DRIVER-VEHICLE INTERACTION IN BRAKING

by

SHINSUK PARK

Bachelor of Science, Mechanical Design and Production Engineering
Seoul National University, Seoul, Korea, 1989

Master of Science, Mechanical Design and Production Engineering
Seoul National University, Seoul, Korea, 1991

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Signature of Author.......................................................... Department of Mechanical Engineering
May 9, 1999

Certified by................................................................................ Thomas B. Sheridan
Thesis Supervisor

Accepted by.............................................................................. Ain A. Sonin
Chairman, Department Committee on Graduate Students
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ABSTRACT

While antilock brake systems (ABS) have become more and more popular with the public, statistics reports imply that ABS-equipped cars have no advantage over non-ABS-equipped cars in reducing fatal accidents. While the brake pedal needs to be pushed down (full-brake) to activate the ABS, many drivers on ABS-equipped cars fail to do this simple maneuver, reducing the effectiveness of ABS and even contributing to some accidents. Because of such behavior on the driver’s part, the major feature of this brake assistance system is often ineffective.

The goal of this thesis is to design brake systems that provide intuitive brake control and proper braking performance information for the driver. As a preliminary study in brake system design, the characteristics of human leg motion and its underlying motor control scheme were studied through experiments and simulations. Automotive brake systems were modeled as a type of master-slave telemanipulator. Human force-displacement interaction at the master end (the brake pedal) has a strong effect on the system’s ability to control the operations at the slave end (the braking performance). By providing drivers with “force feel” at the brake pedal, they can obtain information about braking conditions or performance.

This thesis developed novel brake systems based on two new aspects. First, the mechanical impedance characteristics of the leg action of the driver were taken into
consideration in designing the brake systems. Second, the brake systems provide the driver with kinesthetic feedback of braking conditions or performance. Since the effectiveness of brake systems needs to be examined as a combined driver-vehicle system, driving simulations were used to investigate the performance of the proposed designs.

Thesis Committee:

Prof. Thomas B. Sheridan (Thesis Supervisor)
Prof. Robert W. Mann
Prof. Kamal Youcef-Toumi
Prof. Dava J. Newman
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CHAPTER 1

INTRODUCTION

As a solution to the automobile collision avoidance problem, brake assistance systems such as the antilock brake system (ABS) have become more and more popular on modern vehicles. ABS reduces the likelihood of brake’s locking the wheels and causing skidding and resulting in loss of steering ability in panic-stop situations. Thus, ABS provides the driver with an opportunity to steer out of emergencies. However, according to accident statistics, ABS-equipped cars might be worse than non-ABS-equipped cars in emergency braking situations.

Why does the ABS, which is supposed to have superior performance to the conventional brake system, have a worse record? The response of drivers is mostly to blame. Studies indicate that, in panic-braking situations, some drivers do not really slam down on the brake pedal [McCosh (1997)]. To activate ABS the brake pedal should be pushed down (full-brake). However, it is reported that most drivers back off after their first stab, even if emergency braking is required [McCosh (1997)]. Some drivers with ABS-equipped cars tend to pump the pedals as if they were driving non-ABS vehicles, reducing ABS’ effectiveness and even contributing to some accidents. Such human reactions when applying the brake pedal fail to take advantage of the major feature of ABS.

Then, what are the causes of this misuse? First, physical limitations of drivers seem to be one reason. A study in Japan indicates that some people experience trouble in braking in an emergency [Yamaguchi (1997)]; this is plausible for elderly people who are weaker in leg strength. Second, the vibration cues ABS deliver to the drivers are to partly blame. Traditionally, a vibration signal is reserved for indicating a warning or malfunction rather normal functioning of machines. Some drivers are confused by the vibration cue indicating the normal activation of ABS.

There have been several attempts to solve these problems. One attempt is fully automated braking. In this system all maneuvers, including steering, acceleration and braking, are done by an automated system. This system uses short-range radar to sense
the speed of and the distance to the lead car in braking [Morita (1993), Chen (1996), Cogan (1997)]. Another attempt is the brake assist systems developed by several car companies in the United States, Germany and Japan [Reichelt and Frank (1992), McCosh (1997), Yamaguchi (1997)]. These systems sense the rapid depression of the brake pedal, and if the depression is over some threshold, the systems assume an emergency situation and jump to full braking, activating the ABS. The threshold for activation of the systems is a combination of pedal depression and its gradient.

However, these approaches to solving ABS problems have potential drawbacks. The fully automatic system overrides the driver in all driving maneuvers, whereas the brake assist systems are supposed to override the driver only in emergency situations. In the brake assist system, ABS is activated automatically only if the non-human system decides that the situation is an emergency, regardless of the actual condition. Both the fully automatic system and the brake assist systems deprive the driver of responsibility of braking action in an emergency. Since the fully automatic system totally excludes the driver in driving control and braking, it does not seem to be practical in the near future. In the case of the brake assist systems, the excessive braking force produced by the systems, even if the driver intends only gentle braking, might cause rear-end collisions. Moreover, neither the fully automatic system nor the brake assist systems provide the driver with sufficient performance feedback.

The problems with ABS and with the new brake systems raise several questions. First, a brake system should be studied as a combined system including the driver in-the-loop, rather than in isolation. While, in principle, ABS alone has superior performance to non-ABS, the performance of ABS combined with the driver is quite disappointing. The driver needs to be included in a closed-loop system of braking performance. Second, while braking appears to be the simplest form of manipulation, many drivers still have problems in managing the brake pedal. The mechanisms of musculo-skeletal motor control in the driver's braking motion are not well understood; few studies have investigated the operator's motor control in situations similar to braking. Third, current brake systems, including ABS and the new brake systems, lack any provision to give the driver feedback of his braking performance. Conventional brake systems are simple
open-loop systems with no direct feedback save visual and vestibular to the driver, while the artificial vibration cue from ABS could lead to misuse of ABS.

The goals of this thesis were to answer the three questions above. First, characteristics of the human leg and its motion were measured, and the human motor control scheme involved was examined. Based on this analysis, the driver’s initial braking motion is modeled as a preprogrammed action. Second, two new control schemes for ABS are designed. These new brake designs employ the bilateral teleoperation concept rather than the unilateral control employed in conventional brake systems. Teleoperator studies report that force feedback to the operator and the adaptive change of impedance at the master port enhance teleoperation performance [Raju (1988)]. In the proposed designs brake pedal stiffness is controlled depending on braking condition or on road surface condition. Thus, adaptive change of the brake pedal stiffness is intended to provide the driver with intuitive cues of braking condition or of road surface condition—softer pedal for wet/icy road and stiffer pedal for dry road. In addition the preprogrammed nature of emergency leg motions produces further depression of a soft brake pedal on a wet road, which is advantageous for ABS in an emergency situation on wet/icy roads. Third, braking performances of these proposed driver-vehicle systems were evaluated using a simple driving simulator. Driving simulators provide a safe and economical means for testing system performance in controlled environments. Road condition awareness by drivers and situation adaptability by driver-vehicle systems were used for braking performance evaluation. The performance of the two new brake designs and conventional brake systems were compared.

This thesis makes contributions in two particular areas. First, preliminary to the design of new brake systems, the human’s motor control scheme in manipulating the brake pedal is addressed, and a simple model based on leg motion analysis is formulated to explain key features of braking motion. Second, brake systems are modeled as a teleoperator, and force feedback and adaptive stiffness control at the brake pedal in new brake system designs help drivers in using ABS.

The proposed designs of brake systems introduce two new aspects in brake system design. First, the automotive brake systems are considered as a type of master-
slave teleoperator, and human force-displacement interaction at the master end (the brake pedal) have a strong effect on ability to control the operations at the slave end (the braking performance). Provided with “force feel” at brake pedal, the driver will obtain information about braking or road condition. Second, the motor control scheme of human leg motion is considered in the design of the brake pedal. Utilizing the preprogrammed nature of human leg motion, adaptive change of brake pedal stiffness induces full braking as well as providing force feel.

This thesis is divided into six chapters. The chapter contents are summarized as follows:

Chapter 1 - Introduction:
This chapter introduces the thesis goals and objectives and motivates the research effort.

Chapter 2 - Background:
This chapter provides background on ABS and their problems. It describes how ABS works and how the driver misuses ABS. Several attempts to resolve the misuse and their drawbacks are presented.

Chapter 3 – Human Leg Motion Analysis:
This chapter is devoted to leg motion analysis. A brief background on pertinent human motor control is presented. Experiments to measure human leg stiffness and motion are presented. From the experimental results a simple model for testing the motor control of foot reaching motion is developed. Simulation results using this model are compared with experimental results.

Chapter 4 – Design of Brake Systems as a Teleoperator:
This chapter develops new control schemes for ABS. A background of teleoperation is presented. The brake system is modeled as a teleoperator, and two new brake systems with adaptive pedal stiffness are designed using the teleoperation concept. In these two models motor control scheme for the driver’s braking motion is taken into account.
Chapter 5 – Simulator Tests:
This chapter applies new control schemes to simulator tests. A simple driving simulator to test braking performances is described. Braking performance of proposed brake systems and conventional brake systems are compared.

Chapter 6 – Summary and Conclusions:
The final chapter discusses the results and summarizes the thesis work. The conclusions from this thesis are provided. Based on these conclusions, possible topics for future work are proposed.
CHAPTER 2

BACKGROUND

Despite its popularity with the public, studies of Highway Loss Data Institute (HLIDI) and National Highway Traffic Safety Administration (NHTSA) concluded that accidents are not reduced by antilock brake systems (ABS). Even worse, the Insurance Institute for Highway Safety reported that cars with ABS are more likely to be involved in fatal crashes than those without it.

Antilock brakes show excellent performance on the test tracks. Indeed, antilock braking helps stability and maneuverability on a wide variety of surfaces. Many drivers, however, seem to be unfamiliar with how ABS works and how ABS should be used.

This chapter describes the mechanism of ABS and the drivers’ misuse of this system. Several attempts to circumvent the problems in ABS are introduced, and their disadvantages are discussed.

2.1 How ABS Works

ABS consists of several hydraulic and electronic components. It employs sensors that constantly monitor how quickly each of the wheels is rotating. If the wheel begins to lock, the system effectively diminishes the brake pressure to allow it to roll more than slip. If the driver depresses the brake pedal and one wheel’s speed is out of synch with the others, the on-board computer activates ABS to rapidly modulate the hydraulic pressure. This controls the braking force between the wheels and the road surface on the verge of skidding. The fluctuation in brake pressure is the vibration the driver feels at the brake pedal when antilock braking is working. ABS can be considered as automatic brake-pedal pumping, roughly 10 times as fast as the driver can stroke the pedal.

Knowledge of the tire-road interface is essential to the understanding of ABS activation. The braking force generated at a wheel of a vehicle is a function of the normal force on the wheel and the coefficient of friction between the tire and the road.
The simplified relationship between the normal force on the wheel and the resulting frictional braking force can be presented as:

\[ F = \mu N \]  \hspace{1cm} (2-1)

where \( F \) = frictional braking force
\( \mu \) = friction coefficient of tire-road contact
\( N \) = normal force on the wheel

The friction coefficient \( \mu \) of tire-road contact is not a constant, but rather a function of the road surface condition and the relative longitudinal slip between the tire and the road. Wheel slip is the difference between rolling speed and longitudinal forward speed of the wheel. Wheel slip may be defined as slip ratio \( \lambda \):

\[ \lambda = \frac{v - rw}{v} \]  \hspace{1cm} (2-2)

where \( v \) = forward speed of the vehicle
\( r \) = radius of wheel
\( \omega \) = angular speed of wheel

Figure 2.1 illustrates general curves relating the friction coefficient to wheel slip on various road surfaces. The friction coefficient has its maximum value when the slip ratio is around 0.2. Note that beyond the peak friction coefficient on a given road condition, the slope of the curve becomes negative. Beyond this point, more pedal force without proper slip control results in less braking. Also, the magnitude of the peak in the friction coefficient curves varies widely with road conditions. With the application of slip control, travel over surfaces such as ice may gain more braking force benefit than surfaces like dry asphalt.
Figure 2.1 Friction coefficient – slip ratio curves on various road surface conditions

[Jurgen (1997)]

Often, excessive wheel slip results in loss of lateral friction force on the wheels of a vehicle. When a wheel is locked up (i.e. 100% slip), the friction coefficient falls to its sliding value and its ability to sustain lateral force is nearly reduced to zero. Steerability or stability of the vehicle depends on high lateral force on the wheels. Wheel slip control can contribute to improve this stability by keeping the wheels near the peak frictional force range.

The main function of an antilock brake system is to keep the friction coefficient at or near its maximum, which will in turn lead to shorter stopping distance and better maneuverability. An antilock brake system usually consists of wheel sensors, a hydraulic modulator, and an electronic control unit (Figure 2.2).
In practice, the slip of the wheel is difficult to measure directly. Thus, the control logic is usually formulated based on some easily measurable parameters such as the angular speed and the angular acceleration of the wheel. The wheel sensor monitors these parameters and generates signals that are transmitted to the control unit. In the control unit, after the signals have been processed, the measured parameters and those derived from them are compared with the corresponding predetermined threshold values. When certain requirements that indicate the impending lockup of the wheel are met by the measured parameters and their derivatives, a command signal is sent to the modulator to relieve the brake pressure to keep the friction coefficient or frictional braking force near its maximum value.

Figure 2.3 illustrates braking force versus wheel slip during ABS activation. As the brake pressure is applied, braking torque applied by the brake system increases and the angular speed of the wheel decreases, causing the wheel slip to increase. The braking force at tire-road interface increases to reach its peak value as the wheel slip increases. After the peak braking force is reached, the control unit commands the modulator to reduce the brake pressure. As the brake pressure is reduced, wheel slip is reduced and the braking force again passes through the peak.

![Braking force-slip relationship during ABS activation](image)

Figure 2.3  Braking force-slip relationship during ABS activation
2.2 Misuse of ABS

The driver’s understanding of how ABS works and how it should be used is critical for it to serve properly. ABS will be interrupted by pumping the brake pedal or by relieving the pedal pressure. Most drivers are known to have a tendency to stab the brakes, then back off, which makes for longer stopping distances [McCosh (1997)]. Also, some people have physical limitations that prevent them from applying the brakes fully in panic situations [Yamaguchi (1997)]. These actions defeat ABS, because the system relies on the hydraulic pressure generated by the driver’s foot to engage the brakes at each wheel. When ABS is activated, the brake pedal will pulse noticeably underfoot. Such pulsing could also be felt on wet or icy road conditions. This serves as a signal of normal functioning of ABS or as a warning that the road surface is slippery. However, most drivers lack the skill to apply exactly the right amount of brake-pedal pressure, to sense when the brakes are about to lock, since ABS demands only a forceful foot on the brake pedal. The ABS-human interface lacks dimensions that could provide a more comprehensive grasp of the road conditions. This defect combined with the driver’s insensitivity is the main shortcoming of ABS.

2.3 Attempts to Solve ABS Problem

Several attempts to assist the driver by automatic systems are being made. One example is a fully automatic radar-activated system (Figure 2.4) [Morita (1993), Chen (1996), Cogan (1997)]. Specifically, the radar braking system is controlled by the vehicle’s short-range optical or electromagnetic radar that constantly monitors the distance to the lead car. Fully automatic braking is rather ambitious and poses sensor liability problems, so will not be realized in the near future. Semiautomatic braking, where the radar triggers deceleration but bears the driver in charge of the brakes, is more acceptable.
Another attempt, developed in Germany, Japan and the United States, senses the pedal position and the speed at which the brake pedal is depressed [Reichelt and Frank (1992), McCosh (1997), Yamaguchi (1997)]. This system uses the criterion of exceeding a certain threshold value by the position and the actuating speed of the brake pedal by the vehicle’s driver. A sudden stab on the brakes is interpreted by the system as a panic stop, activating a brake for a quick, hard, full ABS stop. Figure 2.5 illustrates the automatic braking with various pedal position thresholds. This system may cut the vehicle’s stopping distance from that for a non-assisted stop in an accident-avoidance situation. However, this proposal has potential problems in subtle activation of the system. It may be activated in situations when the full ABS stop is not needed. For example, the excessive braking force produced by the system, while the driver intends gentle braking, could cause rear-end collisions.
In both systems described above, responsibility for a major part of the vehicle control, if not all, is placed in the intelligence of the machine rather than the human driver. This poses questions about relinquishing the decision making process to the machine, especially in emergency situations. Abandoning the "responsibility of the operation" is also questionable since machine sensing and control can never be fail-proof. Furthermore, neither of two systems above is capable of providing the braking performance feedback to the driver. The cue of braking performance or road surface condition may be crucial in emergency braking situations.
CHAPTER 3

HUMAN LEG MOTION ANALYSIS

The preceding chapter discussed drivers' common misuse of ABS. Pressing down on the brake pedal appears to be the simplest form of maneuver compared with other maneuvers required of mechanical devices such as of joystick, handgrip, and steering wheel. While braking is a relatively simple task, some drivers still have trouble in maneuvering the brake pedal in ABS. While many studies have investigated the effect of feedback to the operator in machine control [Bejczy and Salisbury (1980), Raju (1988)], little research has been done on the operator's motion analysis or on the operator's leg motor control scheme in braking.

The lower limbs of Human have features which are unique among animals. Humans have relatively strong leg extensor muscles and long lower limbs, characteristics well suited for the requirements such as locomotion and posture. When the functional requirements of the lower and upper limbs are compared, contrasting characteristics are evident. The muscles involved in movements of the lower limb have specific features that are compatible with their functional requirements: support and move the mass of the body. Muscle features include pennate fibers and relatively large cross-sectional areas, allowing the muscles to develop large forces. These features contribute to the relatively large mass of the lower limbs. Since the upper limbs are subjected to loads which are small compared to the weight of the body, their muscles are weaker and lighter than those of the lower limbs. These musculo-skeletal features of the human limb strongly influence motion and interaction with mechanical devices such as pedal.

As a preliminary study in brake system design, this chapter provides a background on human movement generation and a detailed description of experiments and simulations to define the characteristics of human leg motion and underlying motor control scheme.

The first section reviews some of the relevant work in the fields of the human movement generation and its underlying motor control schemes. In the second section of this chapter, details of simple reaching motion, impulsive motion and postural stiffness of
the human leg are examined through experiments. The third section illustrates simulations of a simple leg motion using equilibrium point control, which is discussed further in this chapter. The last section discusses the results from these experiments and simulations.

3.1 Background on Human Movement Generation

While humans can plan and perform a variety of movements with ease and dexterity, explaining the entire process of planning and generating movements remains essentially a black box. A great number of studies have attempted to reveal the basic properties of the human neuromuscular control system, but as yet are unable to explain the exact methods of translating the envisioned movement into the muscle activity required to generate it. However, it seems natural to assume that certain fundamental principles underlie the organization and performance of human motor behavior.

In human motor control, a multi-staged process in transforming sensory input into motor output seems plausible and consistent with known neural architectures [Bernstein (1967), Arbib (1972)]. It is argued that a multi-stage process is hierarchically organized with multiple levels ranging from an abstract specification of task goals to a concrete specification of motorneuron activities [Saltzman (1979)]. This is also compatible with our existing knowledge of brain structures. Much of the motor control capability of the central nervous system (CNS) is organized functionally and physiologically into a series of levels that govern successively more complex behaviors [McMahon (1984)]. Though there is little direct evidence for the existence of such a hierarchy in motor control, it is an implicit assumption in most human motor control studies.

One of the common assumptions of hierarchical organization is that the production of motor behavior occurs in at least two stages: planning and execution. Then, at what level of abstraction is the motor plan formulated? One possibility is that planning for most tasks takes place at the level of kinematics. While the trajectory of the limb is planned, joint torques and muscle forces used to carry out that plan are not considered in the planning stage. Rather, they are determined by the subsequent process of executing the motor plan.
The viewpoint that argues that planning takes place at the kinematic level raises the question of coordinate frames. Considering a hand movement, for example, the motion can be described in various representations such as the trajectory of the hand, as a sequence of joint angles and as a time pattern of muscle lengths. These may be considered as descriptions of the same behavior in alternative coordinate frames: hand coordinate, joint coordinate, and muscle coordinate. Then, which one of these coordinate frames is the basis of motor planning?

One of the early studies in self-paced point-to-point movements of the hand postulated that hand paths were roughly straight with unimodal tangential speed profiles. Compared with the corresponding joint trajectories, these features of hand motion in hand coordinate have showed little variation with movement duration or location in the subject’s workspace. From this, Morasso (1981) suggested that the central command for hand motion is formulated in a body-centered hand coordinate frame.

For many limb movements, motor planning appears to be represented and planned at a kinematic level. Even if motor behavior is planned in terms of the kinematics of limb motion, the dynamics of the peripheral musculo-skeletal system heavily influence the execution of that plan. Inertial dynamics introduces nonlinear coupling between body segments. The motion of one limb segment induces an acceleration of connected segments (the Coriolis and centrifugal forces). The effect of such coupling can be quite complex and difficult to capture without simulation.

Despite this complexity of multi-link dynamics, humans are capable of performing a wide variety of movements with ease. How do humans circumvent this complexity? One possibility is the so-called “inverse dynamics” approach. Hollerbach and Atkerson (1987) proposed that the CNS solves the inverse kinematics problem to determine joint trajectories from the desired limb endpoint trajectory, then explicitly derives the necessary muscle forces using an inverse dynamics solution. Such computations imply internal estimates of body segment inertial parameters and dimensions and muscle moment arms by the CNS. It also implies that the central nervous system explicitly performs an extremely demanding computation. However, this approach does not take into account the mechanics and dynamics of the muscles and neural feedback circuits. An alternative approach assumes a look-up table instead of the
complex computation [Albus (1975), Raibert (1976)]. However, such tables may become very large, making this approach less likely. An alternative and simpler approach suggests that the CNS utilizes the effective dynamic and mechanical behavior of the muscles and neural feedback circuits to circumvent the computational complexities of coordinating multi-joint motions. The muscles and neural control circuits have the "spring-like" property: muscle force varies with muscle length under constant neural input. For a single joint, the combined action of a group of muscles spanning the joint, both agonists and antagonists, defines an equilibrium posture for the joint. Changing the inputs to the muscles defines another equilibrium position, and the joint will tend to move to a new equilibrium position. The equilibrium point control hypothesis for single-joint motions was originally proposed by Feldman (1966).

Two versions of the equilibrium point control hypothesis exist: "alpha" and "lambda" models. While both models are based on spring-like property of a muscle or a muscle-reflex system, the assumed inputs to two models are different. The alpha model is based on the inherent spring-like property of muscle without sensory feedback [Bizzi et al. (1984)]. The lambda model pioneered by Feldman (1966) attempts to explain that the spring-like behavior results from the muscles coupled with their reflex loops.

This equilibrium point control hypothesis applies to the control of both static posture and voluntary movement [Bizzi et al. (1992)]. Central command may generate a series of equilibrium points for a limb, and the "spring-like" properties of the neuromuscular system will tend to drive the motion along a trajectory that follows these intermediate equilibrium postures.
Figure 3.1 One-dimensional model of equilibrium point control

Figure 3.1 illustrates a mechanism of equilibrium point control in one-dimensional motion. Mass $M$ is driven by the force caused by stiffness $K$ and damping $B$, and the difference between equilibrium position $x_0$ and actual position $x$. Here, equilibrium position $x_0$ serves as a control input to the simple mechanical system. Flash (1987) and Won and Hogan (1995) demonstrated that equilibrium point control can be used to model two-link planar reaching motions of the arm at moderate speeds. Using experimentally measured stiffnesses and equilibrium point trajectories with a bell-shaped velocity profile, the simulations captured the kinematic features of experimentally measured trajectories.

In limb movements, the actual trajectory depends on environmental perturbations as well as the equilibrium point trajectory, commanded impedance, and limb dynamics. Equilibrium point control applies the same strategy to tasks requiring interaction with the environment, unrestrained motions, and the transition between the two. Control of contact force can also be achieved through the use of an equilibrium point. Simply moving the equilibrium point within a contact object will cause the limb to exert a force on that object. This in itself does not guarantee contact stability. However, studies by Colgate and Hogan (1988) proved that an actively controlled manipulator can maintain stable contact with an arbitrary passive object if and only if the mechanical impedance of the manipulator is equivalent to the passive object. Equilibrium point control circumvents the stability problem, which is common in contact tasks using robots.
However, there have been years of controversy over the validity of the equilibrium point control hypothesis. Many investigators argued against the equilibrium point control hypothesis, claiming that the brain sends as a motor command only an equilibrium-point trajectory similar to the actual trajectory. They provided experimental evidence that the brain controls the movement, doing all the calculations to figure out all muscle activities. It is reasoned that complex computations are required to generate the motor command because of nonlinear interaction forces between many degrees of freedom of the limb [Pennisi (1996), Gomi and Kawato (1996)]. Indeed, there is considerable evidence that the motor control system takes into account the dynamic properties of the limb as can be seen in preprogrammed or anticipatory reactions [Shadmehr and Mussa-Ivaldi (1994)].

3.2 Experiments of Human Leg
In this section, characteristics of the human leg are explored through measurements of performing simple reaching motion, impulsive motion, and postural stiffness.

3.2.1 Experimental Setup
A two-link manipulator measures the position of the foot and the force exerted by it. A 486 PC is used to control the movement of the manipulator and to sample the position and force data from the manipulator at a frequency of 200 Hz. Two D.C. motors apply torques at the elbow and shoulder joints to generate manipulator motion. Position is measured at the manipulator's joints by optical encoders while force is measured from torques at the elbow and shoulder joints of the manipulator using Jacobian transformation. To eliminate the effect of gravity, subjects lie laterally so that their sagittal planes are parallel to the horizontal plane, and the movements of their legs are contained in the plane. Trunk of the subject is fixed to the table, serving as a base. The hip and knee joints are free to move allowing a two degree-of-freedom motion. A brace is used to lock the ankle joint at 90°. The foot is pin-jointed to the endpoint of the manipulator between the arch and the heel of the foot. Specifically, this position is determined by extending the imaginary line which joins the knee and ankle joints. A
sling supports the other leg of the subject to prevent interference with the motion of the measuring leg. Figure 3.2 shows the computer-controlled two-link manipulator and the subject.

![Diagram of experimental setup]

Figure 3.2 Experimental setup for leg movement measurement

### 3.2.2 Measurement of Reaching Motion

**Methods**

In experiments which examined reaching motion, subjects were instructed to move their feet between two *unspecified* targets as they would normally reach their feet from one point to another. Movements of two degrees-of-freedom, with free hip and knee joints, were measured using the manipulator described above. Here, a brace was used to immobilize the ankle.

The data from the movement experiments consisted of the time history of the manipulator joint angles during each movement. Since the manipulator was equipped solely with encoders, numerical differentiation of the position data were necessary to estimate joint velocities and accelerations. From this estimation, the position, velocity and acceleration of the foot could be found by Jacobian transformation.

\[
\nu = J_M \omega \tag{3-1}
\]

\[
a = J_M \dot{\omega} + J_M \ddot{\omega} \tag{3-2}
\]
where \( J_M \) is the manipulator Jacobian matrix.

**Results**

Figure 3.3 shows the trajectories of foot reaching motion from four subjects. The trajectories were roughly straight. They show the same curvature while they all have different starting and finishing points.

Figure 3.4 shows velocities corresponding to the point-to-point movements. It is noteworthy that the velocity profiles have asymmetric unimodal bell shape.

![Trajectories during foot reaching motion](image)

**Figure 3.3 Trajectories during foot reaching motion**
The point-to-point movement by foot showed nearly identical features as planar hand reaching motion demonstrated in previous arm experiments [Morasso (1981), Abend et al. (1982), Flash (1987), Won and Hogan (1995)]. While all the trajectories of foot reaching movements were fairly straight, movements with locked ankle showed unique curvature. Velocity profile during point-to-point motion had a characteristic bell shape. Arm movement experiments showed that the hand of the subject generates essentially a straight path from start to finish with a characteristic bell-shaped tangential velocity profile during self-placed point-to-point reaching movements [Morasso (1981), Abend et al. (1982)].
3.2.3 Measurement of Impulsive Motion

Methods
In impulsive movement experiments, subjects were instructed to make a series of sharp jerky motions or kick-and-return motions of the foot. They were informed that the amplitude of their movements was not important but that they should attempt to make their movements as abrupt as possible. As in the reaching experiments, the time history of foot position was recorded. The data was processed to yield its discrete-time Fourier transform and power spectral density. It was reasoned that an impulse as an extremely abrupt movement would include the highest frequency components that the subject was capable of producing. Thus, power spectral density was used as an estimation of the bandwidth of foot motion.

Results
Some typical results are shown in Figures 3.5 and 3.6. Figure 3.5 illustrates the foot displacement from one subject during impulsive motion. Rise times were typically between 200 and 300 milliseconds. Figure 3.6 shows power spectral density of the displacement, where the unit of power spectral density is arbitrary. The bandwidth of the motion was lower than 5 Hz.

Figure 3.5 Displacement during impulsive motion

(Subject D)
In his hand motion study as a part of teleoperator design, Paines (1987) reported that rise time for a human arm motion is around 60 milliseconds and that its bandwidth is between 20 and 30 Hz. The results in this study showed much slower leg response. This probably results from the fact that the human leg has larger inertia and longer limb length than arm.

3.2.4 Measurement of Postural Stiffness

Methods
The static components of the human leg impedance were measured by a procedure similar to the experiment used by Mussa-Ivaldi et al. (1985). While no such tests have been performed for the lower limb, it seems reasonable to assume that common mechanisms apply to both the arm and the leg. The basic method is as follows: provide a perturbation that induces a displacement of the foot and then relate the evoked force to the input displacement to estimate the stiffness. The ankle of the subject was locked by a brace so that only the hip and knee joints were free. After the foot of the subject was moved to a reference position, displacements in three different directions were applied to the foot by the manipulator. The displacements were given in directions of 90°, 135° and 180° from x-axis as shown in Figure 3.7. The magnitude of these displacements ranged from 3 to 5 cm, and the resulting displacement and force imposed at the foot were
recorded. During the procedure, the subject was instructed “not to resist voluntarily,” so that only passive static response could be measured.

![Diagram of displacement application in stiffness measurement](image)

**Figure 3.7** Directions of displacement application in stiffness measurement

Each of the two manipulator joints was controlled independently by using linear position and velocity feedback law:

\[
\tau = J_M^T (P(x - x_o) + D\dot{x})
\]  

(3-3)

where \(\tau\) is composed of the controlled motor torques, \(J_M\) is the manipulator Jacobian matrix, \(x\) is the actual endpoint position, \(x_o\) is the desired position, and \(P\) and \(D\) are control gains for manipulator motors. The perturbation applied was a ramp in the commanded position vector \(x_o\) from a reference posture of the subject in a given direction. The procedure was assumed to be quasi-static since the ramp occurs over a long enough period.

The collected data consisted of \(x\)-and \(y\)-position of the foot and controlled motor torques at the manipulator joints. Force at the foot or at the endpoint of the manipulator can be found using the manipulator Jacobian \(J_M\):

\[
F = J_M^{-\tau} \tau
\]

(3-4)

where \(F\) is reaction force at the foot.
From the data set collected in three directions, the stiffness field at the foot was estimated by the procedure similar to the experiment used by Mussa-Ivaldi et al. (1985). While the force-displacement function for muscle is fundamentally nonlinear, the function can be considered linear for small displacements about the equilibrium. Therefore the two dimensional relationship of the displacement and corresponding force can be expressed as

\[
F_x = -K_{xx} \Delta x - K_{xy} \Delta y \quad (3-5a)
\]

\[
F_y = -K_{yx} \Delta x - K_{yy} \Delta y \quad (3-5b)
\]

where \(F_x\) and \(F_y\) are the components of the restoring force, \(\Delta x\) and \(\Delta y\) are the components of the imposed displacement, and \(K_{xx}, K_{xy}, K_{yx}\) and \(K_{yy}\) are the linear stiffness terms in the posture. These two equations can be expressed in the form of a stiffness matrix \(K\).

\[
F = - K \Delta x
\]

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} =
\begin{bmatrix}
K_{xx} & K_{xy} \\
K_{yx} & K_{yy}
\end{bmatrix}
\begin{bmatrix}
\Delta x \\
\Delta y
\end{bmatrix}
\]  

(3-6b)

From three sets of force and displacement data measured in three directions, four elements of linear stiffness matrix can be estimated.

The endpoint stiffness field measured at a reference posture can be transformed into the stiffness in joint space using the leg Jacobian matrix \(J_L\). The joint stiffness \(K_J\) can be estimated as follows:

\[
K_J = J_L^T K J_L
\]

(3-7)

**Results**
The linear stiffness matrix estimations from force and displacement measurements are given in Table 3.1. The stiffness matrices are averaged from four experiments for each subject. The stiffness matrices can be characterized by their eigensolutions. The eigenvalues represent major and minor stiffness, and their corresponding eigenvectors
represent their directions. The directions of minor axes point approximately to the hip for all the subjects. Note that the minor stiffness is nearly null for subject $D$. Null stiffness implies that the leg can not impede the force applied in this direction.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Endpoint stiffness matrix (N/m)</th>
<th>Eigensolution: Eigenvalue (Direction of Eigenvector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$\begin{bmatrix} 562.7 &amp; 587.8 \ 741.2 &amp; 955.1 \end{bmatrix}$</td>
<td>Major: 1448 ($56.4^\circ$) Minor: 140 ($-40^\circ$)</td>
</tr>
<tr>
<td>$B$</td>
<td>$\begin{bmatrix} 269 &amp; 778.6 \ 294.5 &amp; 897.2 \end{bmatrix}$</td>
<td>Major: 1156 ($49^\circ$) Minor: 10.4 ($-18.4^\circ$)</td>
</tr>
<tr>
<td>$C$</td>
<td>$\begin{bmatrix} 979.1 &amp; 760.5 \ 797.7 &amp; 1162.9 \end{bmatrix}$</td>
<td>Major: 1855.3 ($56.4^\circ$) Minor: 286.7 ($-42.3^\circ$)</td>
</tr>
<tr>
<td>$D$</td>
<td>$\begin{bmatrix} 536.7 &amp; 849.4 \ 733.0 &amp; 1160.2 \end{bmatrix}$</td>
<td>Major: 1696.9 ($53.8^\circ$) Minor: 0.082 ($-32.3^\circ$)</td>
</tr>
</tbody>
</table>

From the endpoint stiffness field measured at a reference posture, the stiffness in joint space was calculated using Equation 3-7. The estimated joint matrices are given in Table 3.2. The joint matrices appear to be nearly symmetric. The directions represent the angle between the major axis and horizontal axis in joint space. The directions of the major axes point approximately $-35^\circ$ for all the subjects. Note the minor stiffness of four distinct subjects have similar major and minor eigenvalues. When the endpoint stiffness is transformed into the joint stiffness, the minor stiffness becomes even smaller compared to the major stiffness. This suggests that the stiffness field can be marginally stable or slightly unstable. The system instability will be further discussed later in this chapter.
### Table 3.2 Joint stiffness matrices

<table>
<thead>
<tr>
<th>Subject</th>
<th>Joint stiffness matrix (Nm/rad)</th>
<th>Eigensolution Eigenvalue (Direction of Eigenvector)</th>
</tr>
</thead>
</table>
|         | \[
| A       | \[
|         | \[
| B       | \[
| C       | \[
| D       | \[

The symmetric component of the stiffness matrix \( K_{symm} = \frac{K + K^T}{2} \) can be graphically represented as an ellipse characterized by the magnitude (area of ellipse), shape (the ratio of major and minor axes), and the orientation (direction of the major axis). In their arm stiffness study, Mussa-Ivaldi et al. (1985) plotted the stiffness ellipses of one subject in several different arm configurations. In each arm posture the ellipse was oriented to keep the *major* axis pointed toward the shoulder. Postural stiffness of the leg shows characteristics which are somewhat different from those of arm stiffness as can be seen in Figure 3.8. For all the subjects, the *minor* axes of the endpoint stiffness pointed toward the hip.
Mussa-Ivaldi et al. (1985) also postulated that the shape and orientation of the stiffness ellipse in joint space is invariant over all tested postures and that the change in endpoint stiffness could be explained by the geometric transformation of the joint stiffness to the endpoint stiffness. This consistency in joint space can also be found in the leg stiffness. Figure 3.9 illustrates the stiffness ellipse in joint space. While eigensolutions in Cartesian coordinate vary from subject to subject (Figure 3.8), those in joint space show an impressive consistency.
In measuring stiffness, the experimenter relied on the subjects to not resist voluntarily against the applied displacement. However, it is inevitable that the subjects respond to the disturbance by applying sudden force to the manipulator. The validity of the data was checked by examining its consistency over a number of different trials and subjects. Both Mussa-Ivaldu et al. (1984) and Shadmehr et al. (1992) showed that consistent results could be achieved with this “do-not-resist-voluntarily” instruction.
3.3 Simulation of Mathematical Model

This section attempts to recreate the experimental results in the preceding section by computer simulations of a mathematical model of the human leg. The findings in the preceding section raise a question of whether there exists a simple motor program in human leg movement. One of the possible candidates is the equilibrium point control hypothesis discussed in 3.1. In simulating a simple reaching motion, the leg is modeled as a simple planar mechanism of two links rotating in a plane. In calculating the motor control input, the equilibrium point control (EPC) model is used.

3.3.1 Mathematical Modeling

The two-link planar model of the lower limb, shown in Figure 3.10, is constrained to move in the sagittal plane, and has two degrees of freedom corresponding to the knee and hip joints. Each segment is modeled as a rigid body, and they are connected to each other by frictionless pin joints. The thigh and shank-foot segments have masses $m_1$ and $m_2$, respectively. Likewise, the respective centroidal moments of inertia are $I_1$ and $I_2$.

![Diagram of two-link model of human leg]

Figure 3.10 Two link model of human leg

Inertial properties of the body segments were estimated by regression equations, which were determined by Jackson (1997). It can be assumed that the centers of mass (CM) of the thigh and shank segment are located along the lines between the proximal and distal joints. In reality, the CM’s of these segments lie approximately 1-2 cm posterior to the lines connecting the joints [Jackson (1997)].
Figure 3.10 shows angular convention to describe the configuration of the linkage. The angular convention $\Phi$ defines the relative joint flexion between adjacent segments. The hip angle $\phi_i$ is defined with respect to the reference position. In this angle convention, joint flexion is positive. Thus, a clockwise rotation of the shank with respect to the thigh is positive, while a counterclockwise rotation of the thigh with respect to $x$-axis is considered positive. The joint torques corresponding to these joint angles are denoted by $Q$. Therefore, flexional torques are positive, adhering to the angular convention.

The dynamics equations governing the motion for this model are derived using a Lagrangian approach [Asada and Slotine (1986)]. The general form for the dynamics equations is given by Equation 3-8:

$$H(\Phi)\ddot{\Phi} + h(\Phi, \dot{\Phi}) + G(\Phi) = Q$$  \hspace{1cm} (3-8)

where $H(\Phi) = 2 \times 2$ moment of inertia matrix

$h(\Phi, \dot{\Phi}) = 2 \times 1$ rate dependent vector

$G(\Phi) = 2 \times 1$ gravitational vector

Here the gravitational terms are zero since the sagittal plane is in the horizontal plane.

The equilibrium point control (EPC) model described in section 3.1 can be extended to the two degree-of-freedom link case. While muscle force is a complicated function with many variables, the mechanical property of a muscle may be simplified to be a function of muscle length and its rate of change. Hence, leg muscle groups may be modeled as a combination of linear torsional springs and dampers as postulated in the arm models by Hogan (1984) and Flash (1987). Thus, the resultant joint torques are assumed to be dependent only on deviation of the actual trajectory from the equilibrium point trajectory and on joint velocity. These joint torques serve as a driving force of leg motions as in one degree-of-freedom case described in section 3.1. The following equation gives the joint control torques as a function of the instantaneous difference of actual and equilibrium point trajectories and joint velocity.
\[ Q = -K_j(\Phi - \Phi_o) - B_j \dot{\Phi} \]  
\[ K_j = \begin{bmatrix} k_{hh} & k_{hk} \\ k_{kh} & k_{kk} \end{bmatrix} \]  
\[ B_j = \begin{bmatrix} b_{hh} & b_{hk} \\ b_{kh} & b_{kk} \end{bmatrix} \]

where \( Q \) = vector of joint torques  
\( \Phi, \dot{\Phi} \) = vector of joint angles and rates  
\( \Phi_o \) = vector of equilibrium point joint angles  
\( K_j \) = joint stiffness matrix  
\( B_j \) = joint damping matrix

Here, subscripts \( H \) and \( K \) denote hip and knee joints, respectively. Note that the form of the damping for the simulation is in terms of absolute velocity rather than velocity relative to the virtual velocity.

The EPC model was used in simulating a simple reaching motion by foot. Additional assumptions for the EPC model in foot reaching motion are as follows:

- Linear and time-invariant impedance:
  Stiffness matrix \( K_j \) and damping matrix \( B_j \) are assumed to be linear about the equilibrium position and the velocity, respectively. They are also constant over the entire range of movements regardless of the posture.

  In addition, this model also assumes that matrices are constant during the entire movement. Consequently, the joint impedance remains linear and time-invariant although the endpoint impedance or Cartesian impedance at the foot continues to vary with leg configuration. From study of the human arm, change of passive impedance appears not to occur until more than 1200 ms after onset of a transient force, while the human sensorimotor response times are typically 250 ms or less [Fayé (1983), Hogan (1989)].

- Minimum-jerk equilibrium point trajectory as a motor program:
The driving input to the EPC model is a equilibrium point trajectory that is a straight line in Cartesian space from the initial position $x_i$ to the final position $x_f$. This trajectory has a minimum-jerk velocity profile taking the equilibrium point from the start to the finish. The minimum-jerk displacement and velocity functions are determined by the following equations and are shown in Figure 3.11.

\[ x(t) = x_i + (x_f - x_i)(10\tau^3 - 15\tau^4 + 6\tau^5) \quad (3-10) \]
\[ v(t) = (x_f - x_i)(30\tau^2 - 60\tau^3 + 30\tau^4)/t_f \quad (3-11) \]

where $\tau = t/t_f$.

Here, $\tau$ is normalized time, and $t_f$ is the duration of movement.

Motor programs for all reaching movements of the EPC model can be generated simply by translating and scaling the minimum-jerk functions described above.

![Minimum-jerk displacement](image1.png)

![Minimum-jerk velocity](image2.png)

Figure 3.11 Minimum-jerk equilibrium point trajectory
3.3.2 Simulation of Foot Reaching Movement

Methods

The procedure to simulate reaching motion of the foot is similar to works of Flash (1987) and Won (1993). With a minimum-jerk equilibrium point trajectory and the measured postural stiffness as simulation inputs, a point-to-point reaching motion was recreated and compared with the experimentally measured movement. Figure 3.12 illustrates the simulation procedure. The equilibrium point trajectory in Cartesian coordinate is transformed into leg joint coordinate Φ using geometry of the two-link leg model. Under the assumption that stiffness is greater in motion than in static posture, the value of each element in the measured stiffness matrix was multiplied by a scaling factor. The scaling factor ranged between 9 and 13 for outward reaching motion. For inward motion, the scaling factor was between 4 and 6. While each element of the stiffness matrix was multiplied by different scaling factors, the scaled matrix is nearly identical in shape to the postural stiffness matrix. Also, damping matrix is assumed to be proportional to the scaled stiffness matrix with a time constant τ = B/K. The time constant was chosen to be 0.05 sec as in works of Flash (1987) and Won (1993) for arm movement.

Figure 3.12 Simulation procedure
Results
Simulation results from four subjects are shown in Figures 3.13 and 3.14. Figure 3.13 compares the simulated trajectories with the actual trajectories from measurement. All the motions were outward with the exception of subject A. While the simulated paths closely resemble the measured ones, the paths resulting from the simulations failed to reproduce the unique curvature existent in those from measurement. Figure 3.14 compares simulated and measured velocity profiles. The simulations produced the typical bell-shaped velocity profiles, and the profile peaks were close to those of the measured velocities.

![Graphs a) Subject A, b) Subject B, c) Subject C, d) Subject D](image)

Figure 3.13 Comparison of trajectories from measurement and simulation
(solid line: measured trajectory, dashed line: simulated trajectory)
Figure 3.14 Comparison of velocity profiles from measurement and simulation
(solid line: measured profile, dashed line: simulated profile)

Simulated trajectories showed features such as straight paths and bell-shaped velocity profiles. With a single minimum-jerk equilibrium trajectory as an input, the features of simulated trajectories paralleled those of measured movement. As postulated by Flash (1987) and Won and Hogan (1995) in their arm motion studies, an equilibrium point control model was able to recreate the kinematic features of leg reaching motion.
3.3.3 Stiffness Estimation

Methods
This section attempts to estimate stiffness from the difference between measured reaching motion and assumed equilibrium point trajectory. First, inverse dynamics of the two-link leg model calculated joint torques at hip and knee joints from the measured movement. Using these calculated joint torques along with the measured movement and assumed minimum-jerk equilibrium point trajectory, stiffness was estimated and compared with the measured stiffness. This procedure is nearly identical to the simulation of the three-link model by Jackson (1997). Figure 3.15 illustrate the estimation procedure.

The stiffness and damping matrices are constrained to be symmetric \((K_{HK} = K_{KH}, B_{HK} = B_{KH})\), which seems reasonable from the results of stiffness measurements. Based on the symmetry of the matrices, three independent stiffness elements and three independent damping elements were estimated. The joint torques at hip and knee joints were estimated using the inverse dynamics solution. Since joint torques, joint angles and
their rates are determined, Equation 3-9 provides two simultaneous equations with six
unknowns at each sampling time. These equations can be restated in a form conducive to
a least squares estimate of the unknown elements:

\[
\begin{bmatrix}
\Delta \phi_{hi} & 0 & \Delta \phi_{ki} & \dot{\phi}_{hi} & 0 & \dot{\phi}_{ki} \\
0 & \Delta \phi_{ki} & \Delta \phi_{hi} & 0 & \dot{\phi}_{ki} & \dot{\phi}_{hi} \\
\end{bmatrix}
\begin{bmatrix}
k_{hi} \\
k_{kk} \\
k_{hk} \\
b_{hh} \\
b_{kk} \\
b_{hk}
\end{bmatrix}
= 
\begin{bmatrix}
\cdot \\
\cdot \\
\cdot \\
-\dot{Q}_{hi} \\
-\dot{Q}_{ki} \\
\cdot
\end{bmatrix}
\] (3-12)

where \( \Delta \phi = \phi - \phi_o \)

\( \phi_o \) = equilibrium joint angle for joint

\( i \) = sample number

This can be presented in a matrix form as follows:

\[ A \cdot X = T \] (3-13)

where \( A \) = matrix of joint angle deviation and joint rates

\( X \) = vector of stiffness and damping elements

\( T \) = vector of joint torques

Using least-squares estimation, the stiffness and damping elements can be estimated by:

\[ \hat{X} = (A^T \cdot A)^{-1} A^T T \] (3-14)

where \( \hat{X} \) = estimated stiffness and damping vector
Each sample provides two independent equations, which means at least three data samples are required to estimate the six independent elements.

**Results**
The estimated stiffness matrices from four subjects are given in Table 3.3. The estimations are compared with the stiffness from measurement in the table. Figure 3.16 illustrate the corresponding stiffness ellipses in joint space. The stiffnesses of subjects $B$, $C$, and $D$ were estimated during outward reaching motion, while the stiffness of subject $A$ was estimated from inward motion.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Stiffness matrix from estimation (Nm-rad)</th>
<th>Stiffness matrix from measurement (Nm-rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$\begin{bmatrix} 247.0 &amp; -121.5 \ -121.5 &amp; 245.4 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 642.1 &amp; -511.1 \ -478.0 &amp; 387.8 \end{bmatrix}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$\begin{bmatrix} 697.1 &amp; -144.7 \ -144.7 &amp; 27.5 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 616.8 &amp; -366.3 \ -468.8 &amp; 279.3 \end{bmatrix}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$\begin{bmatrix} 3663.2 &amp; -1263.7 \ -1263.7 &amp; 568.9 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 778.0 &amp; -574.7 \ -565.8 &amp; 459.1 \end{bmatrix}$</td>
</tr>
<tr>
<td>$D$</td>
<td>$\begin{bmatrix} 1335.4 &amp; -674.4 \ -674.4 &amp; 342.5 \end{bmatrix}$</td>
<td>$\begin{bmatrix} 849.3 &amp; -583.6 \ -609.0 &amp; 418.5 \end{bmatrix}$</td>
</tr>
</tbody>
</table>
Figure 3.16 Estimated stiffness ellipse in joint space

The most puzzling result from this estimation is the large dispersion in estimates of stiffness magnitudes. While the signs of the matrix elements show consistency, the magnitudes ranged widely from the order of 100 to 1000. In Figure 3.16 the shape of the estimated stiffness matrix appears to be similar to that of the measured matrix in spite of the dispersion in magnitudes. Despite some discrepancy in stiffness estimation from movement, it appears that the equilibrium point control model recreates qualitative features of experimental results of planar leg motion.

This discrepancy between estimated and measured stiffness seems to result mainly from the sensitivity of the stiffness estimate to the difference of the assumed equilibrium point trajectory and measured trajectory. If the equilibrium point trajectory is too far from or too close to the measured trajectory, the stiffness estimate will be in
error and will be too small or too large in magnitude, respectively. Moreover, selecting
the starting and finishing points of the reaching motion from measured data was not
trivial. Unfortunately these values have a strong effect on shaping the equilibrium point
trajectory and in turn, on the stiffness estimation. Also, the inertia parameters used in the
simulations were calculated from simple regression equations based only on gender,
height, and weight of the subject. It is unclear whether these parameters are sufficiently
accurate for the purpose of the simulations. Since human legs have relatively large
inertia, errors in the inertia parameter may have had a considerable effect on the
simulation results.

3.4 Discussion on Human Leg Motion Analysis
This chapter examined the general features of human leg motion through experiments and
numerical simulations. The findings from the experiments and simulations are:

- Point-to-point reaching motion by foot travels in a roughly straight path.
- The motion has a bell-shaped velocity profile with a single peak.
- Leg movements are much slower than arm movements.
- Postural stiffness of the leg appears to be marginally stable.
- Preprogrammed open-loop motion.

The features found in the experiments were similar to those which can be found in
arm motion studies [Mussa-Ivaldi (1985), Flash and Hogan (1985)]. In her arm
movement simulations, Flash (1987) showed that the equilibrium point control
hypothesis is competent to predict simple point-to-point reaching motion. As one of the
candidates for motor program producing foot reaching motion, this equilibrium point
control hypothesis was tested by numerical simulations. While the stability of the
stiffness field is questionable, the equilibrium point control model seems to consistently
recreate experimental results. It is an implicit assumption that the equilibrium point
hypothesis requires the stability of the limbs during movement as well as posture.
However, stability is not a requirement for the movements of human limbs [Bizzi et al. (1992)].

It should be noted that the purpose of this chapter was not to validate any particular motor control theory, but rather to explore and understand the representative properties of the drivers' braking motion as it relates to the characteristics of the human leg movement.
CHAPTER 4

DESIGN OF BRAKE SYSTEMS AS A TELEOPERATOR

The poor performance of conventional brake systems even with ABS results from the open-loop nature of braking maneuvers. In braking the driver depends on his senses (visual, vestibular, auditory, etc.) to receive information about on-going traffic, and his task is to manipulate mechanical devices – brake pedal or gas pedal - in order to stop his vehicle according to on-going traffic. The driver is usually represented as a system having mainly a visual input and a displacement or force output into the brake pedal. To produce a desired pedal displacement the driver must produce a force determined by the mechanical stiffness or impedance of the brake pedal; to produce a desired force requires a particular displacement, also determined by the impedance. The impedance characteristic of the brake pedal may have a strong effect on the driver’s braking performance.

In manual control studies, it is recommended that the control handle be designed so that the dynamics between force on the handle and handle displacement are similar to the dynamics between force on the handle and system output [Herzog (1968)]. This makes the handle a tactile-kinesthetic display of output as well as an input device and provides better dynamic compatibility between system output and the operator’s response. However, currently the brake pedal is not designed to display the braking performance, but rather as a simple input device. Even with ABS, pulsing at the brake pedal only indicates ABS activation; this signal does not serve as an intuitive cue of braking performance since vibration is commonly used as a warning or an indicator of malfunction of the system.

An automotive brake system can be considered to be a type of teleoperator rather than a simple open-loop manipulator. The foot-pedal interface can be modeled as a master port, and tire-road interface as a slave port. Teleoperator studies report that force feedback enhances teleoperator performance [Bejczy and Salisbury (1980), Raju (1988)]. In fly-by-wire aircraft, the control stick delivers the force “feel” to the pilot when the
plane is near stall. This kind of force feedback can also be applied to the design of brake systems.

This chapter introduces background on teleoperators and develops idea for new brake systems as teleoperators.

4.1 Background on Teleoperator

Sheridan (1992) defined a teleoperator as “a machine that extends a person’s sensing and/or manipulating capability to a location remote from that person.” A teleoperator includes sensors of the environment, communication channels to and from a human operator, and a manipulator to apply forces and perform mechanical work on the environment. The operator in a remote location gives direct and continuous commands that are executed in real time by the manipulator. Problems may be encountered owing to the remoteness of the tasks. Many of the sensations necessary to perform a task may not be available. Performance can be improved by providing the operator with some of these sensations.

A master-slave manipulator is a teleoperator where the manipulator mimics the operator’s own motions, usually hand motions. The human operator, the master-slave manipulator, and the remote task comprise a remote manipulation system. The manipulation requires the transfer of energy between the operator and the manipulator as well as between the manipulator and the task. At the master port, the master-slave manipulator interacts with the operator; at the slave port it interacts with the task in the remote environment. The important variables in the interactions are those that describe the power flow: the contact forces and the velocities (and positions). Raju (1988) suggested the master-slave manipulator be modeled as a two-port mechanical system, analogous to two-port electrical networks. Figure 4.1 shows the electrical network model and bond graph model of the remote manipulation system: the human operator, the master-slave manipulator, and the task.
Figure 4.1 Network and bond graph model of a remote manipulator system
[Raju (1988)]

One of the technical issues in teleoperation is how to reproduce the bidirectional properties of mechanical energy flow. The term “force feedback” suggests that the teleoperator sense velocity or position of the operator and apply the appropriate force to the operator. The operator’s positioning tool (joystick or handgrip) can be driven to apply reaction forces to the operator’s hand while he attempts to move it to the desired position. This results in a transfer of energy that mimics the transfer between the manipulator and the environment. The operator feels as though he is applying the force to the environment directly. In fact, force feedback is a popular method of simulating kinesthetic interaction, but the opposite method is also possible; the teleoperator senses force and applies velocity feedback to create the same mechanical energy flow. Force
feedback is useful in interacting with remote tasks up to a certain level, beyond which performance will not improve significantly. Other criteria such as operator fatigue, comfort and limb strength should be considered in force feedback design of teleoperators.

The level of force feedback that the operator feels can be determined by the specification of the master port impedance. Raju (1988) showed that it is advantageous to adjust master and slave impedances depending on the task characteristics. In a contact task using the teleoperator, before the manipulator contacts with the task object, the slave port impedance should be low, while the master port impedance should be high, so that contact can be sensed but without the excessive force on the task object. After contact, the slave port impedance should be increased so that the task can be executed with adequate position control, while the master port impedance should be reduced to provide a comfortable yet adequate level of force feedback to the operator. The selection of impedance at master and slave ports depending on the characteristics of the operator and the task is an area to be explored further.

Studies in teleoperation continue to try to eliminate the sense of remoteness, to let the operator perform the task as easily as if he is doing it directly; this concept is known as “telepresence.”

4.2 Design Considerations for Brake Systems

For design of new brake systems, two aspects are considered: the driver’s braking motion and the modeling of brake system as a teleoperator.

4.2.1 Modeling of Braking Motion

While manual or hand controls are more widely employed than foot controls in operating machines, a brake pedal is used in conventional brake systems. Indeed, the feet are slower and less accurate than the hands. Besides this, foot controls restrict the posture of the operator. Several important design parameters affect performance with foot controls, such as the placement of the pedal relative to the operator, whether the ankle is used in pressing the pedal and the location of the fulcrum (if needed). In evaluating pedal designs various criteria are employed, such as reaction time, travel time, speed of
operation, precision, force produced and subjective preference [Sanders and McCormick (1993)]. This section is not intended to provide detailed design guidance on brake pedal design, but rather to illustrate how characteristics of human leg motion have a bearing on design of brake pedal.

In chapter 3, the general features of leg motion were examined. To summarize the results from the proceeding chapter, the features of leg motion are as follows:

- Foot reaching motion with locked ankle travels in a slightly curved path.
- Foot reaching motion with locked ankle has bell-shaped speed profile.
- Foot motion is much slower than hand motion.
- Results from planar foot reaching motion simulation are consistent with the equilibrium point control hypothesis.

![Figure 4.2 Action path of brake pedal](image)

In conventional brake pedals, the lever arm is pivoted from above the pedal (Figure 4.2), and this makes the action path of the pedal nearly normal to the natural path of the foot. This allows the driver to produce his maximum leverage [Woodson and Conover (1964)]. The leg motion with a locked ankle has the same curvature as that of the pedal action path. The longer length and larger inertia of the leg makes the leg motion slower than arm motion. Simulation of the EPC model in the preceding chapter suggests the open-loop nature in foot reaching motion. From the general leg motion analysis and features of the brake pedal, the braking motion by a human leg can be modeled as follows:
• Braking motion has two degrees of freedom with free hip and knee joints.
• Initial braking motion is a simple open-loop reaching motion by the foot with no visual target.
• Braking motion is a movement in free space followed by contact with the brake pedal.
• Braking motion is a preprogrammed motion with no closed-loop feedback until after initial brake pedal depression.

The fact of preprogrammed braking motion suggests that drivers have the same command from the central nervous system (CNS) in movements both in free space and in contact with the brake pedal. It also suggests the input commands are the same for different brake pedal impedances. It can be inferred that further pedal depression will be induced with a softer brake pedal under the same CNS command. This assumption is key to a proposed brake system design described below.

4.2.2 Modeling of Brake System as a Teleoperator
While control of conventional brake systems with or without ABS is performed initially in open-loop manner, the brake system can be modeled as a teleoperator with poor performance feedback to the operator, where at the tire-road interface the braking task is performed by the remote driver using the brake pedal. If ABS is modeled as a teleoperator (Figure 4.3), the braking task in an automobile is analogous to a contact task or to grabbing an object using a teleoperator.

In grabbing an object using a teleoperator, the operator should apply enough force on the handgrip or joystick to achieve enough contact force between the manipulator and the task object. In a braking task using ABS, the driver should apply enough force to the brake pedal to achieve enough braking force at tire-road contact. Keeping the maximum braking force in ABS can be considered as keeping contact with the task object in teleoperation. In ABS the signal indicating the maximum braking is a non-intuitive vibration from the brake pedal; in teleoperation contact with a task object can be sensed.
by force feedback to the operator. As noted earlier it is believed that the required force with force feedback can be achieved by change of impedance at the master port or the brake pedal.

![Diagram of brake system as a teleoperator]

While visual or auditory signal is also available, force feedback or kinesthetic display appears to be more promising in the braking task, where the driver’s visual or auditory sense is usually occupied by other information. While much importance is typically placed on our visual sense, it is the kinesthetic sense that provides us with much of the information necessary to modify and manipulate the world around us. There is a fundamental difference between kinesthetic information and that of visual and auditory displays. The visual and auditory channels are unidirectional information flows, and they do not involve energetic interaction in the physical variables being sensed [Barfield and Furness (1995)]. In the kinesthetic channel a transfer of energy is involved, and this enables the joystick or brake pedal to serve as a kinesthetic display as well as an input device.

4.3 New Brake System Designs

Two new brake systems are designed based on teleoperator principles.

4.3.1 Proposed Design 1

This system employs the same ABS components, except that it has a servo system to change the pedal impedance instead of pulsing of the pedal on ABS activation. Upon
detection of wheel slippage by ABS sensors, the brake pedal is tuned softer. On a wet/icy road the driver can sense yielding of the pedal instead of vibration from it. If braking motion of the driver is preprogrammed, a sudden change of the brake pedal impedance will induce further depression of pedal, which is advantageous in ABS since large pedal depression induces ABS activation on a wet/icy road. This design is analogous to the teleoperator with adaptive impedance at the master port performing a contact task. For the teleoperator contact task, Raju (1988) suggested softer master impedance and stiffer slave impedance upon contact. This idea is directly applied to brake system design; upon activation of ABS, brake pedal impedance is tuned softer while tire-road contact gets firmer. Figure 4.4 illustrates this brake system design.

![Figure 4.4 Schematic view of design 1](image)

### 4.3.2 Proposed Design 2

Current development of optoelectronic sensors allows us to detect the road surface condition as well as wheel slippage as in ABS. This sensor uses backscattered and reflected light information to detect the presence of ice, water, or mud on road surface [Ciamberlini et al. (1995)]. This new brake system employs the road surface sensor to control the brake pedal impedance in addition to usual components of ABS including the wheel slip sensor. In the proposed design upon detection of a wet/icy road, the impedance of the brake pedal is tuned softer. The driver is able to sense the road condition as he presses down on the pedal. This system is similar to a power steering wheel on icy road; the steering wheel can be turned more easily on an icy road than on a
dry road. This system depends on the correct sensing of road surface condition. Figure 4.5 illustrates this brake system design.

Figure 4.5 Schematic view of design 2
CHAPTER 5

SIMULATOR TESTS

In the study of automobile performance, driving simulators are used for economic and safety reasons. In simulation, the parameters of a car model can easily be modified, and any kind of situation can be simulated without endangering the driver as in a crash or emergency braking incident. Simulators also allow us to investigate the behavior of a combined system of the driver and the vehicle, rather than that of the vehicle by itself.

In driving vehicles, the driver perceives his surrounding environment through visual, auditory and vestibular senses. Among the senses, visual inputs provide the predominant cues. Visual inputs consist of front and side views, subsidiary view (rearview mirror), and instrument signals (speedometer, gages, etc.). Auditory inputs include sounds such as engine and road noise, tire squeal, crash, and wind. Vestibular inputs provide important cues of the vehicular motion. All of these modalities are combined together by the human brain allowing the driver to perceive his surroundings. The driving simulators are intended to provide the driver with these sensory information generated by a computer to produce illusions of being present in a real driving environment. This is an example of so-called virtual presence or virtual reality [Sheridan (1992)]. Throughout the United States, Europe and Japan, a number of driving simulators exist, and their effectiveness in creating the virtual driving environment has been proven in driver-related studies [Yoshimoto (1982), Kappler (1986), Chen (1996)].

To test the applicability of new brake designs developed in Chapter 4, a simplified version of the driving simulator was developed for braking simulations. Using this braking simulator, the performances of new designs were evaluated and compared with conventional brake systems.

5.1 Simulator System

The objective of the braking simulator was to provide a tool to test the braking performance of driver-vehicle systems equipped with various brake systems. The
simulator developed for this study was a simple version of a fixed-base driving simulator. The block diagram for the braking simulator is illustrated in Figure 5.1. The whole simulation system was under control of a PC-Pentium computer, which managed the hardware control, visual display, and braking situation sequence encountered by the driver.

![Block diagram of braking simulator](image)

Figure 5.1 Block diagram of braking simulator

The PC provided the driver with interactive speed control through the brake pedal. The PC processed the brake pedal position or command signal by calculating vehicle and brake system dynamics to yield vehicle motion on the visual display. While a gas pedal was not provided in the simulator, the speed of the car was gradually accelerated back to the reference speed upon release of the brake pedal. A speedometer was also provided to indicate the speed of the driver car. All this information was displayed on the PC monitor screen in front of the driver. The screen was updated at about 20 frames/sec yielding the minimum smooth motion. A general scene viewed by the driver from the seat is shown in Figure 5.2.

![Screen scene](image)

Figure 5.2 Screen scene
To produce a relatively large brake pedal force, an AC motor was used, and the motor output torque was also controlled by the PC.

Braking conditions were fed back to the driver mainly by the visual display. An additional cue to braking conditions was provided by controlling the pedal force exerted on the driver’s foot.

5.2 System Modeling

To save computation time, simplified vehicle dynamics and brake system dynamics were used.

5.2.1 Vehicle Dynamics

The braking simulator used a simple two degree-of-freedom model for vehicle motion [Ohba et al. (1990)]. Figure 5.3 shows the overall model developed for this simulator. The vehicle system consists of a single wheel with mass $M$ and moment of inertia $I$. The equations of motion based on above modeling are described as follows:

$$M\ddot{v} = F$$  \hspace{1cm} (5-1)

where $I$ = moment of inertia of wheel  
$M$ = mass of wheel  
$r$ = radius of wheel  
$\omega$ = rotational speed of wheel  
$v$ = forward speed of wheel  
$F$ = frictional force on wheel  
$T$ = braking torque on wheel
Friction force on the wheel is modeled as a function of road surface condition and wheel slip:

\[ F = \mu(\lambda)Mg \]  
\[ \lambda = \frac{v - r\omega}{v} \]

(5-2)  
(5-3)

where \( \mu \) = friction coefficient of road  
\( \lambda \) = wheel slip ratio

Figure 5.4 shows the relationship between the friction force and wheel slip on dry and wet/icy roads.

![Friction Coefficient vs Slip Ratio](image)

Figure 5.4 Friction force-wheel slip curves on dry and wet/icy roads
5.2.2 Brake System Dynamics

Figure 5.5 shows a simplified brake system model employed by the braking simulator. This brake system consisted of a vacuum booster, a master cylinder, a wheel cylinder, and a brake pad.

![Brake System Model Diagram]

Figure 5.5 Brake system model

The relationship between pedal displacement and booster output force is shown in Figure 5.6 [Kahn et al. (1994)]. This can be modeled as a first order system as follows:

\[
\frac{F}{X} = \frac{K_1}{\tau_s s + 1}
\]  

(5-4)

where \( F \) = vacuum booster output force
\( X \) = brake pedal displacement

![Vacuum Booster Input and Corresponding Output](image)

Figure 5.6 Vacuum booster input and corresponding output  
[Kahn et al. (1994)]
Brake system hydraulics between master cylinder and wheel cylinder can also be modeled as a first order system [Ohba et al. (1990)]:

\[ \frac{P}{P'} = \frac{K_2}{\tau_2 s + 1} \]  \hspace{1cm} (5-5)

where \( P \) = brake pressure at wheel cylinder

\( P' \) = pressure at master cylinder

Figure 5.7 illustrates that the relationship between wheel cylinder pressure and brake torque is nearly linear. This can be formulated as follows:

\[ T = Kp \]  \hspace{1cm} (5-6)

where \( K \) = brake gain or brake effectiveness

![Brake torque-brake pressure relationship](image)

Figure 5.7 Brake torque-brake pressure relationship
[Gerdes et al. (1995)]

For antilock brake systems, brake pressure is modulated depending on the wheel slip. This braking simulator used a simple logic of ABS activation: when wheel slip exceeded a threshold, brake pressure was relieved. Figure 5.8 shows the change of wheel
slip during ABS activation with the dynamics described above. As can be seen in the figure, the ABS cycle was around 10 Hz.

![Wheel slip during ABS activation](image)

Figure 5.8 Wheel slip during ABS activation

### 5.2.3 Dynamic Computation

The control signal from the driver was processed by dynamic computations. The basic computation consisted of the equations of motion of vehicle and brake system dynamics, which generated vehicle accelerations and velocities as a function of control commands (brake pedal position) and road surface condition. The vehicle velocities and accelerations were then integrated to yield vehicle state variables (e.g., distance to the lead car, travel of the driving car) which commanded the visual display. Outputs from the dynamic computation were also processed to command the brake pedal force.

In determining the degree of complexity for the dynamics of the vehicle and brake systems, computational delay had to be considered. Significant computational delay could destabilize the driver’s closed-loop-control behavior, which reduced simulator realism and invalidated experimental results. The dynamics employed were simplified to reduce computational delay, but without sacrificing appropriate realism.
5.3 Test Models

Vehicle models with five different brake systems were tested using the brake simulator. The brake systems consisted of three conventional brake systems and two new brake systems developed in Chapter 4. The test models are detailed as follows:

- Model 1:
  This model was a passenger car that is not equipped with antilock brake system.

- Model 2:
  This model was a passenger car equipped with a conventional antilock brake system. Activation of ABS is cued by vibration at brake pedal.

- Model 3:
  This model was a passenger car equipped with an antilock brake system and servo system to control brake pedal stiffness. Stiffness of the brake pedal was softened 50% upon activation of ABS instead of vibration as in Model 2.

- Model 4:
  This model was a passenger car equipped with an antilock brake system and road surface condition sensor. Upon detection of wet/icy road surface, stiffness of the brake pedal was reduced by 50%. This model assumed detection of road surface condition by a perfect sensor.

- Model 5:
  The last model was a passenger car equipped with an antilock brake system. While the ABS functioned normally, the vibration at the brake pedal was filtered out in this model.
5.4 Experimental Tasks

The performances of the five test models described above were tested using the braking simulator. Road condition awareness and situation adaptability of the drivers was evaluated under different braking situations and road surface conditions.

In the simulator, the driver followed one lead car at the speed of 100 km/h keeping a 2-second headway before the lead car braked to stop. The driver was able to control the speed of the driving car only through the brake pedal. In the first experiment, the emergency braking experiment, the driver was instructed to follow the lead car on a dry or a wet/icy road and upon a signal to brake as quickly as possible. For the second experiment, the pedal-pumping experiment, the driver was instructed to follow the lead car on a dry or a wet/icy road and to pump the brake pedal to stop the car. In the last experiment, the situation adaptation experiment, the simulation produced various braking situations according to the behavior of the lead car and road conditions. The drivers were instructed to follow the lead car and to react as they would in an actual driving situation. In this experiment, four situations were devised combining two different lead car behaviors and two different road surface conditions: gentle braking on a dry road, gentle braking on a wet/icy road, emergency braking on a dry road, and emergency braking on a wet/icy road. The four situations appeared in random order.

In all experiments, the driver was asked to estimate the road surface condition and decide whether it was dry or wet/icy. The driver’s estimates were rated on five scales. The driver could choose one from five different responses: definitely dry, maybe dry, undeterminable, maybe wet/icy, and definitely wet/icy. When the estimate was correct with certainty, it was rated +2. When the estimate was correct but without certainty, the rating was +1. When the driver was not able to recognize the road surface condition at all, the rating was 0. If the driver was uncertain about the estimate, and the estimate was incorrect, it was rated −1. If the driver was certain about the estimate, while it was incorrect, the rate was −2. For example, if the driver chose “maybe dry” as his response, while the actual road condition was wet, the rating for his estimation was −1.

In the situation adaptation experiment, the adaptability to four situations that randomly appeared was rated. In the emergency braking situation, the driver’s task was to avoid rear-end collisions. In the gentle braking situation, the driver’s task was to stop
the car as close to the lead car as possible without collision. Either collision with the lead car or excessive braking in the gentle braking situation was considered to be a failure in situation adaptation. Table 5.1 illustrates the rating system for the *situation adaptation experiment*.

Table 5.1 Rating system for situation adaptation experiment

<table>
<thead>
<tr>
<th>Situation</th>
<th>Rating (0 to 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gentle braking</td>
<td>If Distance to lead car when stopped &lt; Initial headway:</td>
</tr>
<tr>
<td></td>
<td>2 × (1 – Distance to lead car when stopped/Initial headway)</td>
</tr>
<tr>
<td></td>
<td>If Distance to lead car when stopped &gt; Initial headway:</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Emergency braking</td>
<td>If no collision occurred:</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>If Speed at collision &lt; 48 km/h:</td>
</tr>
<tr>
<td></td>
<td>2 × (1 – Speed at collision/48 km/h)</td>
</tr>
<tr>
<td></td>
<td>If Speed at collision &gt; 48 km/h:</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Before the experiments, the drivers were first given oral and written instruction describing the brake system and the task of the experiments. They were then given unlimited practice sessions until they felt confident to manipulate the brake pedal in a variety of situations that would appear in actual experiments. The practice sessions were followed by three different experiments described above. Each experiment was conducted in about 10 minutes with 5-minute breaks between them.
5.5 Results of Simulation

This section presents the major findings from the simulator tests. The performances of the five driver-vehicle systems were compared in terms of the performance indices such as road condition awareness and situation adaptability.

5.5.1 Pedal Displacement Phase Plane

Figure 5.9 illustrates typical phase plane plots, where pedal depression speed is plotted against pedal travel. These phase plane plots compare the driver’s pedal maneuver on dry and wet/icy roads. Plots are presented only for Models 2, 3 and 4 since Model 1 and 5 have the same pedal stiffness on either dry or wet/icy road. Among these three models, Model 4 indicates the largest phase plane difference for the two different road conditions; the area of plot on the wet/icy road is much larger than that on the dry road. Model 3 shows a sudden change of pedal depression speed, which appears as a spike just before full braking in Figure 5.9 b). This indicates a sudden yielding of the pedal upon ABS activation as described in Chapter 4. Model 2 indicates no substantial change in pedal depression on different road conditions. This phase plane plot provides a good format for comparing the driver’s kinesthetic perception. Since neuromuscular systems provide sensing of muscle stretch and stretch rate (spindle afferent) as well as force sensing (Golgi tendon afferent), the brake pedals in Model 3 and 4 provided the driver with a kinesthetic display of braking or road condition.
Figure 5.9 Phase plane plots of brake pedal depression on dry and wet/icy roads (Driver $E$)
The phase plane plots were characterized by their areas, peak pedal depressions, and peak pedal-depression speeds. The areas of the phase plane plots were taken to include only the region above the pedal-depression axis. The mean values and the associated 95% confidence intervals of the means (using Student’s t-distribution) of the three characteristic parameters are presented for each driver with Models 2, 3, and 4 for dry and wet/icy roads in Table 5.2. The phase plane plots were drawn from data obtained from five drivers during the pedal-pumping experiment. Unless otherwise noted in the tables, four independent plots were estimated for each driver on each road condition. Using an unpaired, two-tailed Student’s t-test, the significance of changes in the phase plane plots for different road conditions were evaluated. For Model 2, no significant changes (p<0.05, Student’s t-test) in the phase plane plots were observed for wet/icy road conditions (Table 5.2 a). Model 3 showed significant increases in peak depression and peak depression speed near full pedal depression under wet/icy road conditions (Table 5.2 b). Model 4 exhibited significant increases in area and peak depression on wet/icy roads (Table 5.2 c). Clearly, Models 3 and 4 appear to provide a kinesthetic display to the drivers.

Table 5.2 Characteristic parameters in phase plane plots on dry and wet/icy roads

a. Model 2

<table>
<thead>
<tr>
<th>Driver</th>
<th>Area Dry</th>
<th>Wet/Icy</th>
<th>Peak Depression Dry</th>
<th>Wet/Icy</th>
<th>Peak Depression Speed Dry</th>
<th>Wet/Icy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.554±2.364</td>
<td>3.426±1.189</td>
<td>1.141±1.003</td>
<td>1.180±0.081</td>
<td>5.950±2.151</td>
<td>4.763±1.203</td>
</tr>
<tr>
<td>C</td>
<td>2.184±1.268</td>
<td>2.171±0.710</td>
<td>0.839±0.185</td>
<td>0.829±0.214</td>
<td>4.294±0.940</td>
<td>4.588±0.525</td>
</tr>
<tr>
<td>D</td>
<td>4.485±3.044</td>
<td>4.480±9.801</td>
<td>1.015±0.018</td>
<td>0.980±0.023</td>
<td>7.300±5.520</td>
<td>9.088±7.143</td>
</tr>
<tr>
<td>(2 Samples)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2.498±0.708</td>
<td>2.932±0.438</td>
<td>0.942±0.084</td>
<td>1.008±0.031</td>
<td>4.025±1.120</td>
<td>4.513±0.947</td>
</tr>
<tr>
<td>All Drivers</td>
<td>3.430±0.862</td>
<td>3.123±0.589</td>
<td>0.984±0.071</td>
<td>1.002±0.089</td>
<td>5.392±1.170</td>
<td>5.259±0.988</td>
</tr>
<tr>
<td>Difference between Means</td>
<td>p (t-test)</td>
<td>Difference between Means</td>
<td>p (t-test)</td>
<td>Difference between Means</td>
<td>p (t-test)</td>
<td></td>
</tr>
<tr>
<td>0.307</td>
<td>0.5332</td>
<td>0.018</td>
<td>0.7376</td>
<td>0.133</td>
<td>0.8702</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.2 Characteristic parameters in phase plane plots on dry and wet/icy roads
(Continued)

b. Model 3

<table>
<thead>
<tr>
<th>Driver</th>
<th>Area</th>
<th>Peak Depression</th>
<th>Peak Depression Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet/Icy</td>
<td>Dry</td>
</tr>
<tr>
<td>A</td>
<td>4.295±0.822</td>
<td>4.429±0.263</td>
<td>1.154±0.104</td>
</tr>
<tr>
<td>B</td>
<td>3.317±0.793</td>
<td>3.135±0.364</td>
<td>1.229±0.004</td>
</tr>
<tr>
<td>C</td>
<td>2.665±0.542</td>
<td>2.790±0.647</td>
<td>0.970±0.190</td>
</tr>
<tr>
<td>D</td>
<td>5.258±1.631</td>
<td>3.986±1.008</td>
<td>1.161±0.125</td>
</tr>
<tr>
<td>E</td>
<td>4.064±0.439</td>
<td>3.612±0.358</td>
<td>1.177±0.085</td>
</tr>
<tr>
<td>All</td>
<td>3.849±0.463</td>
<td>3.591±0.320</td>
<td>1.142±0.055</td>
</tr>
</tbody>
</table>

Drivers Difference Between Means p (t-test)

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Difference Between Means</th>
<th>p (t-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.258</td>
<td>0.3418</td>
</tr>
<tr>
<td></td>
<td>0.061</td>
<td>0.03123</td>
</tr>
<tr>
<td></td>
<td>1.231</td>
<td>0.00006111</td>
</tr>
</tbody>
</table>

c. Model 4

<table>
<thead>
<tr>
<th>Driver</th>
<th>Area</th>
<th>Peak Depression</th>
<th>Peak Depression Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
<td>Dry</td>
</tr>
<tr>
<td>A</td>
<td>3.548±1.018</td>
<td>6.104±2.739</td>
<td>0.887±0.120</td>
</tr>
<tr>
<td>B</td>
<td>4.273±0.929</td>
<td>6.631±1.786</td>
<td>1.178±0.045</td>
</tr>
<tr>
<td>C</td>
<td>2.091±0.849</td>
<td>3.664±0.448</td>
<td>0.877±0.203</td>
</tr>
<tr>
<td>D</td>
<td>4.297±2.012</td>
<td>5.702±1.481</td>
<td>1.083±0.102</td>
</tr>
<tr>
<td>E</td>
<td>6.463±1.312</td>
<td>8.263±2.435</td>
<td>1.136±0.025</td>
</tr>
<tr>
<td>All</td>
<td>4.135±0.759</td>
<td>6.072±0.877</td>
<td>1.103±0.068</td>
</tr>
</tbody>
</table>

Drivers Difference Between Means p (t-test)

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Difference Between Means</th>
<th>p (t-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.937</td>
<td>0.001208</td>
</tr>
<tr>
<td></td>
<td>0.086</td>
<td>0.00004163</td>
</tr>
<tr>
<td></td>
<td>0.982</td>
<td>0.2211</td>
</tr>
</tbody>
</table>
5.5.2 Road Condition Awareness

Drivers were questioned on road surface conditions perceived and reported immediately after each braking situation. The ratings of the road condition estimates from nine drivers are listed in Figure 5.10. Each point represents the sum across all situations in the specified experiments. It is evident from the ratings that the drivers perceived road conditions easily in Models 3 and 4. While there were variations in baselines among the drivers, for each driver the ratings were considerably higher for Models 3 and 4. Especially in Model 4, the drivers recognized the road conditions correctly in most situations. This result can be explained by the discussion in the previous section about the driver’s kinesthetic perception. Clearly, change in phase-plane portrait of pedal depression appears to help the drivers perceive the road surface conditions.

![Graph showing road condition awareness results](image)

a) Ratings from all three experiments (14 situations)

Figure 5.10 Road condition awareness results
5.5.3 Situation Adaptability

From the situation adaptation experiment, the drivers’ situation adaptation for each model was evaluated. For each model eight drivers had four or five sessions of the experiment where in each session the four situations were ordered randomly, and the performance in each session was rated. The highest ratings among these sessions are given in Figure 5.11 for each driver and model. Model 4 had the highest ratings for four of the drivers (Driver A, D, F, and G), and Model 3 and Model 5 had the highest ratings for two of the drivers, Driver C and I and Driver B and H, respectively. While the drivers appeared to be aware of the road conditions in Models 3 and 4, their performances did not seem to improve appreciably.


5.6 Discussion on Results from Simulator Tests

The performance of driver-vehicle as a combined system was examined using a simple driving simulator. The results were somewhat mixed. They showed that the new brake systems developed in Chapter 4 helped the drivers perceive the road surface conditions through the kinesthetic cue from the brake pedal. While the drivers perceived the road conditions more accurately under the proposed designs, it appears that the perception of the road conditions did not have a great effect on their performance in various braking situations.

Difficulties arose in attempting to simulate the braking situations with limited visual input generated by the PC. Some of the drivers had trouble recognizing the behavior of the lead car through simple graphics. This degraded the ability of the simulation to differentiate the system performance of the five different models. On the other hand, some of the drivers (Drivers B and H) were able to acclimatize themselves to all the different brake systems so well that the system performances could not be distinguished from one another.
CHAPTER 6

SUMMARY AND CONCLUSIONS

The antilock brake system can save your life only if you know how to use it. Unfortunately, many drivers do not seem to understand how it should be operated. Indeed, the accident statistics report that the implementation of ABS does not necessarily improve or could even impair the safety of drivers. While drivers are the first to be blame for this poor record, the drivers’ misuse is attributed to the unintuitive design of driver-vehicle interface in the brake system.

The goal of this thesis was to design brake systems that provide the driver with intuitive brake control and proper performance information. The thesis develops brake systems based on two new aspects. First, the brake system is considered as a teleoperator providing proper feedback to the driver. Second, the braking motion of the driver is modeled and taken into consideration in designing the brake systems.

6.1 Summary

6.1.1 Human Leg Motion Analysis

As a preliminary study in brake system design, the features of human leg movement were characterized through experiments:

- Point-to-point reaching motions have nearly straight or slightly curved foot paths with a single-peaked velocity profile.
- Leg movements are much slower than arm movements.
- Legs have characteristic postural stiffness field with marginal stability or slight instability.

The findings in the experiments suggest a simple open-loop motor control scheme in planar leg motion. As a possible candidate, equilibrium point control model is consistent in recreating the experimental data in numerical simulations.
6.1.2 Design of Brake System as a Teleoperator

Based on human leg motion analysis, the braking motion is modeled as:

- A two degrees-of-freedom motion with free hip and knee joints
- A simple open-loop reaching motion in free space followed by impeded motion in force field (brake pedal).

The braking task of the driver is modeled as a teleoperation. Brake systems developed in this thesis take advantage of the driver's open-loop motor control and provides intuitive feedback to the driver.

- Proposed design 1:
  An antilock brake system with softening brake pedal upon detection of excessive wheel slip
- Proposed design 2:
  An antilock brake system with softening brake pedal upon detection of a wet/icy road condition by a road surface sensor

6.1.3 Simulator Tests

A simple driving simulator was developed to investigate the behavior of the driver-vehicle system. The proposed designs are shown to improve the system performance by enhancing the driver's road condition awareness.

6.2 Conclusions

The primary contributions of this thesis are discussed as follows:

- The possibility of open-loop motor control has been shown through experiments on human leg motion. The features (i.e. straight path and bell-shaped velocity
profile in reaching motion) found in the experiments were consistent with those reported in arm motion studies [Mussa-Ivaldi (1985), Flash and Hogan (1985)].

- The equilibrium point control model of human leg motion has been developed based on experimental findings. This model is applicable to point-to-point foot reaching motion. Those results are consistent with arm motion studies [Flash (1987), Won and Hogan (1995)] which reported that the equilibrium point control hypothesis is competent to predict simple point-to-point hand reaching motion.

- Two new brake systems have been designed. The new designs account for the characteristics of human leg motion and kinesthetic feedback to the driver. Their effectiveness is confirmed through the simulation described below.

- A simple driving simulator has been designed to investigate the performance of driver-vehicle system. This simulation can be used to test the effectiveness of various brake systems.

### 6.3 Recommendations for Future Work

As recommended future work, the author proposes improvements to the experimental procedure in leg motion analysis as well as in features of the driving simulator, and additional studies on the impedance tuning of the brake pedal.

- Analyzing a certain aspect of the leg motion helped illuminate the mechanisms underlying drivers’ maneuver of the brake pedal. In this research, a rather simple procedure was used in investigating leg motion. In examining the motor control of human limbs, however, precise measurement and rigorous analysis are critical and needed. The two-dimensional motion measurement and linear-time invariant motor control model employed in this study may be replaced by three-dimensional multi-joint motion capture techniques [Bregler (1997), Cipolla and Pentland (1998)] and more sophisticated motor control models [Mussa-Ivaldi et al. (1991), Shadmehr et al. (1992)]. This may result in a more accurate analysis of human motion.
• Driving simulators can provide various scenarios that allow us to evaluate the performance of the brake system combined with the driver. There has been no standard protocol in quantifying the performance of driver-vehicle system. A more realistic scenario that can quantify the braking performance should be designed.

• This thesis showed that change of pedal impedance has an effect on braking performance. Further research can analyze how the impedance parameters should be tuned to optimize the performance of the brake system.
REFERENCES


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