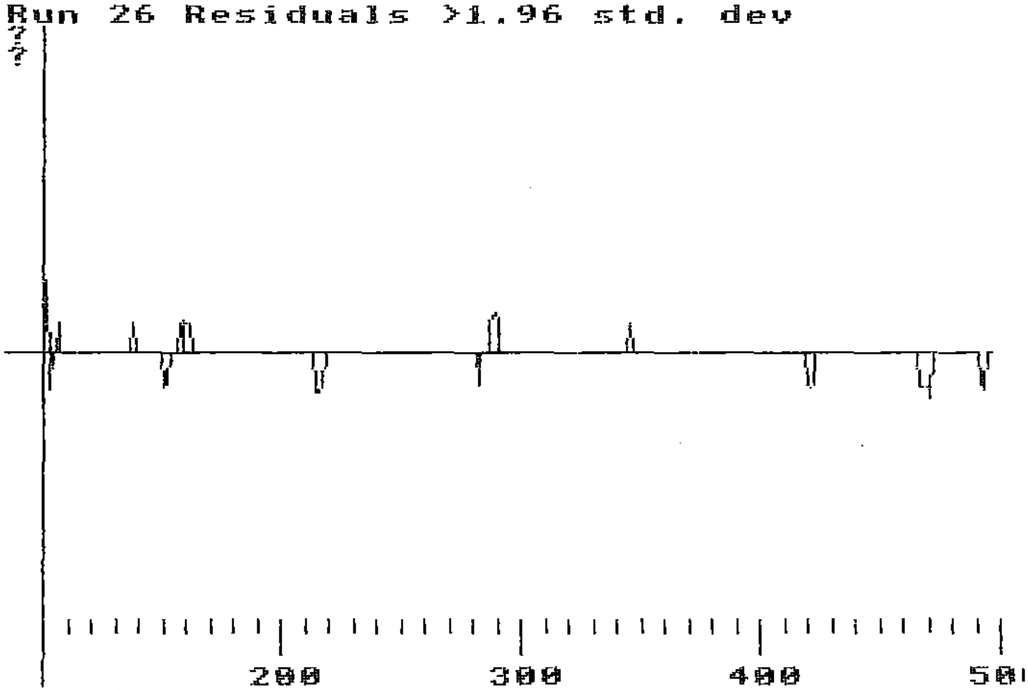



BIKE_C 4 mph Gain 240 Lag 12
Secs
R
(2)
S
(2)
R´´
(20)
S´´
(55)
R´
(5)
3
2
1

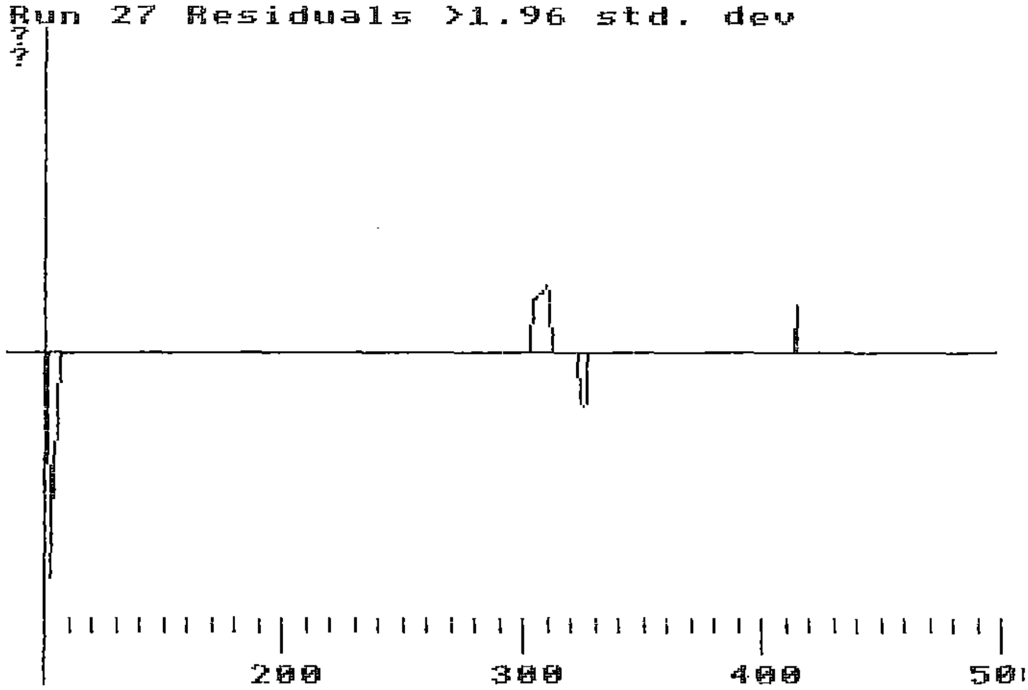
Run 25 Residuals >1.96 std. dev



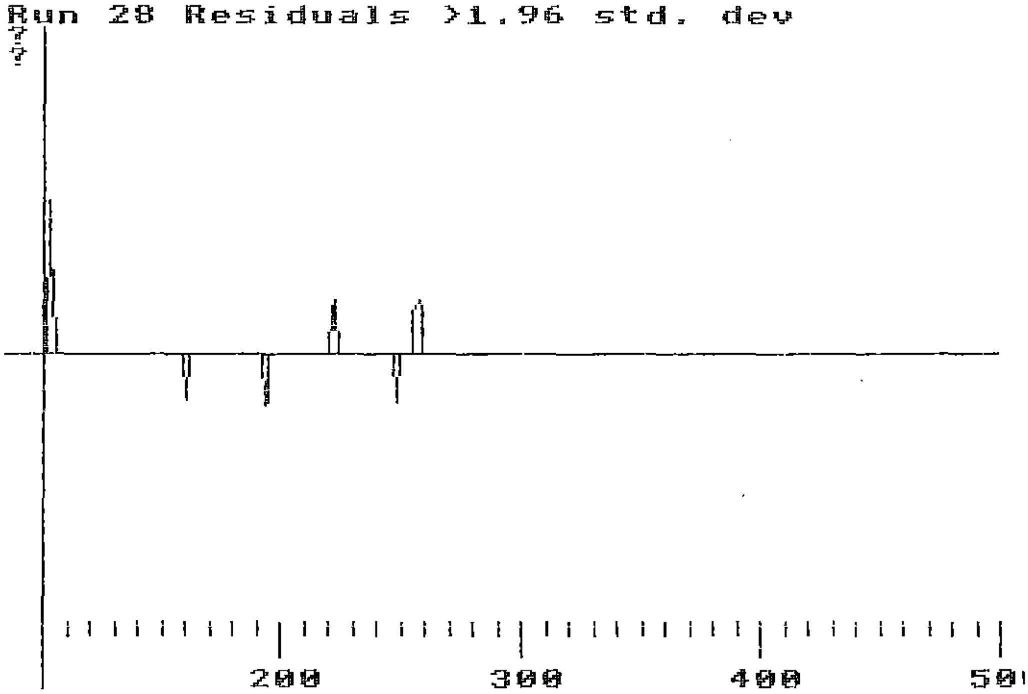
Run 26 Residuals >1.96 std. dev



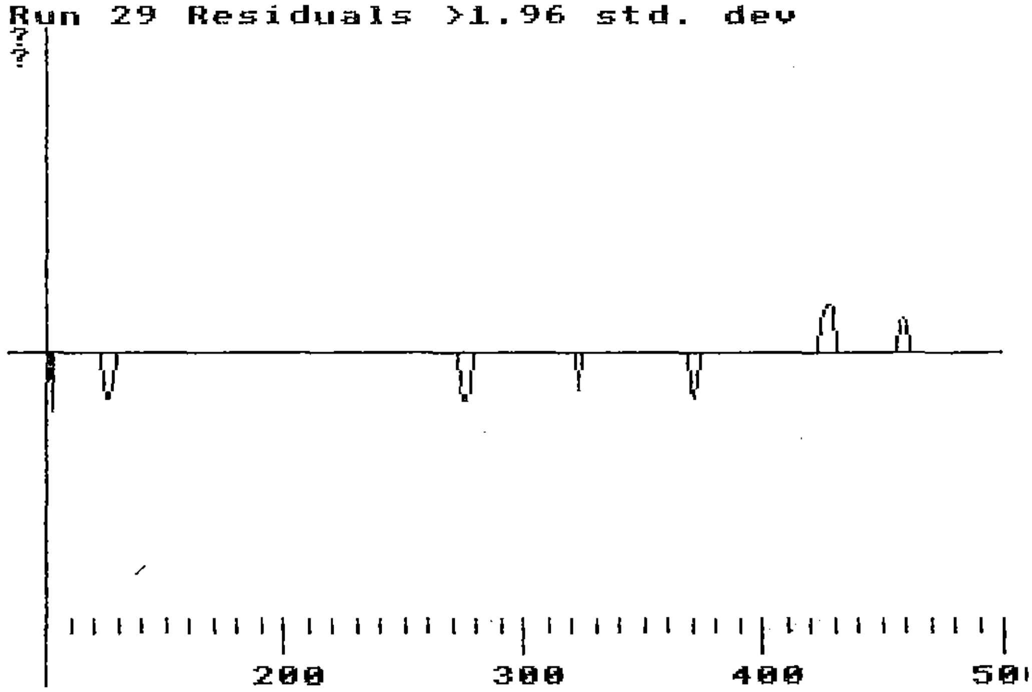
Run 27 Residuals >1.96 std. dev



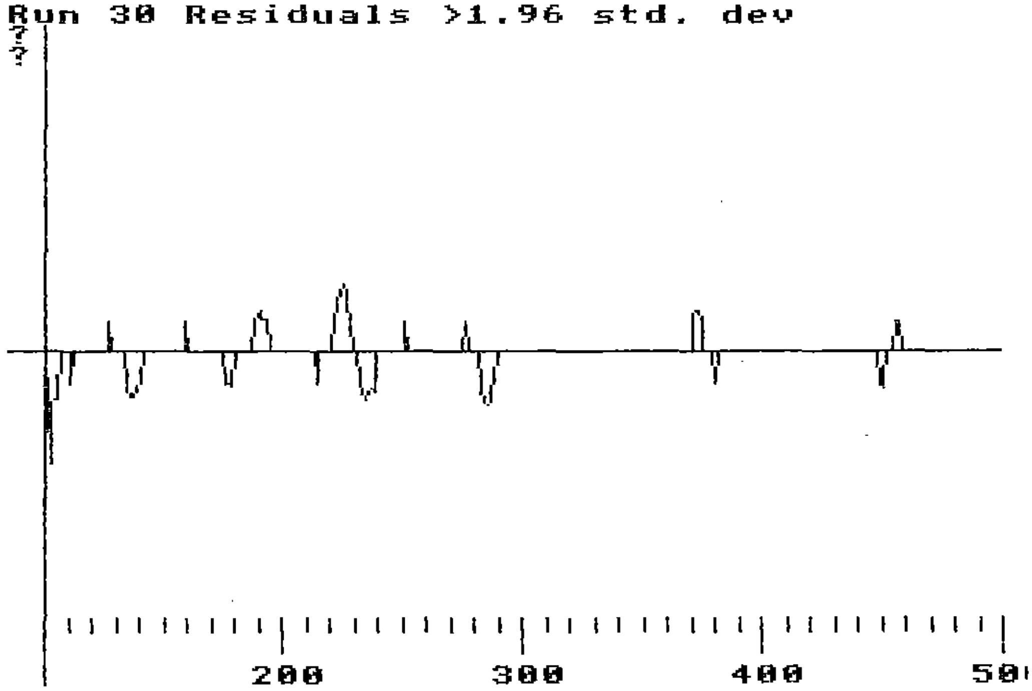
Run 28 Residuals >1.96 std. dev



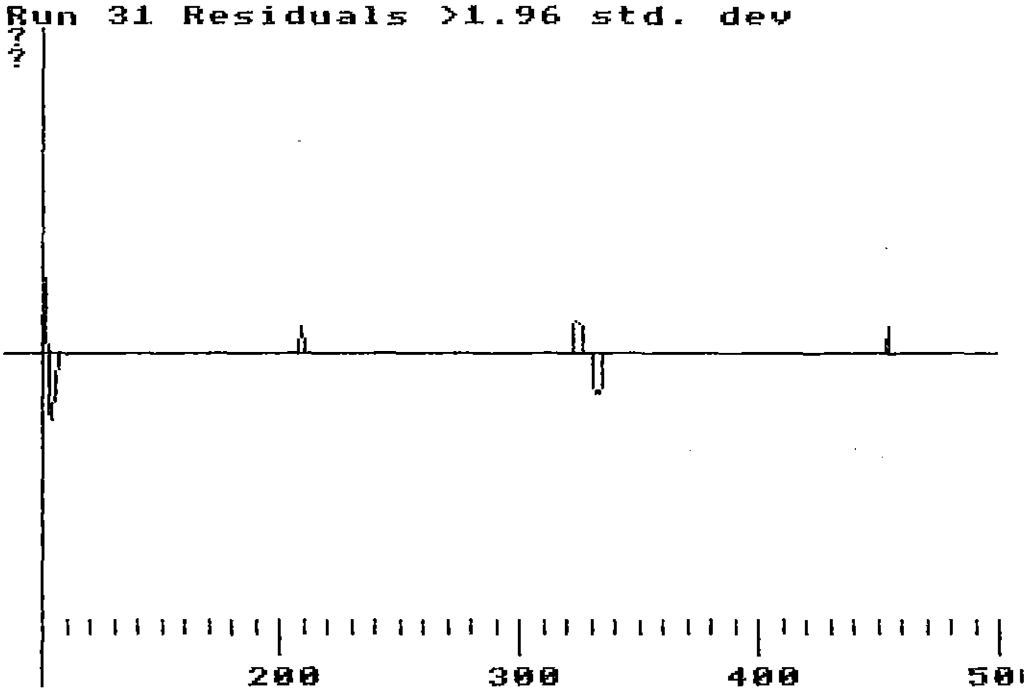
Run 29 Residuals >1.96 std. dev



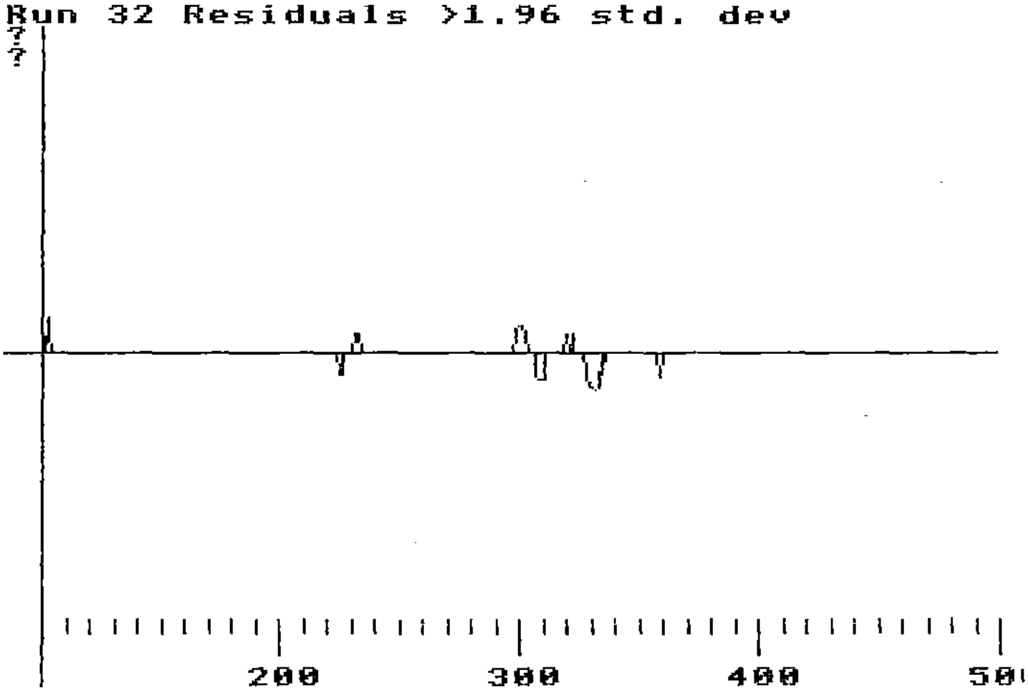
Run 30 Residuals >1.96 std. dev



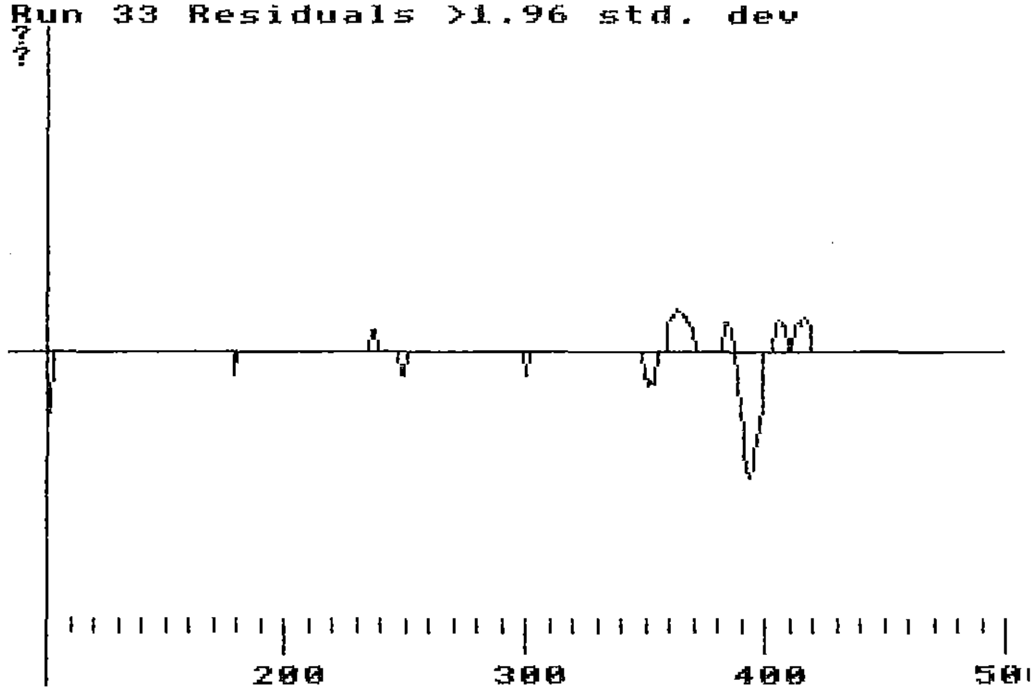
Run 31 Residuals >1.96 std. dev



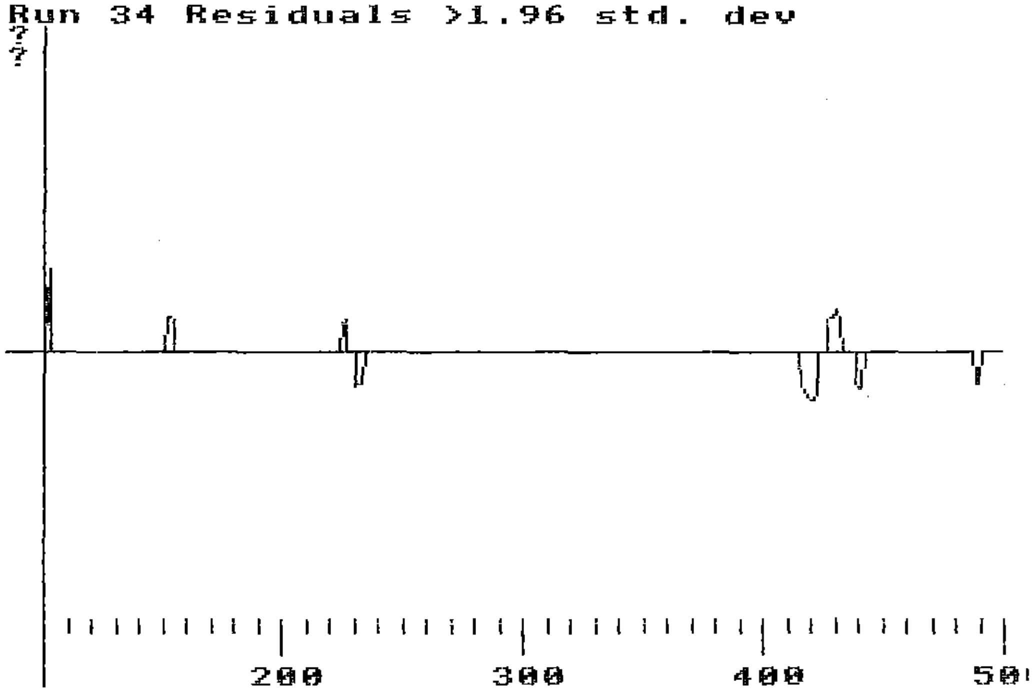
Run 32 Residuals >1.96 std. dev



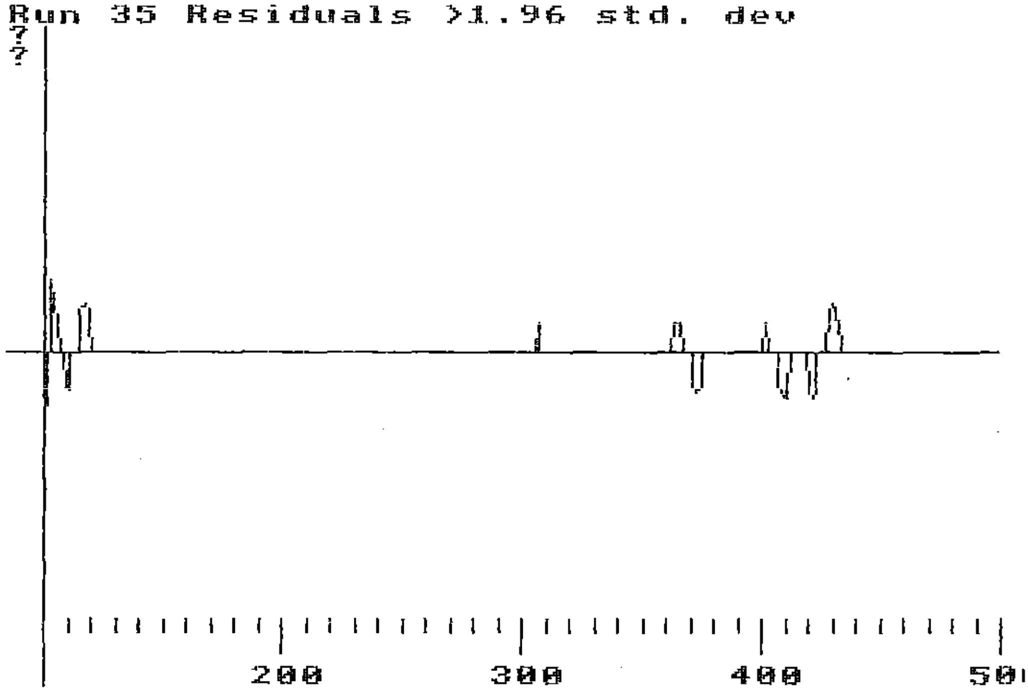
Run 33 Residuals >1.96 std. dev



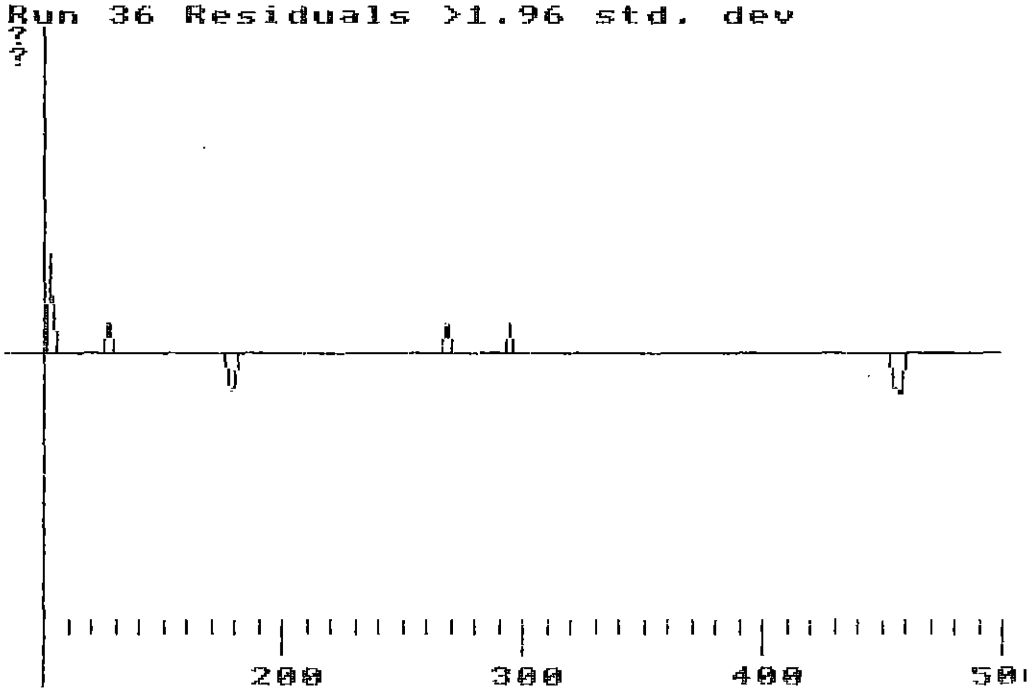
Run 34 Residuals >1.96 std. dev



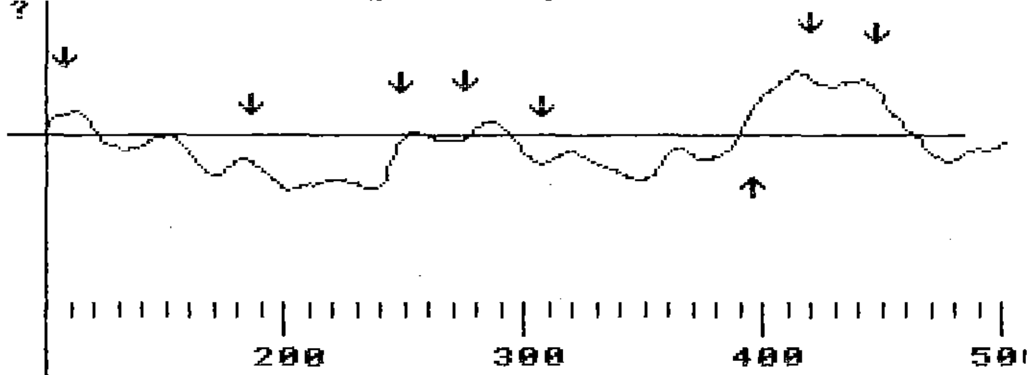
Run 35 Residuals >1.96 std. dev



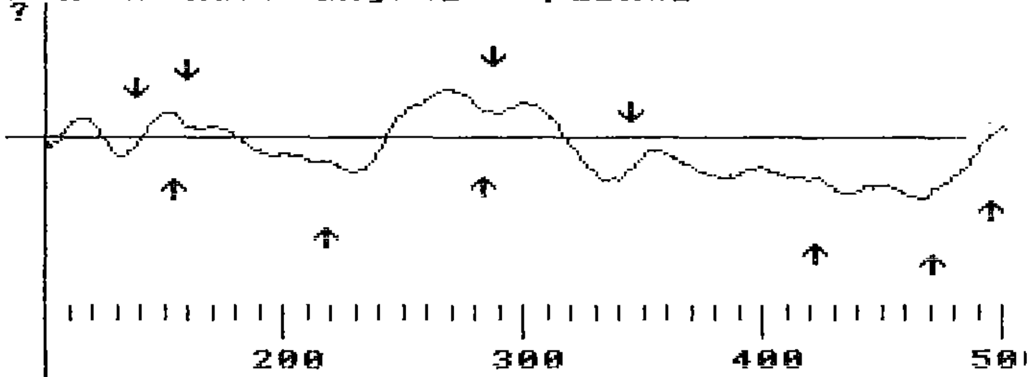
Run 36 Residuals >1.96 std. dev



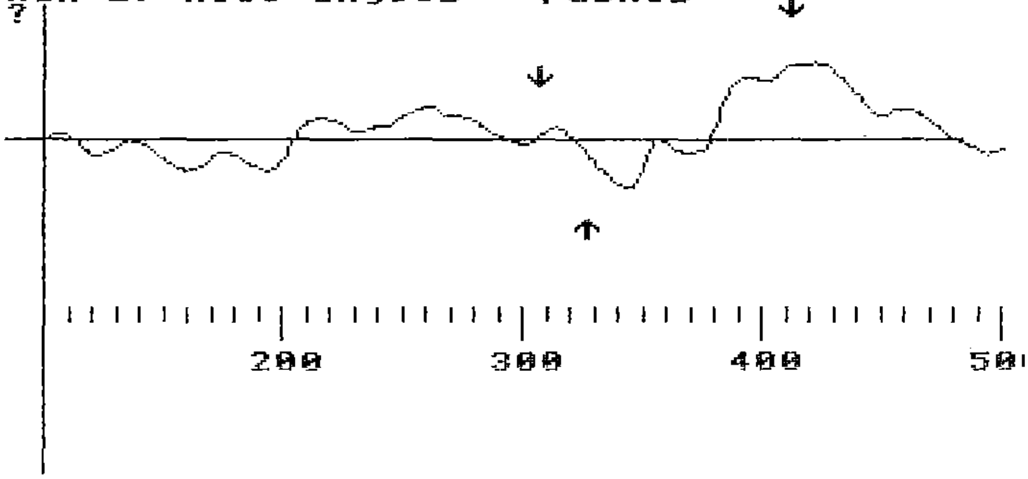
Run 25 Roll angles + pushes



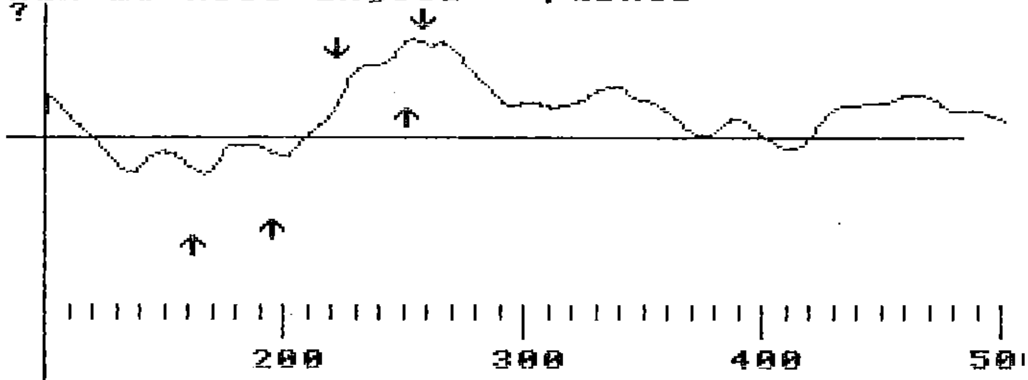
Run 26 Roll angles + pushes



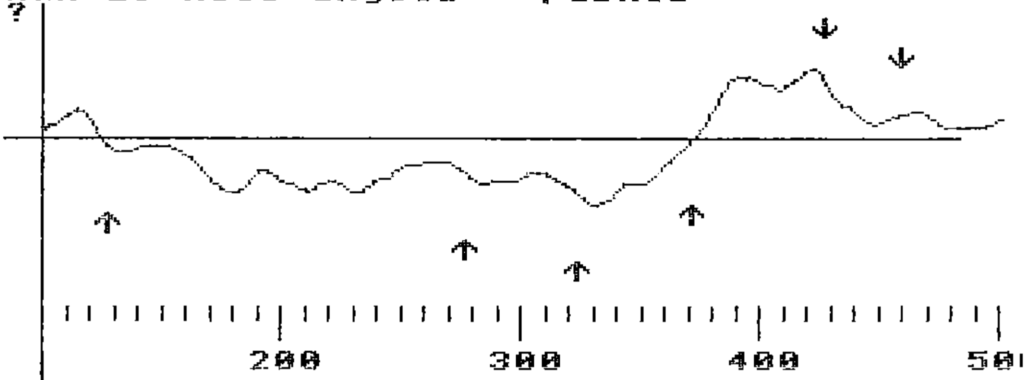
Run 27 Roll angles + pushes



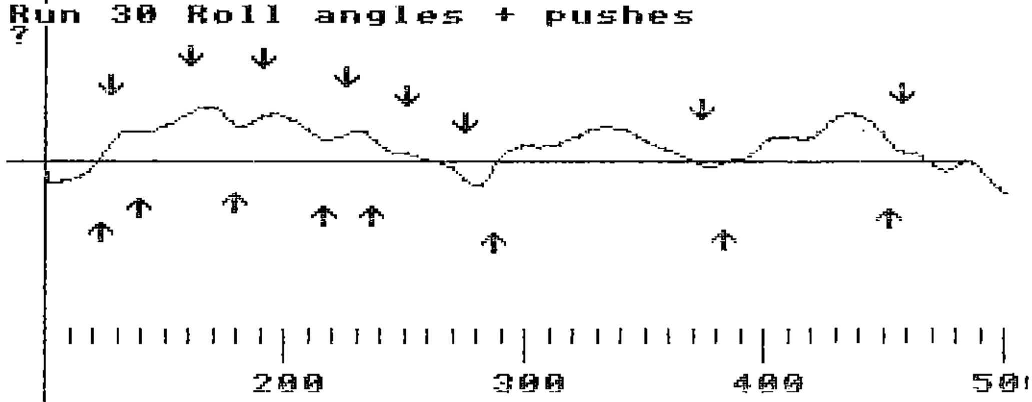
Run 28 Roll angles + pushes



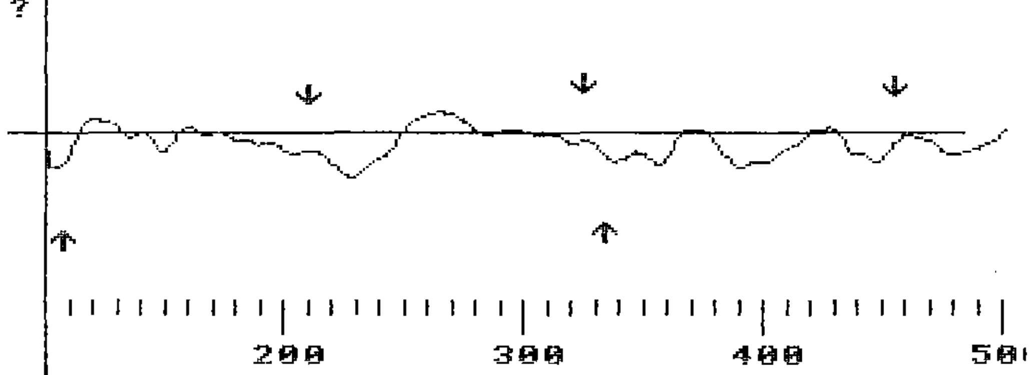
Run 29 Roll angles + pushes



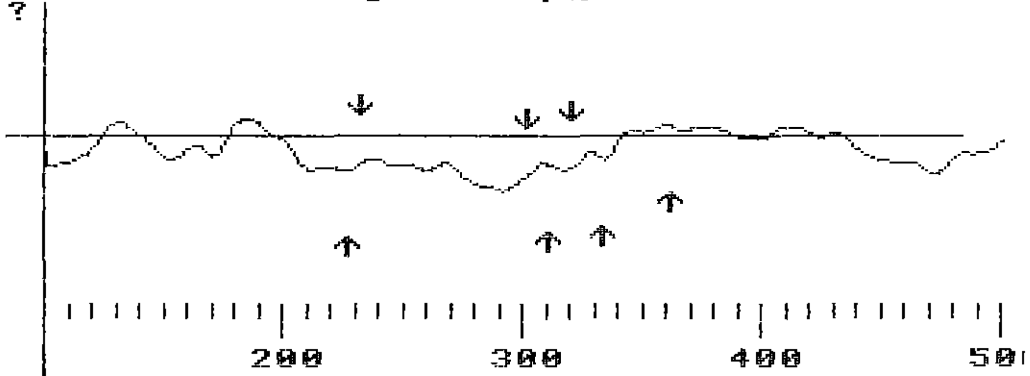
Run 30 Roll angles + pushes



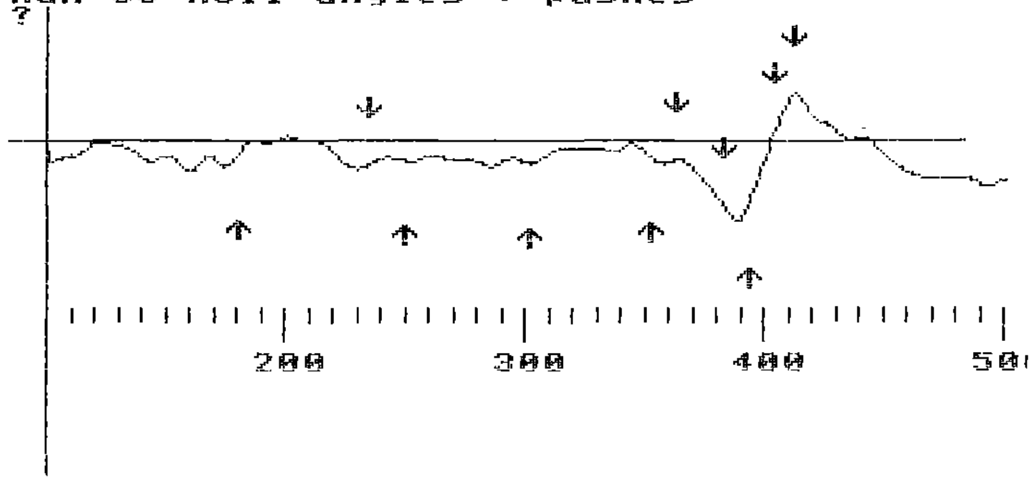
Run 31 Roll angles + pushes



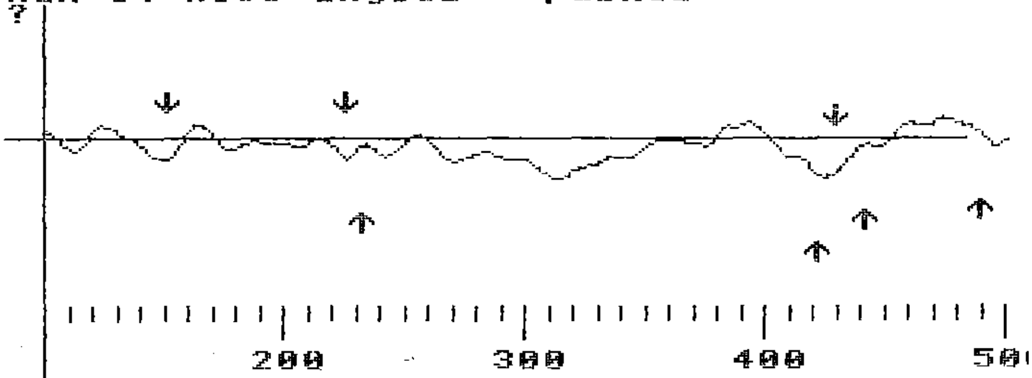
Run 32 Roll angles + pushes



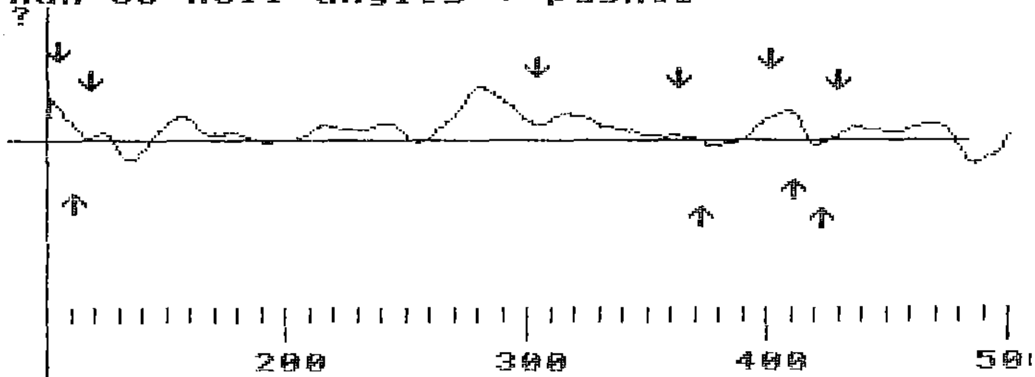
Run 33 Roll angles + pushes



Run 34 Roll angles + pushes



Run 35 Roll angles + pushes



Run 36 Roll angles + pushes