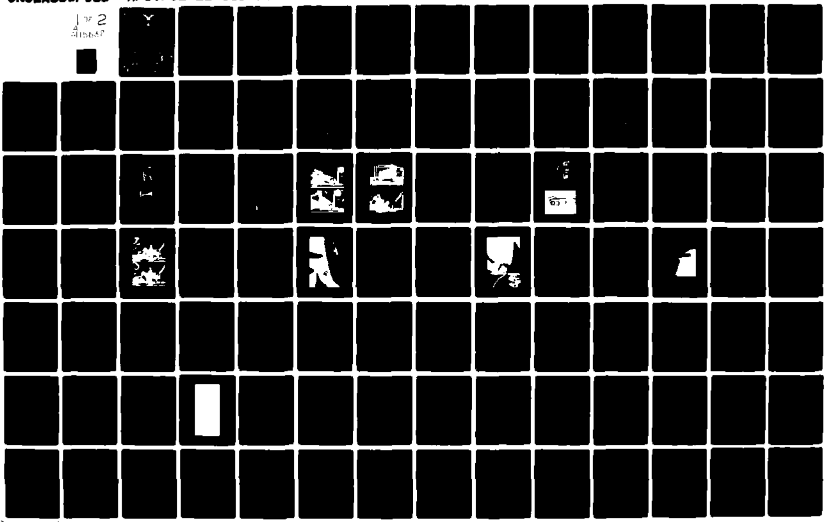
AD-A115 532 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOO--ETC F/G 6/16
FEEDBACK INFORMATION AND ANALYSIS FOR MICROPROCESSOR CONTROLLED--ETC(U)
DEC 81 D J HEICHEL
UNCLASSIFIED AFIT/GE/EE/81D-26 NL

1 of 2
AD
A115532



AD A115532

DTIC FILE COPY

DTIC
ELECTE
JUN 14 1982
S E

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY (ATC)

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

82 06 14 196

AFIT/GE/EE/81D-26

FEEDBACK INFORMATION AND ANALYSIS
FOR MICROPROCESSOR CONTROLLED
MUSCLE STIMULATION

THESIS

AFIT/GE/EE/81D-26 David J. Heichel
2/Lt. USAF

Approved for public release; distribution unlimited.

AFIT/GE/EE/81D-26

FEEDBACK INFORMATION AND ANALYSIS FOR MICROPROCESSOR CONTROLLED MUSCLE STIMULATION

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

By

David J Heichel
2Lt USAF

Graduate Electrical Engineering

December 1981

Preface

Many thanks are given to all those who gave a special effort in assisting me throughout the thesis work. I appreciate the genuine interest, insight, and advice given by the three committee members which include my advisor Dr. Matthew Kabrisky, Dr. Jerrold S. Petrofsky and Dr. Lynn Wolover. I am greatful for the work space and equipment provided by the Biomedical Engineering Department of Wright State University. The cooperative, friendly atmosphere at the University was a plus. Lab personnel, Bill Couch and Debbie Hendershot, were of great assistance from design to experimentation. Special thanks to Harry Heaton for superb photography and ideas generated by his interest and enthusiasm.

Contents

Contents

List of Figures

List of Figures

List of Figures

List of Tables

Abstract

A cat was fitted with feedback sensors which provided information on joint position and foot force during unrestrained locomotion. A harness outlining the rear leg skeleton of the cat was designed. The harness was worn and supported by the animal. It contained position transducers at the joints and followed the movement of the leg throughout the step cycle. The harness restricted the rotational and lateral movements of the leg. Other feedback sensors were developed to sense foot contact and force. A simple contact switch on the ball of the foot of the cat was used with the feedback harness to show exact foot placement. A force transducer designed to mount on the foot of the cat provided additional feedback from the foot. The cat was walked under different conditions to obtain position data for models of the gait. Hip action with respect to a ground plane was observed for leg motion modeling. The cat was also walked on a treadmill with electomyograph activity recordings for the flexor and extensor group of each joint. This joint provided information to model the activity sequence in muscles during locomotion. From the tabulated leg position, foot forces, hip motion and muscle activity a model walk is presented for future microprocessor controlled stimulation project for paralysis.

FEEDBACK INFORMATION AND ANALYSIS

FOR

MICROPROCESSOR CONTROLLED MUSCLE STIMULATION

I. INTRODUCTION

Background

Thousands of accidents every year result in spinal injury. Stroke and brain tumor patients may suffer from similar disorders as a result of nerve damage at levels above the spine. In either case, the neural disruption causes a loss of the feedback control link between muscles and the brain. In some cases, it is just a temporary disruption of normal neural pathways. In many instances, the damage is permanent and causes paralysis below the level of injury. In the case of stroke or brain tumor patients, partial or complete loss of muscle control occurs even though the neuron cell bodies may remain unharmed. In the case of accidents, local control at the level of the injury is lost because of cell body destruction. Below the level of the injury, cell bodies remain intact but are unable to respond to command because of severed control links. In either case, the voluntary control of the muscle is gone, but if the neuron cell body is unharmed the motor units will not die (Guttman, 1976). The motor unit will remain healthy and the muscle will undergo atrophy. The patient, though paralyzed, may have a healthy motor neuron pool unable to maintain muscle health because of the loss of central command control. In the case where cell bodies are destroyed, the motor neurons would not survive causing irreversible denervation atrophy (Dubowitz and Brooke, 1974).

These patients, parapelegics or quadrapelegics, are severely restricted in movement and mobility. Wheelchairs and specially designed hand controlled automobiles help increase the mobility of the pelegic, but only to the point of compatibly designed surroundings, i.e., ramps and elevators for accessibility. Though mobility is slightly increased, this still leaves the otherwise helpless patient with psychological strains which are often unbearable (Burke and Murray, 1975).

Alternatives to the wheelchair have been other mechanical devices which simulate walking with the patient strapped into it. The first of these devices were far from the point of drastic increase in mobility. One such device studied by Townsend and Lepofsky (1976) had operational limits of negotiating ramps no greater than 6° and bumps of 1/2 inch. Today these devices have advanced to well controlled exoskeletons capable of producing complex movements and locomotion (Petrofsky, 1981). At any stage in development, the problems with these exoskeletons are their high power consumption and bulky size (Vukobratovic, et al., 1974).

To restore mobility without these external mechanical devices requires replacing the "central command" to the alpha motor neurons. This is accomplished by electrical stimulation of the muscle in cases where the alpha motor neurons remain unaffected by the injury. With electrical stimulation techniques, the deterioration of muscle into fiberous tissue (Guyton, 1976) is not inevitable. The contractile power can be preserved and fiberous build-up reduced by electrical stimulation treatment of centrally denervated muscle (Guttman, 1976).

Electrical stimulation has been used to restore voluntary movement to the bladder for urination (Nashold, et al., 1972) by direct application of electrodes to the bladder wall. Leg movement has been achieved by muscle stimulation through surface electrodes (Milner et al., 1970). An additional method of stimulation currently used is the intramuscular electrode. All these stimulation methods have two problems. The first problem is maintaining placement of electrodes during movement. Electrodes become dislodged with skin movement over the muscle. The second problem is the high power demand, sometimes resulting in injury to the muscle or irritation to the patient (Scott, 1968).

A technique involving stimulation of the motor nerve itself is under investigation by Petrofsky (1978, 1979b). It offers the advantages of lower voltage and current than is needed to elicit stimulation with surface or intramuscular electrodes. The stimulation system developed must be able to control isometric tension, velocity of contraction and coordination of movement, all with minimally induced muscle fatigue. The work of Petrofsky and Phillips (1978, 1979 a,b, 1980) has centered on these areas for the past four years and is currently moving toward restoration of movement and locomotion for paralyzed persons.

Objective

Before microprocessor controlled stimulation of paralyzed muscle (Petrofsky and Phillips, 1979) can be achieved on test animals, the walking model and feedback parameters must be studied. With a walking model, the computer can reproduce a gait cycle through the use of the feedback sensors. The object of this thesis was to gather position and force information for feedback and modeling of the rear limbs of a walking cat. The design of a harness to measure the position of the cats limbs without supporting the cat was of major concern. To accurately assess the muscle activity of the leg with position information, a harness was designed to be worn and supported entirely by the cat. The cat is restricted in lateral movement by the harness. The harness measured the motion of the leg in one plane.

Six muscles determined essential to the two dimensional movement of the leg (Carroll, 1980) were studied. Electrodes implanted in the muscles transmitted the signals for recording of muscle activity. The recorded muscle activity and harness position record provided the basis for a model of the free walking cat. The necessary information for sequence and strength of muscle activity can then be reproduced by a microprocessor using the harness as feedback. Additional information is necessary to determine the actual forces generated by the recorded muscle activity. For this purpose, a force transducer was mounted on the foot of the cat. It provided the force on the foot throughout the step cycle, and by means of lever analysis, the forces in the remainder of the leg. This also will provide feedback information for the microprocessor controlled stimulation of muscles.

Scope

The work for this project was conducted at Wright State University, Department of Physiology and Bioengineering, under supervision of Dr. Jerrold S. Petrofsky. Formally defined as feedback information and analysis for microprocessor controlled muscle stimulation, the goal was to provide the necessary feedback for use with other physiological information and computer designs to complete an overall project. The results of these combined projects should provide the microprocessor controlling unit necessary to make a paralyzed cat walk by artificial electrical stimulation. After success with test animals, development will center on human subjects for a similar unit to perform basic tasks and eventually walking.

II. Cat Anatomy and Physiology

The cat was the experimental model for this work because of the amount of data on record from physiological studies and experimentation. Studies on stimulation control, endurance, and fatigue characteristics by Petrofsky and Phillips (1978a, 1979a, c, 1980) form the basis for the overall microprocessor controlled stimulation (Petrofsky and Phillips, 1979) project. Skeletal anatomy is reviewed to outline the lever system of the hind leg. The muscle system, physiology, and walking model dealt with as they pertain to this study.

Skeletal Anatomy

The lever system of bones and muscles provide the basis for locomotion. With the joints as fulcrums and bones as levers, the muscle provides the force for movement. With a complex sequence of movements by three interconnected levers, the leg provides walking motion.

The skeletal structure of the left leg of the cat is shown in Figures 1 and 2. Both lateral (outer side view) and medial (inner side view) aspects are not crucial for accurate depiction of the skeleton, but are presented for familiarization as they will be necessary in muscle depiction later. The major sections of the skeletal structure are labelled.

The lever system made up by the bones and joints can be simplified by using straight line representation of the bone and single pivot points as the joint. For this simplified system, the rotational movement is intentionally neglected to show movement of the leg in a single plane.

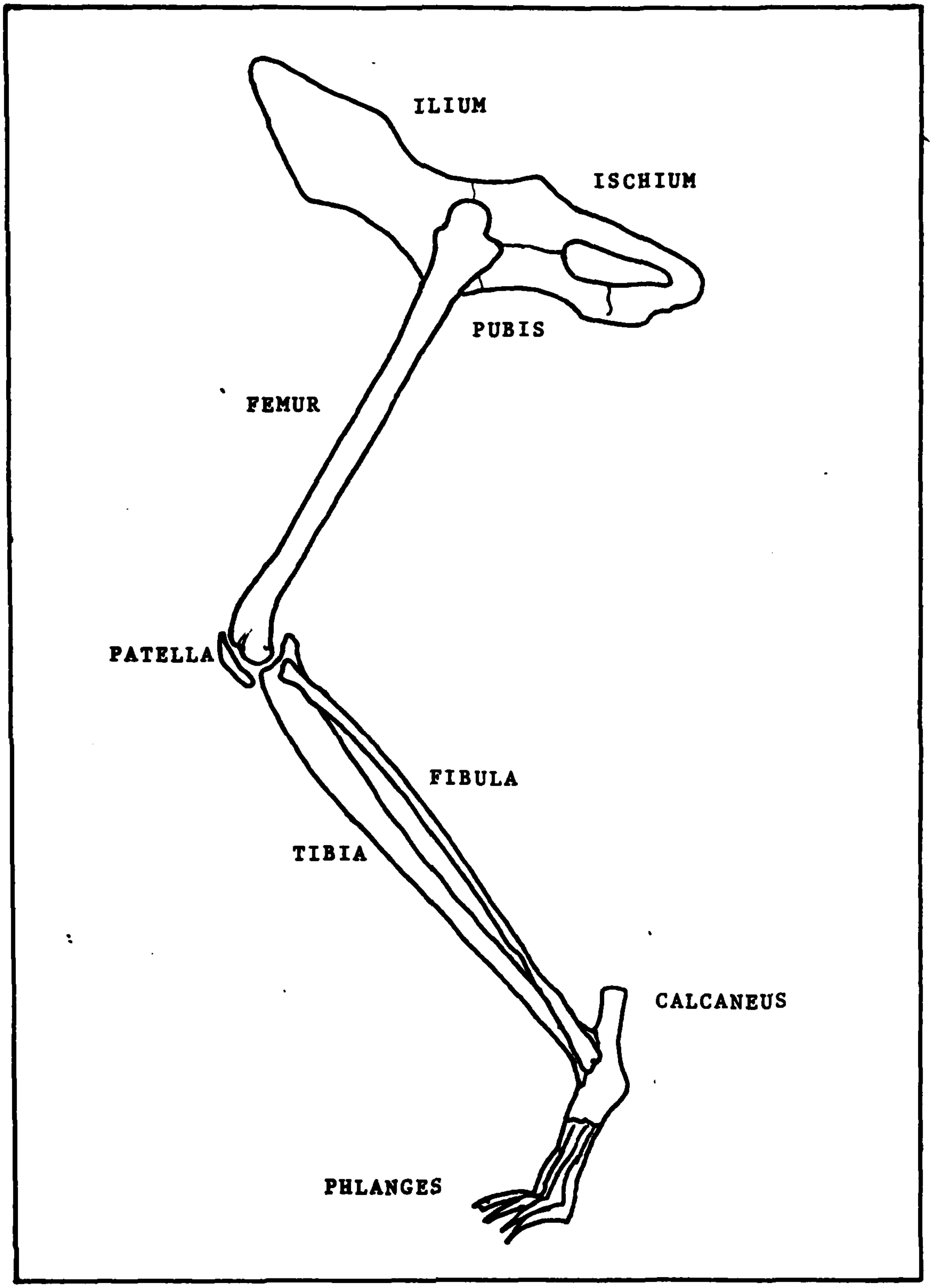


Figure 1. Skeletal Structure: Left Leg Lateral View

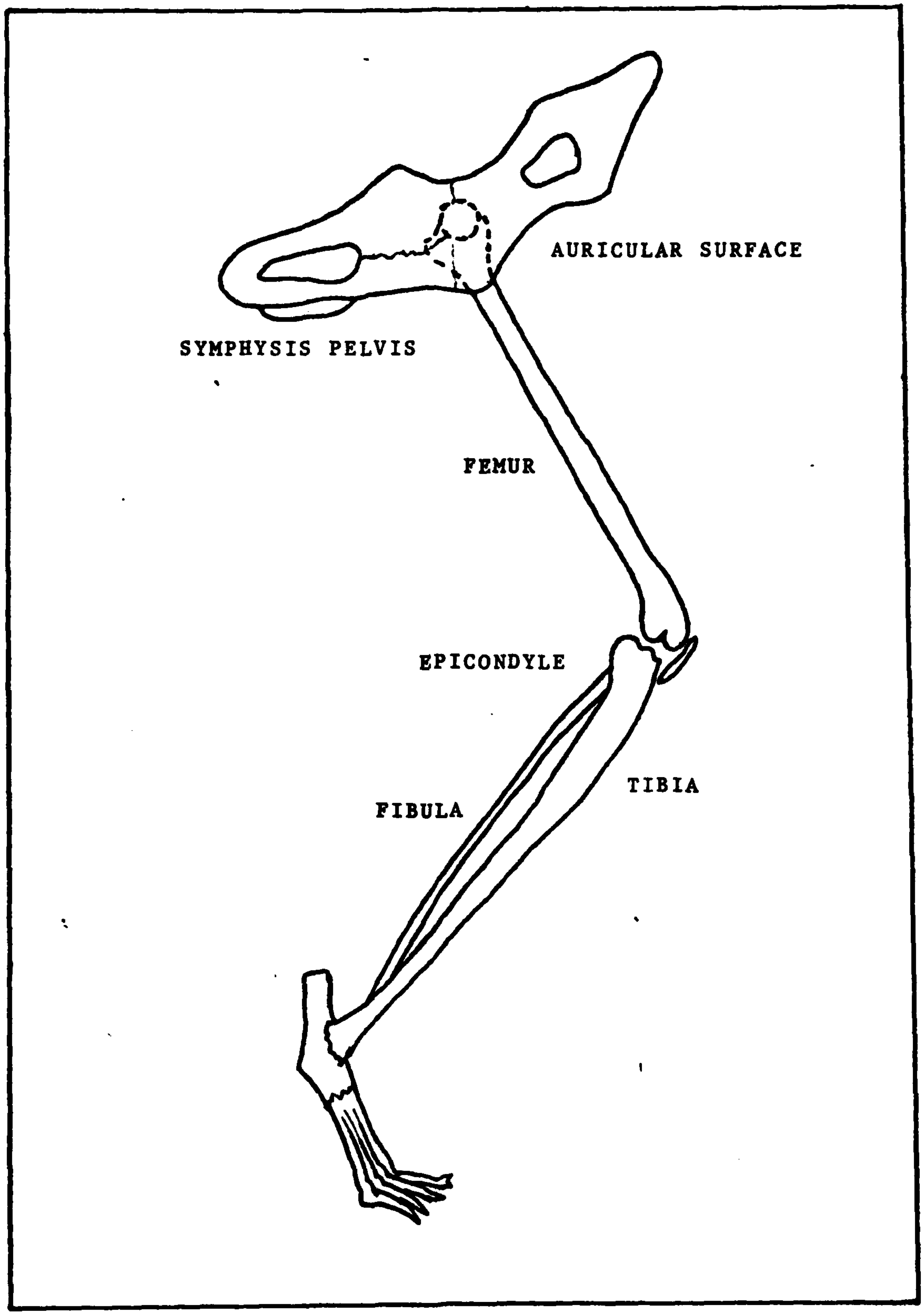


Figure 2. Skeletal Structure: Left Leg Medial View

Figure 3 shows the lever system and points of application of force to extend and flex the individual levers. The muscles which provide the forces are outlined later in the chapter. The extension forces (E_1, E_2, E_3) give only an example of the major influencing force for movement. The actual forces extending the levers are provided by various individual forces (muscles) acting over many points. The flexation forces (F_1, F_2, F_3) are also simplified to forces acting at single point of application. By physical measurement and approximation of a single point of force application, the individual forces necessary to maintain a given force at the foot can be calculated.

Muscle System

The muscles provide the forces necessary to move the leg. They can be found in two arrangements. In a long arrangement, the contraction parallels the direction of movement. The second arrangement has contractions perpendicular to the movement and is termed pennate. Muscles may be a combination of both. The actual muscles are not all single points of force application as represented in the previous section. They are often wide bands of tendon which insert along a length of the bone. Different muscles also may insert in almost the same place on the bone or ligament, but the direction which the force is applied may differ. These muscles, not depicted in the simple lever system, produce the rotational and lateral movement of the leg.

The complex system of muscles provide the forces for posture and locomotion. This system of more than twenty major muscles is much too complicated to study and simulate at the present time. Therefore, a simplified model of muscles for locomotion or walking gait, is proposed

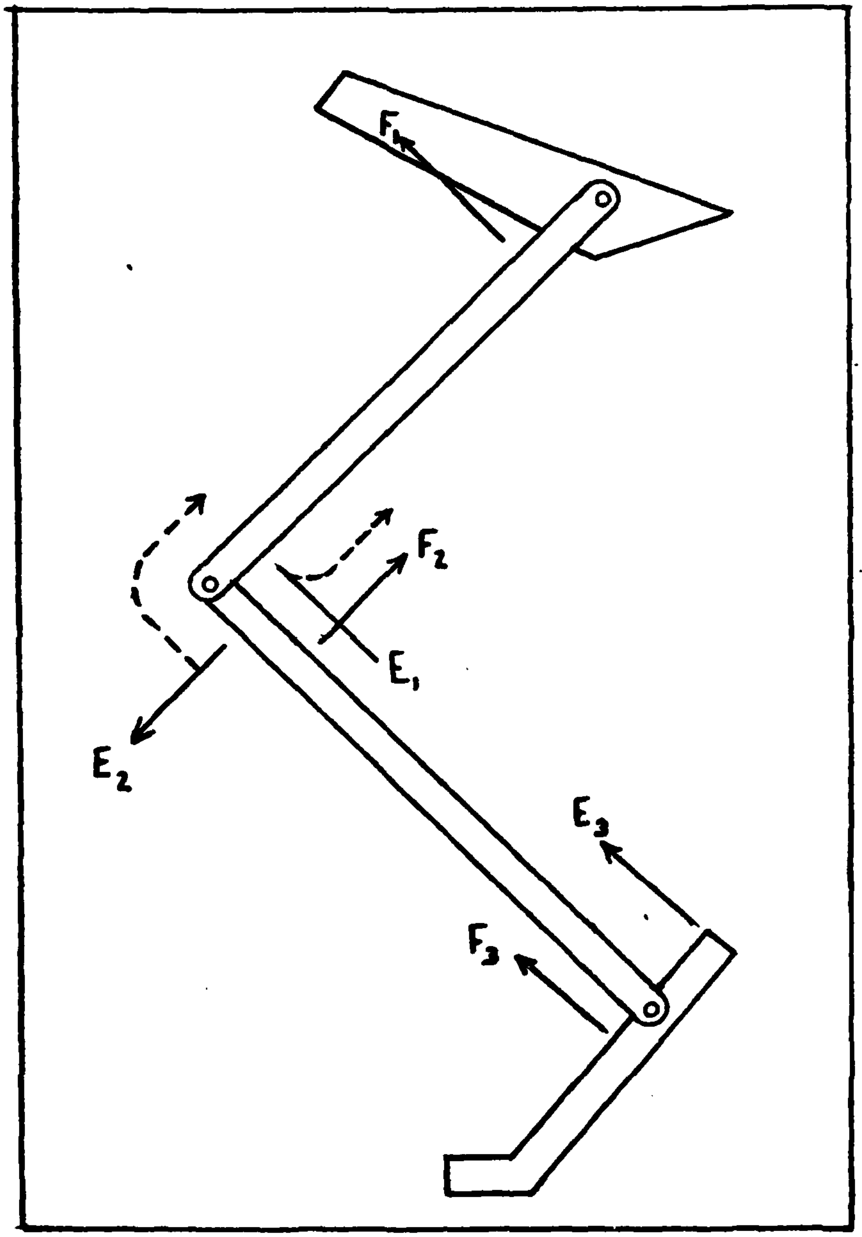


Figure 3. Straight Line Approximation of Leg With Points Of Insertion

in studies by Carroll (1980). This reduced model is made up of six "essential" muscles. One pair of muscles for each lever. A flexor and extensor theoretically supply the necessary single plane motion of the leg. Figure 4 shows the lateral view of the reduced muscle model, and Figure 5 is the medial view. The semimembranosus provides the extension force (E_1) for the thigh or femur, and the iliopsoas is the flexor (F_1) for the thigh. The shank flexor (F_2) and extensor (E_2) are the biceps femoris and vastus lateralis respectively. The foot is flexed (F_3) by the tibialis anterior, and the gastrocnemius is the extensor (E_3) of the foot. These muscles provide the extension and flexion forces referred to in Figure 3. This is only a simplified model. A more complete list of muscles in the leg is in Appendix A.

Muscle Physiology

The muscles are made up of bundles of fibers. Contractions in these fibers is controlled by the central nervous system. The motor portion of the nervous system innervates the skeletal muscle. Each muscle fiber is innervated by only a single nerve, but a single motor nerve fiber branches to as many as thousands of different muscle fibers (Guyton, 1974).

This nerve bundle can then control muscle contraction in two ways. The single nerve can transmit impulses at a fast or slow rate to all of its muscle fibers. This temporal summation gives strong contraction for a high number of impulses per unit time and weak contraction for low impulse rate. The other control of muscle contraction is spatial summation. The single motor nerve can innervate many muscle fibers, but the fibers are not necessarily adjacent to one another. While one muscle

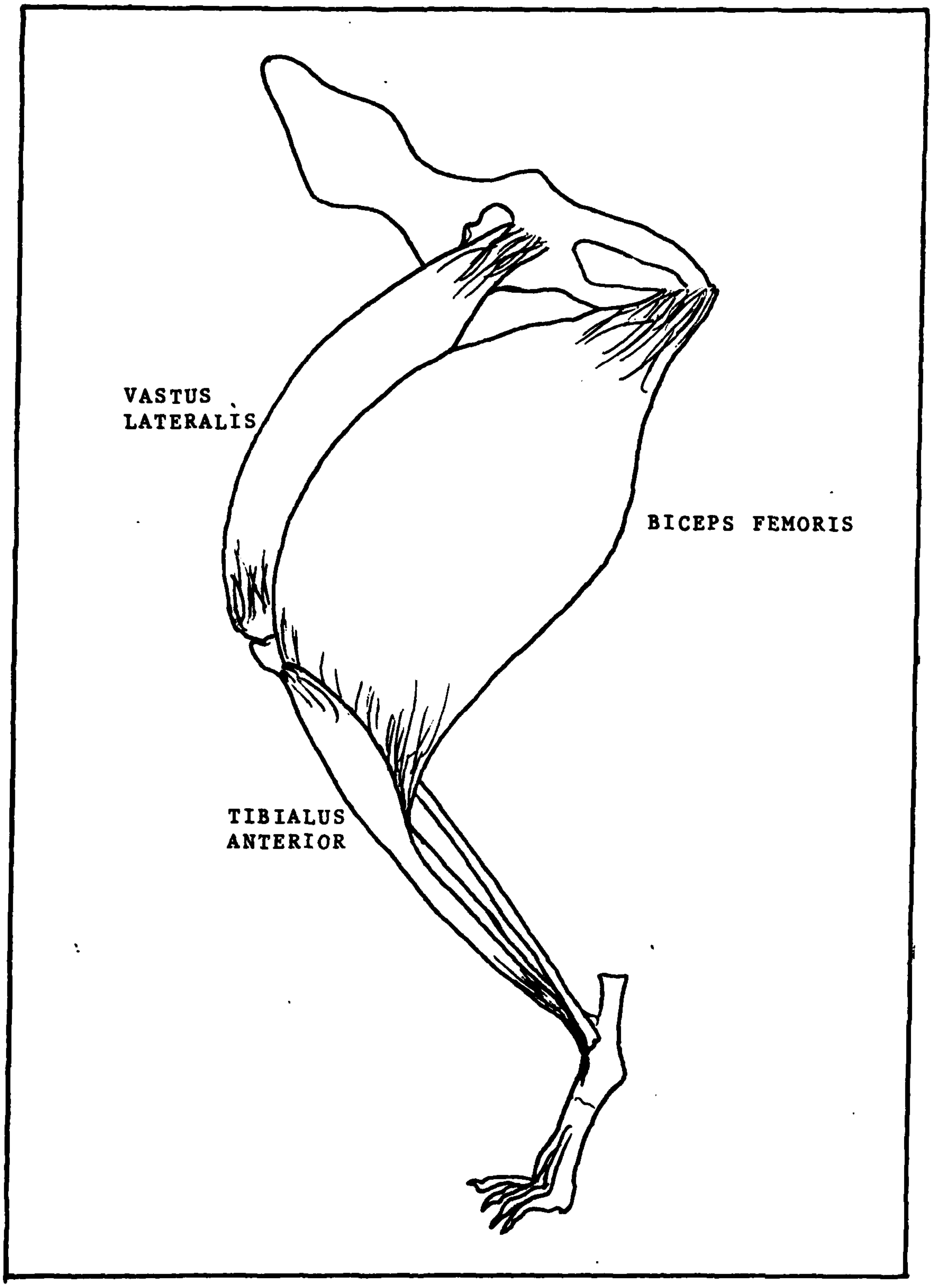


Figure 4. Reduced Muscle Model: Left Leg
Lateral View

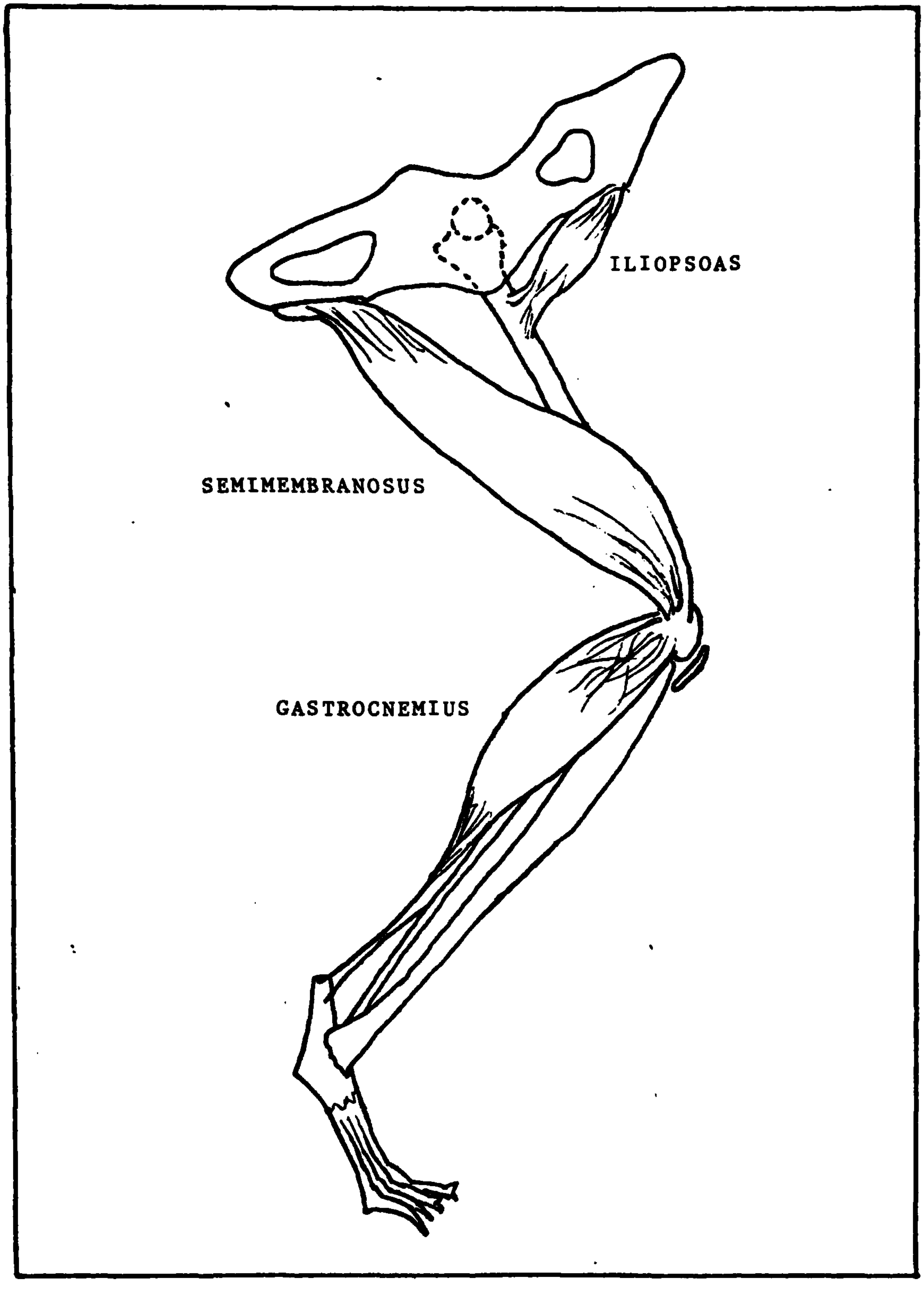


Figure 5. Reduced Muscle Model: Left Leg Lateral View

fiber is activated by a motor nerve, the adjacent fiber is controlled by an entirely different motor nerve. Many individual nerves enter the muscle, and each is stimulated independently. If only a few are stimulated, the result is a weak contraction. As more are stimulated or recruited, the muscle activity increases. This provides a very fine control over muscles in both force and fatigue characteristics.

During isometric contraction up to one-half of the strength is developed by recruitment, remaining muscle strength is developed by firing frequency (Milner-Brown and Stein, 1975). Under sustained contraction, fatigue is overcome, and tension is maintained by first recruiting all fibers available then increasing frequency of firing (Figure 6). Work by Petrofsky (1978) has successfully developed a method to control both recruitment and firing rate in a muscle much the same as the brain. The method provides precise control over movement and fatigability necessary to replace control through use of a computer.

The muscle moves the leg with precise control. The central nervous system locates the position of the bones by a system of sensors in joint capsules and ligaments. Another set of sensors provide information for rate of movement. These kinesthetic signals transmitted to the brain give it the ability to "know" where each part of the body is. The methods for obtaining this information for use in a computer controller are the focus of Chapters III and IV.

Walking Model

The walking motion can be defined by phases in a cycle. The cycle starts when the cat lifts the hind foot. The action is a result of movement at all three joints. This is the flexion phase, and it ends when

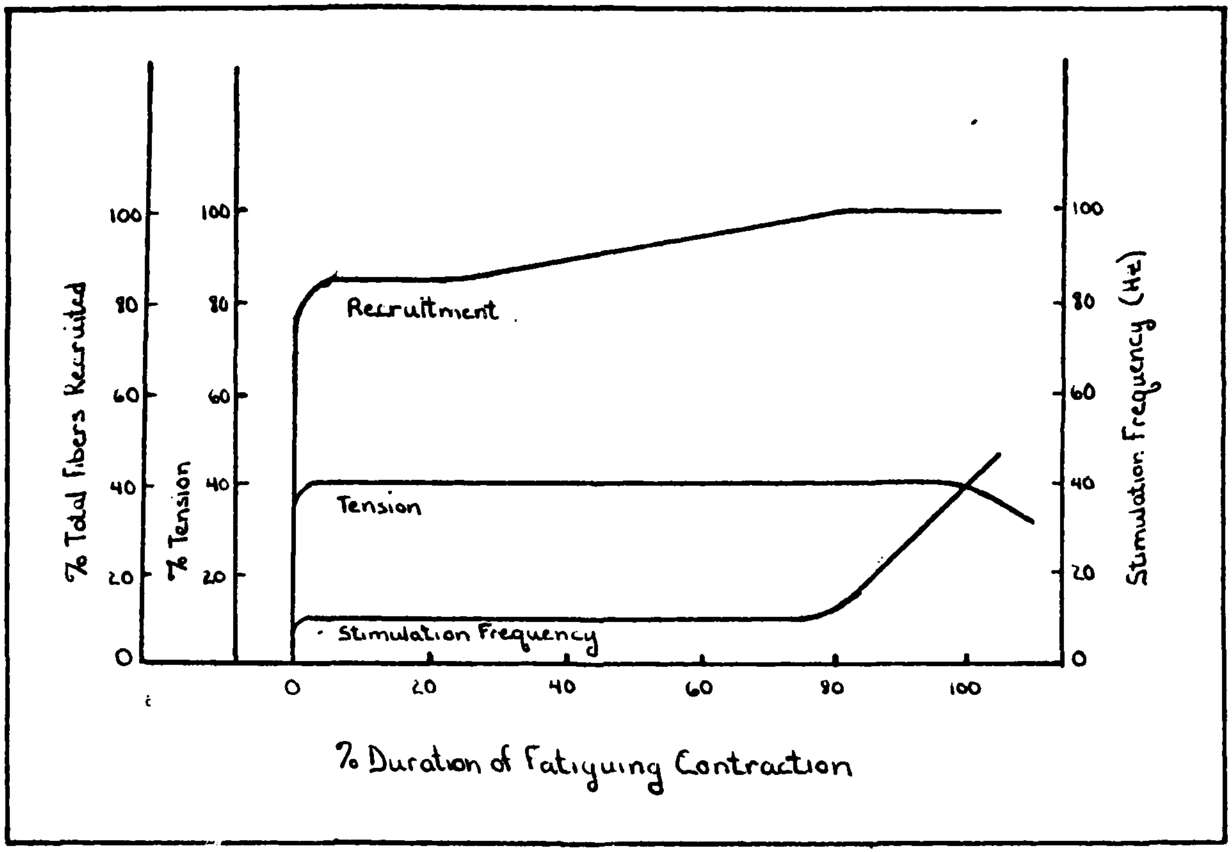


Figure 6. Recruitment And Firing Frequency Generated by Computer During Fatiguing Contraction Of Gastrocnemius Of Cat Of 40% Strength (Modified From Petrofsky; Med. & Biol. Eng. and Compt. 16, 302-308, 1978)

extension occurs at the knee and ankle. This begins the extension phase, a phase having three distinct parts. During the first part of the extension phase, the leg is in the air. The hip flexion decreases speed, and the knee and ankle start extension. The second part of extension occurs when the foot comes into contact with the ground. At this point the ankle and knee cannot maintain extension and yields slightly under the weight of the animal (Grillner, 1972). The effect is more pronounced at higher speeds where hip flexion decreases earlier, and force of contact makes it more difficult to maintain extension. The final phase of extension is a result of similar increase in all three joints.

The four phases can be grouped into two distinct phases. The swing phase is comprised of the flexion and first part of the extension phases. The stance phase is made up of the second and third parts of the extension phase (Goslow, et al., 1973). Essential information necessary to model the walking motion is derived by motion of the hip with respect to a stationary point (Chapter VI). By knowing the motion of the hip in the swing and stance phase, the artificial controller will not be wasting muscle activity correcting for natural motion.

III. Harness

The brain can locate parts of the body by kinesthetic signals feedback from sensors in the extremities. With loss of central control, as in paralysis, these sensor signals are lost to the brain. If a computer is to simulate the brain function for motion, it must be provided with appropriate feedback information. For this purpose, a feedback harness was designed to provide necessary position information to the computer. The harness design worn by the cat should allow freedom of movement in the leg, support of weight slowly by the animal, and provide the feedback position information accurately and reliably.

Freedom of Movement

The harness assembly is made up of two parts. The first of which is a cloth harness of straps and collars (Figure 7). The cloth harness is made up of Vivatex® straps and Velcro® fasteners. A one inch wide strip of material extends the length of the cat's back. Starting at the base of the neck, it is fastened about the neck by a half-inch wide collar. The strip is held centered on the back by a second collar about the thorax behind the front legs. At the sacral vertebrae, a cloth saddle covers the hips. This saddle is kept centered by a set of straps. The straps connect to the thorax collar beneath the cat and criss-cross about the abdomen attaching to the saddle on top of the cat at the ilium.

The strip down the back and saddle provide the base to mount the second part of the harness. The second harness is a flexible plexiglass strip the length of the back with an aluminum semicircular brace over the hips. This brace provides the mount for the leg member feedback braces.

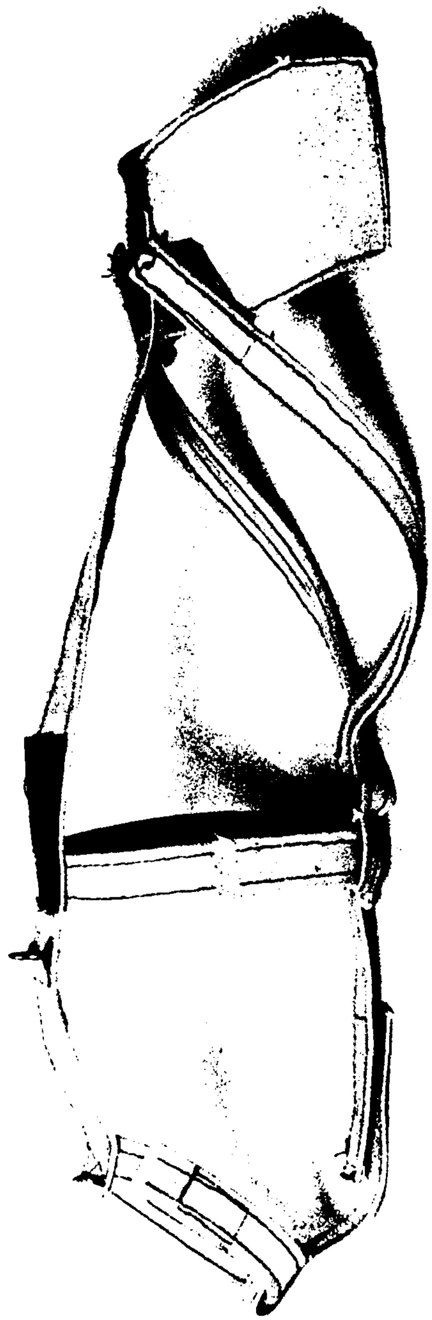


Figure 7. Cloth Harness for Cat

The leg member sections correspond to the skeletal arrangement of the cat (Figure 8). The leg section, corresponding to the femur, pivots at the hip and is held in place by the aluminum brace. The knee joint is another pivot, and a second section followes the tibia movement. The final section with the ankle joint pivot corresponds to the metatarsal. This section was attached to the leg by a contoured styrofoam pad and velcro fastener. With the leg member secure at the hip and ankle, the knee joint followed movement without direct attachment (Figure 9). The arrangement allowed freedom of movement of the leg in a single plane while measuring the angular position of each joint for feedback.

The cat was free to walk within the controlled environment (Figure 10). A plexiglass cage about the variable speed treadmill kept the test animal on the mill surface. It allowed the cat freedom of movement while walking, without the cat walking away. After walking a short period the cat maintained a position within inches at a constant speed. Monitoring the position of the cat is aided by a grid on the plexiglass cage. Another method used in training the animal to obtain the best results was conducted by removing the plexiglass cage and restraining the cat by a leash to a bridge over the treadmill surface. This method provided additional room to work and incentive for the cat to walk. The leash acts as a restraint for changes in treadmill speeds and anxious cats (Figure 11). Special care was used for data collection in the latter method to be sure the leash is not under strain of a pulling cat.

Support of Weight

The cat being free to sustain a natural walk within the treadmill cage must support the harness. A previous harness design (Carroll, 1980)

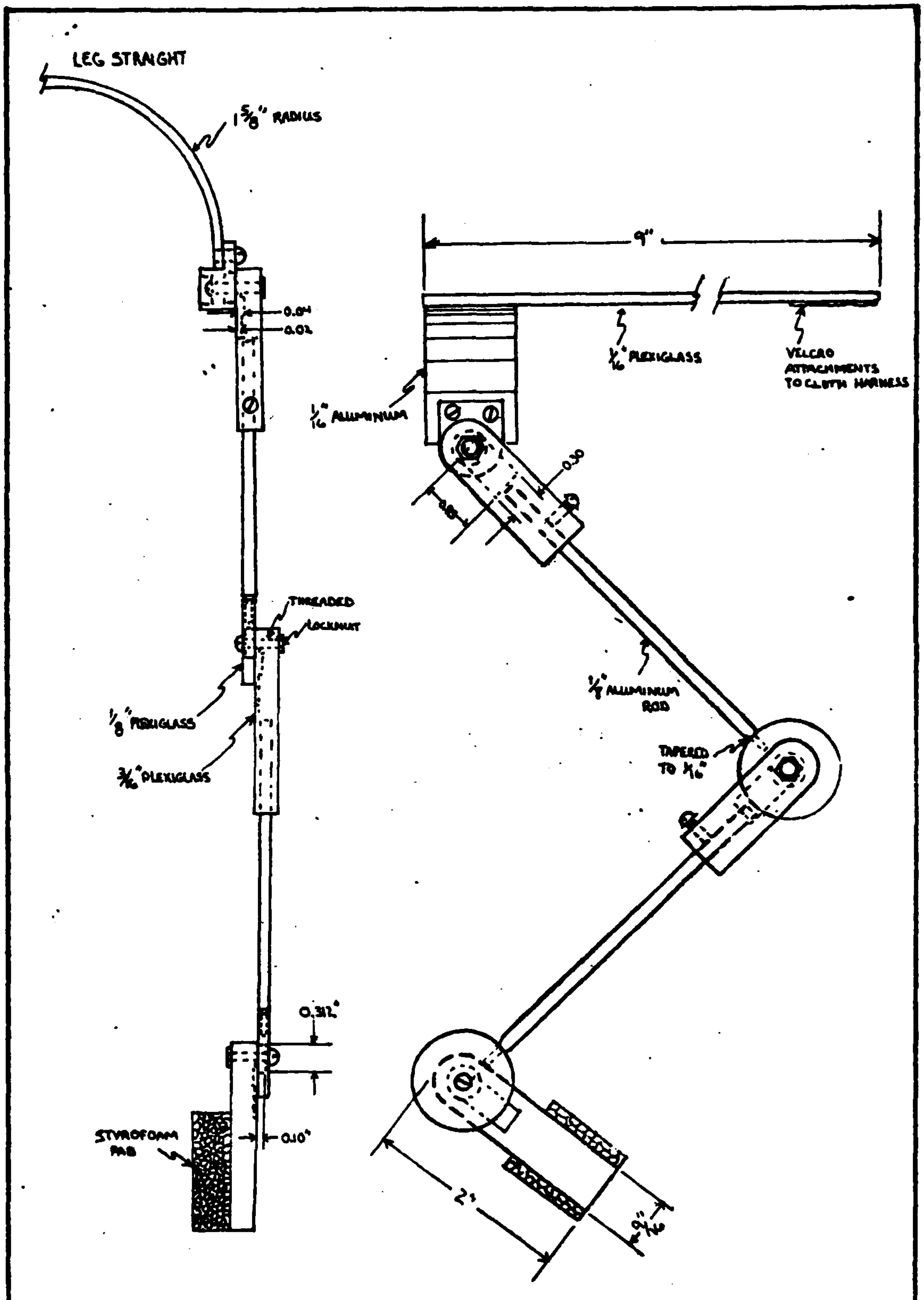


Figure 8. Feedback Harness For Cat

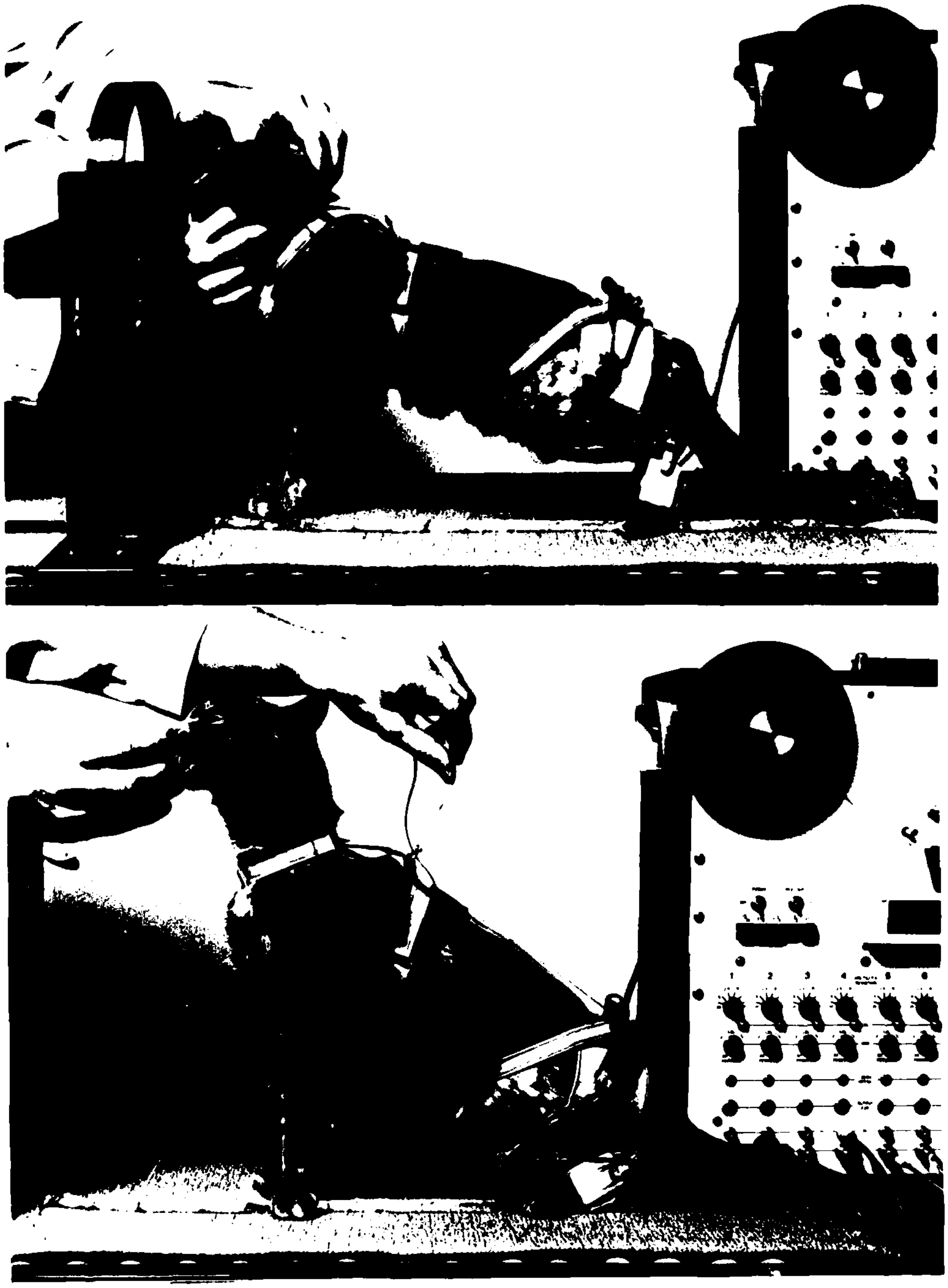


Figure 9. Feedback Harness on Cat

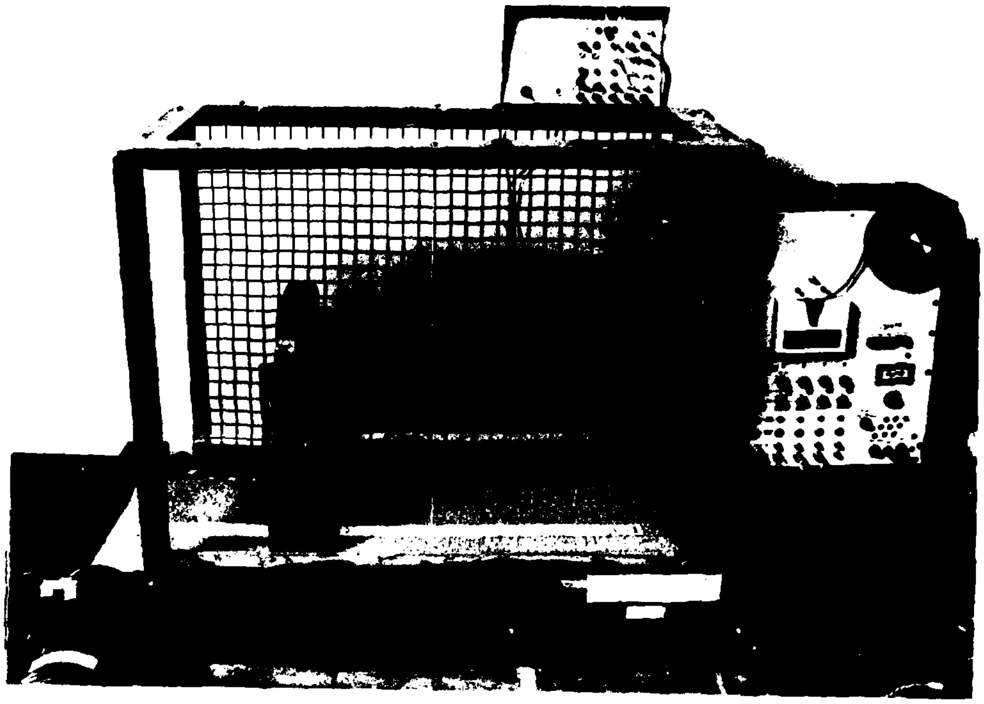


Figure 10. Treadmill and Cage

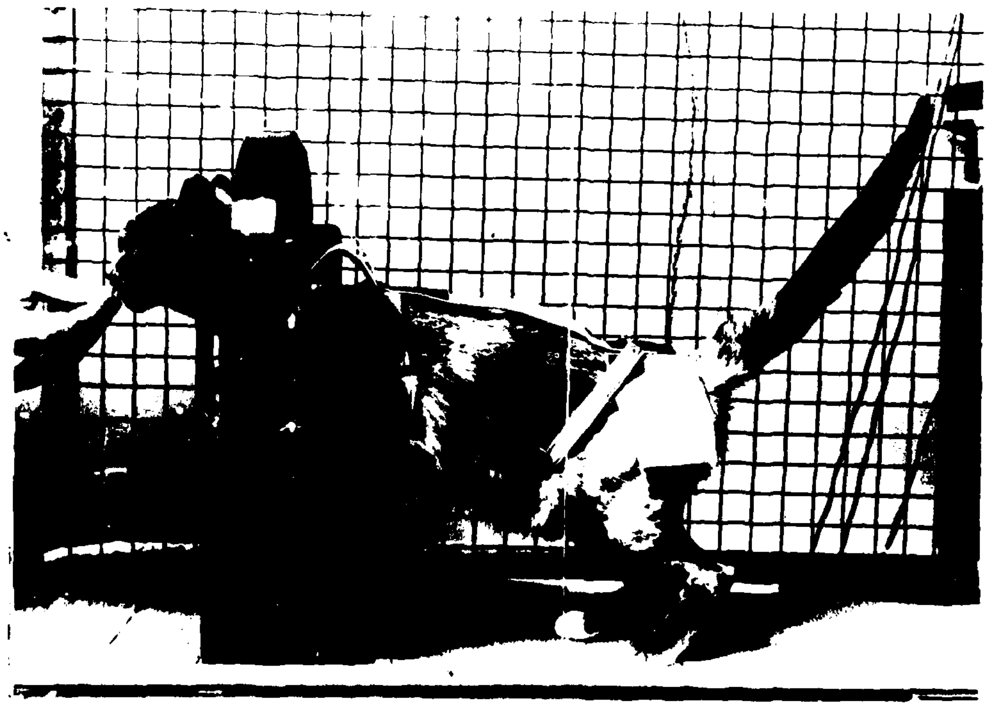


Figure 11. Cat Restrained on Treadmill

supported the entire upper body and torso of the cat along with a clamp about the tail to maintain position of the hip in the stationary harness. The free harness allowed the cat to support its own weight.

The additional weight of the harness posed no major change in the posture of the cat. The cloth harness weighs 42.6 gm, and the feedback harness weighs 80.2 gm. The main weight of the feedback harness is located directly over the hips. Some of this weight can be alleviated by a light tension on the interface wires of the harness. This leaves the cat unrestricted and with little extra weight to carry. The relative muscle activity can be assessed as supporting the cat with the sequence of activity assessed for locomotion.

Position Information

The free moving harness supported by the cat provided the feedback information through the use of transducers or position sensors. The sensors are located at the pivots points of the leg members and correspond to the hip, knee, and ankle joints. These transducers accurately relay the angular position of the animal joints by electrical signals.

The pivot points mimiced the joint motion in one plane. This measurement is accurate for the knee and ankle joint. Both are hinge joints and move the bones in a single plane. The ankle does move in a second plane for lateral movement of the cat. But for walking in straight path the ankle acts mainly in one plane. It is also restricted by the pad attachment. The hip joint is a ball joint allowing rotational and lateral motion of the femur with forward and backward motion in the plane. The measurement of the femur motion in one plane is sufficient for locomotion in a straight path on the treadmill. The test animal did not make radical changes in lateral motion. Changes, as such, would necessitate monitoring the out and inward motion of the femur at the hip joint.

The leg members of the harness are made of plexiglass joints, containing the transducers and aluminum rods, maintaining joint position as the bone. Once again two rods correspond to the femur and tibia. Three transducer joints correspond to the hip, knee, and ankle (Figure 8). The metatarsal is strapped onto just below the joint, therefore no length of rod is necessary. The spine and pelvic region is simulated by the harness plexiglass strip and aluminum brace. The complete harness outlines the cat skeleton from behind the ribs to the top of the foot.

Each joint contains a transducer to convert the angular position of the animal joint into an electrical signal. The sensor feeding back the position information operates on a moving magnetic field. The magnetic field is provided by a magnet mounted in one side of the joint. The sensor is mounted in the other side and pivots on the non-magnetic pin connecting the two. The joint weighs less than 8 gms and has almost no friction (Figure 12).

The position sensor is a linear output hall effect transducer (LOHET) manufactured by Honeywell MicroSwitch Division. The LOHET, about the size of a dime (Figure 13), provides a linear output for the linear change in magnetic field. Operated on twelve volts with no magnetic field, the LOHET has a base output of six volts. Subjecting it to a magnetic field perpendicular to sensory surface will produce a proportional change in output voltage about the six volt reference. In slide-by operation using a magnet with a single pole set, the sensor will give

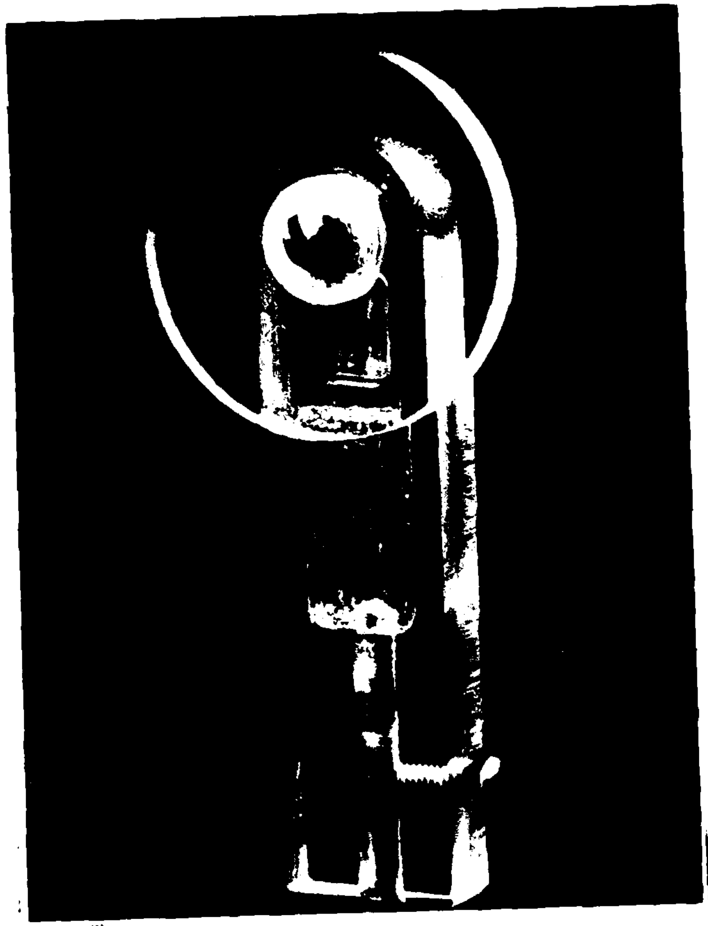


Figure 12. Feedback Harness Transducer Joint

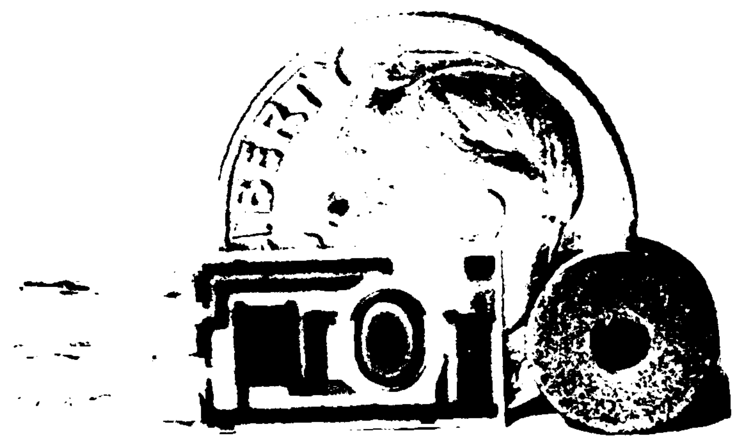


Figure 13. Transducer Sensor (91SS12-2 Linear Output Hall Effect Transducer) and Magnet

maximum output nearest magnetic south and minimum nearest north (Figure 14). At a location equidistant from either pole, the LOHET maintains the reference voltage.

The magnet for the LOHET was chosen to give uniform changes in field strength throughout its length. The circular magnet provides the perpendicular field as the sensors moves along an arc about the pivot (Figure 13). The magnet material Alnico 2 is medium strength, light-weight and low cost. The magnet dimensions are chosen to maintain a large enough arc to center over the sensing surface. In this respect, the magnet used in the joint is not ideal. To avoid special manufacturing delays, a stock magnet was incorporated. The magnet, smaller in radius than desired, reaches only the edge of the sensing surface providing an output lower than originally designed (Figure 15).

The interface electronics for the LOHET is minimal by design. The unit required a plus twelve volt-ground supply. The output is zero volt referenced using a 1458 op amp with unity gain. The output is then compatible for computer interface and analog to digital conversion (Figure 16).

Reliability and Accuracy

The position sensors were checked and tested over a range of conditions and operating voltages. The sensors can be operated over a range of 6-16 volts. The data in Figure 17 shows the operation of the joint at 6, 9, and 15 volt source inputs. Figure 18 shows the operation of the joint at 12 volts under different environmental conditions. The magnet position has a great deal to do with the range about the reference voltage. Figure 18 also shows the range of output increase operating at

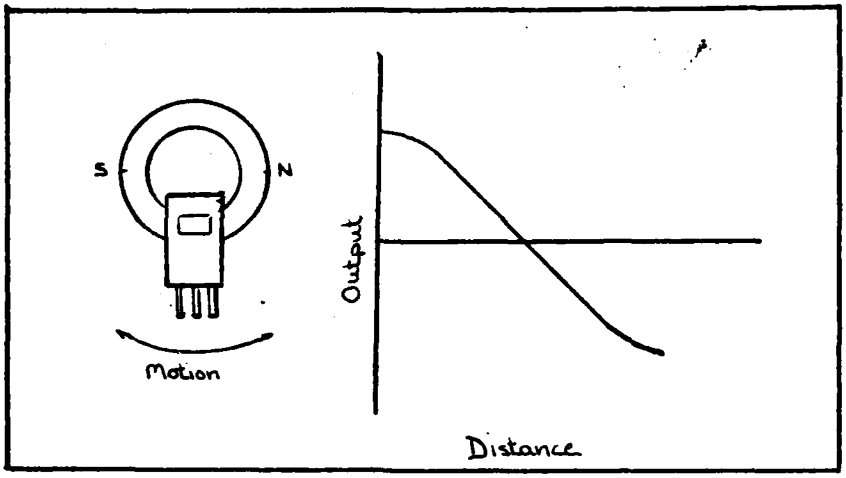


Figure 14. Sensor And Magnet in Slide By Operation

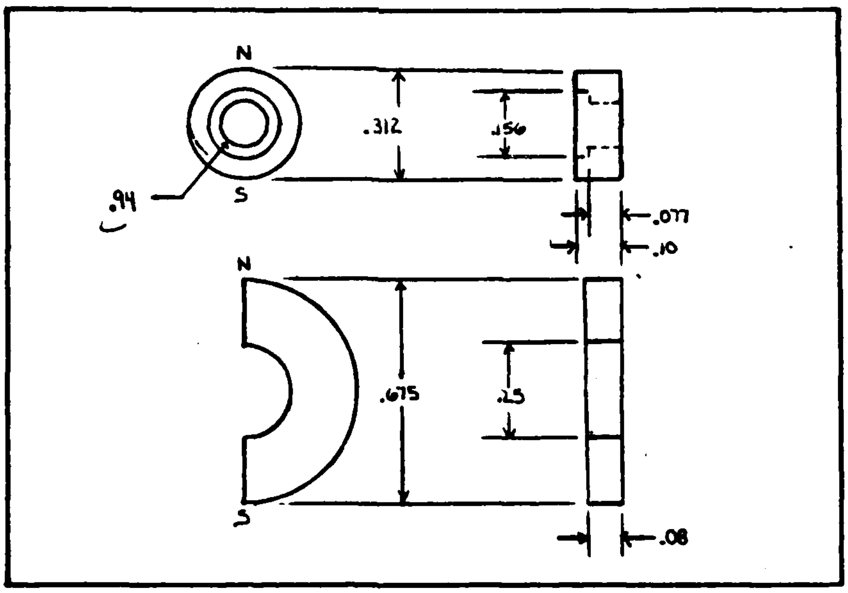


Figure 15. Standard Magnet And Designed Magnet

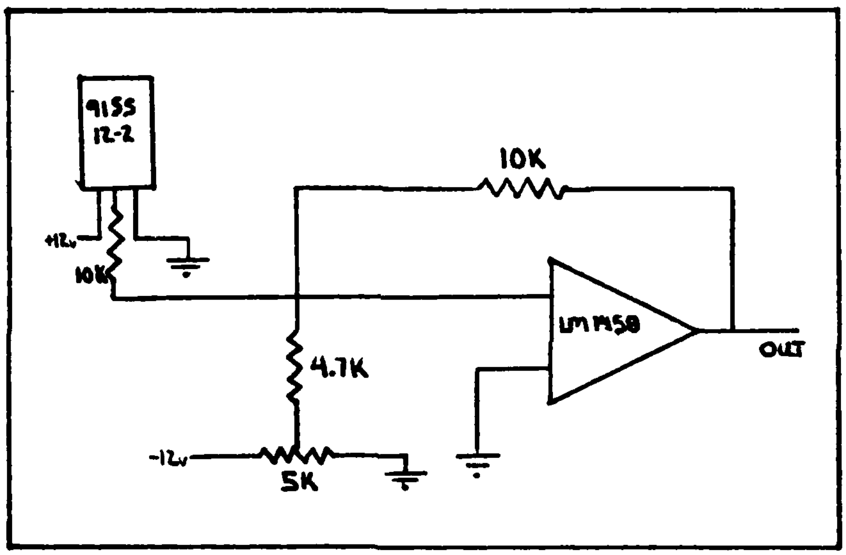


Figure 16. Position Transducer Amplifier Circuit

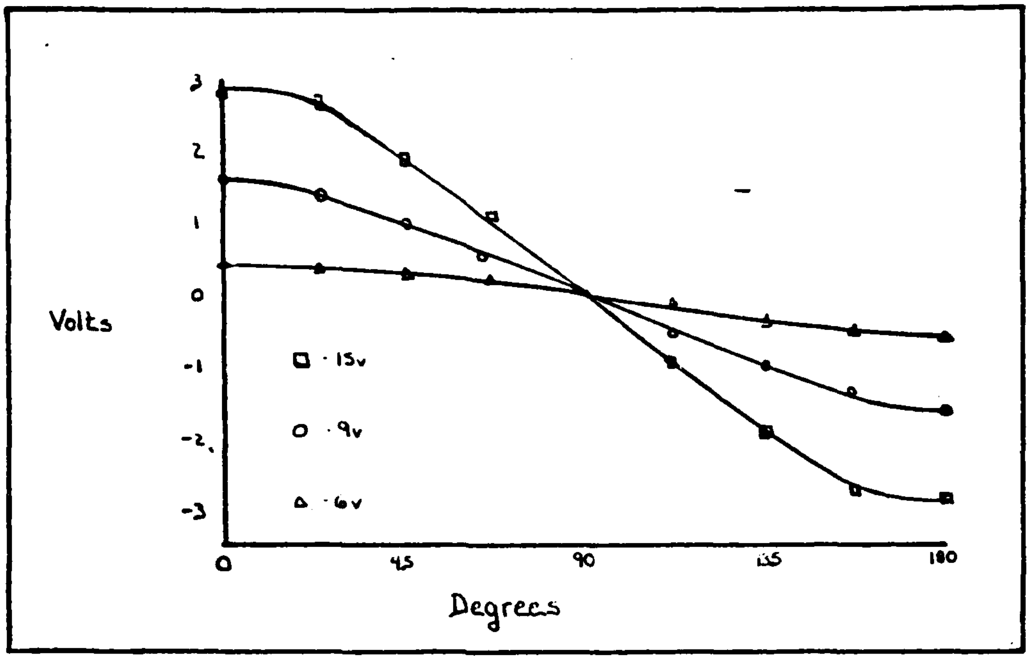


Figure 17. Sensor Operation at 6, 9, and 15 Volts

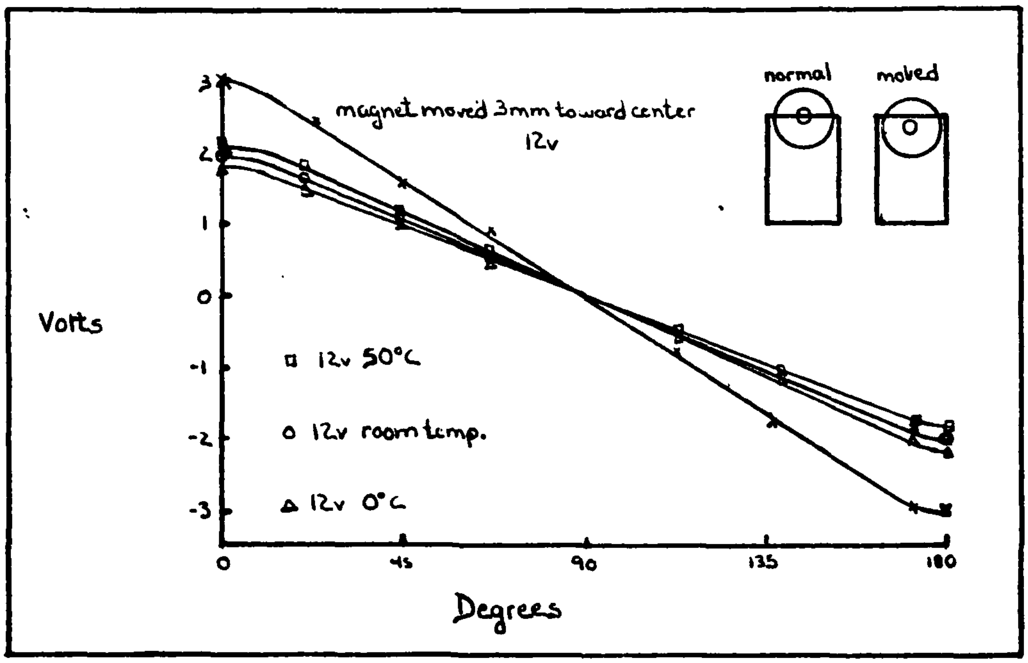


Figure 18. Sensor Operation at 12 Volts at
0 °, 23 °, and 50 °C - Moved Magnet

12 volts incurred by moving the magnet 3 mm toward the sensing face of LOHET. The insets in the figure show the two configurations. The latter configuration though better in range, did not allow a pin for pivot through the center of the magnet. A magnet of larger radius would center over the sensing surface (Figure 15) for optimal operation. It would allow a greater output about a given reference, with additional space for a larger pin pivot. The result is a stronger joint with greater operating range. For this experimentation, the standard magnet provided desirable characteristics with sensor operation at 12 volts.

The sensor, when exposed to temperature changes, provided reliable information. The LOHET was subjected to temperatures ranging from 0°C to 50°C. The set of curves in Figure 18 shows the variation in output. The sensor remains linear at the temperature extremes. This temperature testing becomes more important when the overall project (Petrofsky, 1979a) reaches completion. The stimulated subjects must contend with the changing environment without changes in transducer characteristics. Unlike potentiometers a physical connection between the moving parts of the transducer (magnet and LOHET) does not exist. Therefore, the transducer was much less susceptable to environmental changes while providing a cleaner signal.

The frequency response of the joint was conducted by mechanical rotation of the magnet at a given number of radians per second. The joint rotated up to 2400 rpm showed no indication of output roll off. The response was stopped at this point because of physical strength limitations of the joint. The frequency response of the joint breaks down well past the point of maximum rational velocity (Chapter V) of the normal walking cat joint.

The tests for reliability were conducted on the transducer joint. The tests for accuracy were conducted by video recording of the cat walking. The cat was first walked over a three meter measured course on the floor. For initial tests the animal was walked on a leash. The leash provided guidance to keep the cat on the filming surface. The harness, on the free walking animal, was monitered by a video recording. The recording was used to assess the ability of the harness to accurately follow the leg members. Figures 9 and 19 show various configurations of the stationary and walking cat. The joints maintained position with respect to movement by the animal with excellent accuracy in all configurations.

In later runs, the harness was operated with tape and chart recording. A sample of the harness output is in Figure 20. In addition to the joint recordings, the foot contact with the surface was recorded. The foot contact and force is the subject of Chapter IV. The sample output is recorded for both legs and at various walking speeds on both level and ramp surfaces. The disadvantage to the leash and free walking surface was the inability to choose and duplicate walking speeds. The cat had almost complete control over where and how fast it wants to walk.

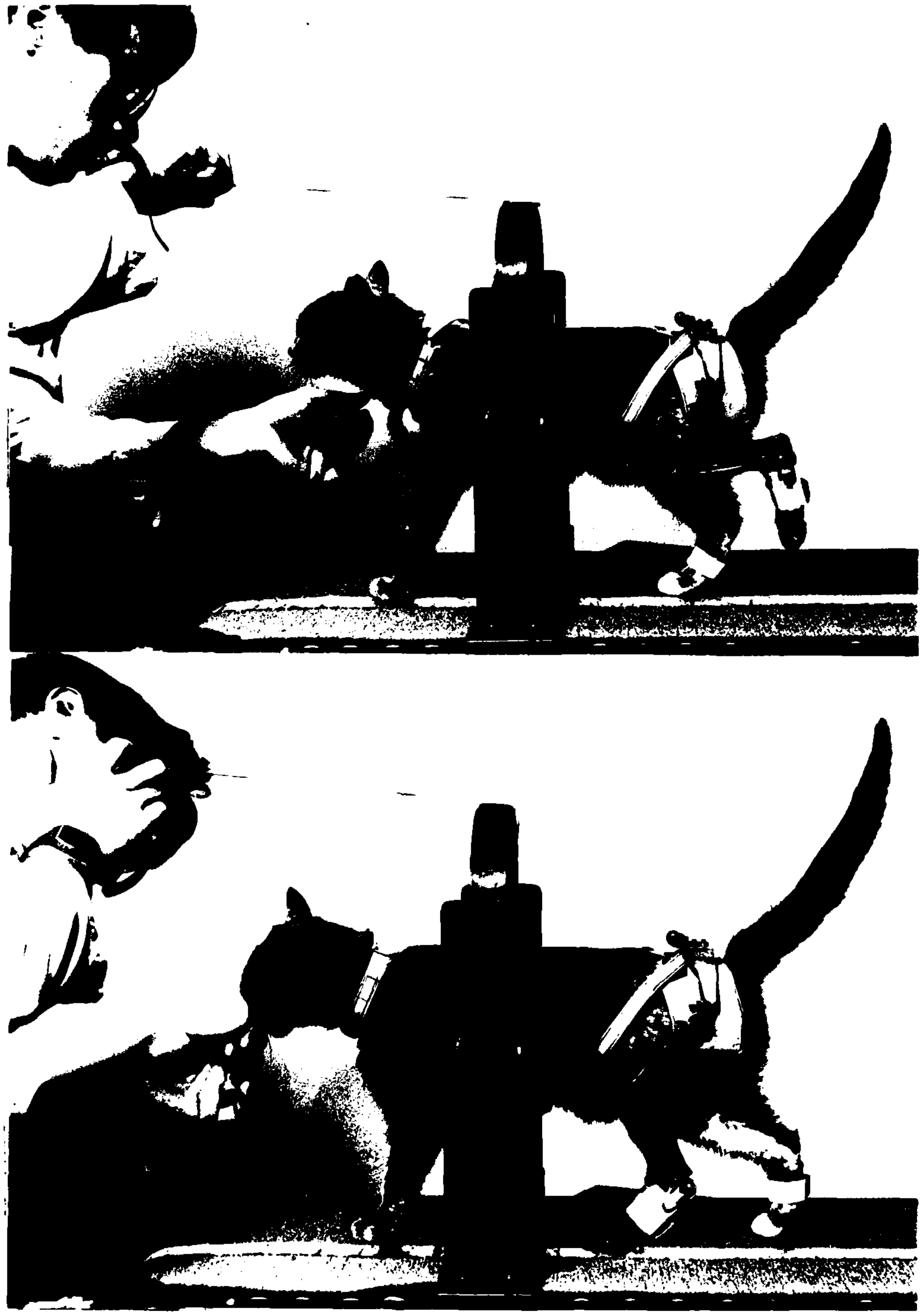


Figure 19. Feedback Harness on Walking Cat

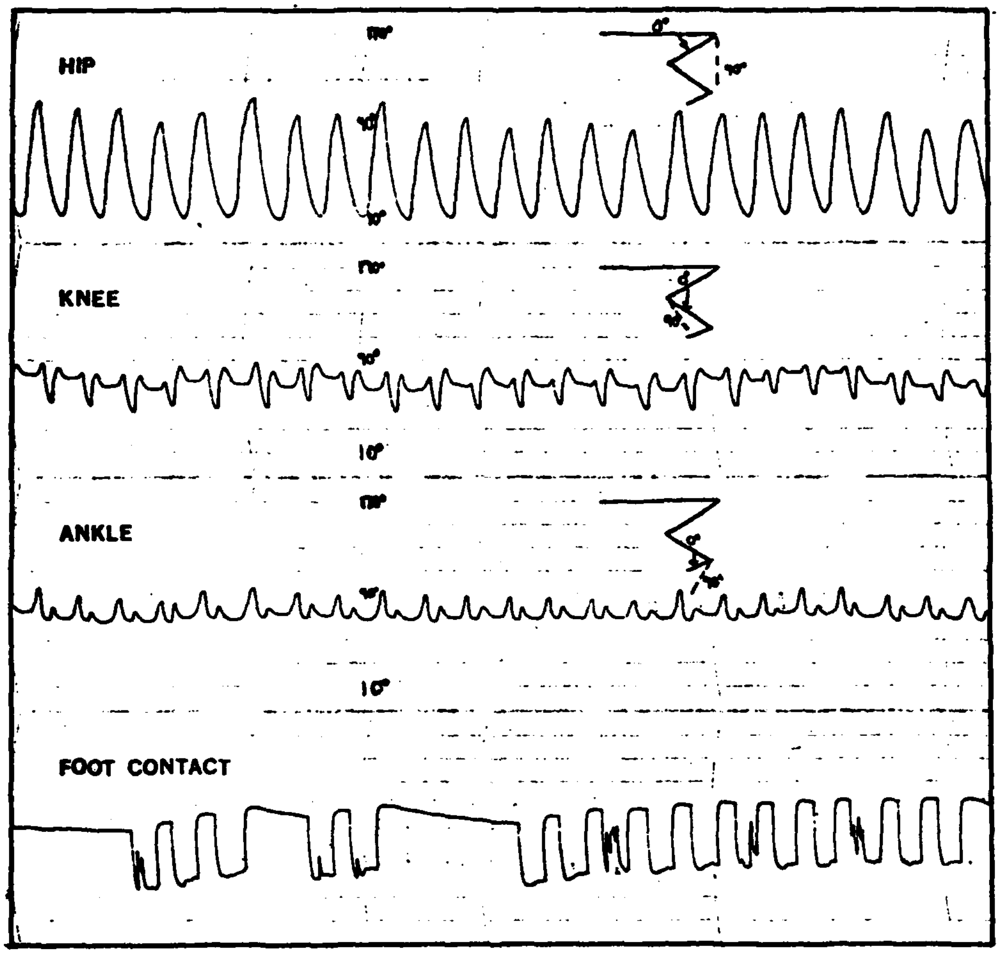


Figure 20. Sample Harness Output - Joint Position and Foot Contact

IV. FOOT ACTION

Another area of concern was the action occuring at the foot. The exact point of contact during the walking cycle is necessary to analyze the extension and flexion of the leg. It is also desirable to know the force on the foot throughout the cycle. For this foot action information a switch for contact and a transducer for force were developed.

Foot Contact

The contact of the foot with the ground is sensed by the receptors in the pads of the foot. In artificial control, this sense is unavailable to the computer controller. Therefore a switch to show foot contact with the ground is required for feedback. The switch must be small to leave the cat unencumbered when free walking. A method of attaching the switch to the foot of the cat adds to the problem.

The switch developed was a simple metal contact switch. It required the walking surface to be partially covered with a conducive metal foil or tape. The other half of the switch consisted of a foam tape and metal strip. The foam tape is covered by the metal strip on one side and attached to the foot of the cat by the tape backing (Figure 21). The metal is connected to a voltage divider circuit through a single 32 gauge wire. The foil surface completed the circuit. The foam switch in contact with the surface gave a 2 volt output for recording. The signal remains as long as the foot is in contact with the surface. The recording gave the exact placement and lifting of the foot. The erratic appearance of the foot placement is a result of the cat missing the two inch contact strip on the treadmill.

Figure 21. Foot Contact Switch on Cat - Switch Alone Inset

The foam tape is placed on the foot of the cat. It is located on the ball of the foot (Figure 21). The switch was on one foot, and the other foot had on it a similar piece of foam but with no metal. This arrangement assured an even walk without the cat favoring either foot. The location of the pad did not interfere with the walk. With the pad on the phalanges, the cat favored the foot slightly. Padding the ball of the foot did not seem to bother the cat, and the cat had no trouble adjusting to the switch from the first wearing. Figure 20 shows an example of the switch output in relation to the joint movement of the harness in a sample run of the cat.

Force Transducers

The foot switch gives contact information for analysis. But for precise modeling and control, force on the foot throughout the step cycle is necessary. For this purpose, a force transducer was designed to be worn on the cat. The unit is made up of three pieces. The aluminum base houses the active portion of the transducer. The top surface of aluminum allows application of foot force to a single point on the transducer, and the transducer itself measures the distance change between the two surfaces of the unit as a result of applied force. Figure 22 is a diagram of the force transducer unit, and Figure 23 shows pictures of the relative size of the unit and mounting on the foot of the cat.

The transducer is a single bridge strain gauge. A semiconductor strain gauge mounted on a single simply supported beam povides the active bridge. The beam is supported at the ends by the base, and the force is transferred from the top and concentrated in the center of the beam. The

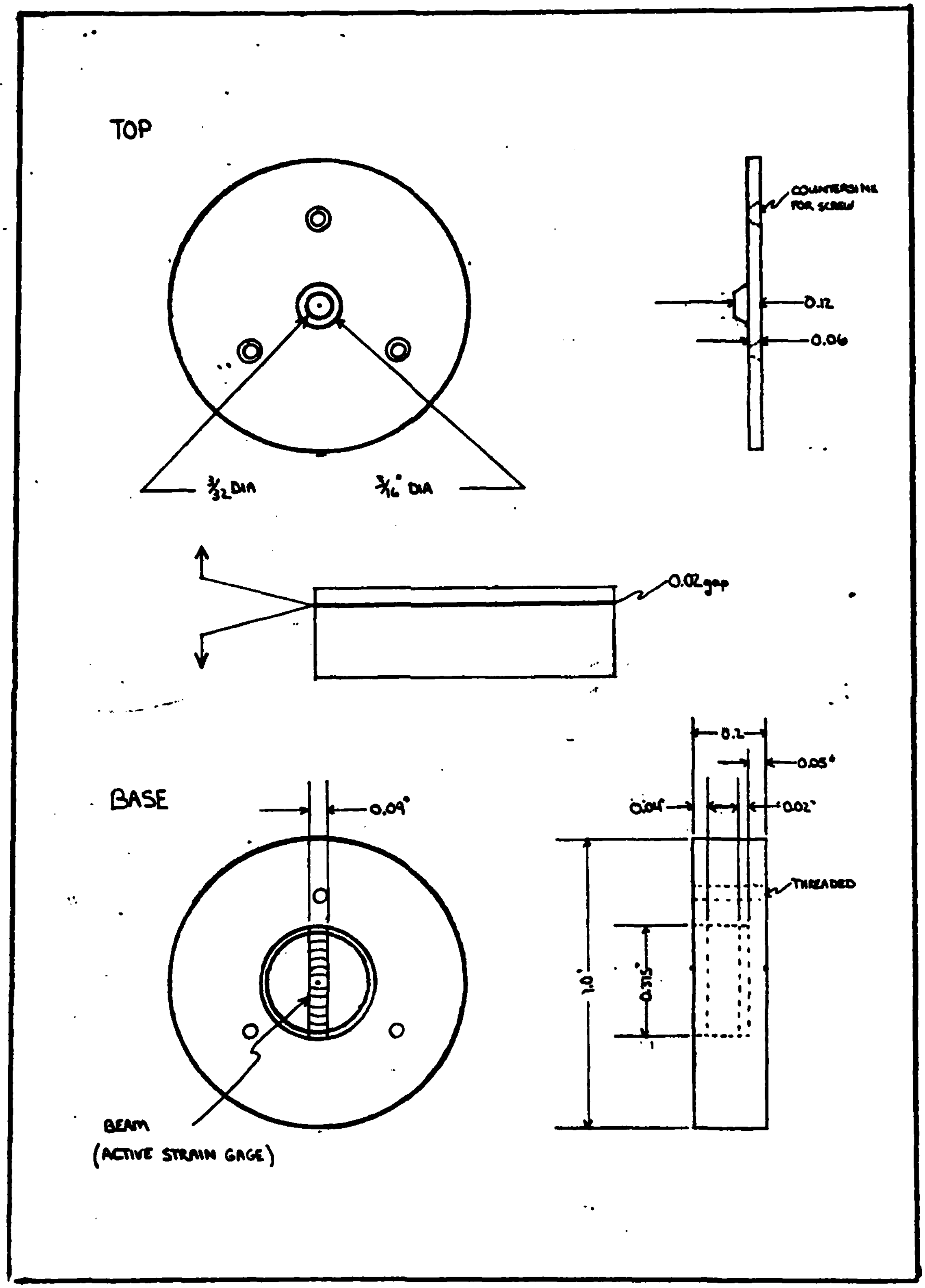


Figure 22. Foot Force Transducer

Figure 23. Foot Force Transducer on Cat - Transducer Alone Inset

design specifications of the beam for a fifteen pound average operating load are as follows: referring to Figure 24.

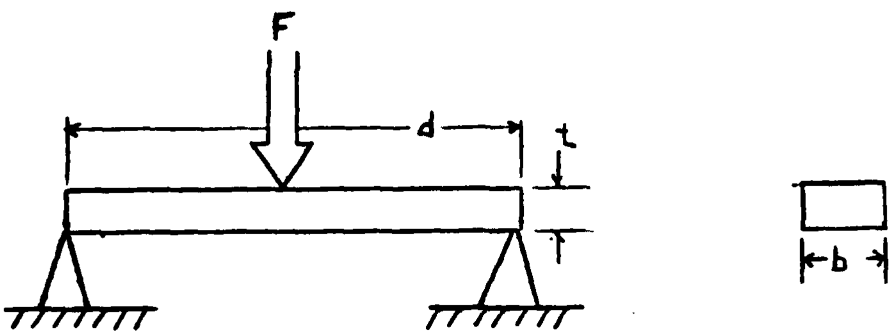


Figure 24. Simply Supported Beam

The strain ε is

$\varepsilon = m(t/2)/E(1/12)bt^3$

where moment $M = F(d/2)$

$\varepsilon = 3Fd/Ebt^2$

For dimensions compatible to strain gauge and base unit specifications with a beam of stainless steel

$b = 0.09$ inches	$d = 0.375$ inches
$F = 15$ pounds	$\varepsilon = 29 \times 10^6$ psi (for st inless)

With an ε of 750 microstrain near the support the equation becomes:

$750 \times 10^6 = \varepsilon = 3(15)(0.375)/29 \times 10^6(0.09)(t^2)$

The thickness design to allow strain to provide adequate output is:

$t = 0.093$ inches

The deflection of the resulting design under strain:

$\delta = Fd^3/48(\varepsilon)[(1/12)(b)(t^3)]$

$= [F/4(b)(\varepsilon)]\ (d/t)^3$

$= [15/4(0.09)(29 \times 10^6)]\ [0.375/0.093]^3$

$= 0.00095$ inches @ center of beam

The strain gauge is from Kulite Semiconductor Products, Inc. It measures 0.25 by 0.01 inches, and is pictured mounted on the beam in Figure 25. The active transducer beam is placed inside the base unit with 32 gauge lead wires.

The electronics for the unit was a two stage amplifier circuit (Figure 26). This provided a two volt output over the 0-5 Kg range of force expected in use with the cat. The unit was calibrated at 23°C and is linear over the operating range desired. The force transducer was tested at 0°C and 45°C. While maintaining linearity, a slight difference exists over the temperature scale. Figure 27 graphs all three operation curves.

The unit was attached to the foot of the cat by foam tape and elastic straps. The force transducer, unlike the contact switch, was noticed by the cat. A second dummy unit was placed on the other foot to balance the walk. As expected, the walk of the cat was altered. The step is modified to a limp because of the insecurity of the cat on the metal unit. Mixed among these "limp" steps are what are considered to be natural steps. The walk was continuous, and natural posture maintained. The foot transducer output, to be used as feedback information for the computer controller, provides much more information than the contact switch at the cost of inconvenience for the cat. The shape, size, and weight of the unit (less than 6.5 gm) necessitates a change in walk by the animal. But the difference in the gait is a fair trade for the added force information feedback from the foot. A sample output is shown if Figure 28 with an expanded view. The expanded step shows the force of the foot initially hitting the surface. After initial impact, the force reflects support of the cat. About halfway through the cycle a small increase in force is

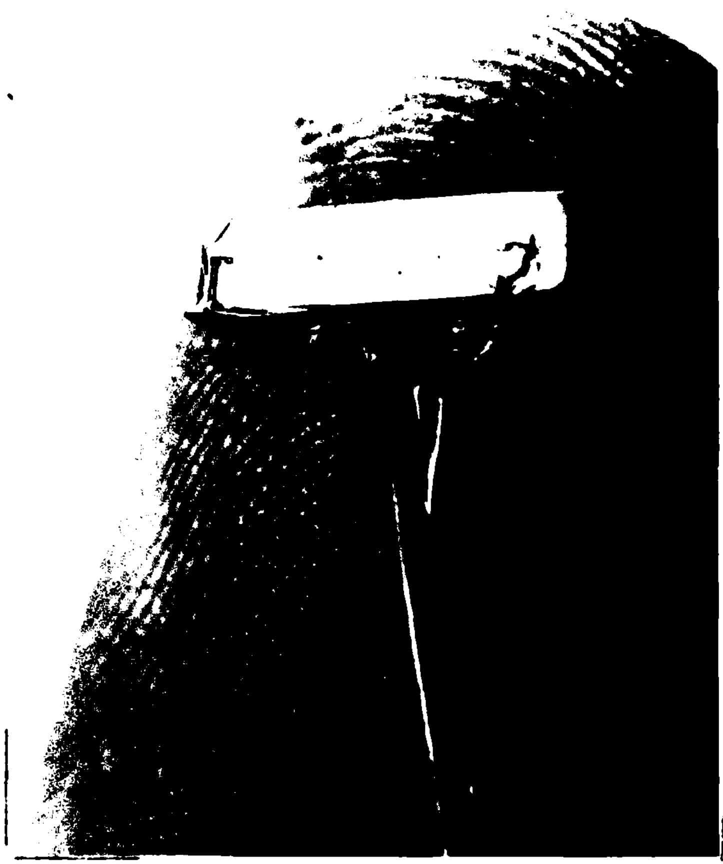


Figure 25. Strain Gage Mounted On Beam

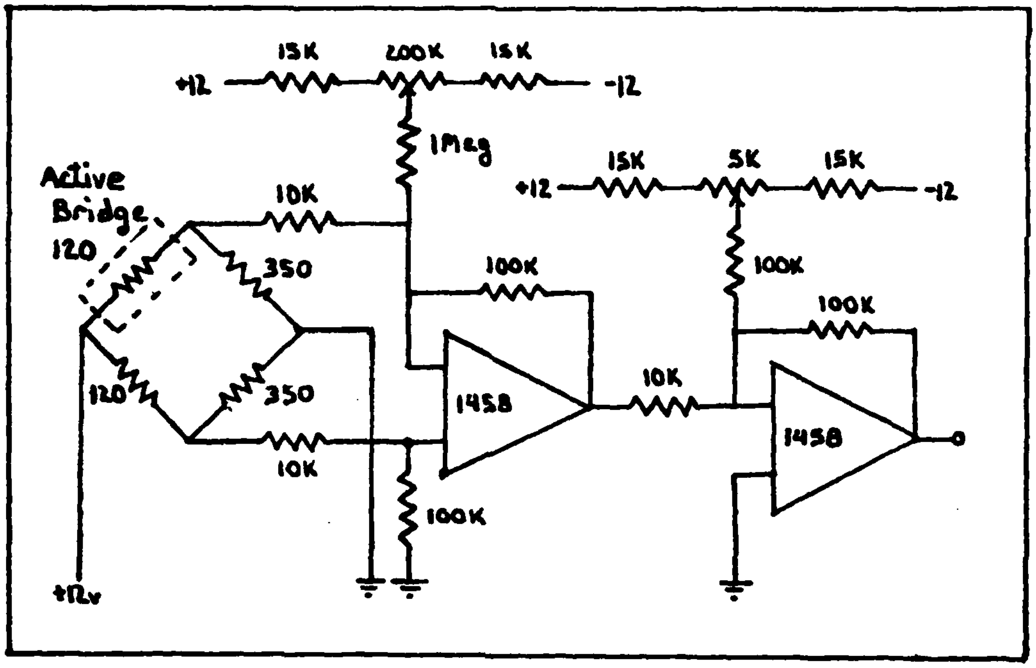


Figure 26. Force Transducer Amplifier Circuit

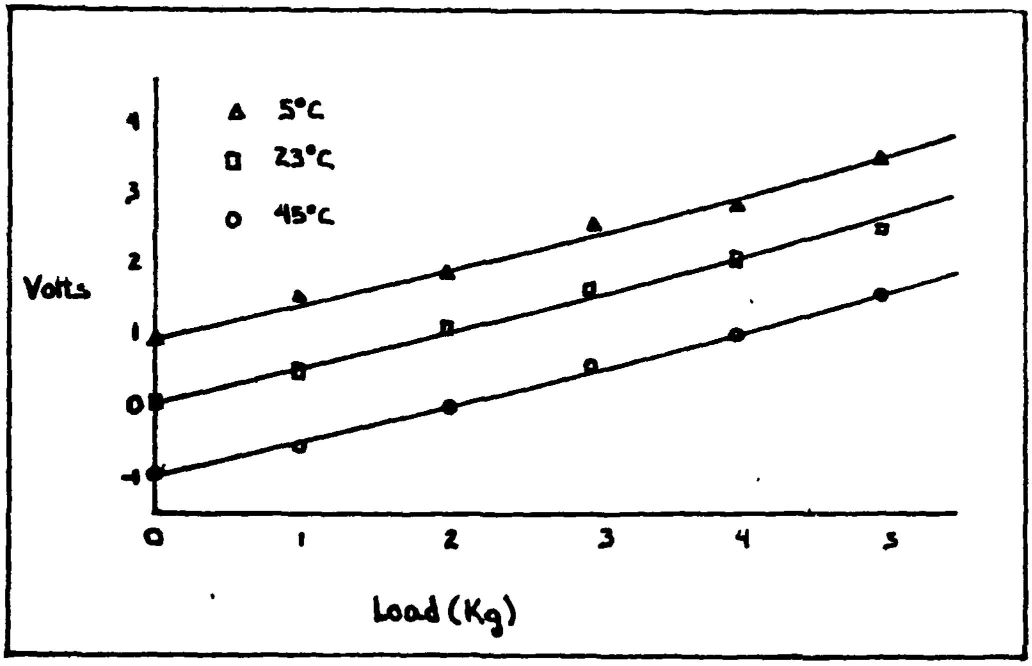


Figure 27. Force Transducer Operation at 5°, 23°, And 45°C

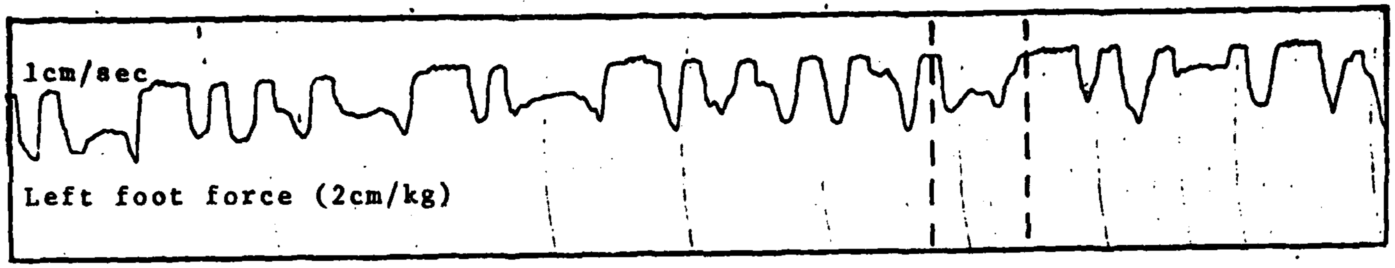


Figure 28. Sample Force Transducer Output

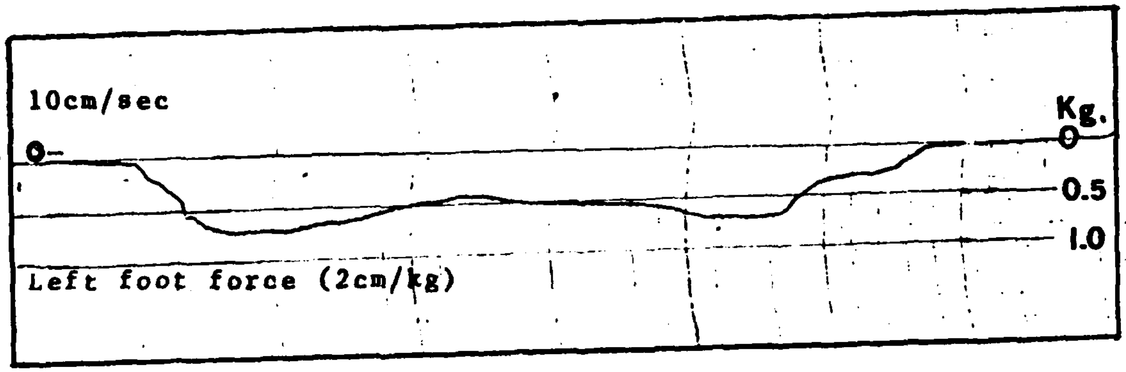


Figure 28 A. Expanded View - Indicated In Figure 28

the result of lifting the opposite foot. Following this, the animal pushes off with the full foot. The roll onto the toe completes the force cycle on the foot. This is assumed to be a normal step. Additional training may produce a more consistant step. But on the other hand it may just produce a totally modified step.

V. Gait Analysis

From the feedback information, the gait of the cat was studied under different conditions for modeling. The methods for obtaining walking data, a comparison of the gait under different conditions, and equations of motion provide the basis for future modeling and compensating for a changing walk.

Methods for walk data

The main two methods for obtaining walking data were conducted by walking the cat over a short measured course on the floor and walking on the treadmill (Chapter 3). The cat was trained to walk on a leash. After short adjustment time the animal walked on either surface with relative ease.

To walk the cat on the floor, the power and electronics were placed on extension cords. Both units were carried by the person leading the cat. The harness was worn by the cat, and interface wires were held by the trainer along with the leash. The cat was then walked over the three meter course with FM and oscillograph recording of the harness feedback array and foot placement. The measured course is covered with a metal foil (Chapter 4) for the foot contact switch. The person leading the cat has control over the speed at which the animal walks. A constant speed was not difficult to obtain. Once the cat was walking, it will maintain the speed established at the beginning of the run. Each run was timed over the measured course. A difficulty arose in duplicating course speeds, and this could only be maintained to the best of the ability of the trainer leading the cat.

The second method, though slightly more difficult, was more practical for obtaining data. The cat was walked on the treadmill enclosure and on the leash, as originally trained. The animal was insecure on the moving surface at first, and it takes additional time and training to obtain a fluent walk. The treadmill was more practical for obtaining data because of the relative confinement of the cat simplifying the interface wire problems. The harness was worn by the cat once again, and the leash attached to a bridge over the cat on the treadmill surface. The treadmill surface has a two inch metal foil strip for foot contact, and FM and oscillograph recordings are taken for both feedback parameters. Another advantage of the treadmill is the length of a run can be extended vastly and the speed can be maintained and reproduced for repeated runs.

Comparisons of Gait

The gait was observed under various conditions. While walking on the floor course, the surface was changed to a ramp. And while walking on the treadmill the speed was changed and maintained at various settings. The alternate legs were observed with foot contact of the same and opposite foot. Generalizations can be made about each condition.

The gait over the three meter floor course is limited to about fifteen steps. Readings of one harness leg output is seven to eight steps. This short sequence is a limitation of the floor course. Figure 29 shows left leg with left foot contact over the course. Only half of the floor course is covered with foil. Thus half of each run shows no foot action. Figure 29A is an expanded view of the dotted section of Figure 29. From the figures, the hip, knee and ankle motion is seen in relation to the foot placement. The defined gait cycle (Chapter 2) is recognized in the recorded limb movement. As the foot lifts, all three joints flex, starting the swing phase. The hip flexion decreases, and extension of the knee and ankle start almost simultaneously. The knee extension starts slightly earlier. This second part of the swing phase ends as the foot reaches the ground. Shortly after touching the ground, the knee and ankle yield slightly under the weight. Then all three joints extend until the foot lifts, and the cycle starts again. The foot switch in this case is on the ball of the foot. The result was an apparent lifting of the foot before the end of extension. Acutally this indicates the cat rolls onto the toe, lifting the ball, then lifts the foot. The dotted line (Figure 29A) shows where the toe is lifted. In placement of the foot, both the toe and ball come down together. The placement indication is correct for the contact switch mounted on the ball of the foot or the toe.

Figure 30 shows the right leg with left foot contact over the course. The walking cycle is easily identified once again. Figure 30A shows the expanded view section gives slightly better depiction of the cycle and left foot placement. The dotted line represents the right foot contact for comparison to the left foot and right leg action. In a low speed gait (approximately 0.4 meter/second) both feet are on the ground for approximately one-tenth of a second during each gait period. As gait speed increases, the stance phase time decreased. The swing phase time remained fairly constant over a wide range of speeds (Shik and Orlovsky, 1976). This study involves only the low speed gait analysis (less than 1 meter/second).

The center of the floor course is then raised to form a ramp of 8°. The recordings of the left leg were taken over the ascending and

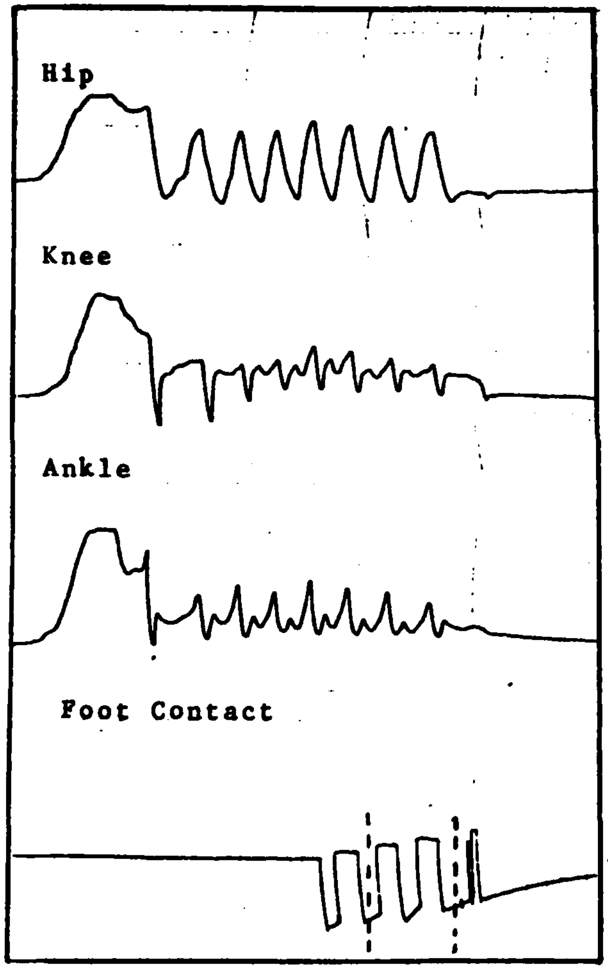


Figure 29. Feedback Data: Harness Left Leg And Foot Contact On Floor Course

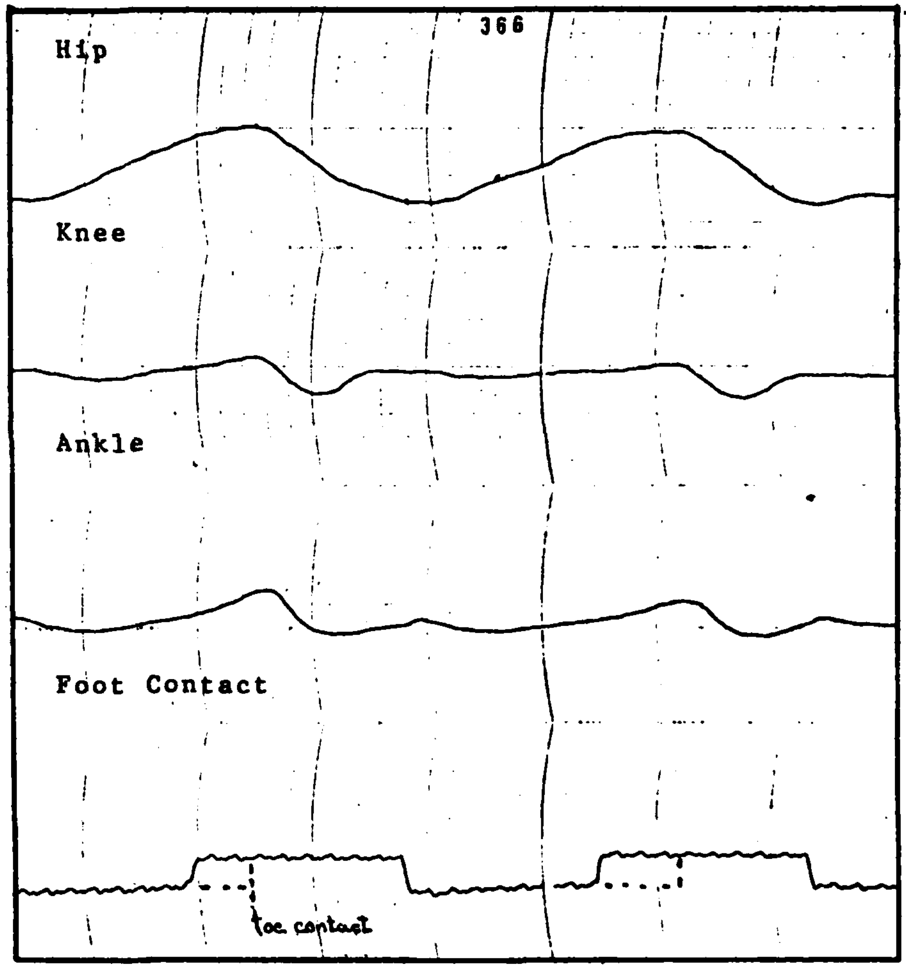


Figure 29A. Expanded View - Indicated In Figure 29

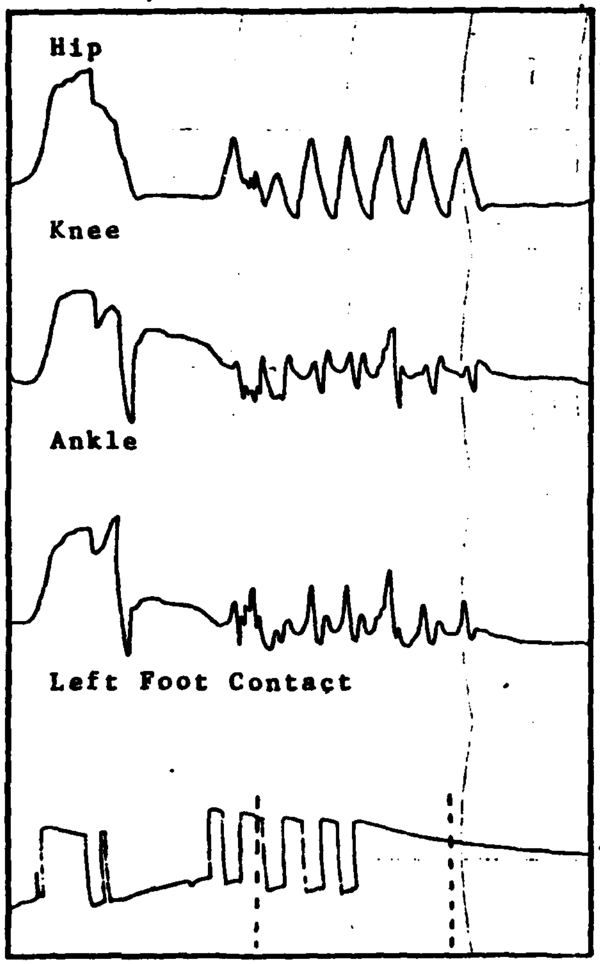


Figure 30. Feedback Data: Harness Right Leg And Left Foot Contact on Floor Course

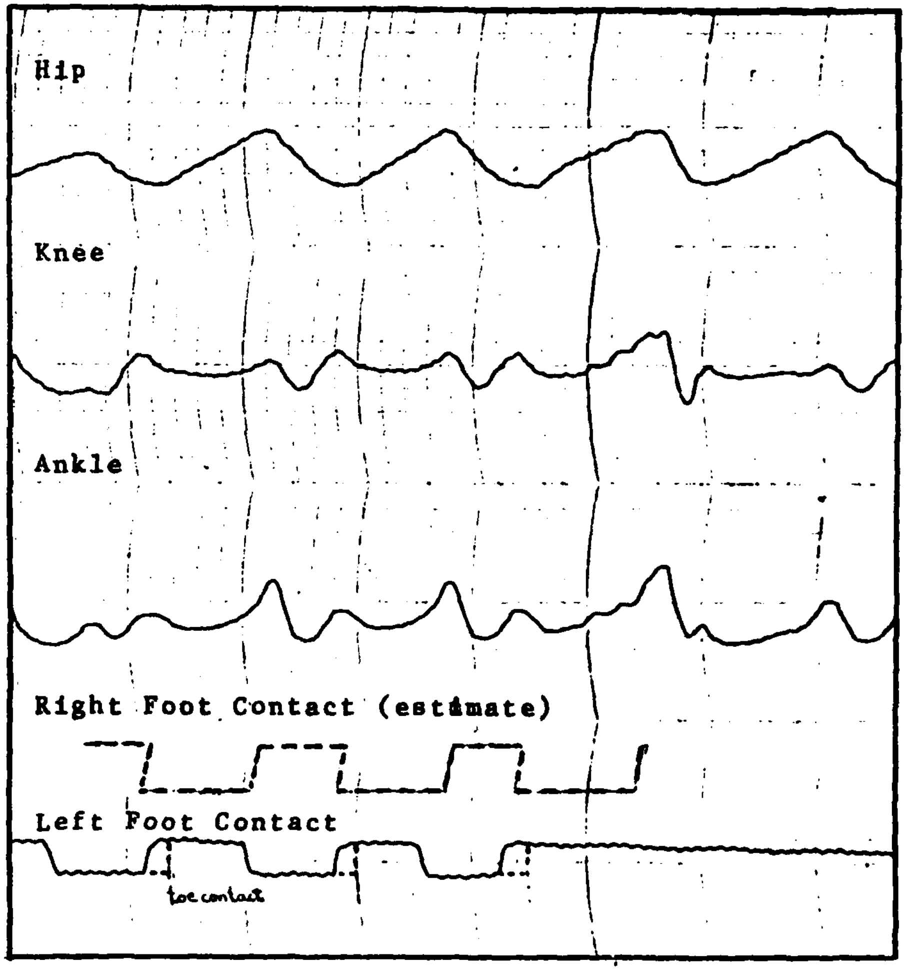


Figure 30A. Expanded View - Indicated in Figure 30

descending ramps of the three meter course. From Figure 31, the change in gait is not obvious. The run in the figure starts uphill and changes downhill about halfway (where the foot contact portion of the course stops). The expanded section (Figure 31A) shows the hip action is approximately the same for both portions of the run. The knee flexion decreases and the ankle extension decreases over the down ramp. The action of both knee and ankle giving under weight after foot placement is more pronounced in the downhill steps. This run shows the main difference in gait occurs at the knee and ankle. Less flexion and extension occur downhill with more pronounced weight effects on both. Comparing these two gaits to a normal gait (Figure 29), as expected, shows a mean of the two curves approximating the normal walk.

The floor course offers the advantage of a shorter training period for the animal. After learning to walk on a leash and with the harness on, data can be taken from the animal. The limiting factor was the relative short length of the steady state walk. For simple comparisons and initial harness tests this method provided satisfactory data.

The next sequence of tests were conducted on the treadmill. The walking sequences are controllable in length and speed. Additional training is necessary to get the animal adjusted to the motor driven surface. The animal is walked on the restrained leash (Figure 11) with a contact switch on the left foot. The erratic appearance of the foot contact was a result of then narrow contact strip on the treadmill surface. The cat did not hit it every step.

The left leg is recorded at various speeds. Figure 32 shows speeds of 0.2 and 0.3 meters/second, while Figure 33 shows gaits at 0.4 and 0.5 meters/second. The walk at 0.2 m/s is somewhat irregular. The leash

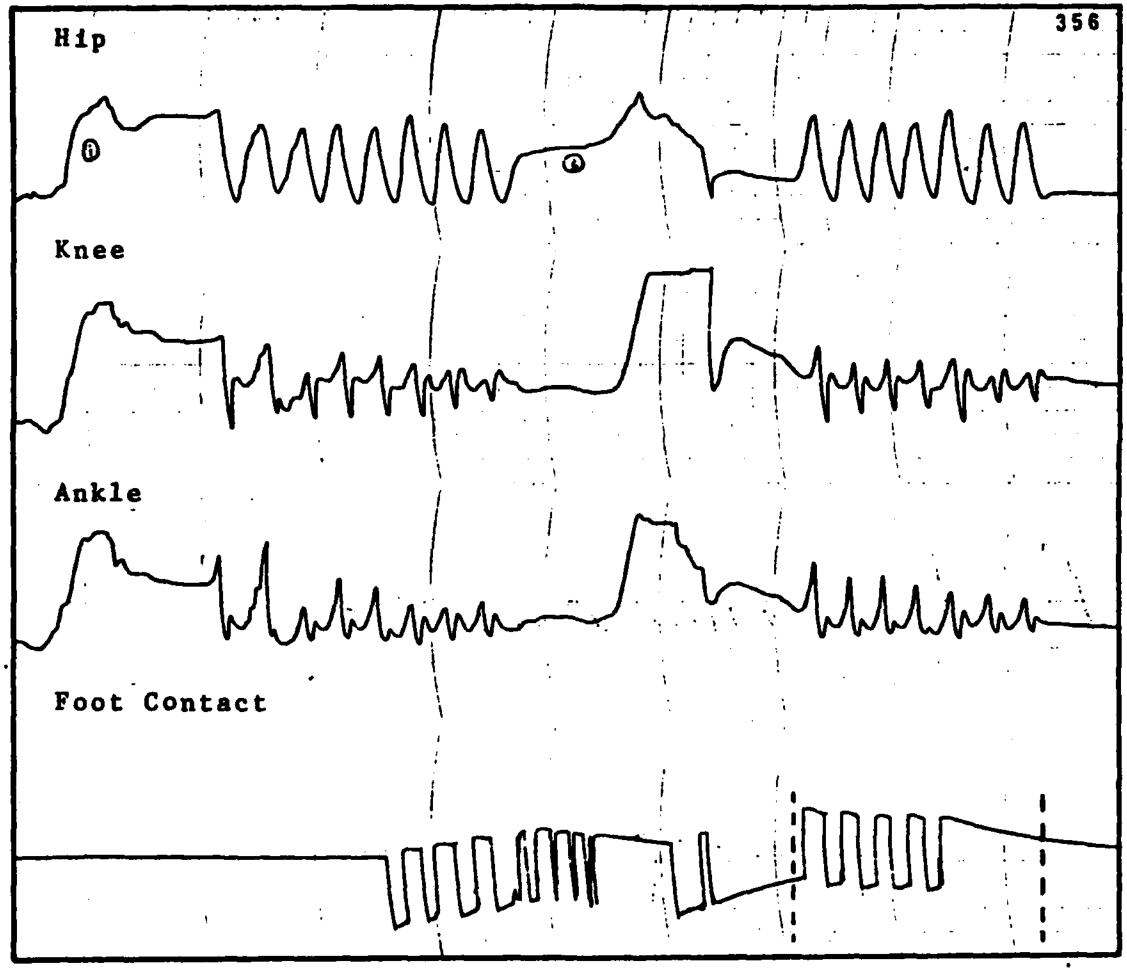


Figure 31. Feedback Data: Harness Left Leg And Foot Contact on Ramp Course

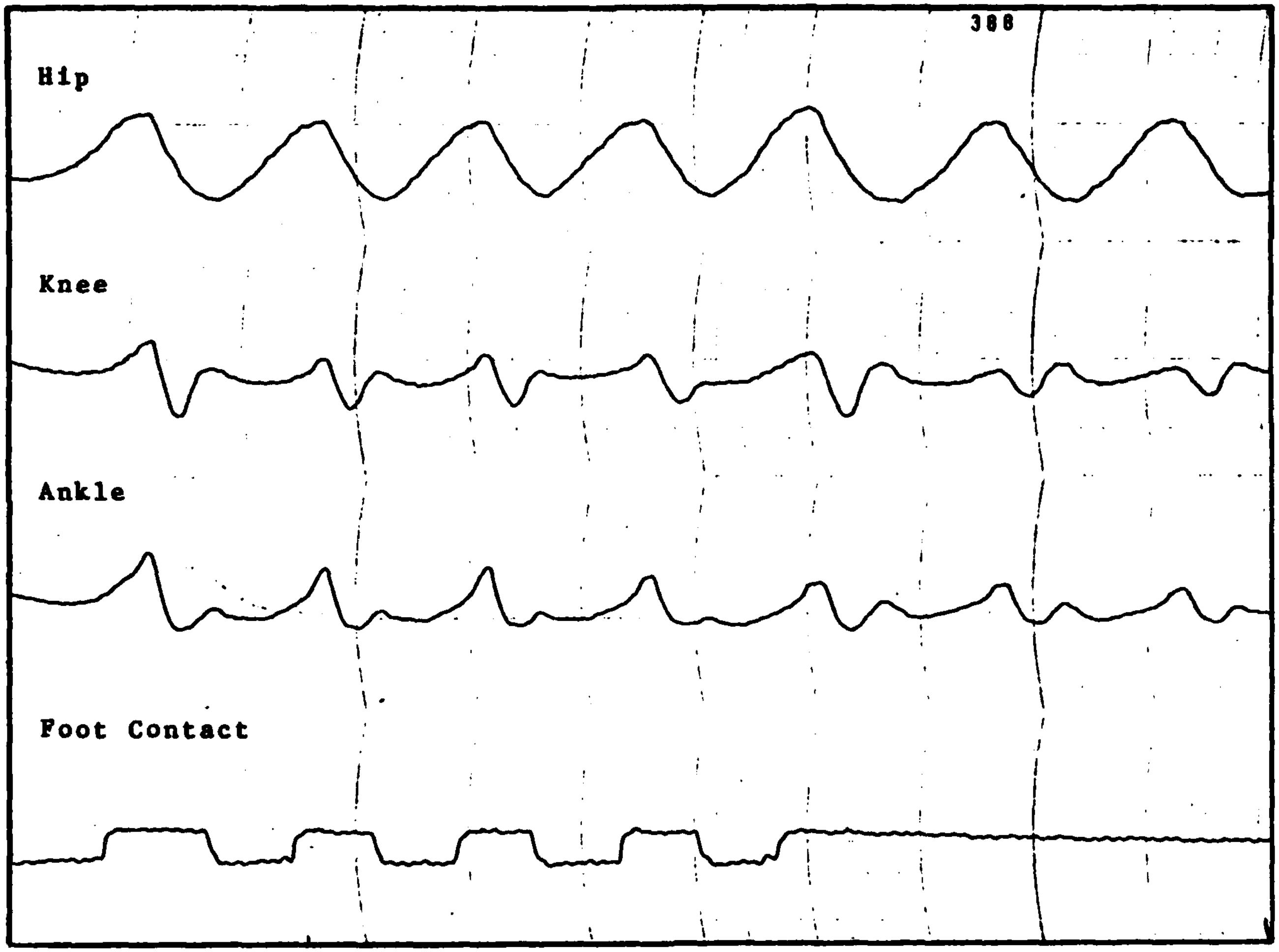


Figure 31A. Expanded View - Indicated In Figure 31

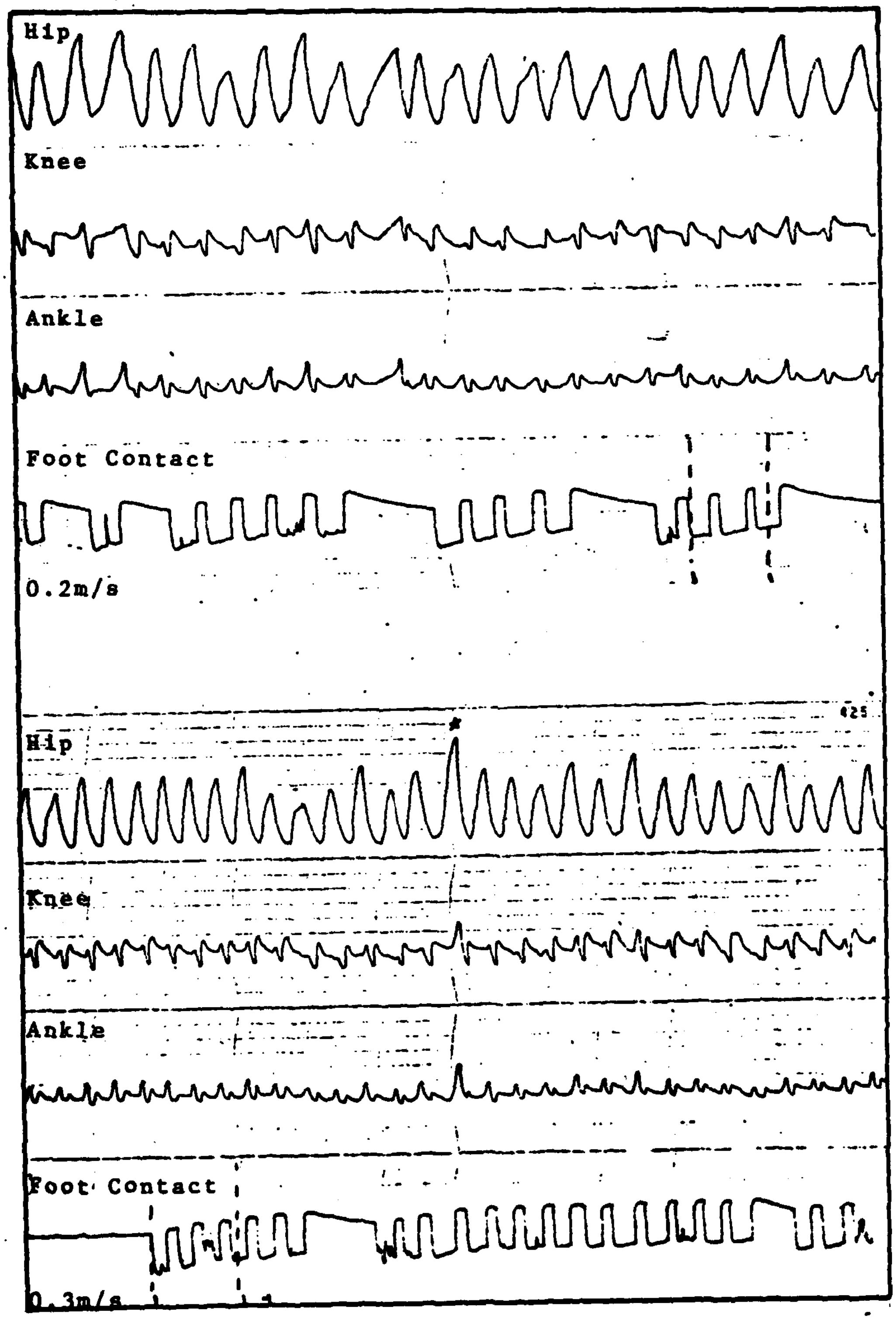


Figure 32. Feedback Data: Harness Left Leg And Foot Contact on Treadmill at 0.2 And 0.3 m/s

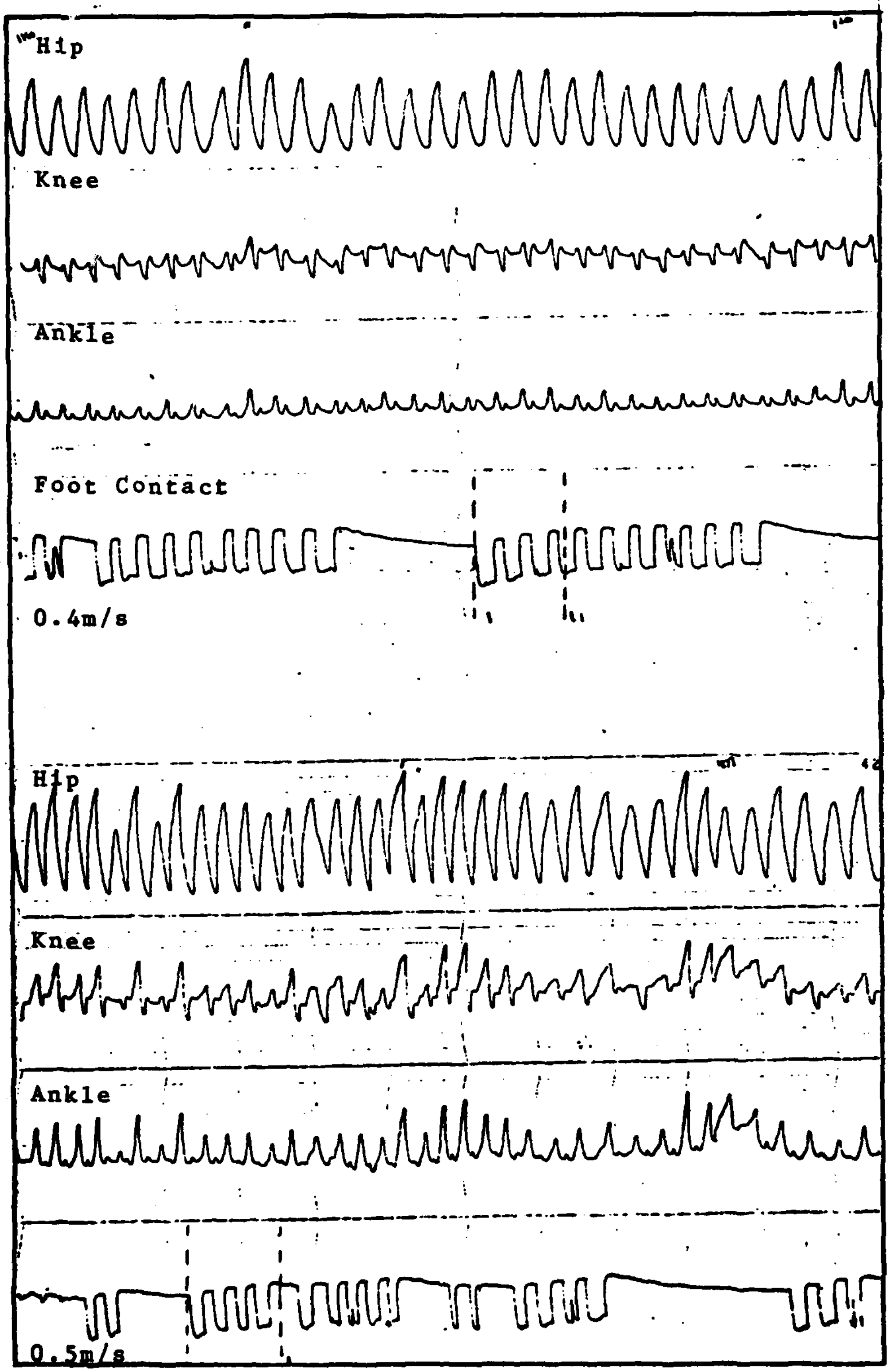


Figure 33. Feedback Data: Harness Left Leg And Foot Contact on Treadmill At 0.4 And 0.5 m/s

allows the cat a degree of freedom. If the treadmill speed is too slow, the cat is easily distracted and wanders over the limits of the leash. At 0.3 m/s the walk becomes more regular with greater flexion of the ankle in the swing phase and extension of the hips in stance phase. As the speed is increased to 0.4 m/s, the knee and hip extension increase in the stance phase, and ankle flexion decreases in the swing phase. Increasing the speed to 0.5 m/s causes the cat to strain on the leash to keep up. This data cannot be taken as extremely accurate. But it shows the general trend of increased extensions in all three joints. The dotted lines in each speed record are taken as representative of the walk. These eye chosen steps are expanded and listed by data points in Appendix B.

The contact switch was changed from the ball of the foot to the toe. Figure 34 shows the configuration at 0.4 m/s. At first examination it is difficult to tell the difference in foot placement betweem this and the configuration in Figure 33. Figure 34A is an expanded section of Figure 34. The reproduction from the FM tape was distorted for the case where the switch is mounted on the toe, and the placement is denoted by arrows. By comparison in extended views, the foot placement during the cycle was the same for both the ball switch (Appendix B) and toe switch. This indicated the foot comes down practically flat during low speed locomotion. The difference occurs in lifting of the foot. At the end of the stance phase, the leg is extended behind the cat, forcing it to roll from the flat foot up on the toes before lifting. One must resort to a force analysis to determine if this is significant. If the foot gives the last push off when still flat footed, the toe roll is just a follow through adding nothing to the resulting movement. If the toe pushes off,

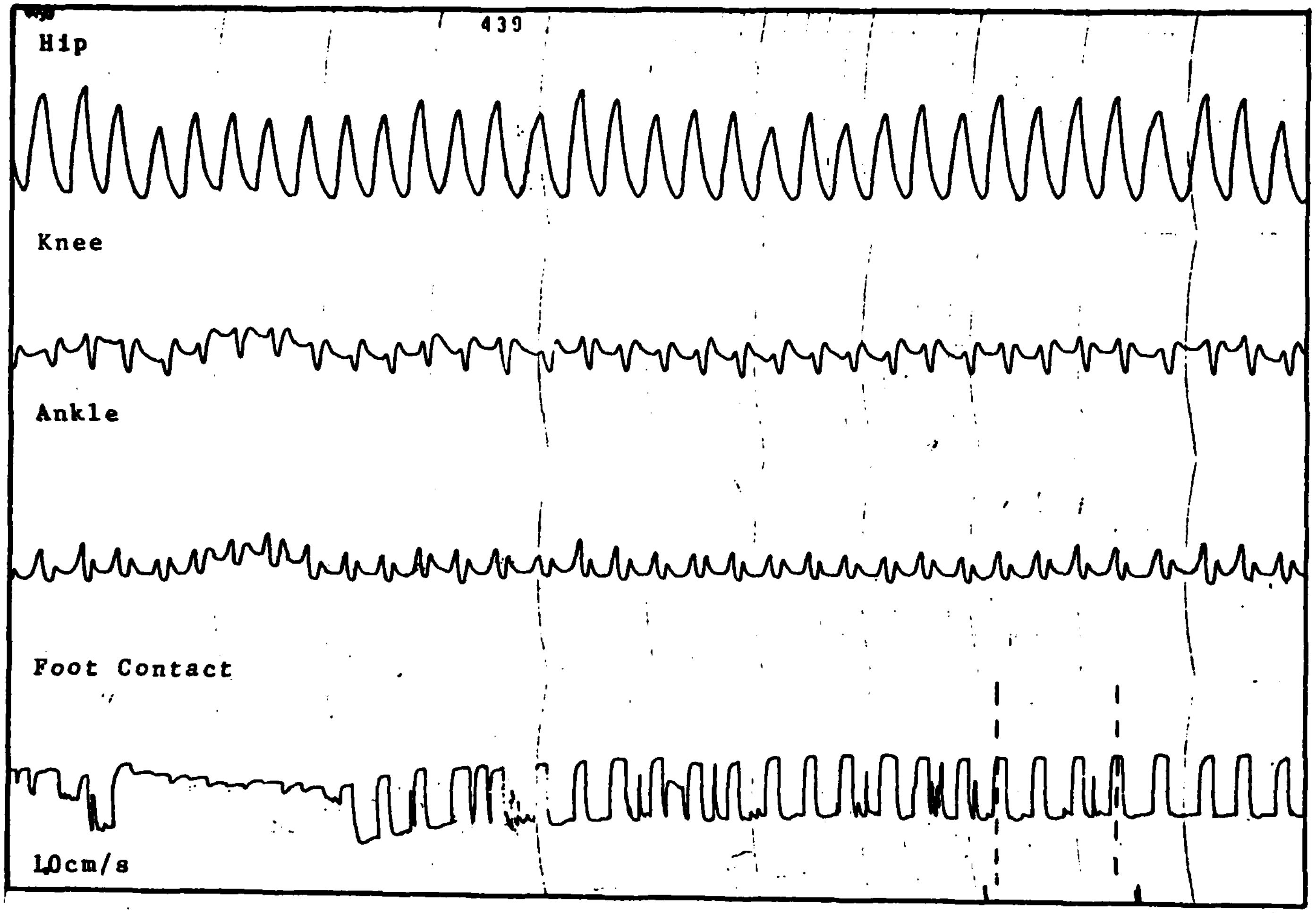


Figure 34. Feedback Data: Harness Left Leg and Foot Contact (toe) On Treadmill (0.3m/s)

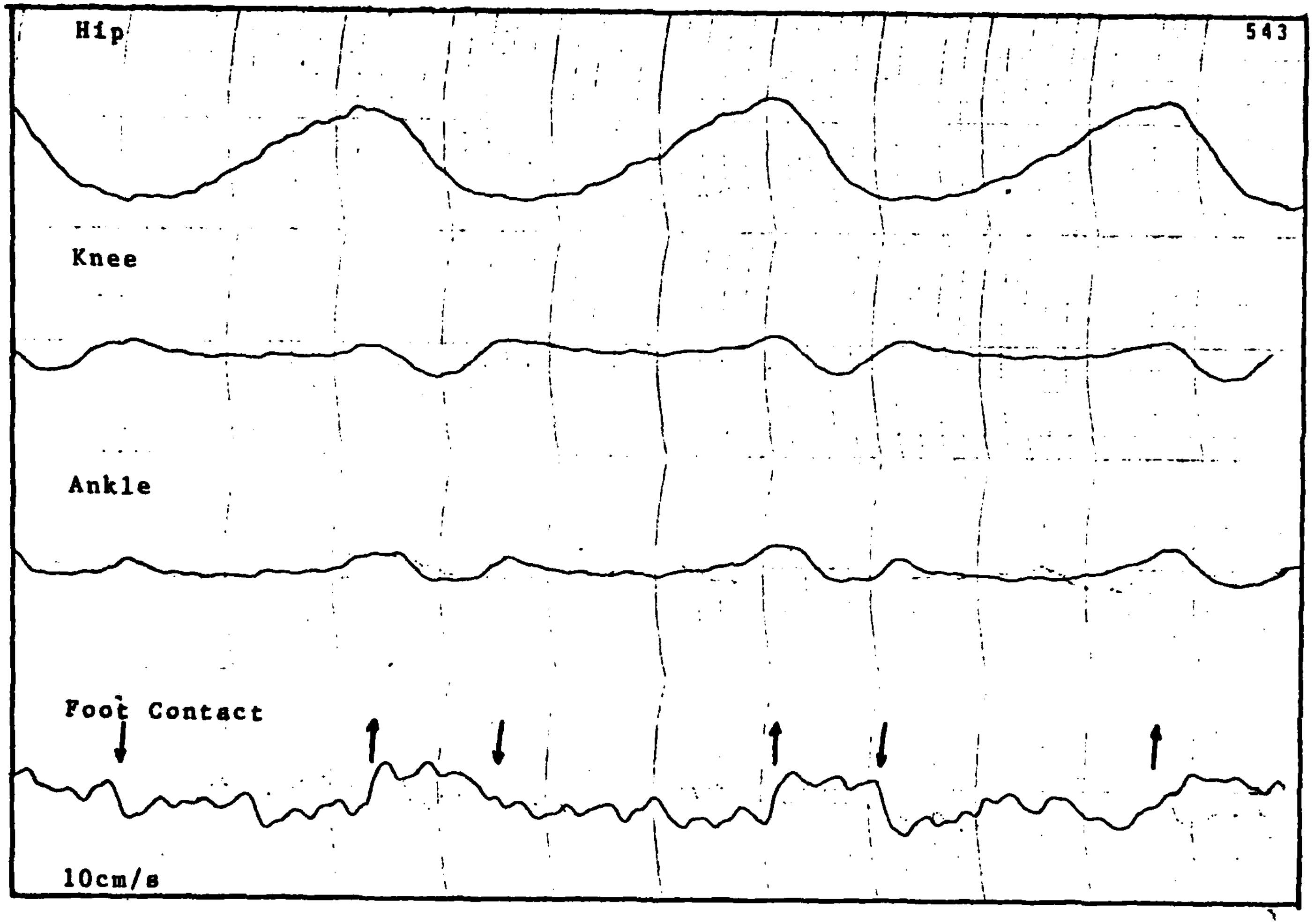


Figure 34A. Expanded View - Indicated in Figure 34 (0.3m/s) it is necessary to use the toe switch in future computer simulations for accurate reproduction of the walking motion.

These are just a few different walking configurations. The minor changes in conditions lead to some significant changes in gait. The recordings were used to generalize about the changes in gait. To study in detail and model each gait, requires muscle activity recordings and a somewhat longer record in the cases of the floor gait. This data is shown only for comparison. The treadmill recordings and later muscle activity recordings (Chapter VI) form the basis for motion equations and computer models for the project.

Motion Equations

The leg was modeled as a three lever system. In this study the levers are considered as acting only in one plane. The harness restricted the motion of the animal to walk in a straight path. Lateral changes in motion requires a more complexed analysis along with additional muscle control. For initial analysis the motion was limited to a single plane.

The model was dealt with as the harness on the cat. Figure 35 is a mechanical illustration of the harness, and each member and angle are labelled as they are referred to. The goal was to arrive at equations showing the position, velocity and acceleration of the foot with respect to the stationary ground. This stationary ground is located off of the treadmill for the case where the cat remains stationary while the walking surface moves. In the case of the free walking cat, the stationary ground is a point with velocity equal to that of the cat. The position of the foot with respect to the ground would be difficult to model as a

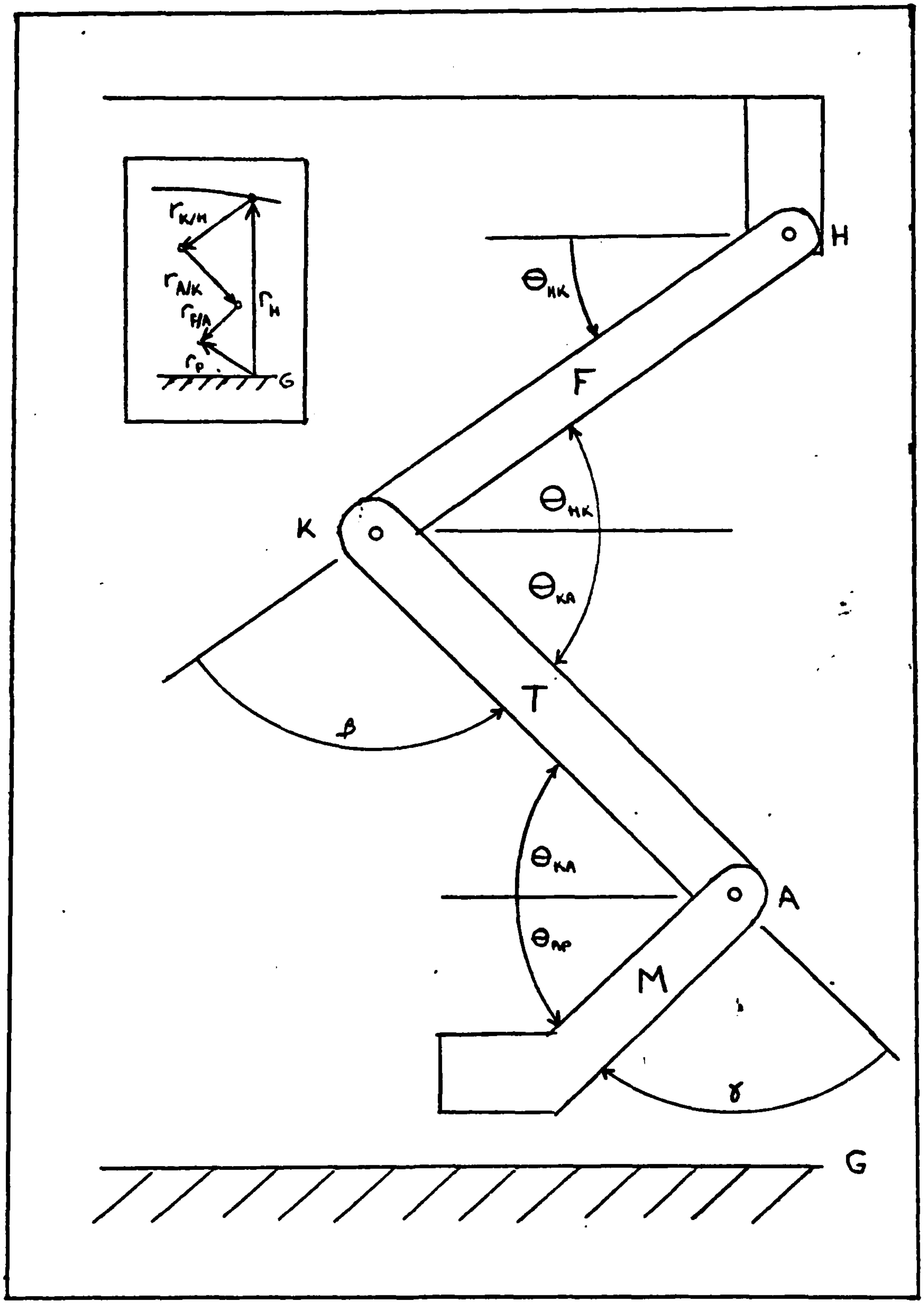


Figure 35. Defined Mechanical Angles for Motion Equations

continuous curve. This becomes more difficult as it is worked into velocity and accelerations. No direct method of measuring foot parameters with respect to the ground was available. If a simple motion could be determined at another joint, with respect to the ground, the foot could be related to the ground through that joint.

To determine the joint motions, a low level light time exposure during a walk over the floor course was taken with a light emitting diode at each joint of the harness on the walking cat. Figure 36 is the picture of the traces. The top light is a timing light mounted on the brace over the hips on the harness. The period is determined by a simple LM 555 timer circuit. The timing light had a one second period with a 50% duty cycle resulting one half second on and one half second off. The next light is mount over the hip joint. The two lower lights are traces of the knee and ankle joints. The periodic light at the bottom is a light indicating foot contact with the floor by a pad on the ball of the foot. This light is mounted at the end of the metatarsal section of the harness approximately one half inch above the top of the foot. From this simple arrangement, no time correlation between the joints was available. The hip was correlated with the one second timer cycle because both are mounted on the semicircular hip brace. But the knee and ankle joint had no mark to time correlate them with the hip. Besides not having any time correlation, the knee and ankle traces are complicated lines. To get these point movements into a relationship with the ground would require complex equations after time correlation. The hip joint in contrast appears to be a sinusoidal trace. The direct timer correlation allows it to be divided into time units for analysis. As an estimate, a simple

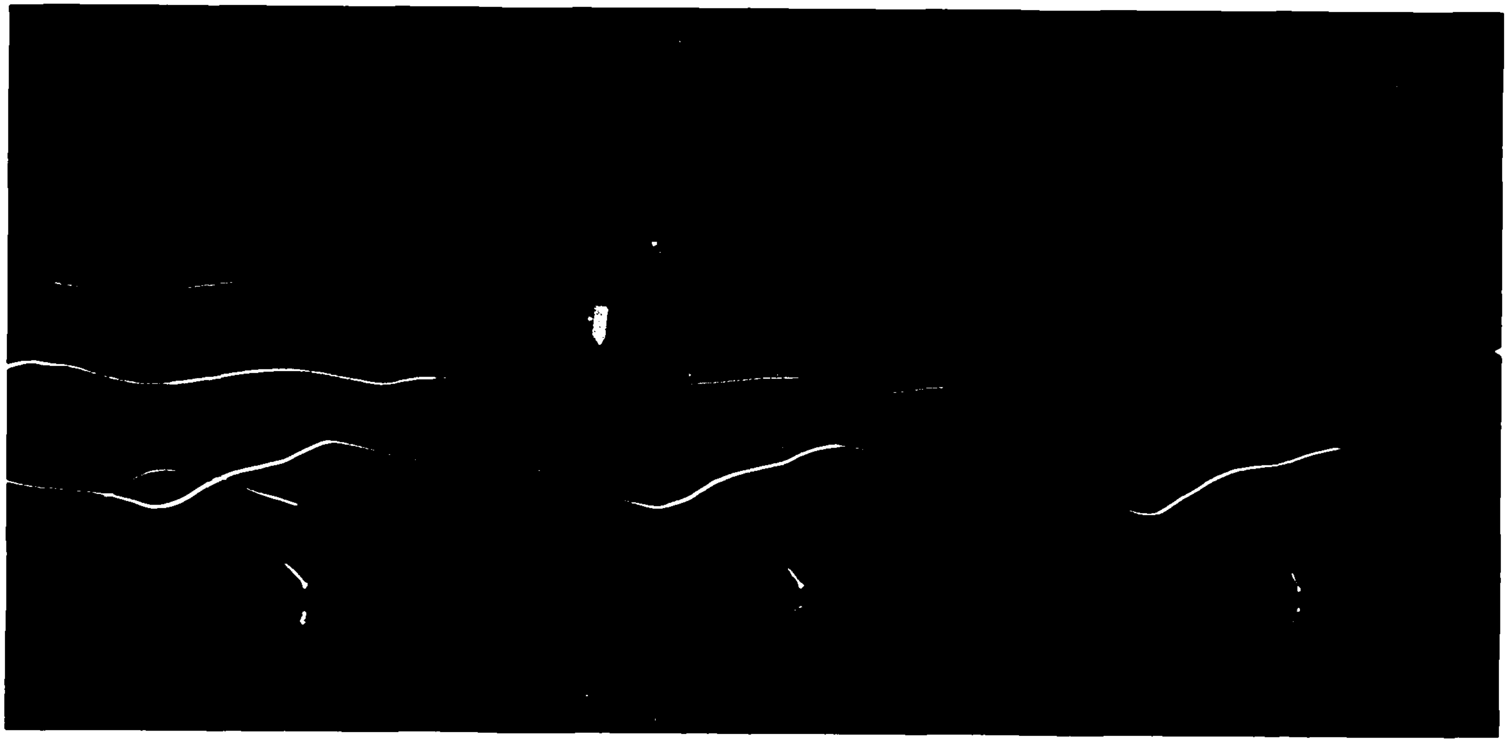


Figure 36. Joint Position Trace During Gait Cycle

sine waveform was chosen of the same amplitude and frequency.

$$r_H = 7 + .2\ \sin(3.927t - 1.571) + .05\ \sin(1.964t) \qquad \text{V-1}$$

Table I is a comparison of this approximation and the actual data. With less than 5% error at any time, the sine approximation is considered valid and used in the remainder of the equation development.

The position equations are written as indicated in the inset of Figure 35. Position of the foot (or paw) with respect to the ground is defined as:

$$\underline{r}_P = \underline{r}_H + \underline{r}_{P/H} + \underline{r}_{A/K} + \underline{r}_{K/H} \qquad \text{V-2}$$

where

$$\underline{r}_{P/A} = -(M\sin\theta_{AP})i - (M\cos\theta_{AP})j \qquad \text{V-3}$$

$$\underline{r}_{A/K} = (T\sin\theta_{KA})i - (T\cos\theta_{KA})j \qquad \text{V-4}$$

$$\underline{r}_{K/H} = -(F\sin\theta_{HK})i - (F\cos\theta_{HK})j \qquad \text{V-5}$$

$$\underline{r}_H = (7 + .25\sin 10.053t)j \qquad \text{V-6}$$

The lengths F, T and M are constant representing the femur, tibia and metatarsal lengths. Angles α, β and γ are taken from data on the walking cat Appendix B. Angles θ_{KA} and θ_{AP} are related to the data by the following equations.

$$\theta_{KA} = 180 - \theta_{HK} - \beta \qquad \text{V-7}$$

$$\theta_{AP} = 180 - \theta_{KA} - \gamma = \theta_{HK} + \beta\ \gamma \qquad \text{V-8}$$

The position vectors $\underline{r}_{P/A}$, $\underline{r}_{A/K}$, and $_{K/H}$ are defined by data at any point in time. The vector $\underline{r}_H$ is the time varying equation for the hip motion derived earlier in the section (Equation V-1). Substituting in Equation V-2, position of the foot with respect to ground becomes:

$$\underline{r}_P = (-M\sin\theta_{AP} + T\sin\theta_{KA} - F\sin\theta_{HK})i + (-M\cos\theta_{AP} - T\cos\theta_{KA} - F\cos\theta_{HK} + 7 + r_H)j \qquad \text{V-9}$$

Table I

Comparison of Hip Position from Light Trace (Figure 36) and Approximation Equation of Motion.

Time (sec)	Hip Position (+ 7 inches)	
	Actual	Approximation
0	-0.2	-0.2
0.2	-0.12	-0.1223
0.4	0.03	0.0354
0.6	0.19	0.1876
0.8	0.24	0.25
1.0	0.19	0.1876
1.2	0.04	0.0354
1.4	-0.12	-0.1223
1.6	-0.19	-0.2
1.8	-0.16	-0.1605
2.0	-0.04	-0.0354
2.2	0.10	0.0952
2.4	0.16	0.15
2.6	0.09	0.0952
2.8	0.03	-0.0354
3.0	0.17	-0.1605
3.2	-0.21	-0.2

The velocity equation can be written as cross products in the same manner as the position vectors. Velocity of the foot with respect to the ground is defined as:

$$\underline{V}_P = \underline{V}_H + \underline{V}_{P/A} + \underline{V}_{A/K} + \underline{V}_{K/H} \qquad \text{V-10}$$

where

$$\underline{V}_{P/A} = \underline{\omega}_{A/P} \times \underline{r}_{P/A} + d\underline{r}_{P/A}/dt \qquad \text{V-11}$$

$$\underline{V}_{A/K} = \underline{\omega}_{K/A} \times \underline{r}_{A/K} + d\underline{r}_{A/K}/dt \qquad \text{V-12}$$

$$\underline{V}_{K/H} = \underline{\omega}_{H/KT} \times \underline{r}_{K/H} + d\underline{r}_{KHA}/dt \qquad \text{V-13}$$

$$\underline{V}_H = \underline{\omega}_H \times \underline{r}_H + d\underline{r}_H/dt \qquad \text{V-14}$$

In equations V-11 through V-13, no change occurs in vector magnitude. The dr/dt term is zero in these cases. And by definition the angular velocity ω equals the product of the rate of change in the angle θ and a unit vector k perpendicular to the plane of motion by right hand rule. For equation V-14, the ω is zero, because no change occurs in the angular position of the hip with respect to ground. The hip always remains at $0i = Yj$, where Y is the time variant vector magnitude. The equations become:

$$\underline{V}_{P/A} = \dot{\theta}_{AP}\, \underline{k} \times \underline{r}_{P/A} \qquad \text{V-15}$$

$$\underline{V}_{A/K} = \dot{\theta}_{KA}\, \underline{k} \times \underline{r}_{A/K} \qquad \text{V-16}$$

$$\underline{V}_{K/H} = \dot{\theta}_{HK}\, \underline{k} \times \underline{r}_{K/H} \qquad \text{V-17}$$

$$\underline{V}_H = d\underline{r}_H/dt \qquad \text{V-18}$$

Substituting into V-9, the velocity of the foot with respect to the ground is:

$$\underline{V}_P = d\underline{r}_H/dt + (\dot{\theta}_{AP}\, \underline{k}\, \underline{r}_{P/A}) + (\dot{\theta}\, \underline{k} \times \underline{r}_{A/K}) + (\dot{\theta}_{HK}\, \underline{k}\, \underline{r}_{K/H}) \qquad \text{V-19}$$

The $d\underline{r}_H/dt$ is the rate of change of $\underline{r}_H$ which is the derivative of the time function in equation V-1. And the $\underline{r}$ vectors are found from data recordings. The $\dot{\theta}$ are derived from data as rate of change of the angles using a small time increment. In cases where the change is positive, the unit vector is in the ($\underline{k}$) direction. For negative $\dot{\theta}$, the unit vector is ($-\underline{k}$) for convention. the velocity equation V-19 becomes:

$$\underline{V}_P = d\underline{r}_H/dt \quad j + [\theta_{AP}\ k\ x(-M\dot{s}in\theta_{AP}\ j - M\cos\ \theta_{AP}]$$
$$+ [\theta_{KA}\ k\ x\ (T\sin\theta_{KA}i - T\cos\theta_{KA}j)]$$
$$+ [\theta_{HK}\ k\ x\ (F\sin\theta_{HK}i - F\cos\theta_{HK}j)] \qquad \text{V-20}$$

The acceleration equations are written as relationships between the three angles and vectors. The acceleration of the foot with respect to the ground may be written as:

$$\underline{a}_P = \underline{a}_H + \underline{a}_{P/A} + \underline{a}_{A/K} + \underline{a}_{K/H} \qquad \text{V-21}$$

where

$$\underline{a}_{P/A} = \underline{\alpha}_{AP} \times \underline{r}_{P/A} - \omega^2_{AP}\underline{r}_{P/A} \qquad \text{V-22}$$

$$\underline{a}_{A/K} = \underline{\alpha}_{KA} \times \underline{r}_{A/K} - \omega^2_{KA}\underline{r}_{A/K} \qquad \text{V-23}$$

$$\underline{a}_{K/H} = \underline{\alpha}_{KA} \times \underline{r}_{K/H} - \omega^2_{HK}\underline{r}_{K/H} \qquad \text{V-24}$$

$$\underline{a}_H = d^2\underline{r}_H/dt \qquad \text{V-25}$$

Equations v-22 through 25 give expressions for the normal and tangential accelerations of each lever. The acceleration of the hip is the rate of change in velocity of the hip along the j axis. The definition of angular acceleration α is rate of change of angular velocity ω, on which is $\ddot{\theta}$. The vector $\dot{a}$ becomes $\ddot{\theta}$ k, the second derivative of θ multiplied by a unit vector perpendicular to plane of motion. Substituting these equations and definitions into V-21, the acceleration of the foot with respect to ground is:

$$
\begin{aligned}
\underline{a_P} = \; & d^2r_H/dt^2 + \\
& \ddot{\theta}_{AP}\ k \times (-M\sin\theta_{AP} i - M\cos\theta_{AP} j) - (\dot{\theta}_{AP})^2(-M\sin\theta_{AP} i - M\cos\theta_{AP} j)] + \\
& \ddot{\theta}_{KA}\ k \times (T\sin\theta_{KA} i - T\cos\theta_{KA} j) - (\dot{\theta}_{KA})^2(T\sin\theta_{KA} i - T\cos\theta_{KA} j)] + \\
& \ddot{\theta}_{HK}\ k \times (F\sin\theta_{HK} i - F\cos\theta_{HK} j) - (\dot{\theta}_{HK})^2(-F\sin\theta_{HK} i - F\cos\theta_{HK} j)] \qquad \text{V-26}
\end{aligned}
$$

The acceleration equation has terms all defined by constants, data or time increments. For determination of α, it requires very small time increments or another curve fitting approximation to achieve any accuracy.

The equations can be used as complete or partial derivations. As it is shown, the complexity of equations requires extensive data reduction for accuracy. Acceleration is of use in force determination if the mass of each limb section is known. Even if determined, the information on force throughout the cycle is of questionable use. In eventual computer control, the force will be excessive information. The computer should be able to maintain limb velocity, and at this point these are the most important equations. To model the walk, the computer mimics these determined limb segment velocities to achieve the proper time correlated positions.

VI. Muscle Activity

The second essential parameter for modeling phase of the study is the muscle activity during the step cycle. With the free harness, the cat supports itself entirely. The muscle activity under these conditions is assumed to be very close to that of any unrestricted normal gait. This chapter shows the activity of the essential muscle groups at various speeds in relation to the feedback harness position. The essential mucles, methods of study, and analysis of muscle activity are discussed.

Essential Muscles

The muscles chosen were the same as those studied by Carroll (1980). The muscles provide flexion and extension for each joint. The sets of muscles theoretically supply the forces necessary to move the leg in a single plane. The six muscles were studied in three sets. This kept the interface to a minimum for each run. The six muscles studied were the tibialis anterior and gastrocnemius for the ankle, the biceps femoris and vastus lateralis for the kenee, and the iliopsoas and semimembranosus for the hip. The listed muscle sets are given ordered as flexor and extensor for the joint.

The muscles were observed in flexor-extensor sets. This not only made less complicated experimental method, it also allowed correlation with resulting joint movement. The observed activity of these essential muscles will be used in modelling the muscle group activity for eventual stimulation experimentation (Chapter I).

Method

An adult female cat weighing 2.4 Kg was trained to walk with the leash, harness and contact switch. Only one animal was successfully tested because of the extensive training time necessary. To find a cooperative animal receptive to training, was a major part of the task. Weeks of training may be lost if the animal stops cooperating at late stages in the process when additional feedback equipemnt is added. Once trained for treadmill walk with all feedback equipment, the next step was observation of the muscle activity.

The muscle activity was isolated by using intramuscular electrodes. The electrodes inserted into the muscle were silver wire (99.99% Ag) of 0.003 inch diameter. The wire was coated with teflon to form an overall 0.0045 inch diameter wire. The wire was threaded through a hypodermic needle and cut to a length approximately one-half inch longer than the needle. The insertion end was stripped of teflon using micro-tweezers, approximately 3 mm. The exposed end was then bent back toward the base to form a barb which will remain in the muscle when the needle is inserted and removed. The remaining wire extending from the base was stripped of the teflon coat about 3 cm using the tweezers. This end is soldered to the lead wires after implantation. The needle-electrode is sterilized and packaged before use.

The animal was prepared for electrode placement by shaving the rear limbs and pelvic area. The cat was anesthesized using halothane and nitrous oxide gas. Initially a 5% halothane combined with the 50% nitrous oxide-50% oxygen mix put the cat out. The concentration of halothane was reduced to 2% to maintain anesthesization. The mixture takes approximately five minutes to act, and the cat can be kept under using a mask for any required time. The gas was administered under supervision of a competant veterinary personel. The leg of the anesthesized cat was scrubbed with a betadine solution for sterilization. The general muscle location was determined from anatomy diagrams (Chapter II). The muscles were located by a skilled physiologist familiar with cat musculature. Once located, the electrode was implanted with the needle into the muscle body. Each muscle required two electrodes placed approximately 3 cm apart. In each case the electrodes were arrayed longitudinal to muscle fiber. A single ground electrode placed in the upper leg just under the skin was used as a ground.

The lead wires were soldered onto the exposed electrode using a low temperature iron. The electrode was secured leaving slack in the silver wire to compensate for skin mevement over the muscle. The lead wires were isolated and taped to the skin above the electrodes to secure them. The cloth harness was placed on the cat prior to recovery. The lead wires attached to the harness with Velcro® to avoid tangling during recovery.

Within minutes after removing gas mask the cat was alert and moving. It took about fifteen minutes for the animal to regain full control. During this time the cat was closely supervised to keep from dislodging the electrode. The cat walked on the leash about the floor for another fifteen minutes after full recovery. The feedback harness was placed on the cat, and the animal was leashed on the treadmill. The feedback interface wires for the electro-myogram and joint position were connected before the run. The time required from anesthetic to recorded walking was about one-half hour.

The treadmill was operated over a range of speeds for approximately three minutes per run. As the cat walks, the leg position and EMG signals were recorded on eight track FM tape. The output of either EMG or position can be observed using a four channel polygraph. The two sets of feedback parameters can be output from the FM recording playback and correlated using the foot switch indication for precise correlation. The harness was checked before each session and recorded for calibration with a sequence of joint positions. The gain and base line of the polygraph can be set from these positions for a 1 volt/cm output corresponding to angular position (equivalent to 40°/cm). The EMG signal was not calibrated so precisely for polygraph output. The polygraph frequency response rolls off around 40 Hz, attenuating the high frequency component of the EMG. For this reason the polygraph recording can be used only for initial activity and low frequency acitivity peaks. The raw EMG from the frequency limited polygraph is not assessed visually with any accuracy. Later computer analysis and RMS filtering were conducted on the data directly from wideband FM tape record.

Analysis of Muscle Activity

The EMG data from the three muscle sets at a speed of 0.4 m/s is displayed in Figures 37, 38 and 39. Appendix C shows the acitvity of the same muscle groups at two other speeds, 0.2 and 0.3 m/s. The tibialis anterior and gastrocnemius are shown in Figure 37. The vastus lateralis and biceps femoris are in Figure 38. And Figure 39 shows the iliopsoas and semimembranosus. The associated figures for each (Figures 37A, 38A, and 39A) are expanded views of the indicated section. The position output for each set of EMG is included for analysis.

Figure 37 (and 37A) show initial gastrocnemius activity occuring at placement of foot, and extensive activity continues until the ball of the foot is lifted. At this point the gastrocnemius is still active until the toe of the foot is lifted (indicated by the dotted line) where activity almost ceases. The push off occurs with the foot remaining on the ground for a period of extension until lifting completely. This corresponds the foot force action discussed in Chapter IV. The tibialis anterior activity starts during the completion of ankle extension after push off before lifting foot. The activity remains high during the swing phase and ankle flexion. The final activity of the tibialis anterior occurs after the foot is first planted and is the result of stabilizing the leg yielding under the weight of the cat.

The vastus lateralis EMG activity shown in Figure 38 is initialized during the extension part of the swing phase. It continues until the stabilization of the leg after foot contact. Throughout this first part of the stance phase the knee is locked and maintaining tension to move the cat forward. This is maintained by the biceps femoris until the leg trails behind the cat and is drawn in to the flexion of the swing phase. The biceps femoris shows initial activity upon foot contact and during the first part of the stance phase when the hip is extending. Additional high activity occurs in the biceps femoris when the foot is lifted and the entire leg flexed.

The EMG activity of Figure 39 and its associated figure (39A) shows iliopsoas and semimembranosus during the step cycle. For this run, the contact switch was placed on the toe of the foot. The initial activity of the iliopsoas occurs in lifting the foot. At the end of the stance phase the foot extends behind the cat. As the extension limit is reached all three joints flex to lift the foot and bring it forward in the swing

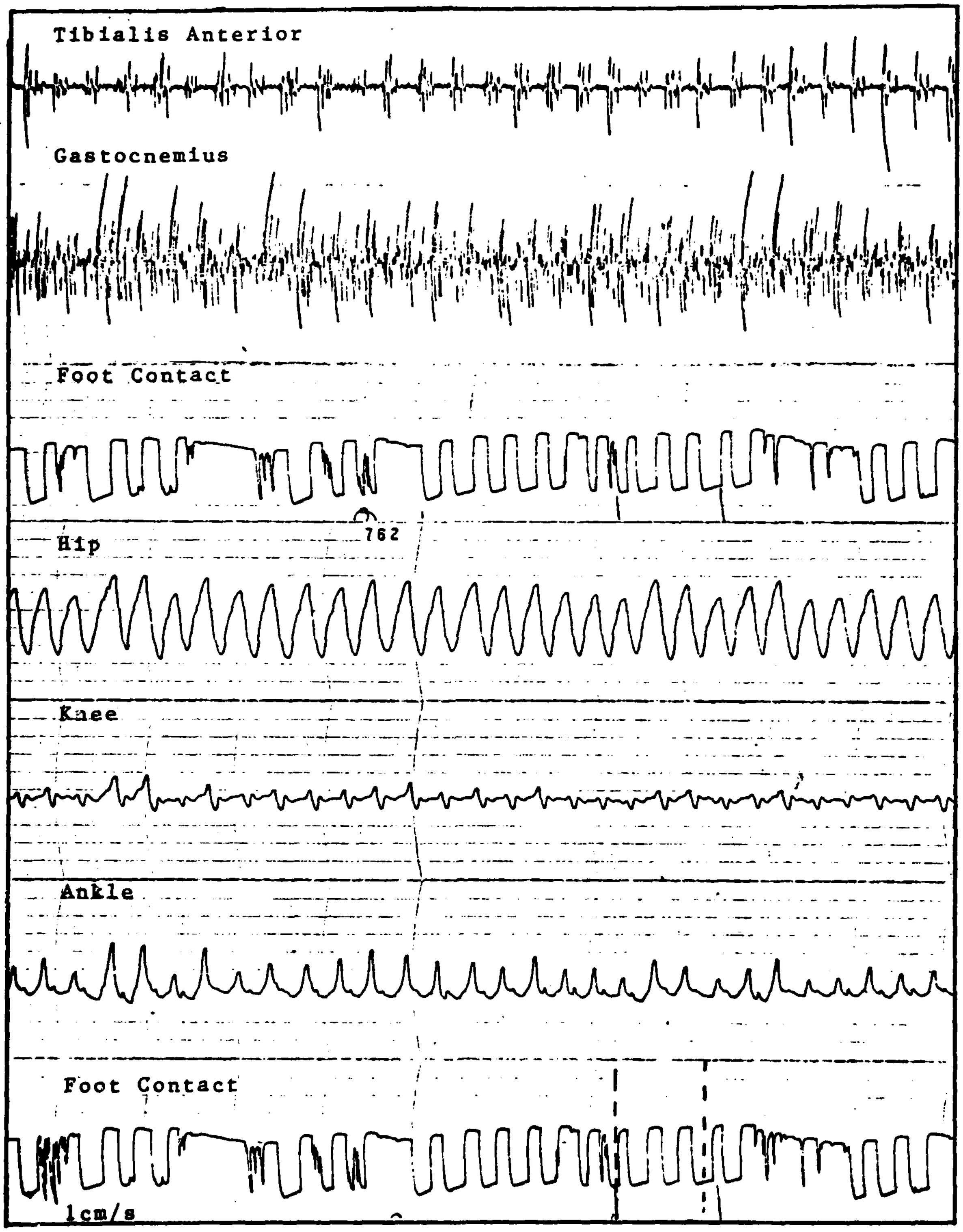


Figure 37 EMG And Feedback Data: Tibialis Anterior And Gastrocnemius (0.4m/s)

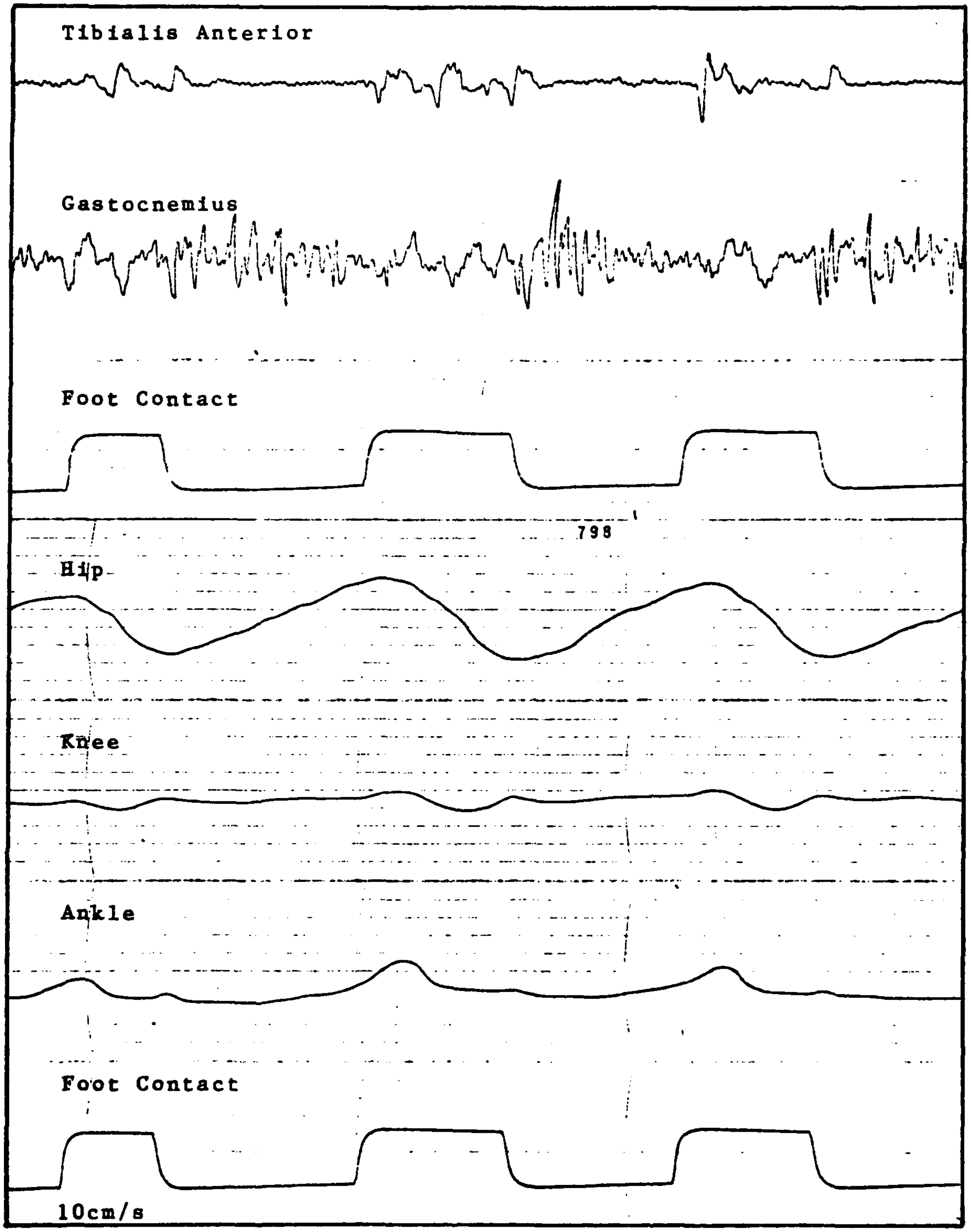


Figure 37A. Expanded View - Indicated in Figure 37

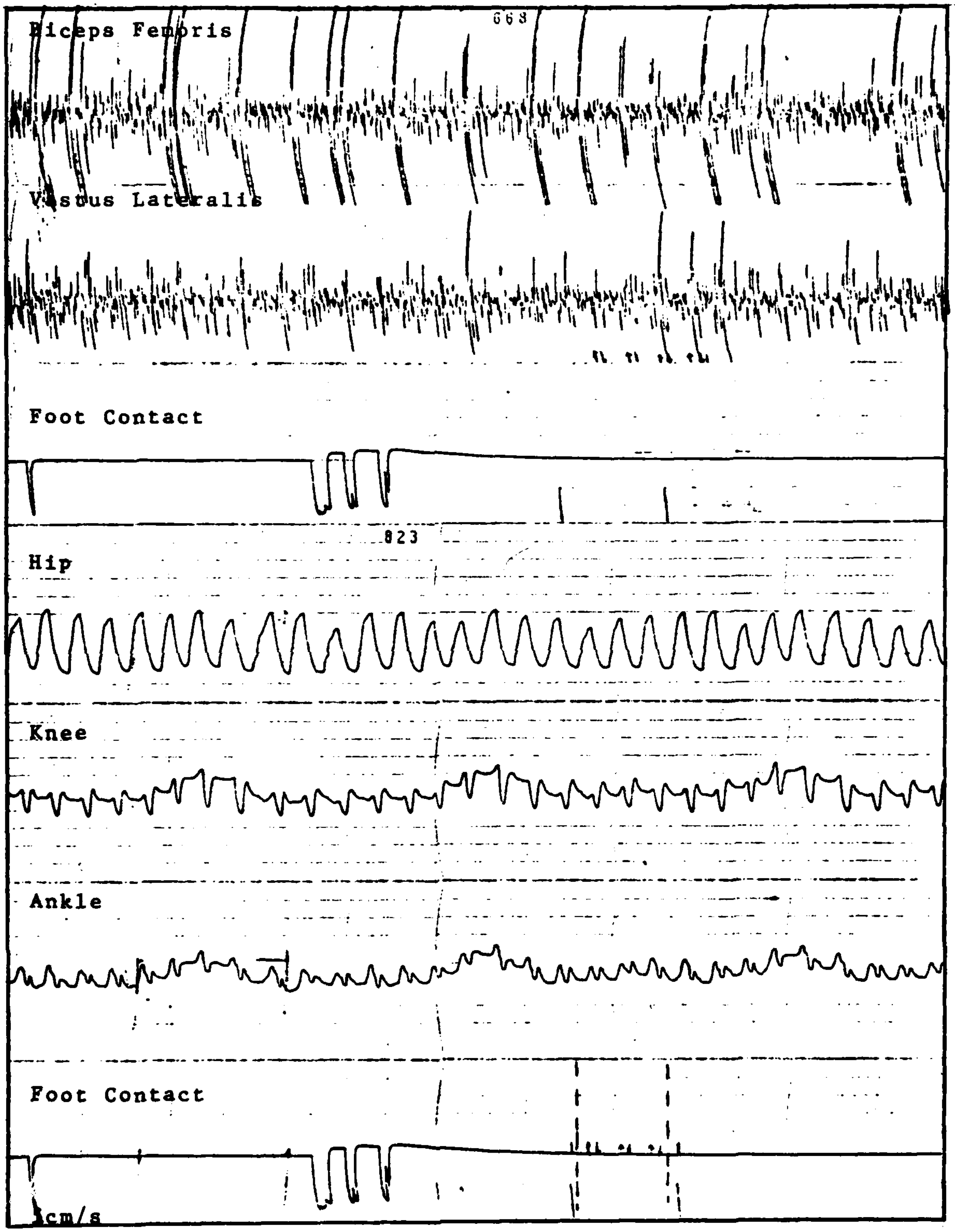


Figure 38. EMG And Feedback Data: Biceps Femoris and Vastus Lateralis (0.4m/s)

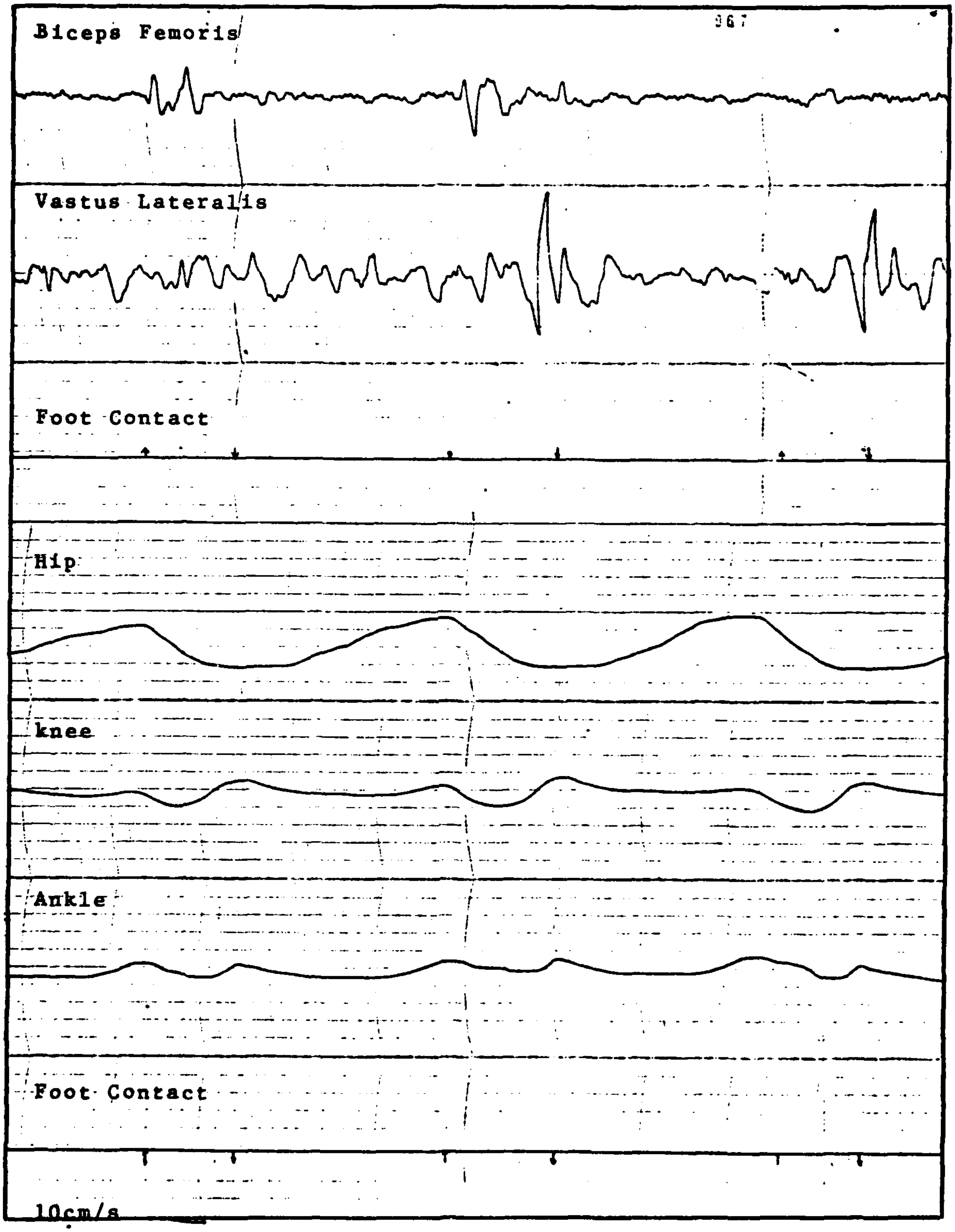


Figure 38A. Expanded View - Indicated In Figure 38

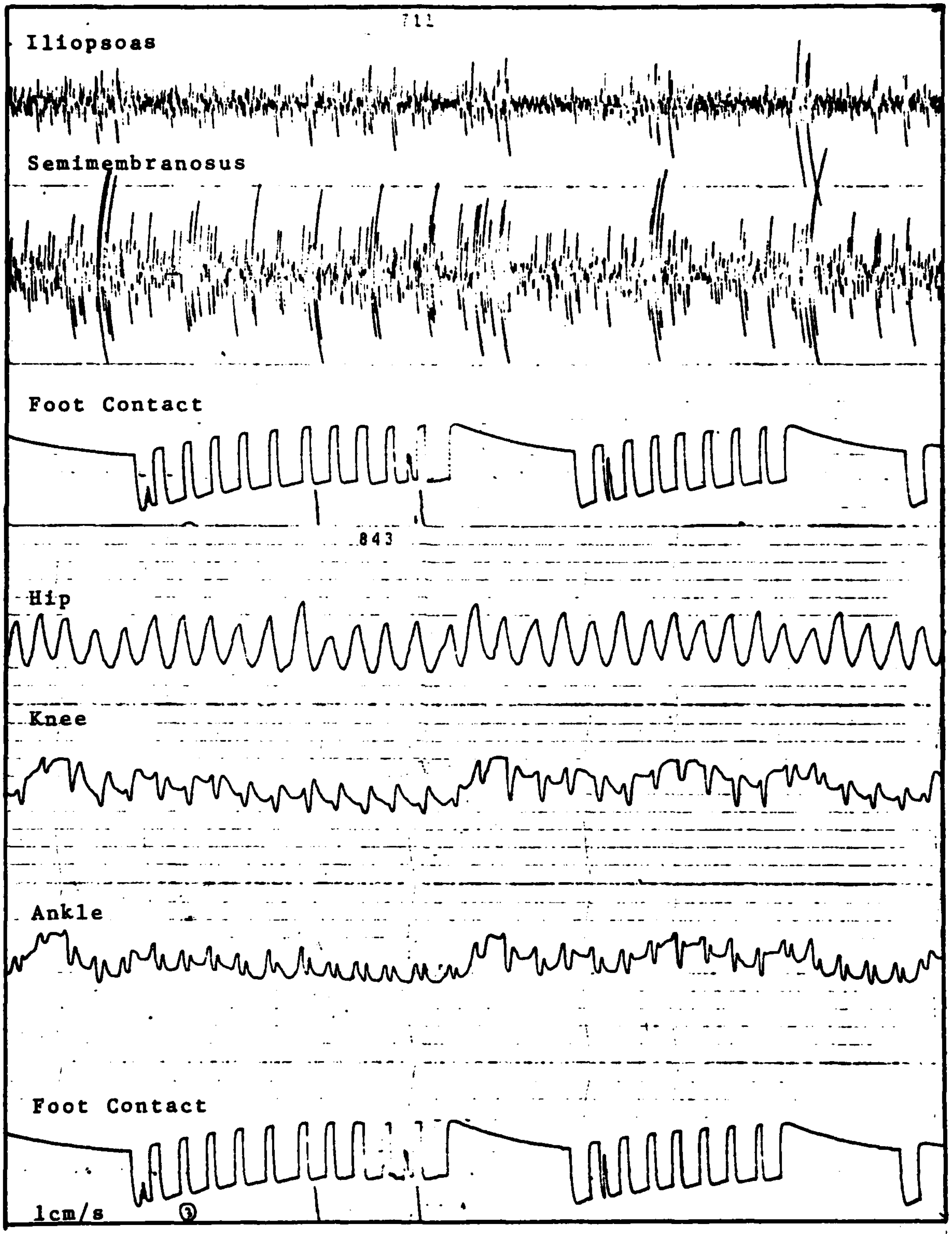


Figure 39. EMG And Feedback Data: Iliopsoas And Semimembranosus (0.4m/s)

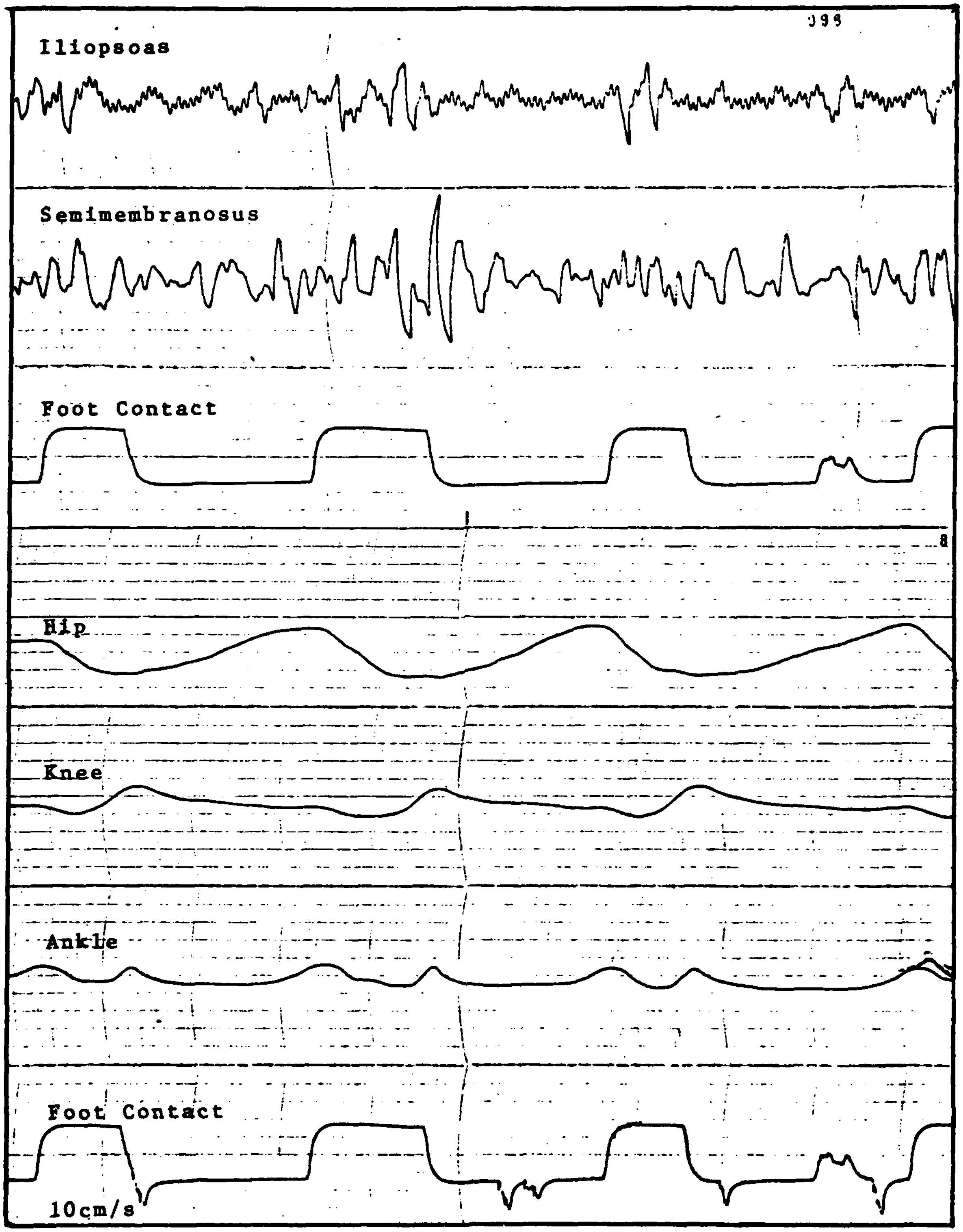


Figure 39A. Expanded View - Indicated In Figure 39

phase. This is seen in the hip position and iliopsoas activity. The hip maintains position as the other joints give under the weight of the cat when the foot is placed. The initial activity of the semimembranosus indicates this absorption in the stance phase. The activity remains relatively high as the knee and ankle remain locked and the hip extends the leg. The semimembranosus activity decreases when the foot lifts as the iliopsoas takes over.

For each run on the muscle sets, the EMG is recorded with the harness off to evaluate the effects of the harness. Appendix D contains the data from this configuration for each muscle set at the three speeds. Comparing individual muscle activity for each muscle (with and without harness) at various speeds, shows little change. A slight decrease in flexor activity without the harness indicates restrictive nature of the harness in the swing phase. The stance phase in general is higher in activity for maintaining posture. The effects of the harness are not as easily observed in this phase. Judging from the limited interference in the swing phase, the harness is considered unrestrictive in the stance phase.

The muscle sets chosen theoretically supply the necessary single plane motion for locomotion. The isolated intra-muscular electrode, even if not placed perfectly in the desired muscle, is placed well enough to pick up the felxion and extension activity in the general area. In a constant pattern of limb movement during locomotion, the entire pattern of EMG's in main limb muscles at any speed can be inferred by using the EMG of only one muscle (Shik and Orlovsky, 1976). The sequence of muscle activity for locomotion is determined thus far using the raw EMG. This muscle activity observed from the EMG is not calibrated for comparison of relative signal strength between muscles. The amplification variation and frequency attenuation in the polygraph recording does not accurately depict strength between muscles or experiments.

The raw EMG signal must be converted to obtain a signal level for modeling. An RMS converter was used to achieve this analysis. The RMS signal data will allow rough estimation of normalized activity level for initial stimulation experimentation.

The EMG signal originally recorded had a small amount of 60 cycle overtone picked up in the original experimentation by the electrodes. The 60 Hz signal adds artificially to the RMS conversion of the true EMG signal. To offset this addition, the zero reference for the RMS converter was set using the 60 Hz noise pickup from the EMG amplifier as the input. With this 60 Hz input, the RMS converter is zero referenced. Then this reference was used to cancel the offset caused by the 60 Hz signal in the actual data. Removing this noise signal from the converter and inputting the actual taped EMG signal gives an RMS value of the EMG minus the 60 cycle RMS value of the amplifier noise. The data was then graphed as an RMS value of the muscle activity. Figures 40, 41, and 42 show the RMS signals for all six muscles over the same intervals corresponding to Figure 37, 38, and 39 at 0.4 m/s. The expanded sections of the RMS (Figures 40A, 41A, and 42A) is listed as a normalized voltage in Table II. The RMS data for 0.2 and 0.3 m/s is listed in Appendix E.

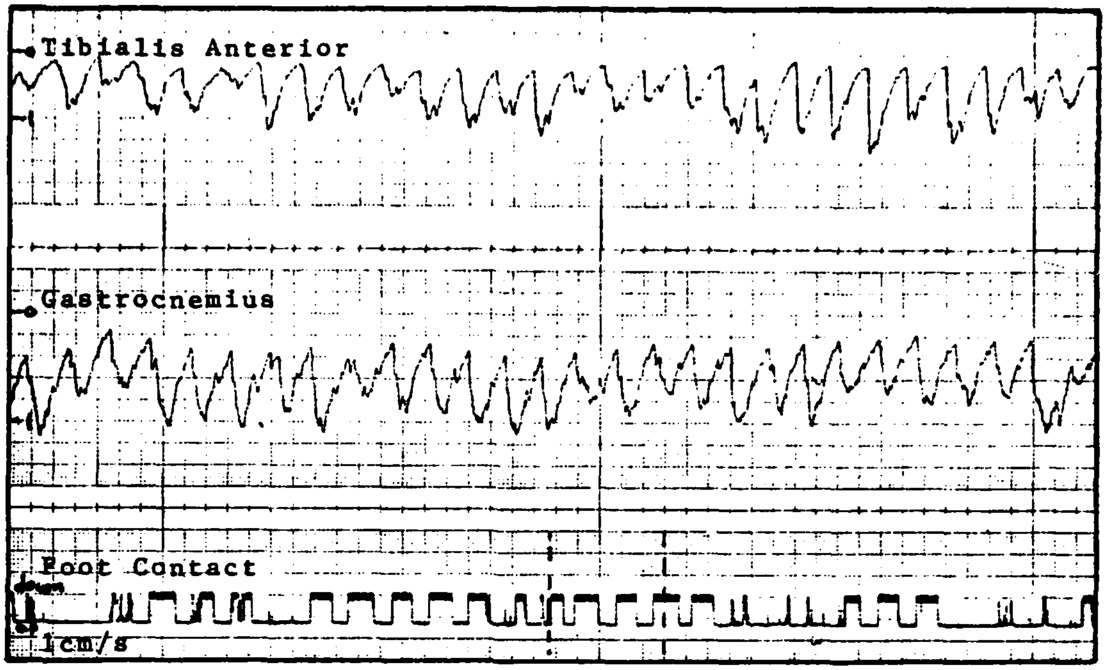


Figure 40. RMS Muscle Activity Data: Tibialis Anterior And Gastrocnemius (0.4m/s)

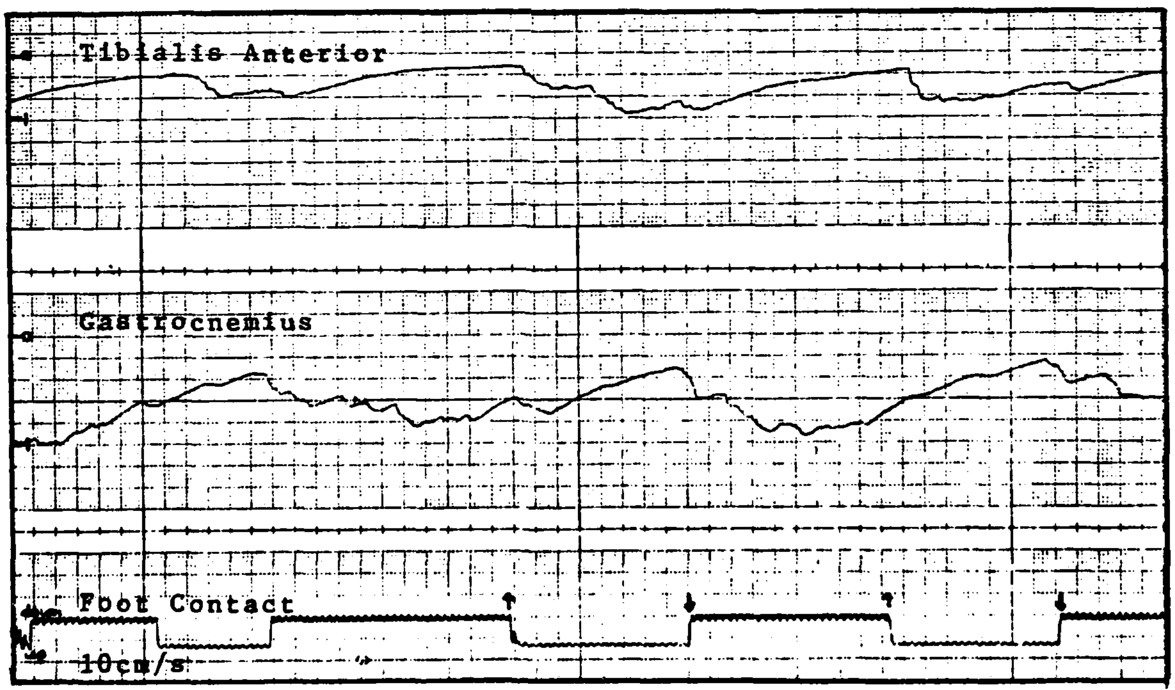


Figure 40A. Expanded View - Indicated in Figure 40

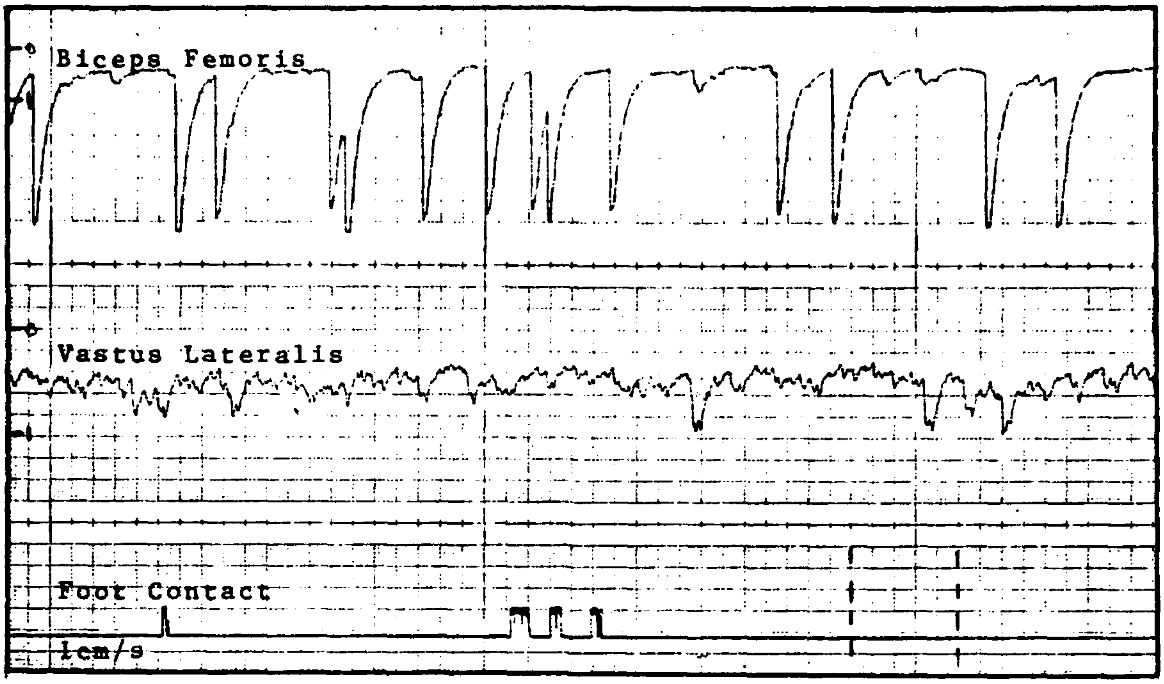


Figure 41 . RMS Muscle Activity Data: Biceps Fermoris And Vastis Lateralis (0.4m/s)

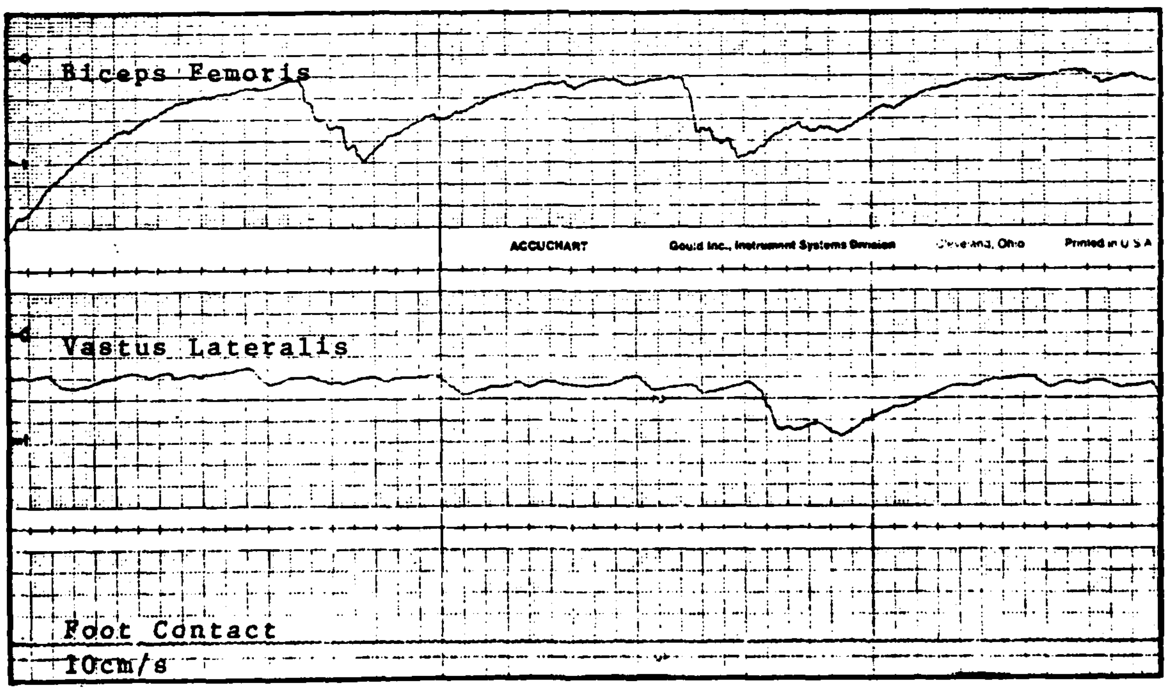


Figure 41A. Expanded View - Indicated in Figure 41

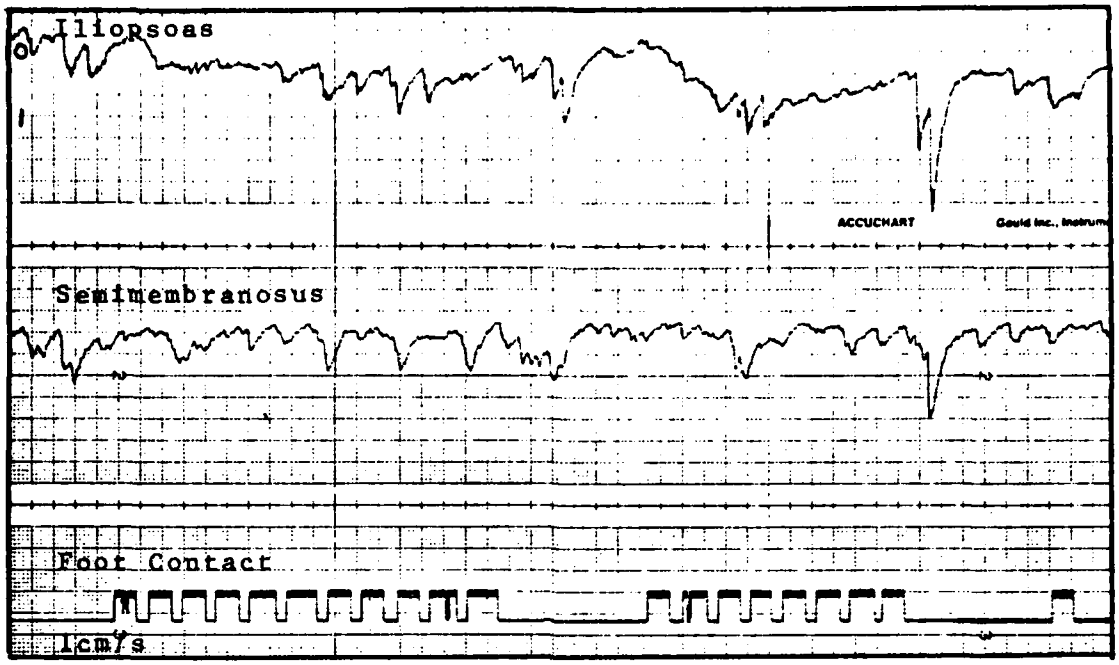


Figure 42. RMS Muscle Activity Data: Iliopsoas And Semimembranosus (0.4m/s)

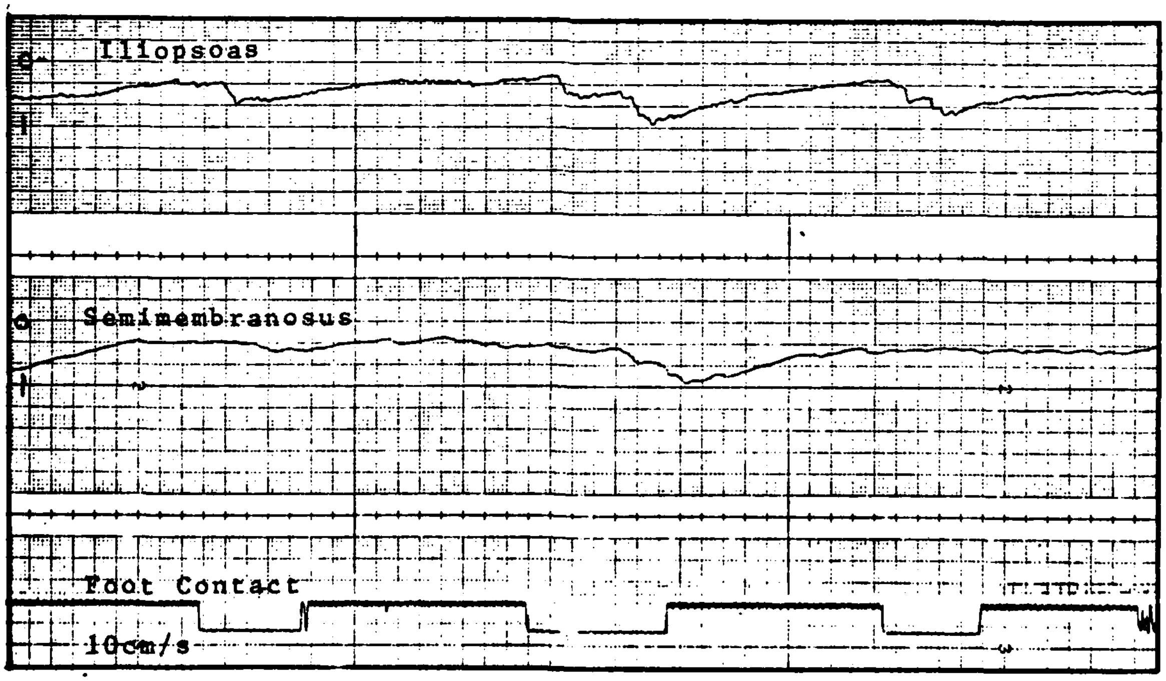


Figure 42A. Expanded View - Indicated in Figure 42

Table II

Tabular listing of Normalized RMS Muscle Activity at 0.4 m/s for the Tibialis Anterior (TA) and Gastrocnemius (G) from Figure 40, the Biceps Femoris (BF) and Vastus Lateralis (VL) from Figure 41, and the Iliopsoas (I) and Semimembranosus (S) of Figure 42.

Time (sec)	RMS (V/V normalized)					
	TA	G	BF	VL	I	S
0	0.47	0.66	0.6	0.96	0.46	0.4
0.05	0.66	0.6	0.6	1.0	0.47	0.47
0.1	0.87	0.5	0.44	0.96	0.47	0.4
0.15	0.9	0.38	0.36	0.83	0.73	0.63
0.2	0.83	0.34	0.3	0.75	0.93	0.67
0.25	0.73	0.4	0.26	0.69	0.86	0.87
0.3	0.86	0.6	0.24	0.63	0.66	0.9
0.35	0.74	0.64	0.24	0.52	0.6	0.8
0.4	0.6	0.8	0.22	0.48	0.53	0.73
0.45	0.53	0.92	0.2	0.43	0.47	0.63
0.5	0.47	0.96	0.6	0.52	0.43	0.53
0.55	0.43	0.88	0.8	0.48	0.4	0.47
0.6	0.4	0.84	1.0	0.52	0.36	0.46
0.65	0.33	0.8	0.84	0.69	0.33	0.4
0.7	0.3	0.76	0.72	0.91	0.3	0.41
0.75	0.27	0.64	0.7	0.91	0.28	0.4
0.8	0.4	0.6	0.72	0.87	0.2	0.43
0.85	0.5	0.58	0.64	0.9	0.36	0.4
0.9	0.47	0.66	0.6	0.96	0.46	0.4

VII. Conclusions and Recommendations

The study centered on the gait model of a free walking cat. The cat was fitted with appropriate feedback sensors and walked under its own power on the treadmill. The measured joint position throughout the step cycle correlated with EMG recordings. The agonist and antagonist muscles for each joint can supply the single plane motion of the leg. The resulting data gathered provides the position sequence for computer programming. The EMG information gives an initial point for controlled stimulation experimentation. The force feedback sensor provided additional information on the step cycle for extra control parameters.

The harness hardware proved to be compatible to computer implementation. The harness itself was limited in restrictive nature. The position sensors within the harnes provided clean, consistent and stable output. The harness was successfully tested under various configurations. Variations in gait were determined for different speeds and variations in surface gradient. A model gait cycle was tabulated for computer simulation. The variations in gait from this model step cycle give information on eventual alteration of an original successful walk to adapt to other conditions making the model more versatile.

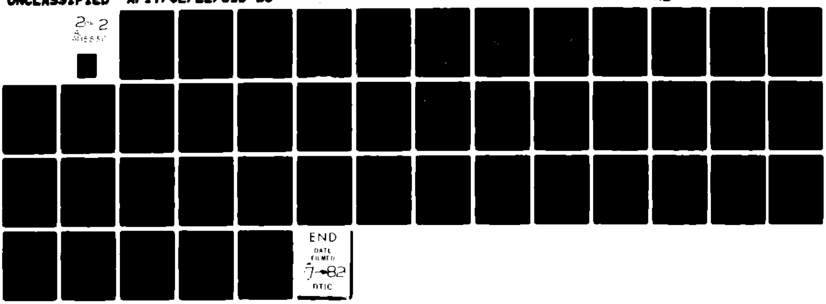
The foot switch provided an essential bit of information necessary for feedback control. It is necessary to know when the foot is on the surface. The foot transducer provided additional information on the gait cycle. The force on the foot can be used as a model to achieve proper muscle control in initial muscle stimulation experimentation where the cat will be restricted in movement. In a severely restricted environment for initial tests, the foot force may be excessive or inadequate for an eventual free walking test. The force transducer should help avoid this problem by allowing the gait force to be accurately accessed and modelled reguardless of the means of supporting the cat.

The EMG initial activity for each flexor and extensor group corresponded with joint movement indicating accurate placement of electrodes. This initial activity along with the RMS converted EMG signal provide the basis for stimulation experiments. This data when reproduced by a computer controller should produce reasonable approximation of the step cycle. From this, the process can be refined and precisely controlled for eventual reproduction of the model gait cycle.

The data compared favorably to that of the preliminary work (Carroll 1980). The restrictive harness used by Carroll provided position information comparable to that of the free walking cat. The EMG initial activity was also in line with those discussed in this report. The data for a comparative run at 0.2 m/s in both harnesses is in Appendix F. The comparison of the support harness versus the free harness show almost identical hip movement with slightly faster flexion (swing phase) in the free harness. The knee and ankle are changed somewhat between the cases. The knee extended more and the ankle less throughout the gait cycle with the free harness. This may be a result of the cat walking more on its toes in the support harness (where posture control is not necessary), thus allowing greater ankle extension. The EMG strength could not be compared because of the difference in placement of electrodes from experiment to experiment. The initial activity sequence for both studies was compatible in the swing and stance phase analysis with foot placement.

The data provided can be used as a model for eventual microprocessor controlled stimulation. The leg position sequence can be stored as a

AD-A115 532 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOO--ETC F/G 6/16
FEEDBACK INFORMATION AND ANALYSIS FOR MICROPROCESSOR CONTROLLED--ETC(U)
DEC 81 D J HEICHEL
UNCLASSIFIED AFIT/GE/EE/81D-26 NL



desired data model for a gait cycle. The stimulation unit under development can provide stimulus to the proper muscle group corresponding to the initial data gathered and stored on muscle activity sequence. If this stimulation achieves the desired time correlated position within a certain error, the sequence continues. If not, the computer stimulator adjusts signal to reduce the error in position within the limits of the error window. This updated stimulation then augments the original data for the next full sequence. First stimulating proper muscle group to go from current position data point to the next. The stimulation is done in the same sequence as original walk data. Finally, correcting for position errors and moving to next position data point. The process of stimulation, location with respect to desired position within error, correction, and update stimulation sequence continues through several step cycles. With each correctly achieved updated stimulation sequence, for a given position error, the size of the error window for position can be decreased. The process continues as before until a complete new set of stimulation sequence data is generated by the computer for implementation to produce the modelled (stored) walk.

For initial experimentation, the support harness of Carroll (1980) should be used. It will provide the restriction and posture control necessary for perliminary study. The free harness can be used in follow-on experimentation, once a crude walk is successfully produced by the microprocessor control unit. Problems may occur with balance in the free harness use. The free harness does not restrict the cat from making lateral moves. The only means of restricting lateral movement in this study was the cooperative nature of the cat to maintain a limited straight course on the treadmill. If walking can be successfully produced and posture control maintained, it will be necessary to get a feedback parameter for balance or restrict the motion to a single axis of freedom. Some means of hinging the free harness to move in a vertical plane containing this axis would allow free walking while restricting hip motion to one plane.

This completes preliminary studies for cat gait cycle analysis. The overall project of microprocessor controlled muscle stimulation should be directed toward initial stimulation experimentation. Some actual experimentation with the microprocessor control unit and implementation of the gait cycle data will provide the only means of ascessing the completeness of this study. I will also indicate direction or need for future support studies on the feedback parameters for control and gait analysis of the cat.

Bibliography

Burke, D.C., and D.D. Murray. Handbook of Spinal Cord Medicine. London: Macmillan Press Limited, 1975.

Carroll, C.D. Feedback Control For Functional Electrical Stimulation Of Paralyzed Muscle. AFAMRL-TR-81-32. Wright-patterson AFB, Ohio: Air Force Aerospace Medical Division, March 81.

Crouch, J.E. Text-Atlas of Cat Anatomy. Lea and Febiges, 1969.

Dubowitz, V. and M. Brooke. Muscle Biopsy, A Modern Approach. Philadelphia: W.B. Saunders Company, 1974.

Field, H.C. and M.E. Taylor. An Atlas of Cat Anatomy. Chicago: University of Chicago Press, 1950.

Goslow, G.E., Jr., R.M. Reinking and D.G. Stuart. "The Cat Step Cycle; Hind-limb Joint Angles and Muscle Length During Unrestrained Locomotion," Journal of Murphology, 141: 1-41 (1973).

Grillner, S. "The Role of Muscle Stiffness in Meeting the Changing Postural and Locomotion Requirements for Force Development by the Ankle Extensor," Acta. Physiol. Scand., 86: 92-108 (1972).

Guttman,L. Spinal Cord Injuries, Comprehensive Management and Research.

Guyton, A.C. Textbook of Medical Physiology. Philadelphia: W.B. Saunders Company, 1976.

Milner-Brown, J. and R. Stein. " The Relation Between the Surface EMG and Muscular Force," Journal of Physiology 246: 549-569 (1975).

Milner, M., A.O. Quanbury and J.V. Basmajian. "Surface Electrical Stimulation of Lower Limb," Arch. Phys. Med. Rehabil., 51(a): 540-545 (1970).

Nashold, B.S., Jr., H. Friendman, J.F. Glenn, W.F. Barry and R. Avery. "Electromicturation in Parapelegia. Implantation of a Spinal Neuroprosthesis," Arch. Surg. 104(2): 195-202 (1972).

Petrofsky, J.S. "Control of the Recruitment and Firing Frequencies of Motor Units in Electrically Stimulated Muscles in the Cat," Med. and Biol. Engr. 16: 302-308 (1978).

Petrofsky, J.S. and C.A. Phillips. " Microprocessor Controlled Stimulation in Paralyzed Muscle," Proceedings of the National Aerospace Electronics Conference. 198-210. Dayton, Ohio: Dayton Section, IEEE, May 1979. a.

Petrofsky, J.S. "Sequential Motor Unit Stimulation Through Peripheral Motor Nerves in the Cat," Med. and Biol. Engr. 17: 87-93 (1979). b.

Bibliography

Petrofsky, J.S. and C.A. Phillips. "Constant Velocity Contractions in Skeletal Muscles by Sequential Stimulation of Muscle Efferents," Med. and Biol. Engr. and Comput. 17: 583-592 (1979). c.

Petrofsky, J.S. and C.A. Phillips. "The Influence of Recruitment Order and Fiber Composition on the Force Velocity Relationship and Fatiguability of Skeletal Muscles in the Cat," Med. and Biol. Engr. and Comput. 18: 381-390 (1980).

Petrofsky, J.S. Associate Professor, Department of Engineering, Wright State University (personal interview). Dayton, Ohio. 1 December 1981.

Scott, R.N. Myoelectric Control Systems. Advances in Biomedical Engineering and Medical Physics, Volume 2, edited by S.N. Levine. New York: John Wiley and Sons Inc., 1968.

Shik, M.L. and G.N. Orbusky. "Neurophysiology of Locomotor Automatism," Physiological Reviews, Volume 56, No. 3, July 1976.

Townsend, M.A., and R.J. Lepofsky. "Powered Walking Machine Prothesis for Parapelegics," Med. and Biol. Engr. 14: 436-443 (1976).

Vukobratovic, M., D. Hristic and Z. Stojilkovic. "Development of Active Anthromorphic Exoskeletons," Med. and Biol. Engr. 12: 66-80 (1974).

Appendix A

This section contains additional anatomical drawings of cat musculature. The six essential muscles studied are shown with relation to the other major muscles. The electrodes inserted into the essential muscles indicate a general muscle activity pattern for the muscle group in which it is located. These muscle groups can be seen in the following figures. Figures 43 and 44 show the lateral views of the superficial and deep muscles. Figures 45 and 46 show the superficial and deep muscles from the medial aspect.

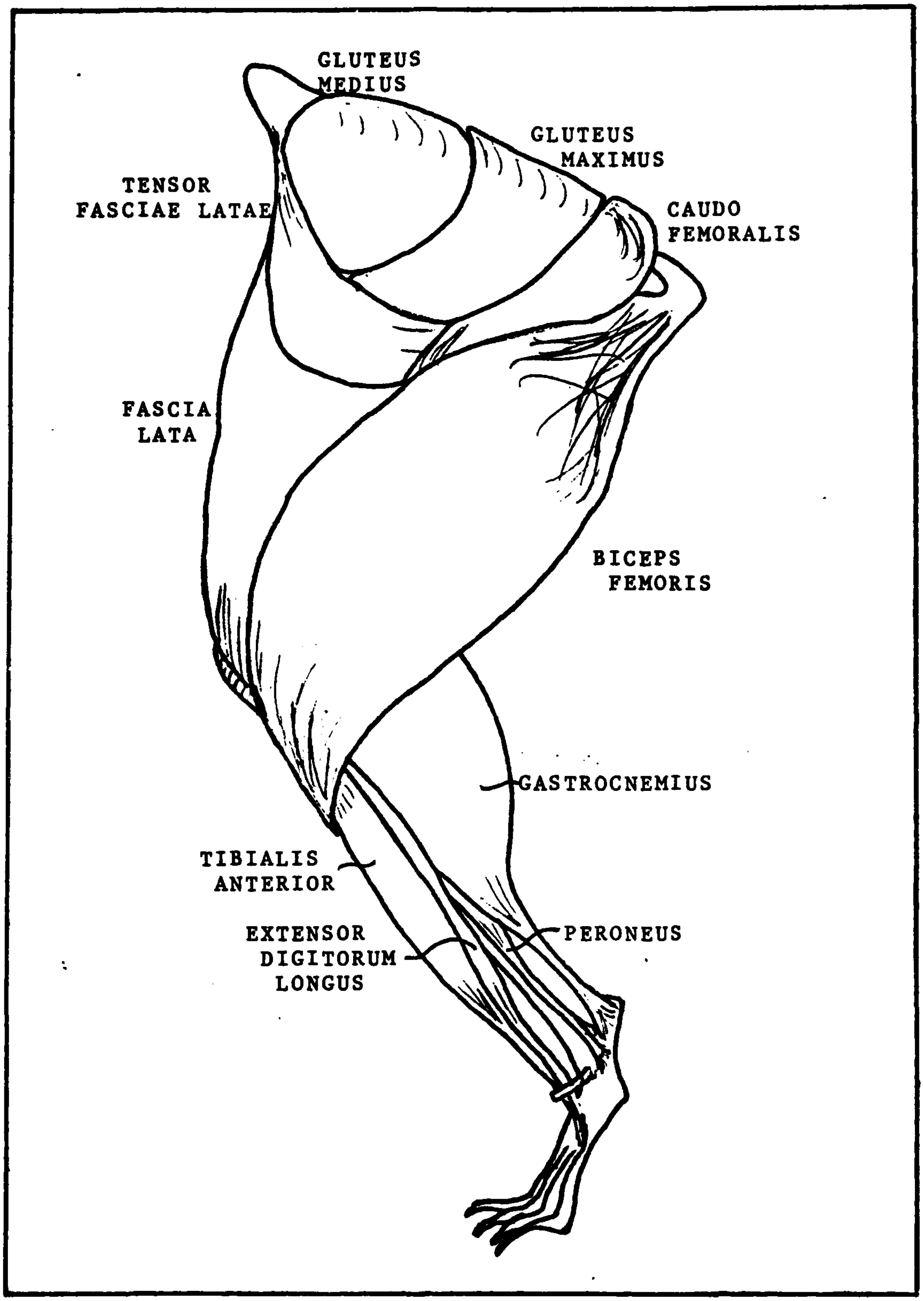


Figure 43. Superficial Muscles: Left Leg Lateral View

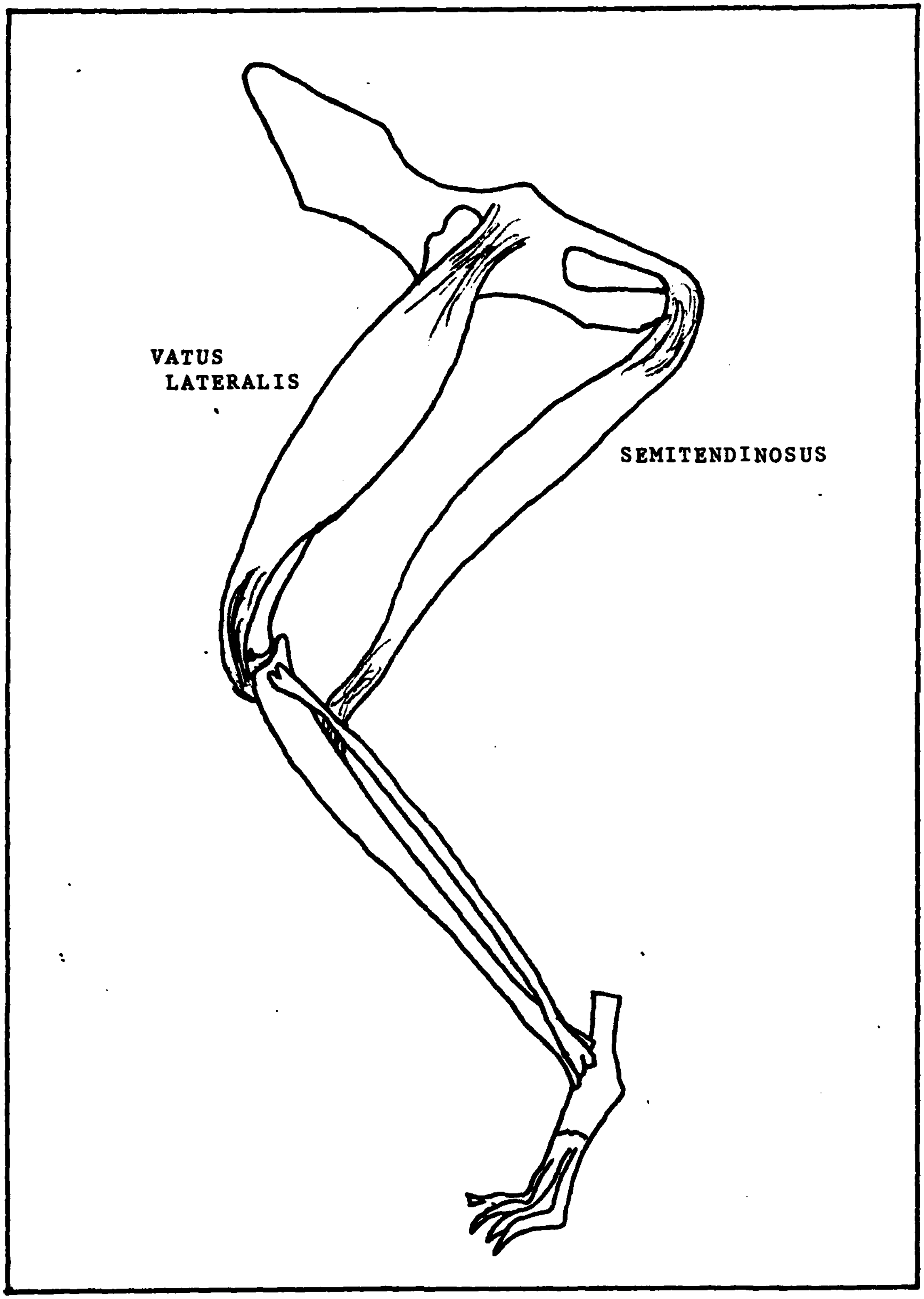


Figure 44. Deep Muscles: Left Leg Lateral View

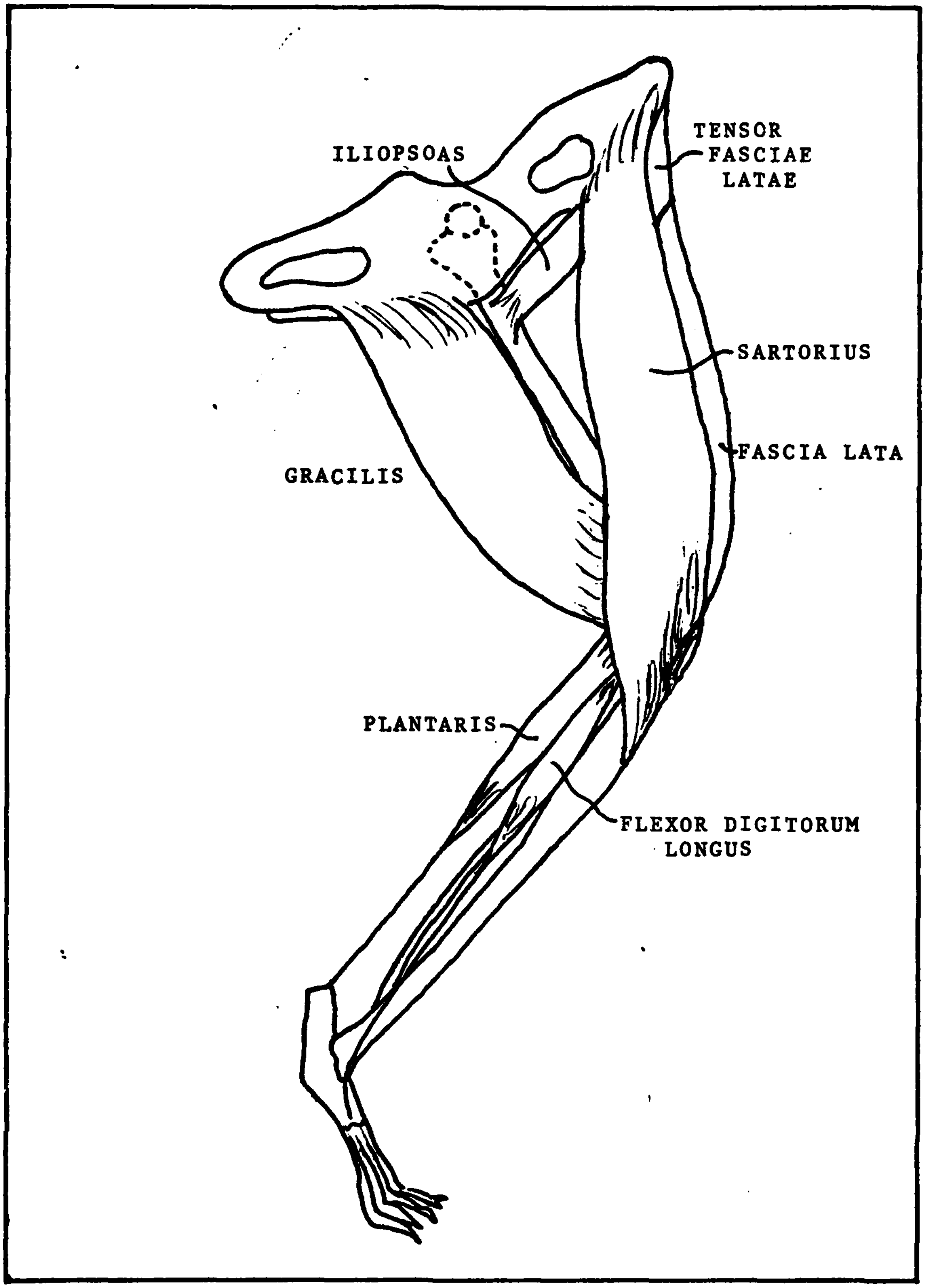


Figure 45 Superficial Muscles: Left Leg Medial View

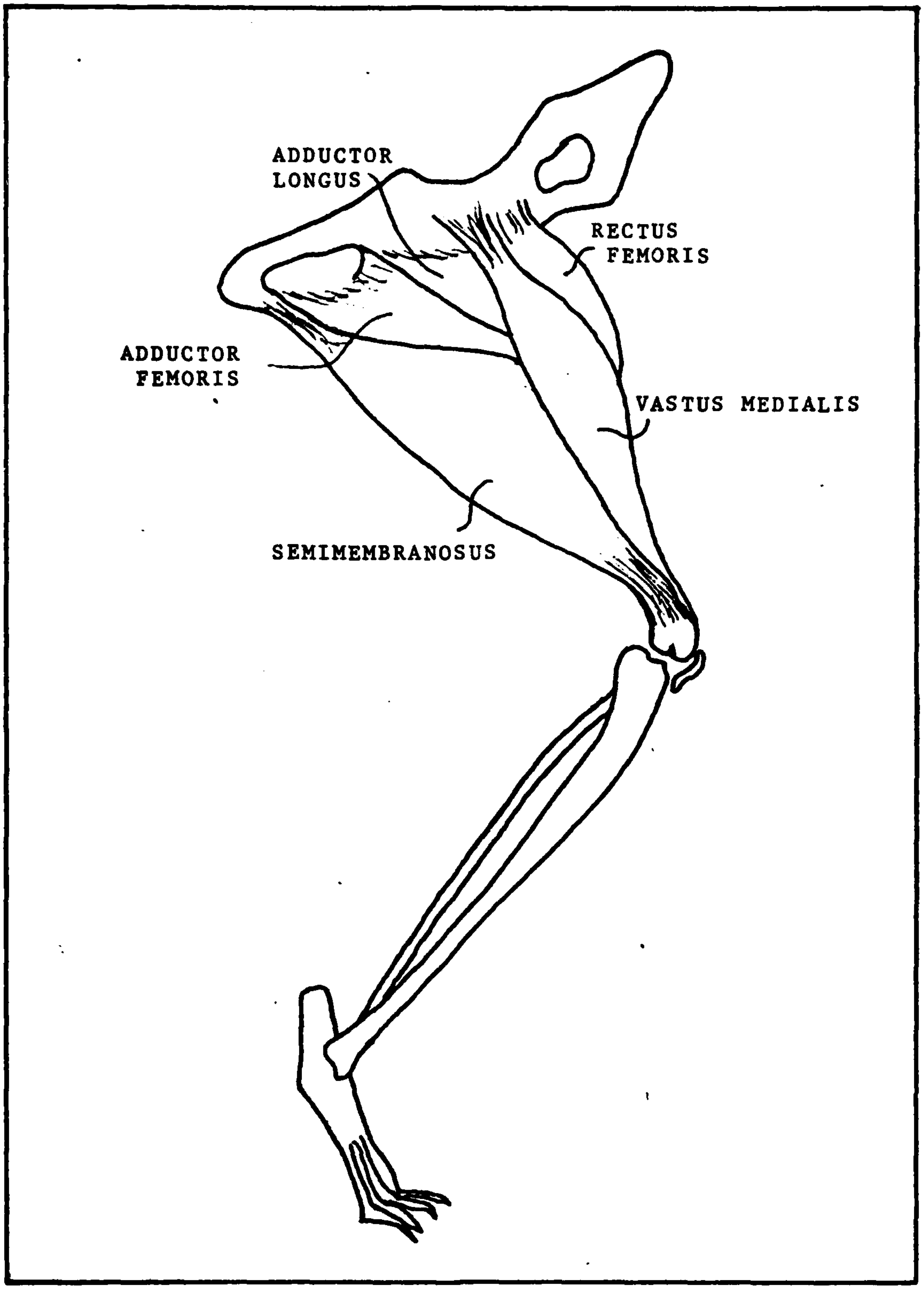


Figure 46. Deep Muscles: Left Leg Medial View

Appendix B

The data in this section is the expanded views of walk data at 0.2, 0.3, 0.4, and 0.5 m/s (Figures 32 and 33). A listing of the joint angle and time throughout the step cycle at each speed is also tabulated. Figure 47 is the 0.2 m/s gait (in Figure 32) and is listed in Table III. The other portion of Figure 32 at 0.3 m/s is expanded in Figure 48 and listed in Table IV. The data in Tables V and VI is shown in Figures 49 and 50. These figures are the expanded view of the walk at 0.4 and 0.5 m/s corresponding to the indicated portions of Figure 33.

This data provides the basis for the model walk to be stored for computer stimulation experimentation. This sequence of movements along with the RMS normalized muscle activity (Chapter 6) should provide the information necessary to model the 0.4 m/s walk.

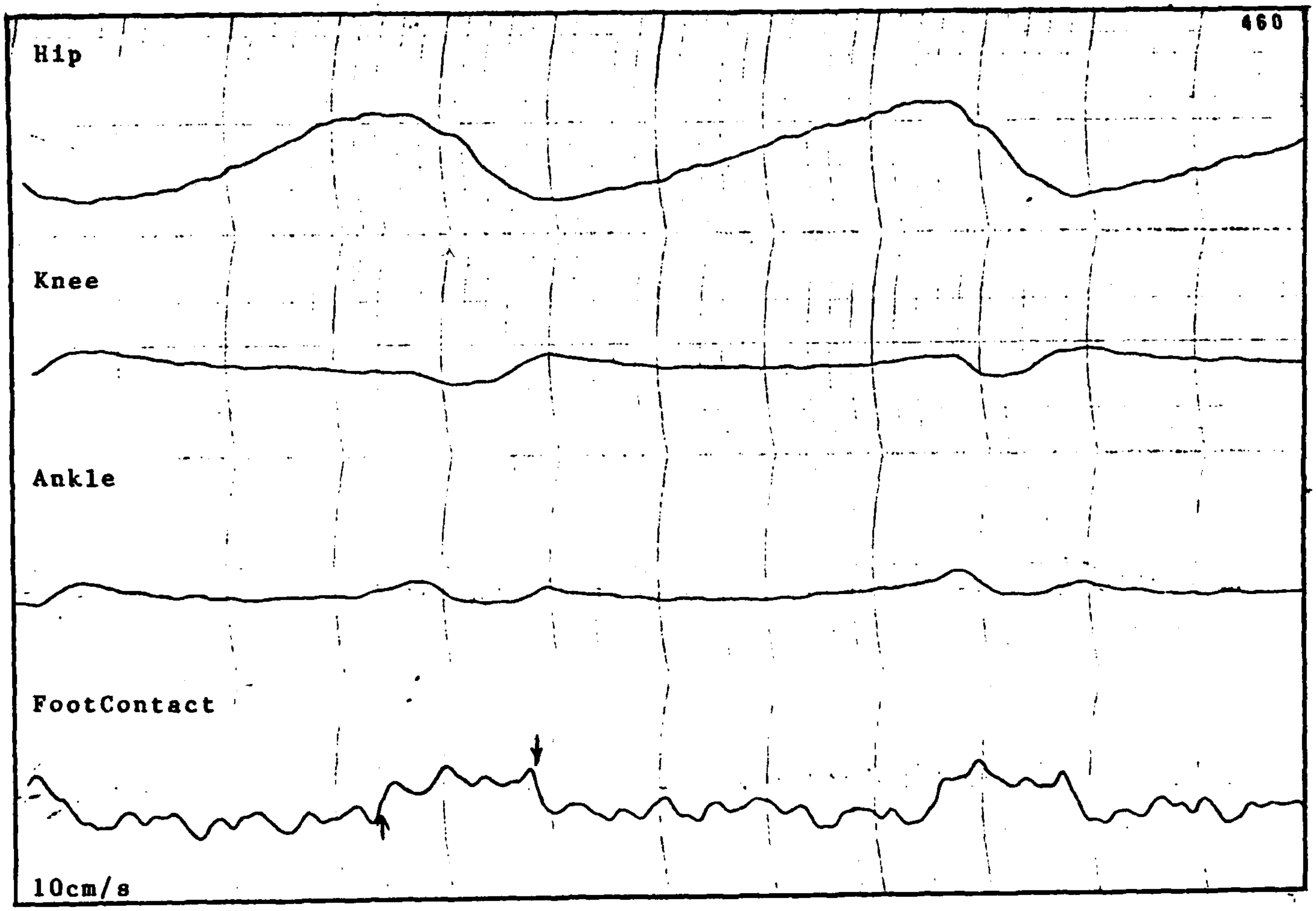


Figure 47. Feedback Data: Harness Left Leg And Foot Contact At 0.2m/s (Expanded View Of Figure 32)

Table III

Tabulation of Joint Position Throughout Step Cycle at 0.2 m/s from Figure 47.

Time (sec)	Position (degrees)		
	Hip	Knee	Ankle
0	23	84	70
0.05	27	80	69
0.1	30	78	66
0.15	34	75	65
0.2	40	73	66
0.25	47	71	65
0.3	53	70	64
0.35	63	71	65
0.4	72	70	65
0.45	83	69	65
0.5	91	68	66
0.55	92	67	66
0.6	93	67	70
0.65	96	63	73
0.7	92	55	78
0.75	80	53	69
0.8	70	54	60
0.85	48	62	58
0.9	32	74	57
0.95	22	81	63
1.0	20	78	71

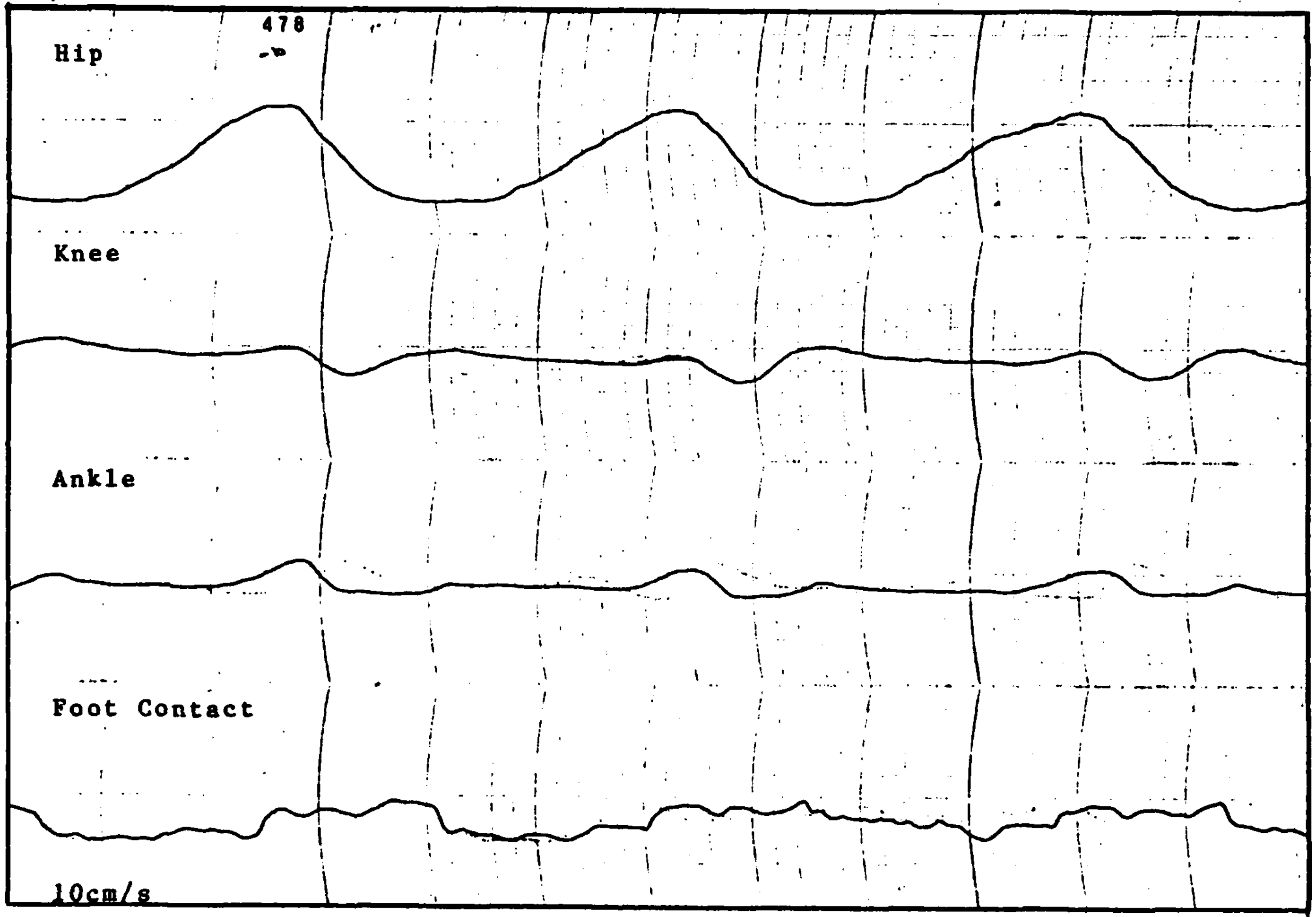


Figure 48. Feedback Data: Harness Left Leg And Foot Contact At 0.3m/s (Expanded View Of Figure 32)

Table IV

Tabulation of Joint Position Throughout Step Cycle at 0.3 m/s from Figure 48.

Time (sec)	Position (degrees)		
	Hip	Knee	Ankle
0	17	85	72
0.05	17	88	80
0.1	18	86	79
0.15	20	82	78
0.2	32	80	76
0.25	38	78	75
0.3	50	77	76
0.35	62	75	75
0.4	72	74	74
0.45	83	73	73
0.5	93	76	78
0.55	100	82	88
0.6	99	81	92
0.65	84	70	88
0.7	60	60	70
0.75	36	61	69
0.8	27	75	70
0.85	20	88	73
0.9	18	91	82
0.95	19	90	80
1.0	21	86	79

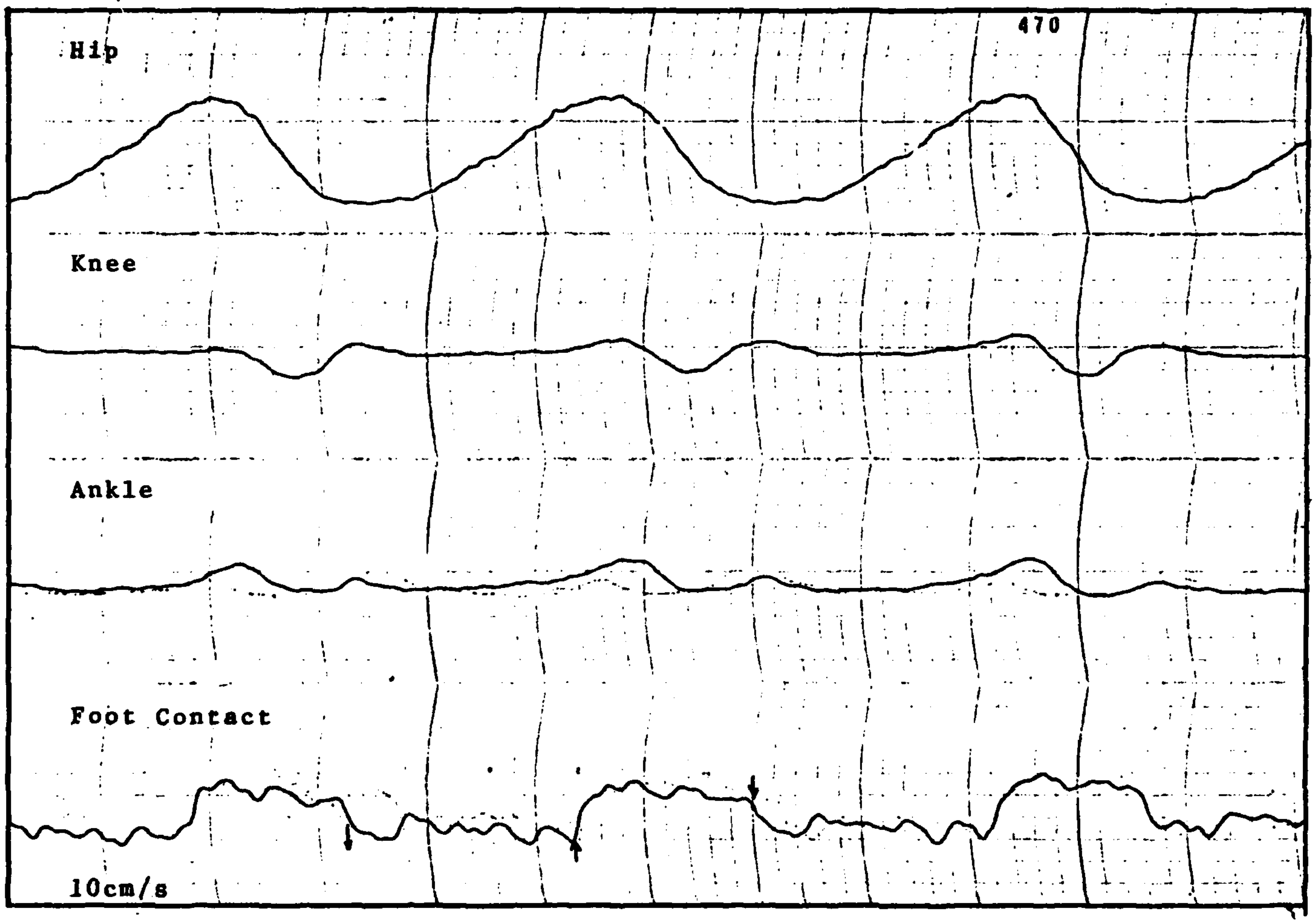


Figure 49. Feedback Data: Harness Left Leg And Foot Contact At 0.4m/s (Expanded View Of Figure 33)

Table V

Tabulation of Joint Position Throughout Step Cycle at 0.4 m/s from Figure 49.

Time (sec)	Position (degrees)		
	Hip	Knee	Ankle
0	27	82	74
0.05	36	83	76
0.1	50	84	78
0.15	60	84	79
0.2	70	84	81
0.25	85	85	82
0.3	100	85	84
0.35	105	90	87
0.4	110	94	94
0.45	111	97	100
0.5	100	88	99
0.55	82	78	84
0.6	55	69	73
0.65	35	72	74
0.7	22	81	75
0.75	19	92	84
0.8	18	94	86
0.85	19	90	76
0.9	22	82	74
0.95	28	83	72
1.0	36	84	73

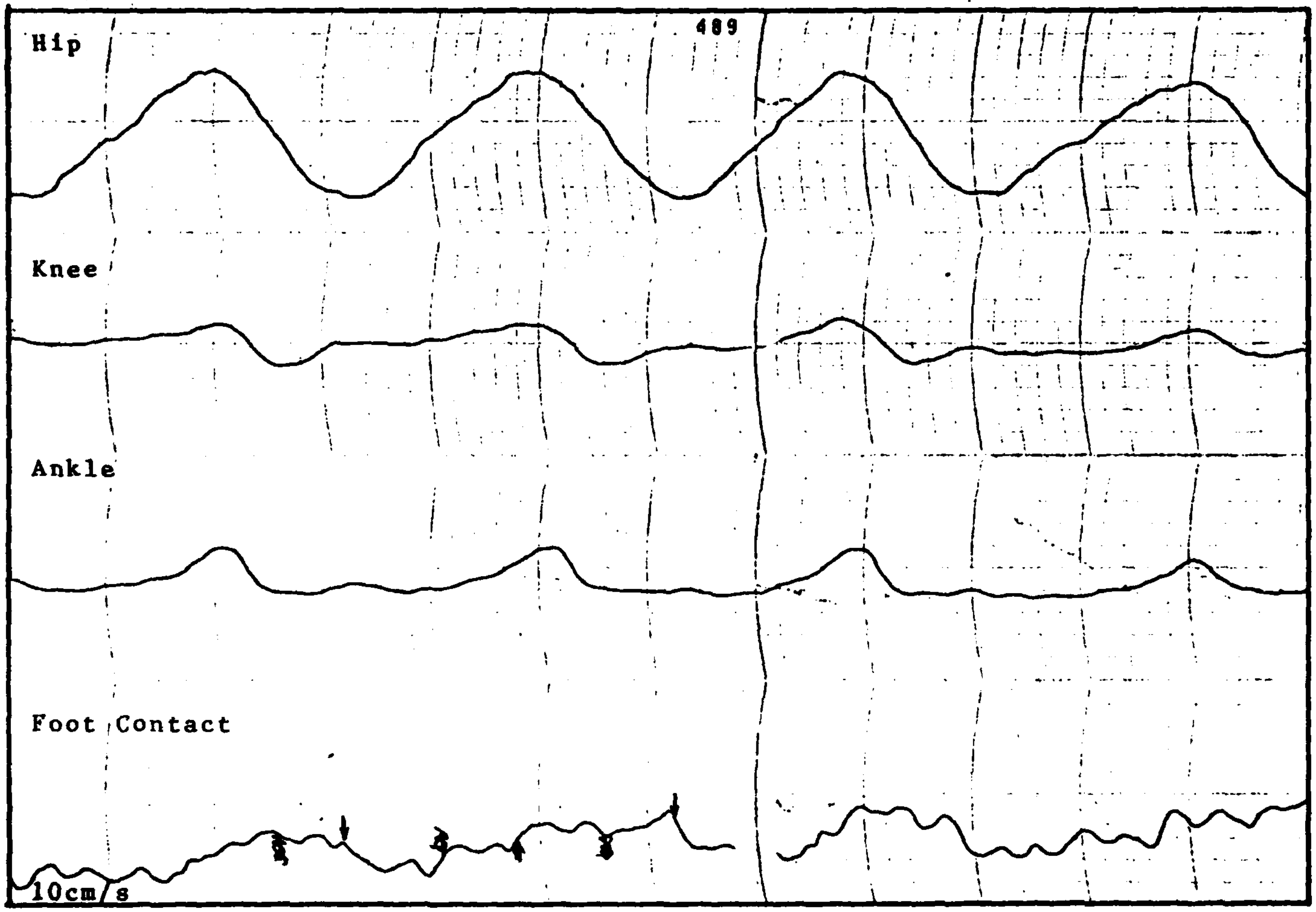


Figure 50. Feedback Data: Harness Left Leg and Foot Contact At 0.5m/s (Expanded View of Figure 33)

Table VI

Tabulation of Joint Position Throughout Step Cycle at 0.5 m/s from Figure 50

Time (sec)	Position (degrees)		
	Hip	Knee	Ankle
0	72	92	70
0.05	87	93	75
0.1	102	94	80
0.15	120	97	82
0.2	132	100	92
0.25	136	108	107
0.3	123	102	105
0.35	100	84	76
0.4	74	70	69
0.45	45	72	68
0.5	27	83	69
0.55	20	90	72
0.6	22	90	73
0.65	34	90	70
0.7	52	89	69
0.75	72	92	70
0.8	89	94	72
0.85	104	100	80
0.9	118	102	87
0.95	131	107	93
1.0	134	106	106

Appendix C

The muscle activity shown in Chapter 6 is from data obtained at a 0.4 m/s gait. The cat was also walked at 0.2 and 0.3 m/s. This section contains data from these two speeds. The activity of each muscle can be compared to itself at the different speeds. As before, the activity between different muscles cannot be compared because of relative location of the electrodes.

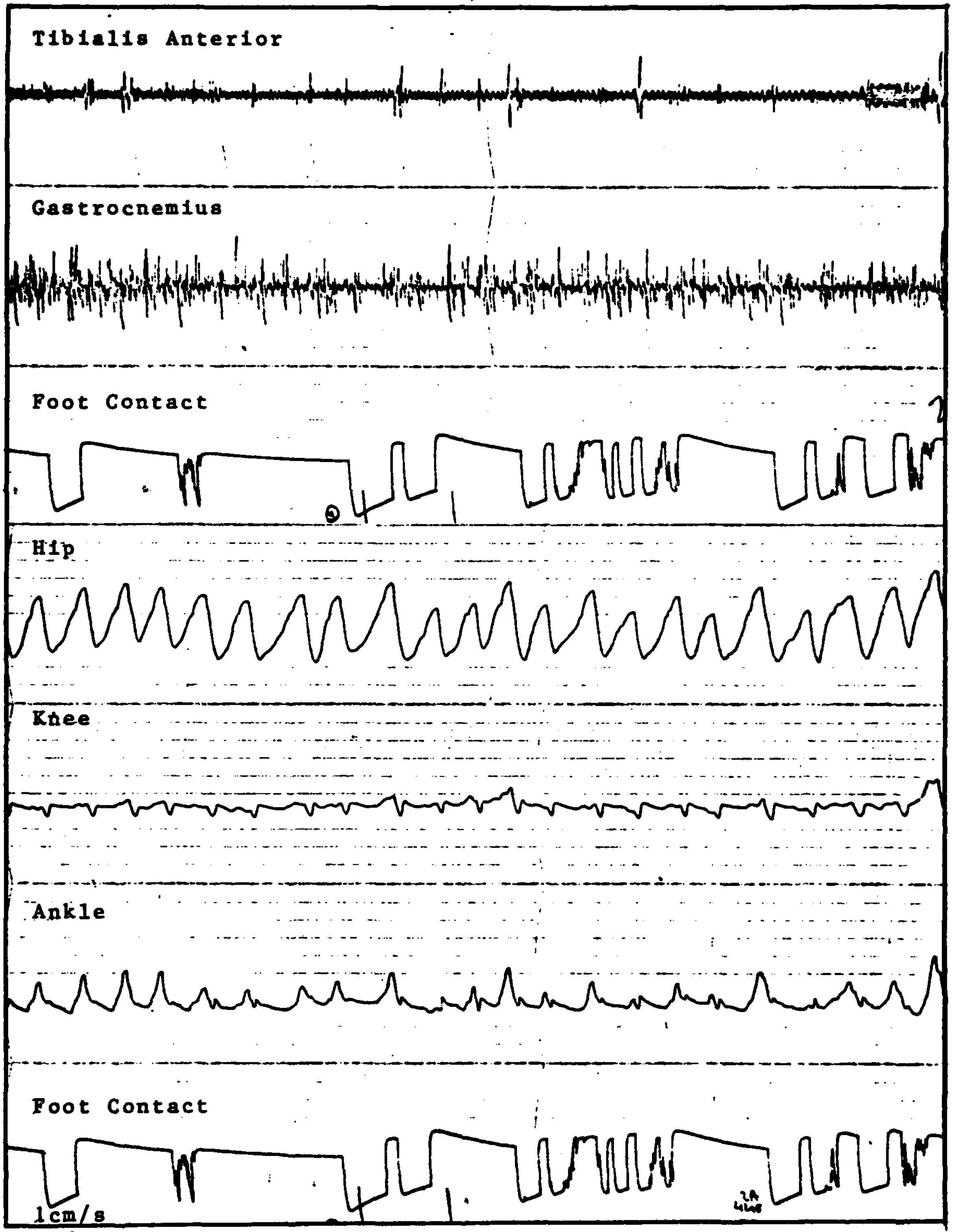


Figure 51. EMG And Feedback Data: Tibialis Anterior And Gastrocnemius (0.2m/s)

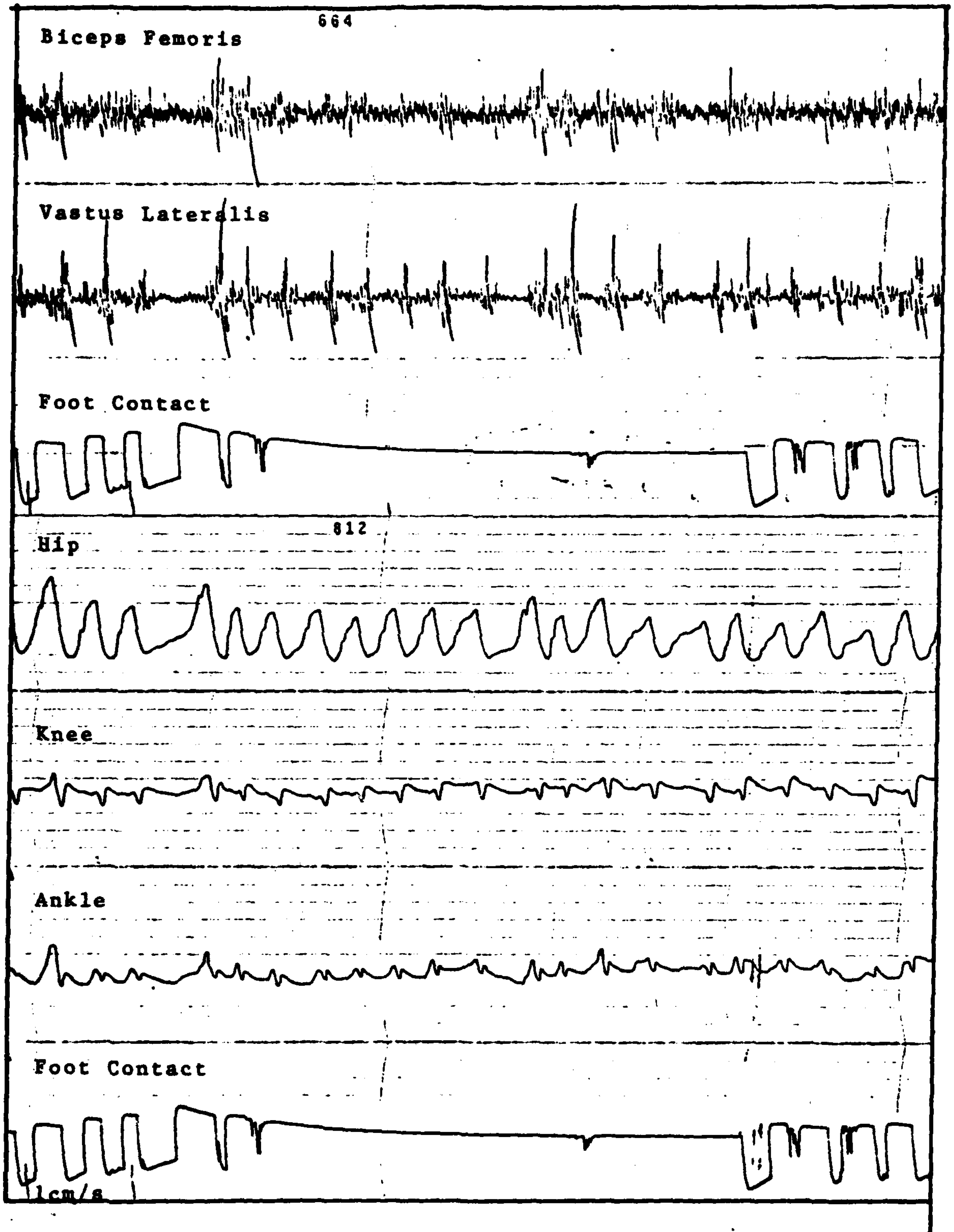


Figure 52. EMG And Feedback Data: Biceps Femoris And Vastus Lateralis (0.2m/s)

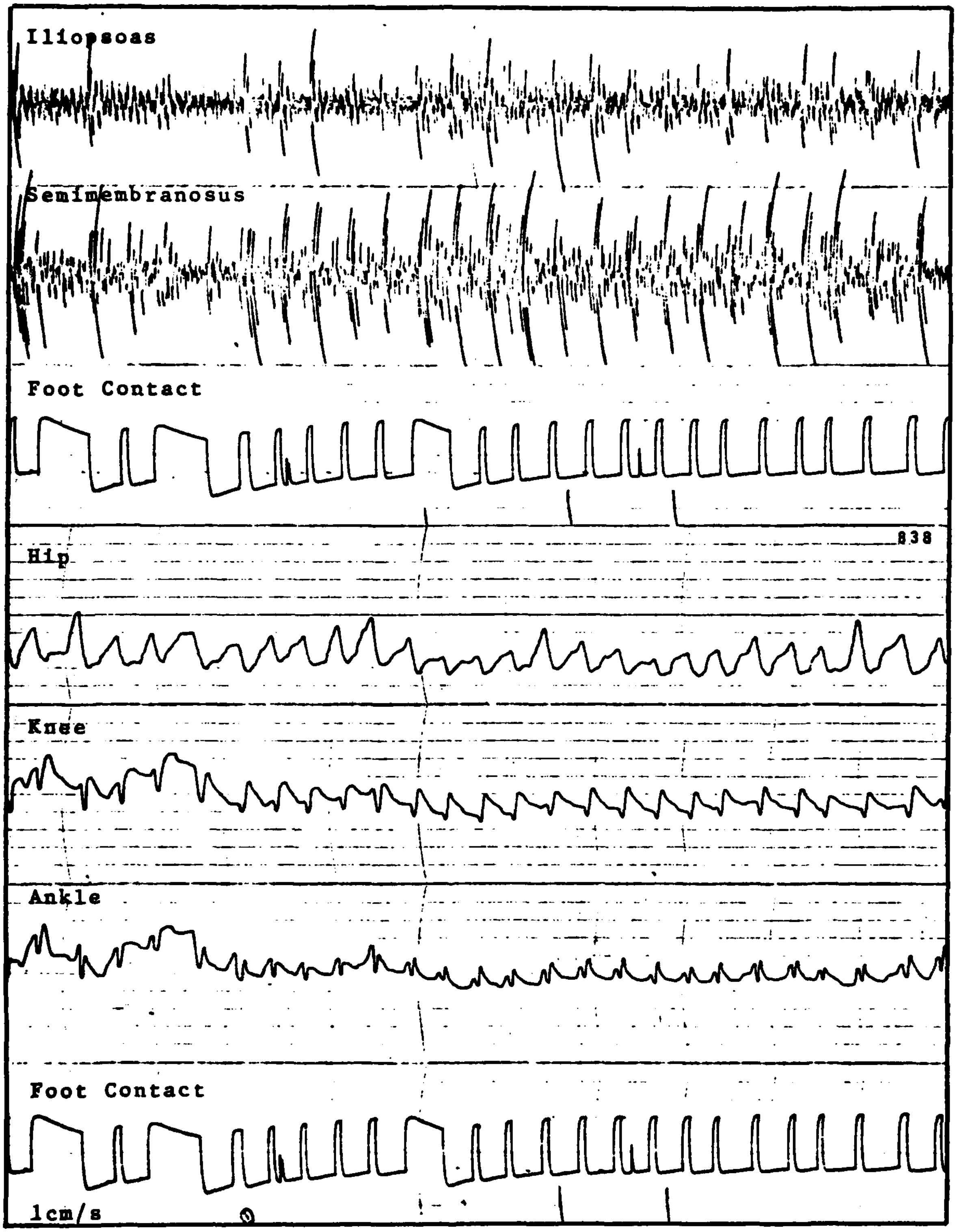


Figure 53. EMG And Feedback Data: Iliopsoas And Semimembranosus (0.2m/s)

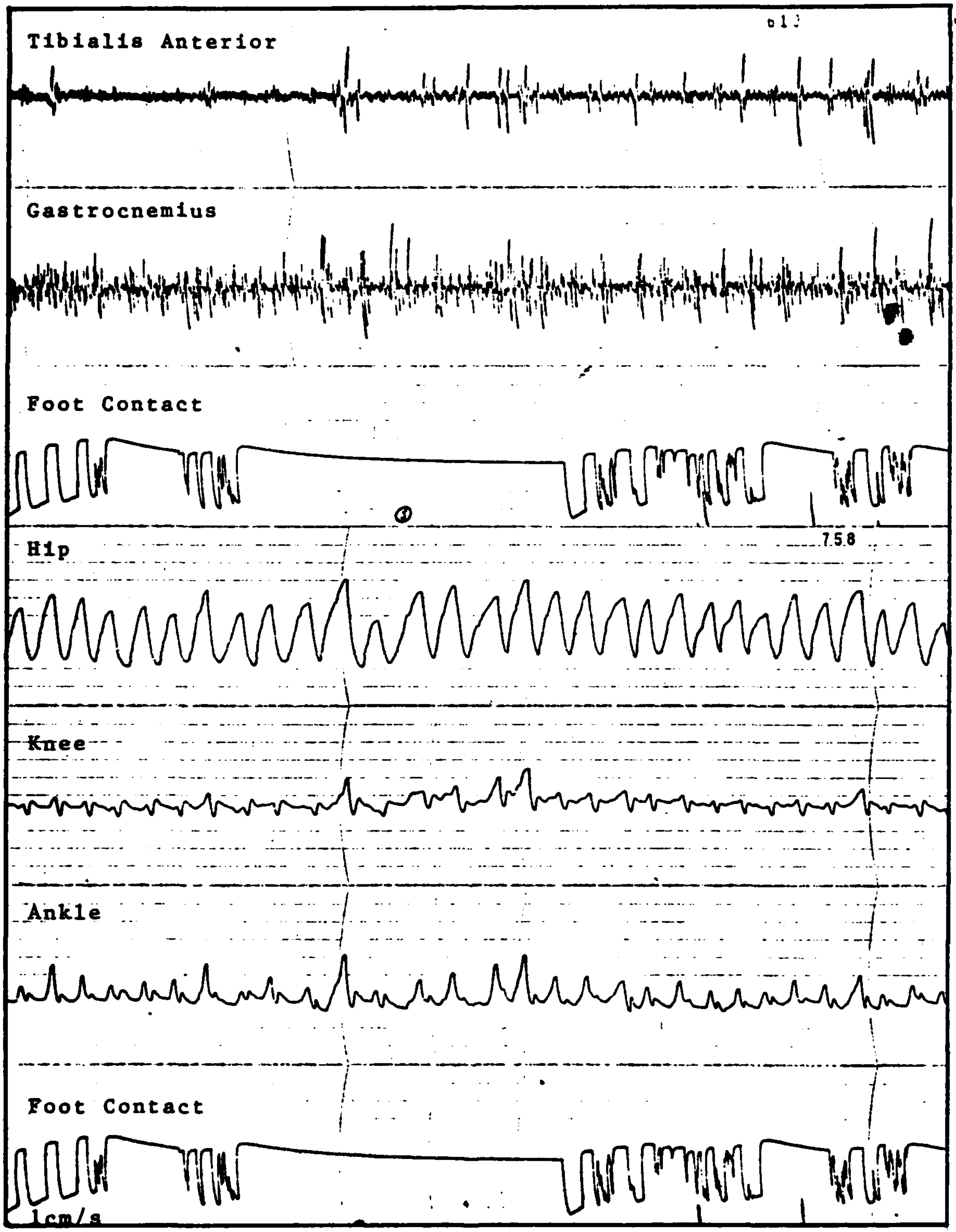


Figure 54. EMG And Feedback Data: Tibialis Anterior And Gastrocnemius (0.3m/s)

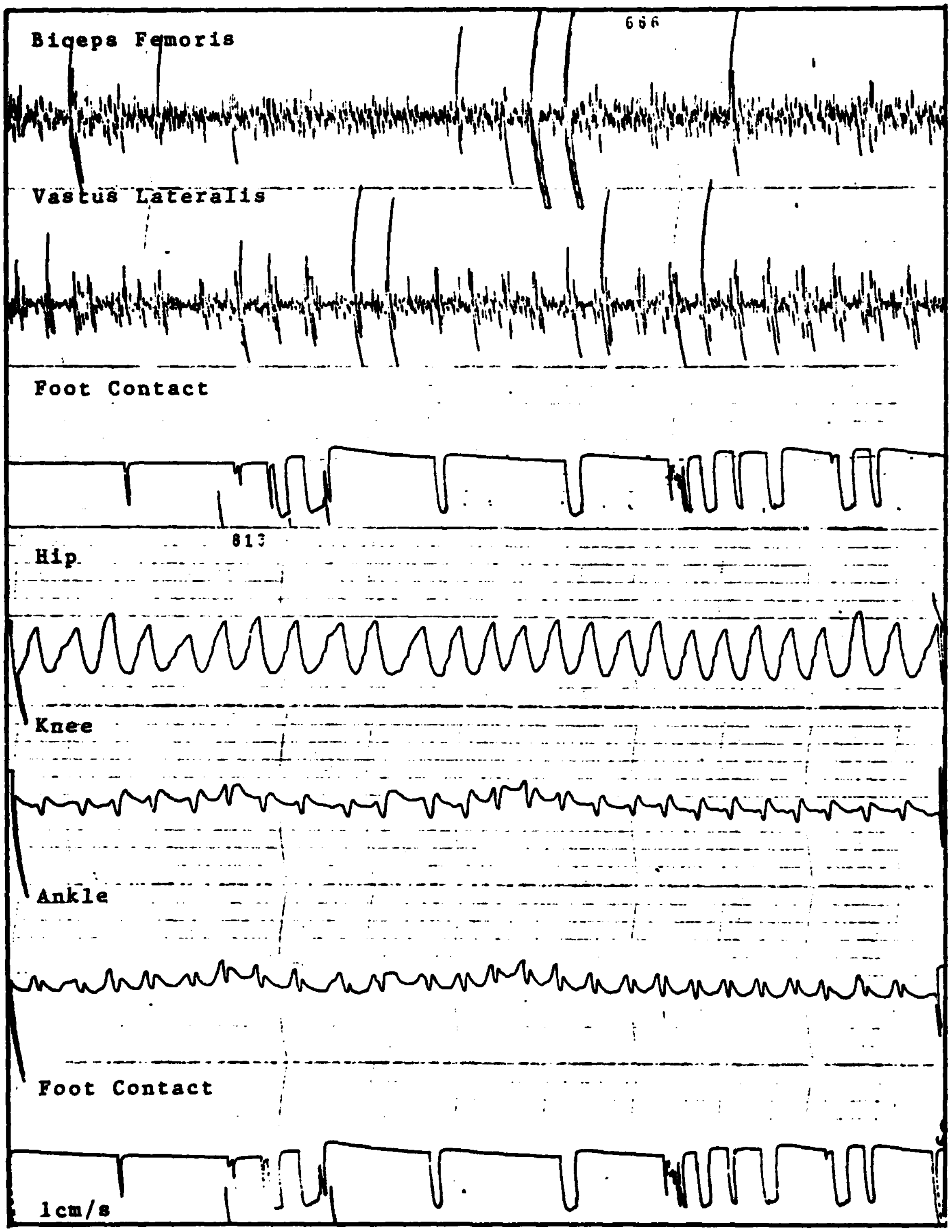


Figure 55. EMG And Feedback Data: Biceps Femoris And Vastus Lateralis (0.3m/s)

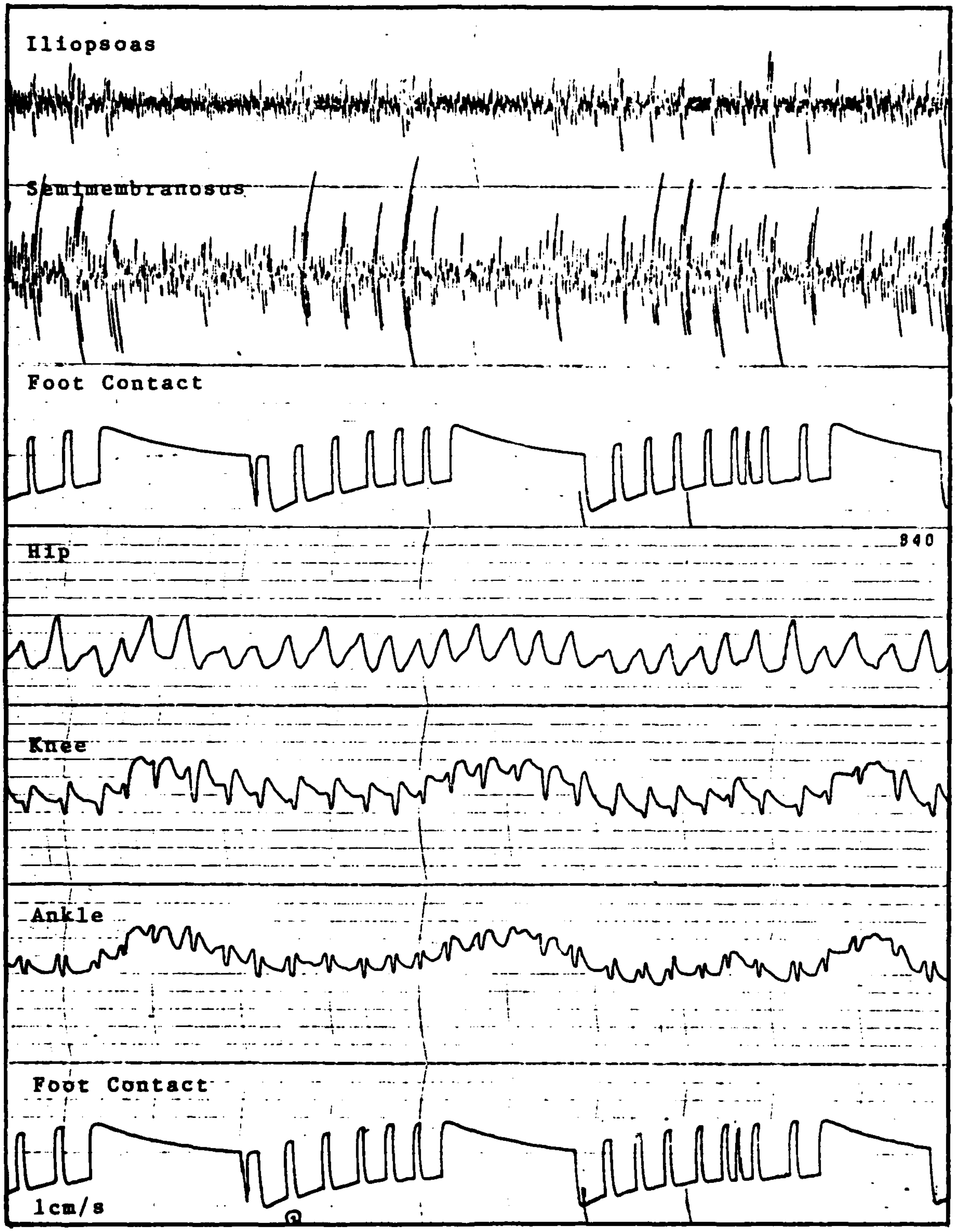


Figure 56. Emg And Feedback Data: Iliopsoas And Semimembranosus (0.3m/s)

Appendix D

This section contains EMG data from the six muscles studied. This data was collected with the cat leashed on the treadmill with no feedback harness. The cat was walked at various speeds. This data was used to assess the restrictive nature of the harness. This data was compared to the data collected from muscle activity with the cat in the harness configuration.

The data shown for all three nuscle sets at 0.2 m/s. The flexor-extensor set for the ankle and knee are shown at 0.3 and 0.4 m/s also. The muscle activity data for the hip flexor-extensor set is not available. The leash broke and the electrodes for the muscle set were dislodged at this point of the experiment. Enough data was collected to accurately assess the restrictive nature of the harness.

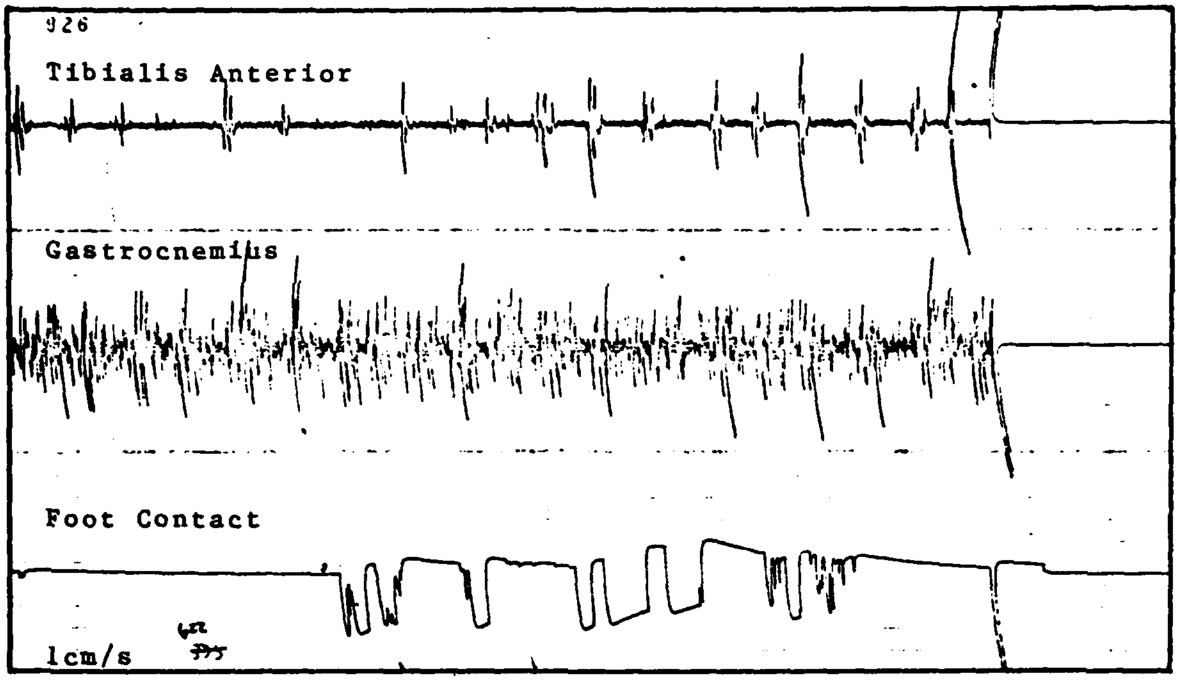


Figure 57. EMG Data: Tibialis Anterior And Gastrocnemius (0.2m/s) No Harness

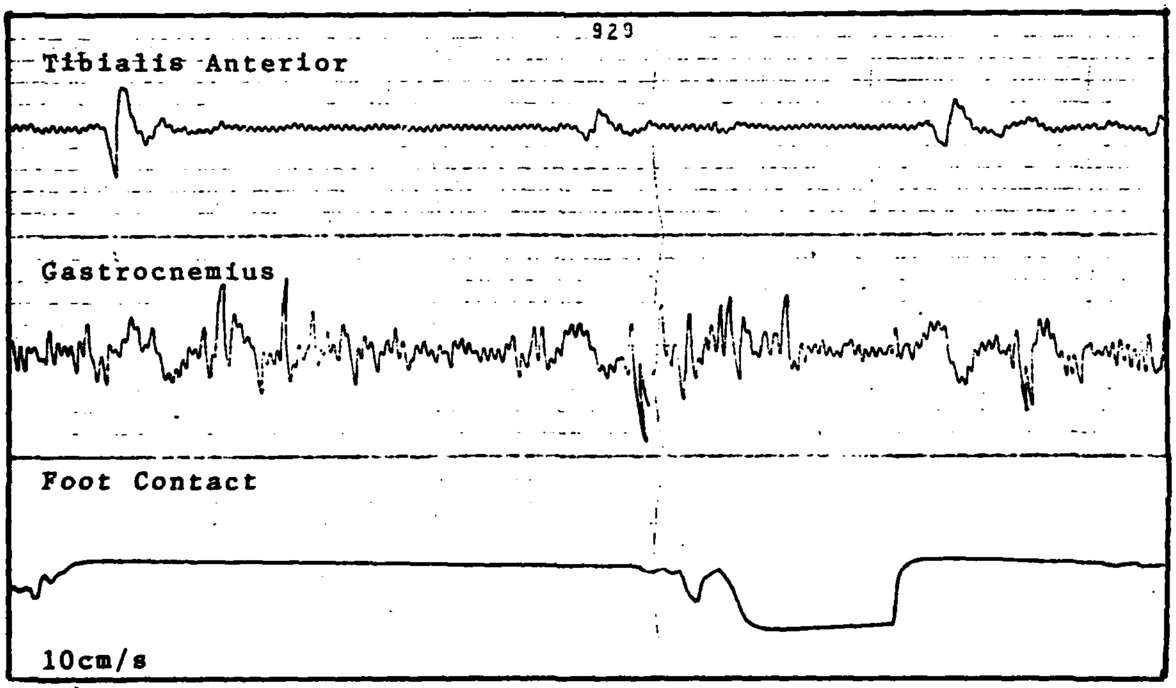


Figure 57A. Expanded View Indicated In Figure 57

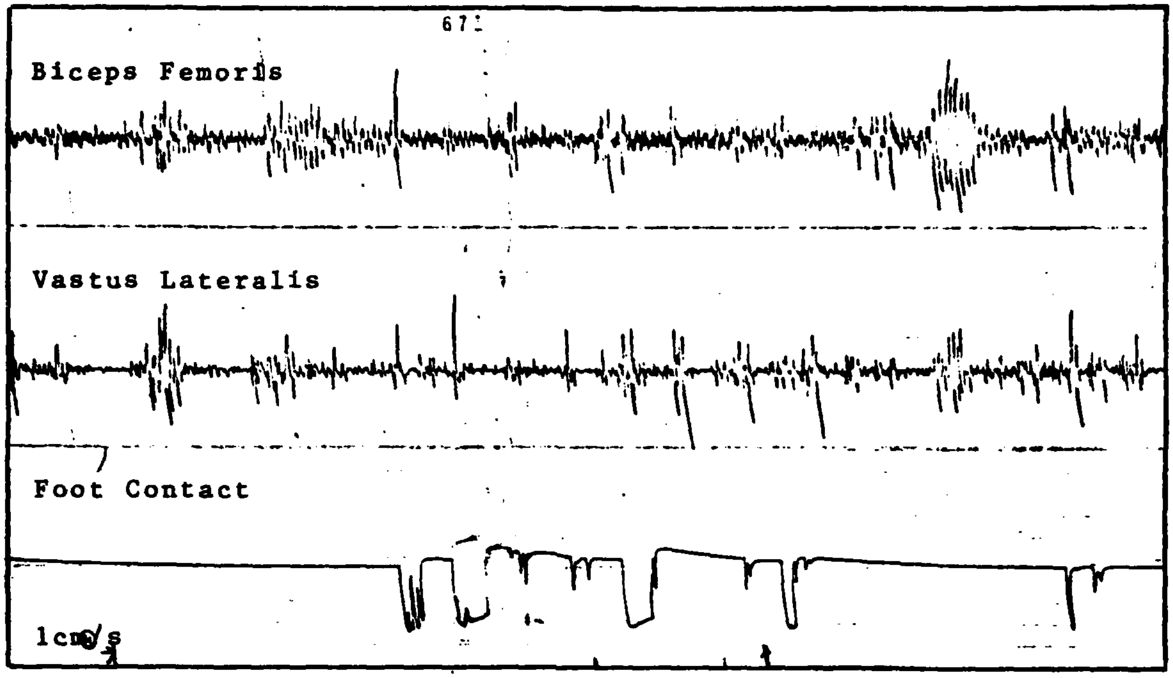


Figure 58. EMG Data: Biceps Femoris And Vastus Lateralis (0.2m/s) No Harness

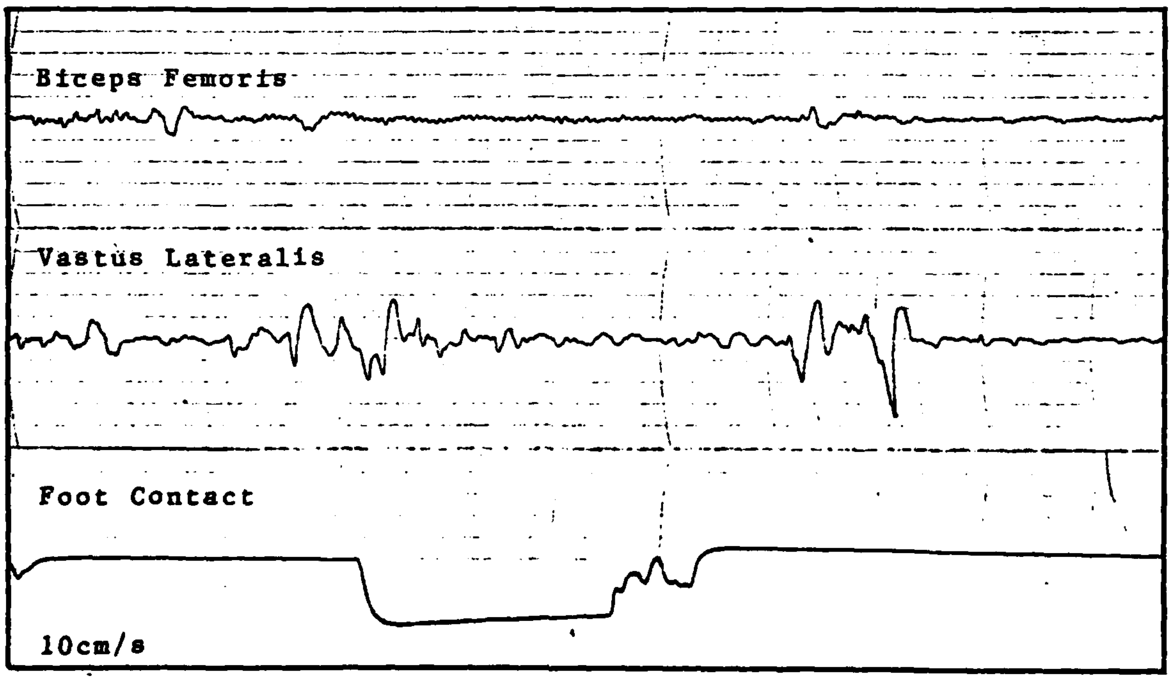


Figure 58A. Expanded View - Indicated In Figure 58

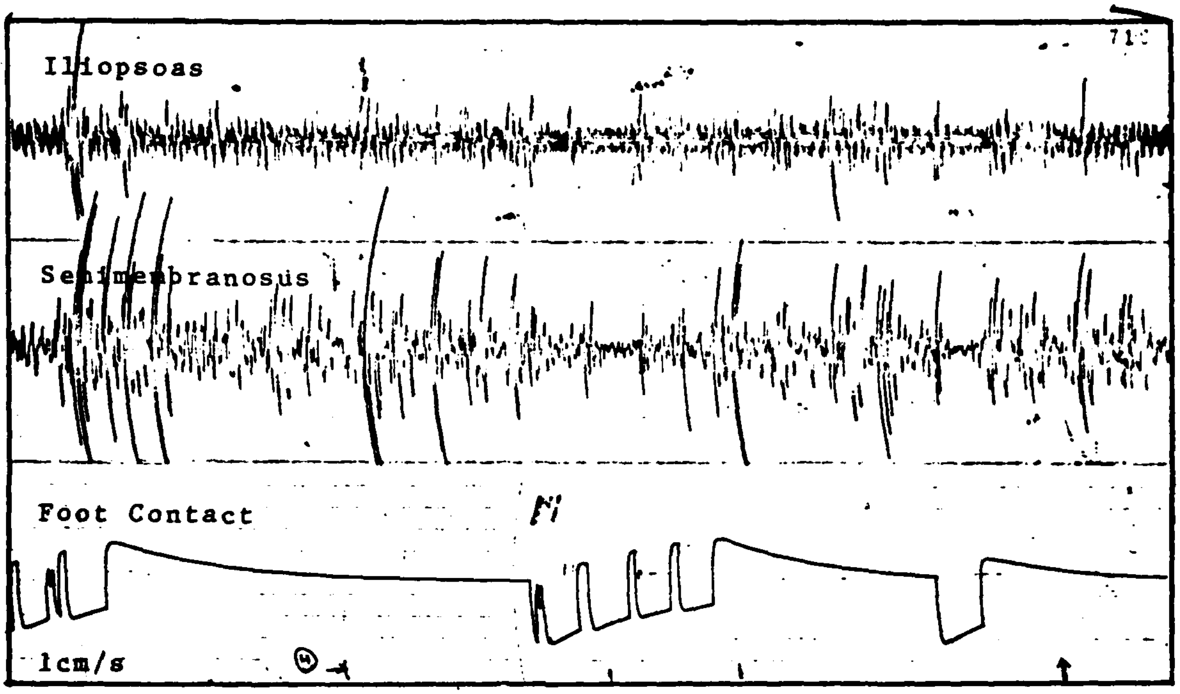


Figure 59. EMG Data: Iliopsoas And Semimembranosus (0.2m/s)
No Harness

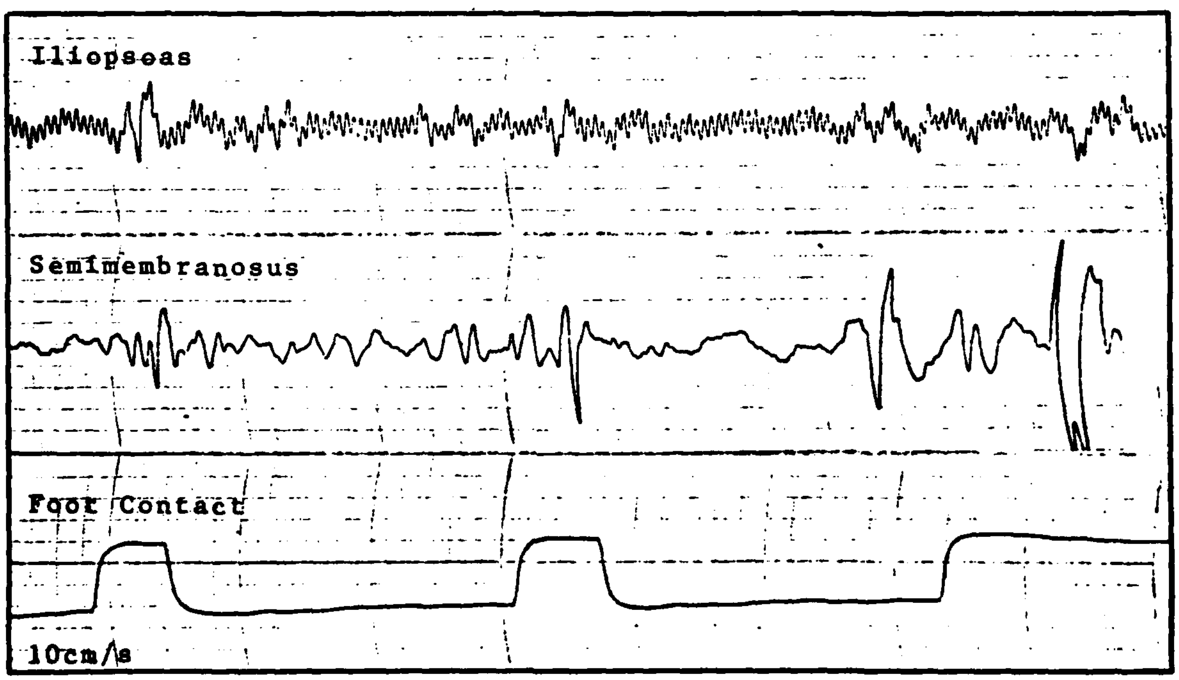


Figure 59A. Expanded View - Indicated In Figure 59

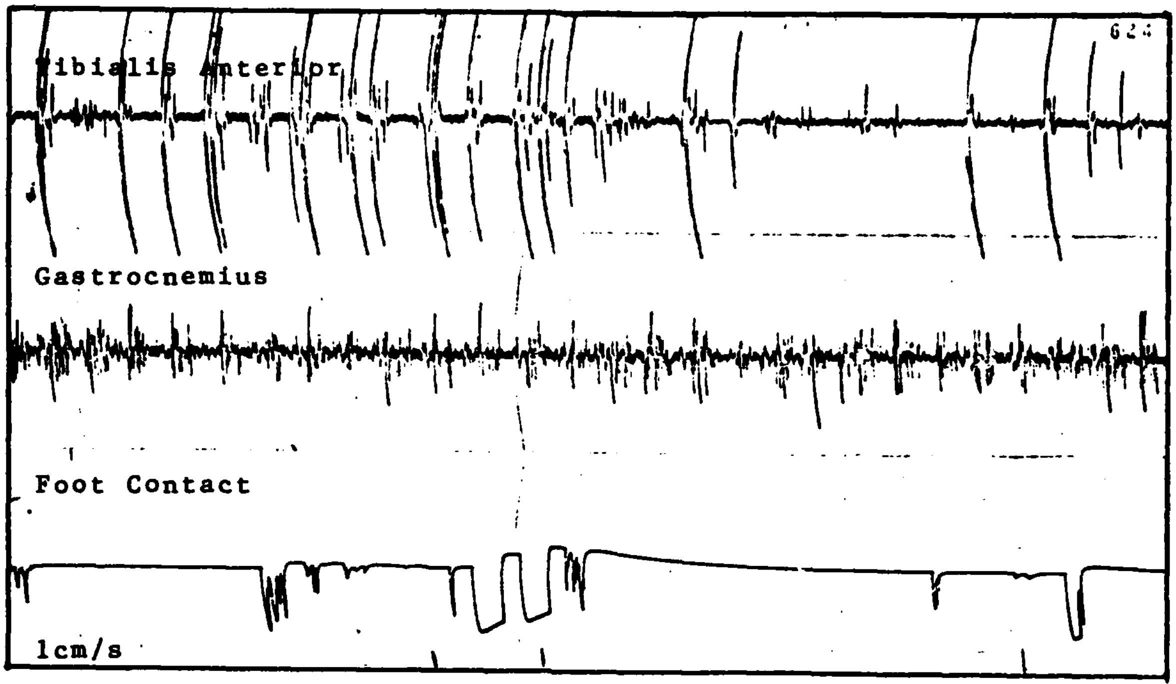


Figure 60. EMG Data: Tibialis Anterior And Gastrocnemius (0.3m/s) No Harness

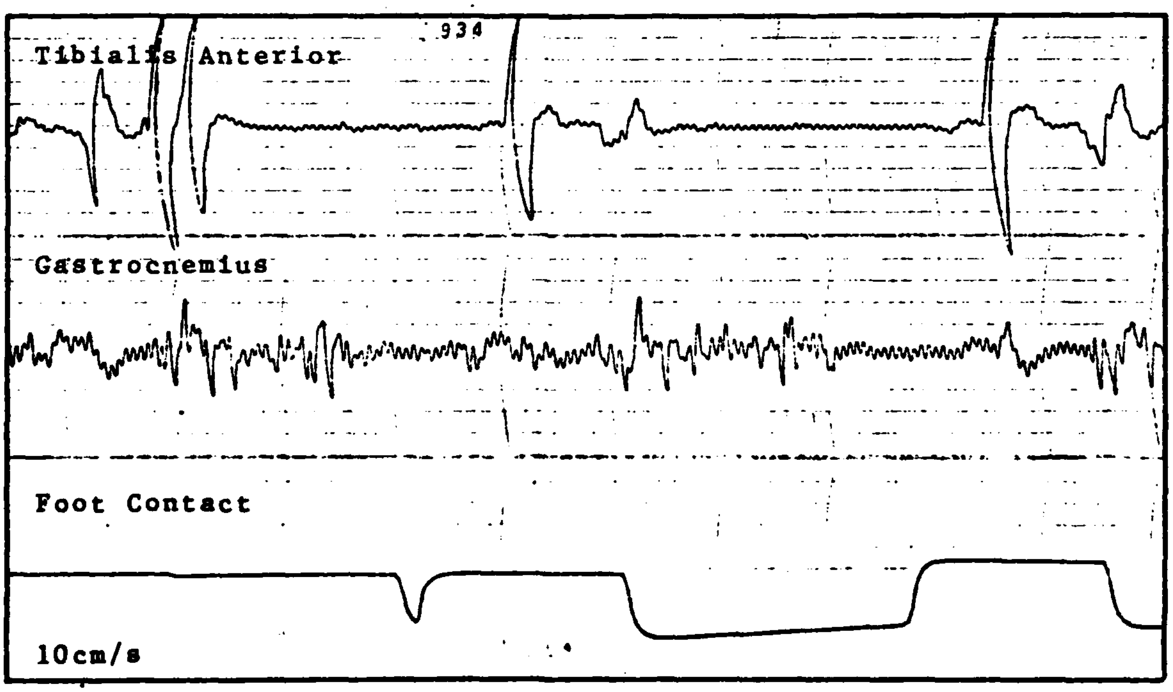


Figure 60A. Expanded View - Indicated In Figure 60

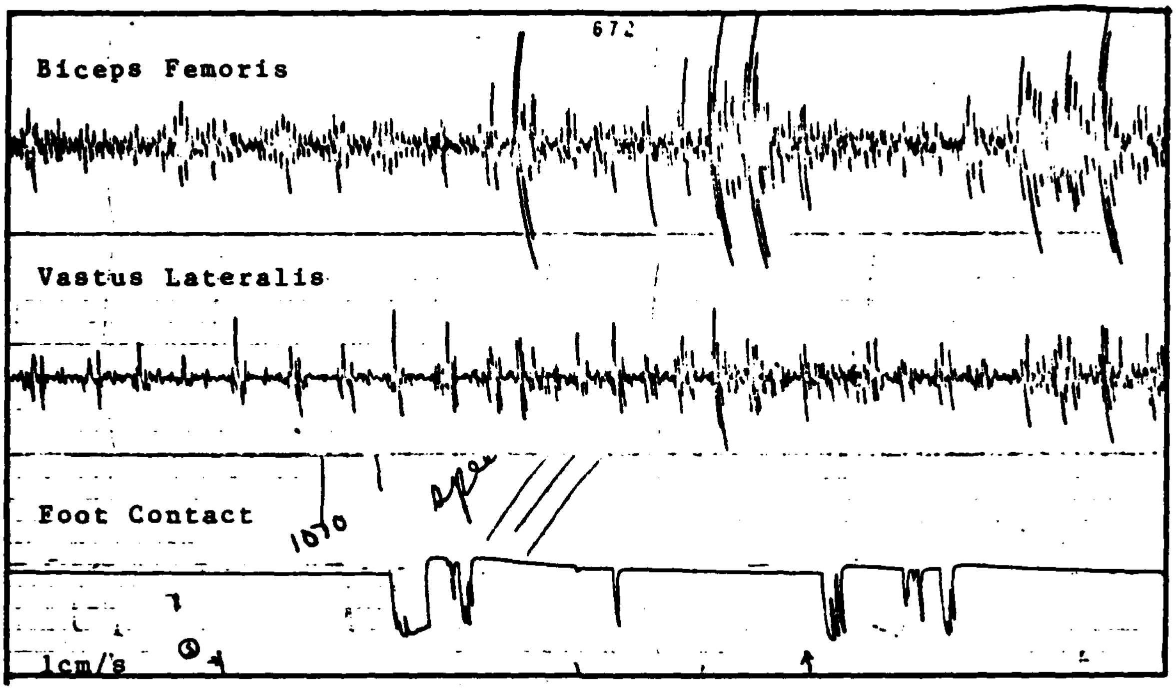


Figure 61. EMG Data: Biceps Femoris And Vastus Lateralis (0.3m/s) No Harness

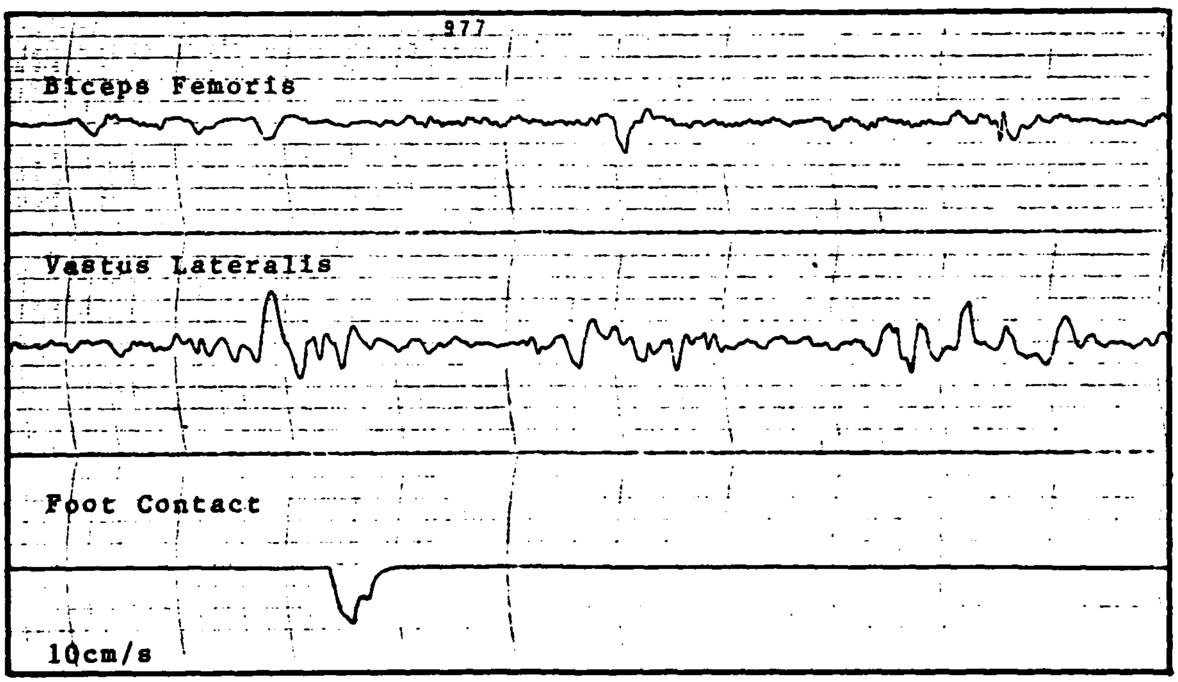


Figure 61A. Expanded View - Indicated In Figure 61

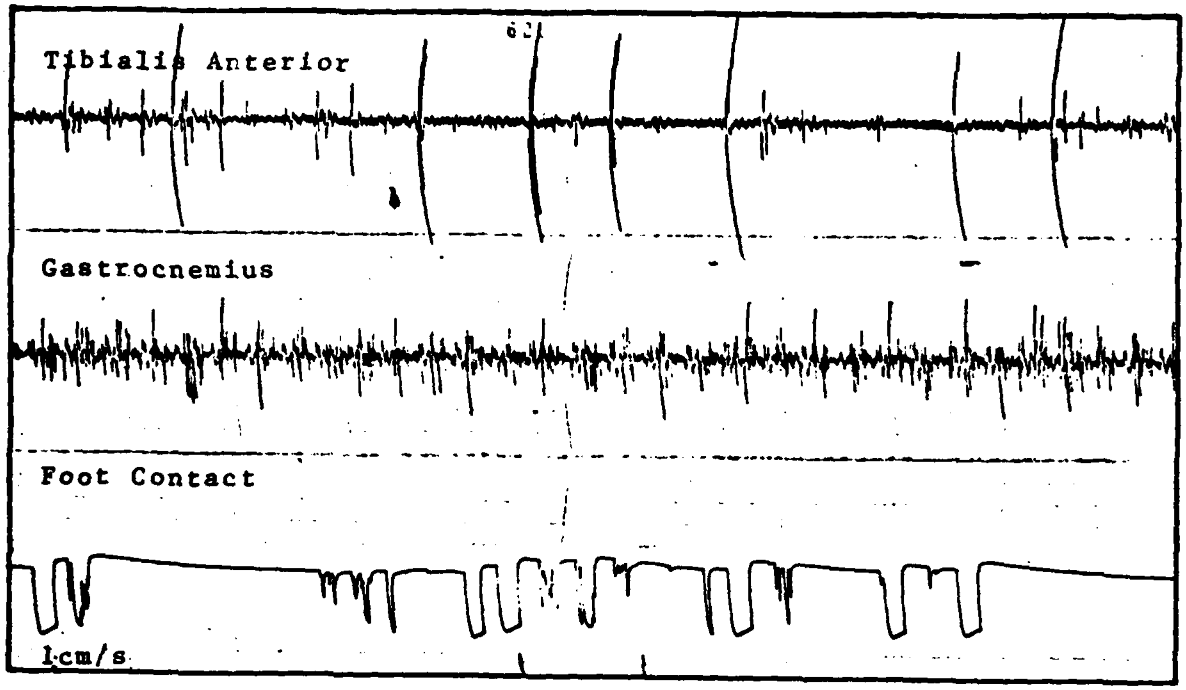


Figure 62. EMG Data: Tibialis Anterior And Gastrocnemius (0.4m/s) No Harness

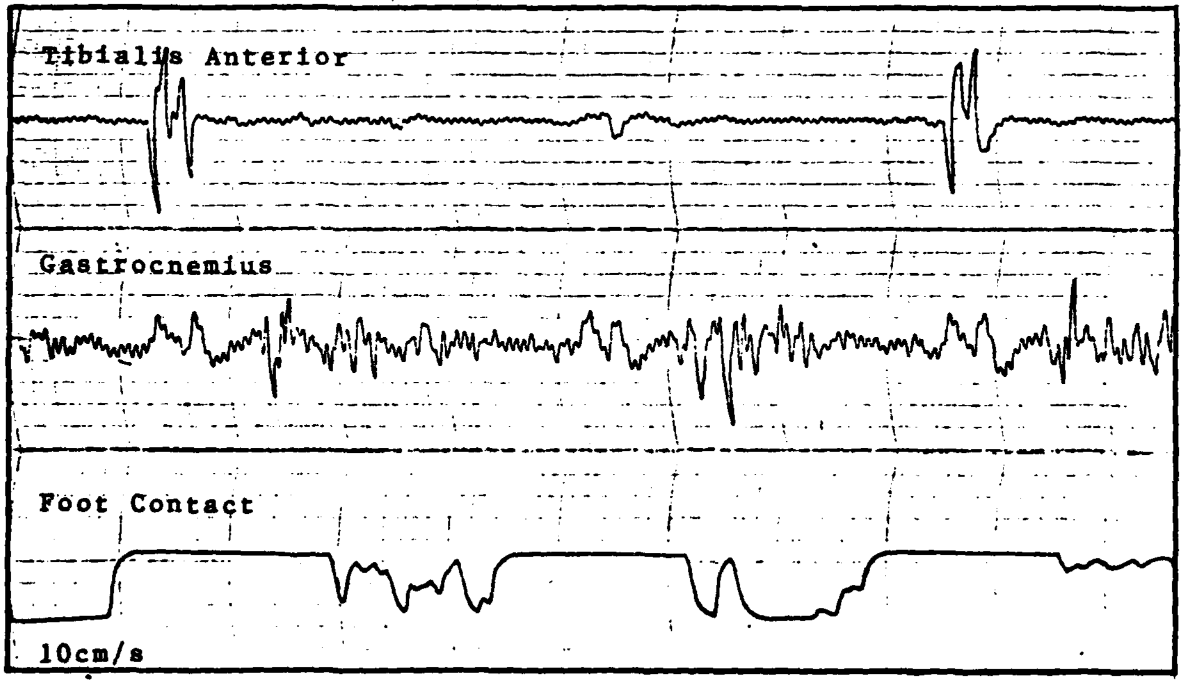


Figure 62A. Expanded View - Indicated In Figure 62

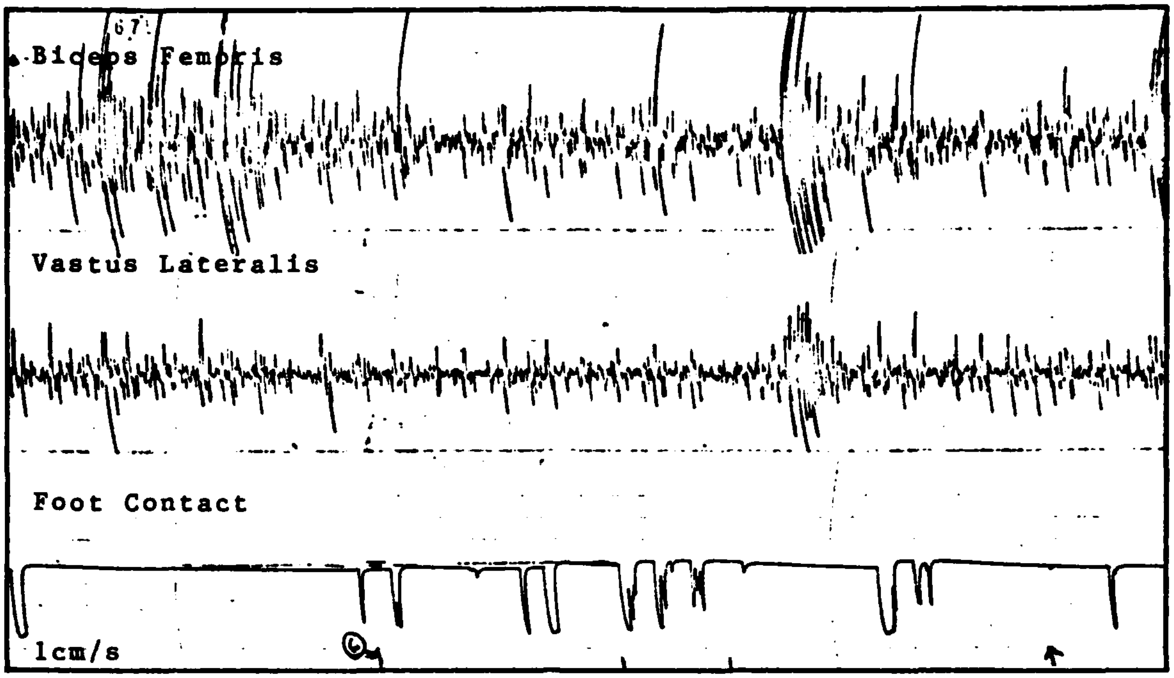


Figure 63. EMG Data: Biceps Femoris And Vastus Lateralis (0.4m/s) No Harness

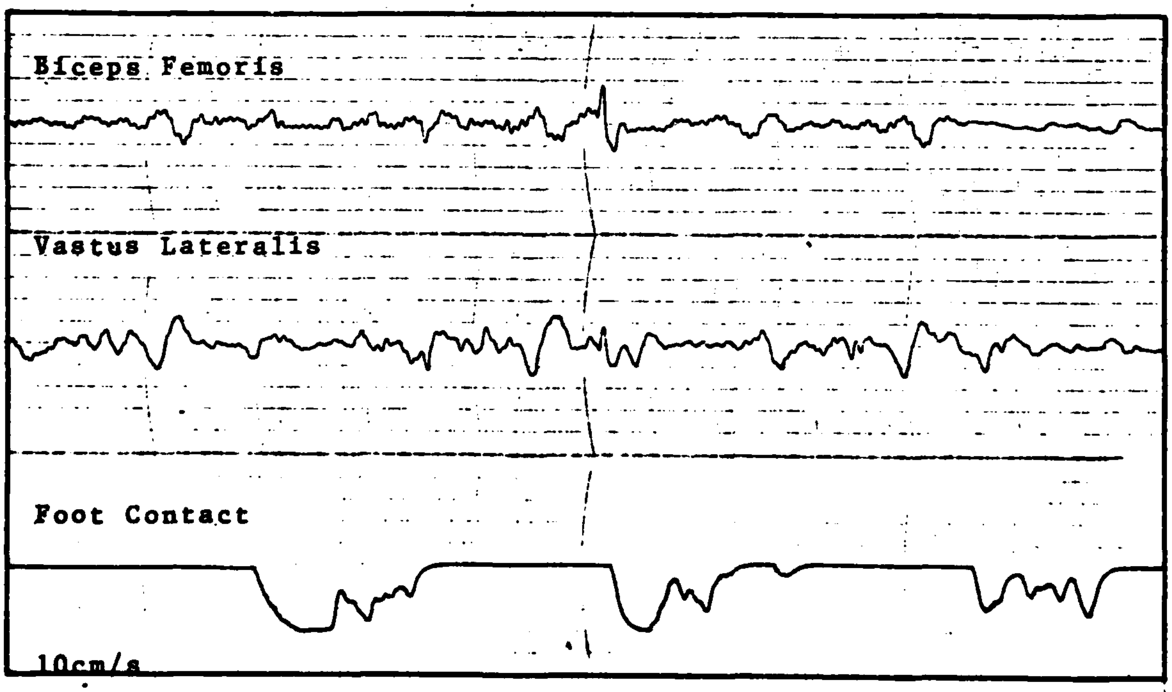


Figure 63A. Expanded View - Indicated In Figure 63

Appendix E

The RMS muscle activity for the two other test speeds (0.2 and 0.3 m/s) is shown in this section. This data can be normalized and to modify the model data to adjust to other speeds.

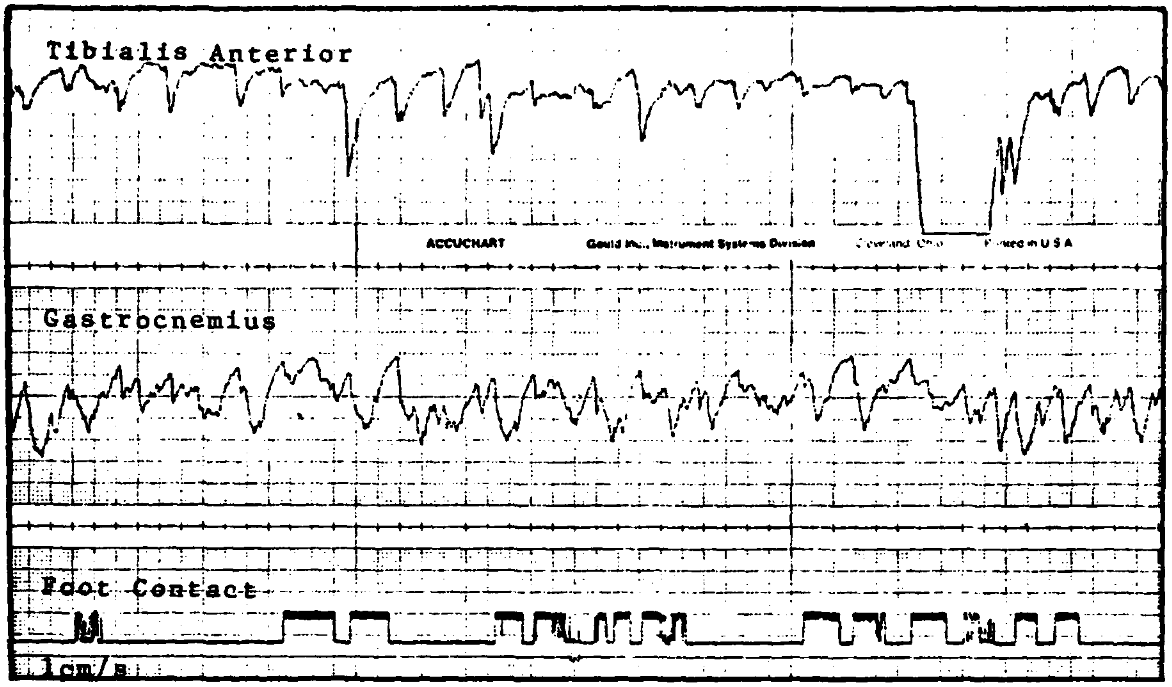


Figure 64. RMS Muscle Activity Data: Tibialis Anterior And Gastrocnemius (0.2m/s)

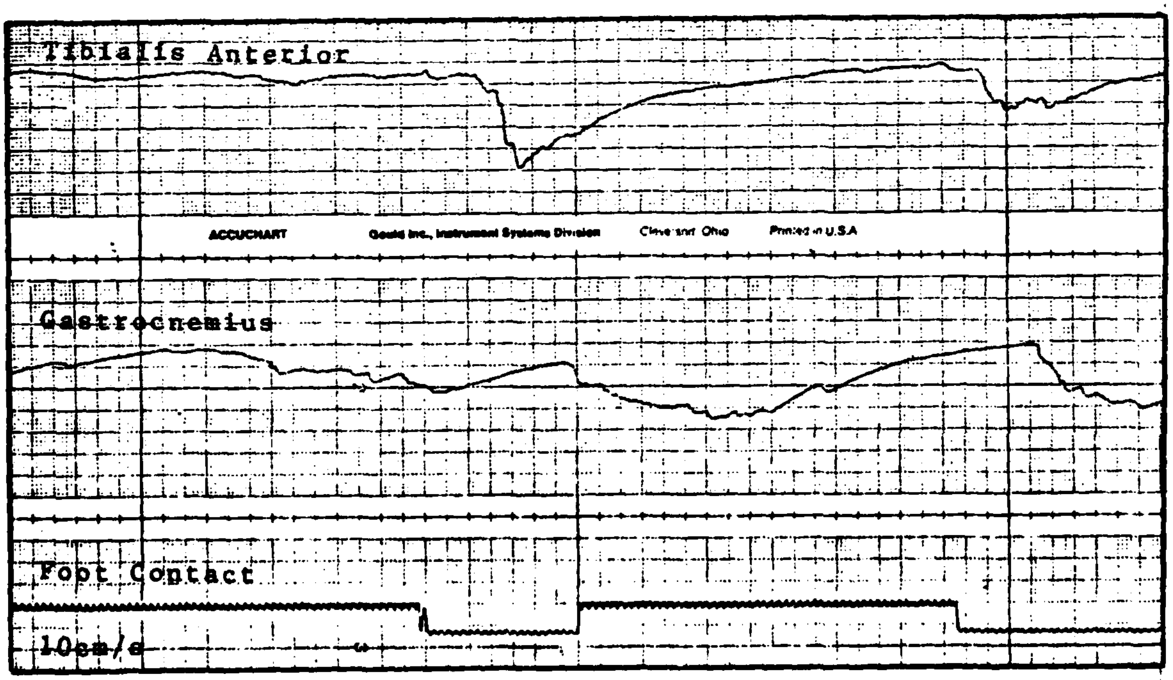


Figure 64A. Expanded View - Indicated in Figure 64

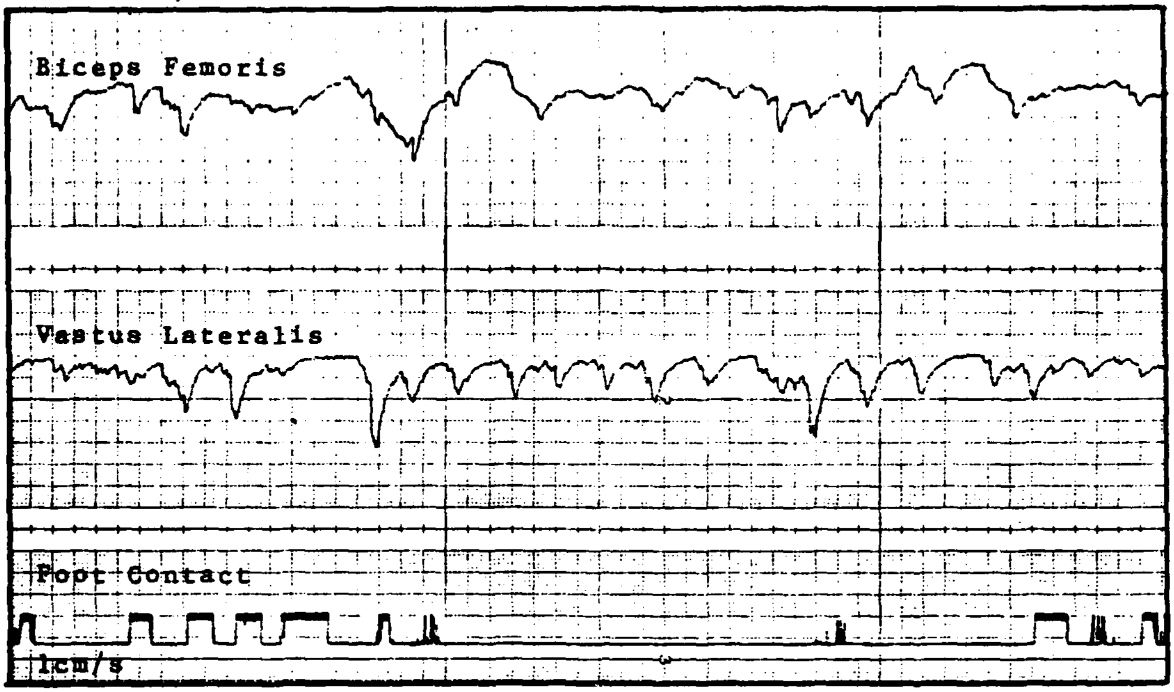


Figure 65 RMS Muscle Activity Data: Biceps Femoris And Vastus Lateralis (0.2m/s)

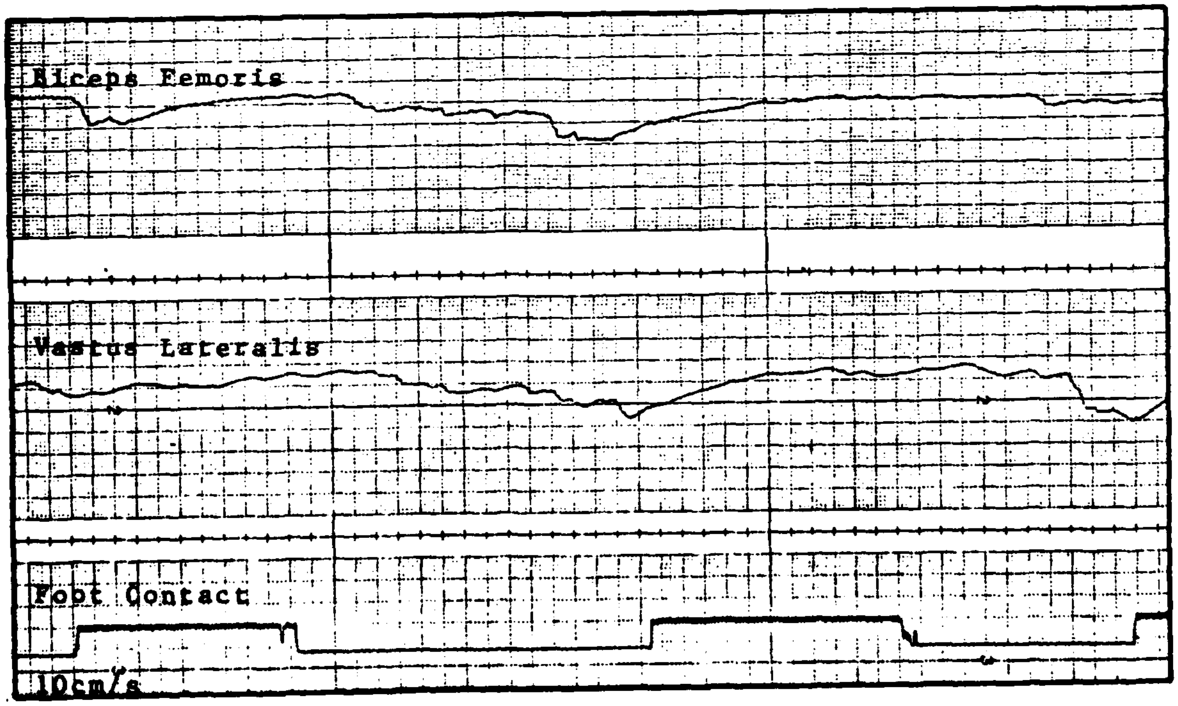


Figure 65A. Expanded View - Indicated In Figure 65

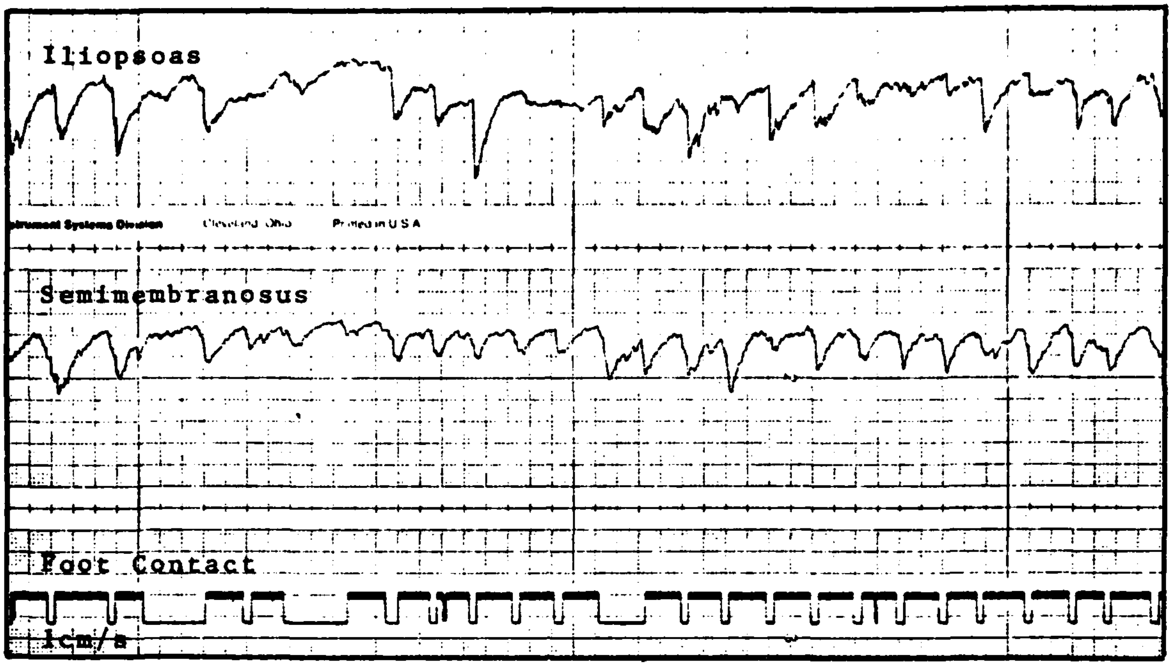


Figure 66. RMS Muscle Activity Data: Iliopsoas And Semimembranosus (0.2m/s)

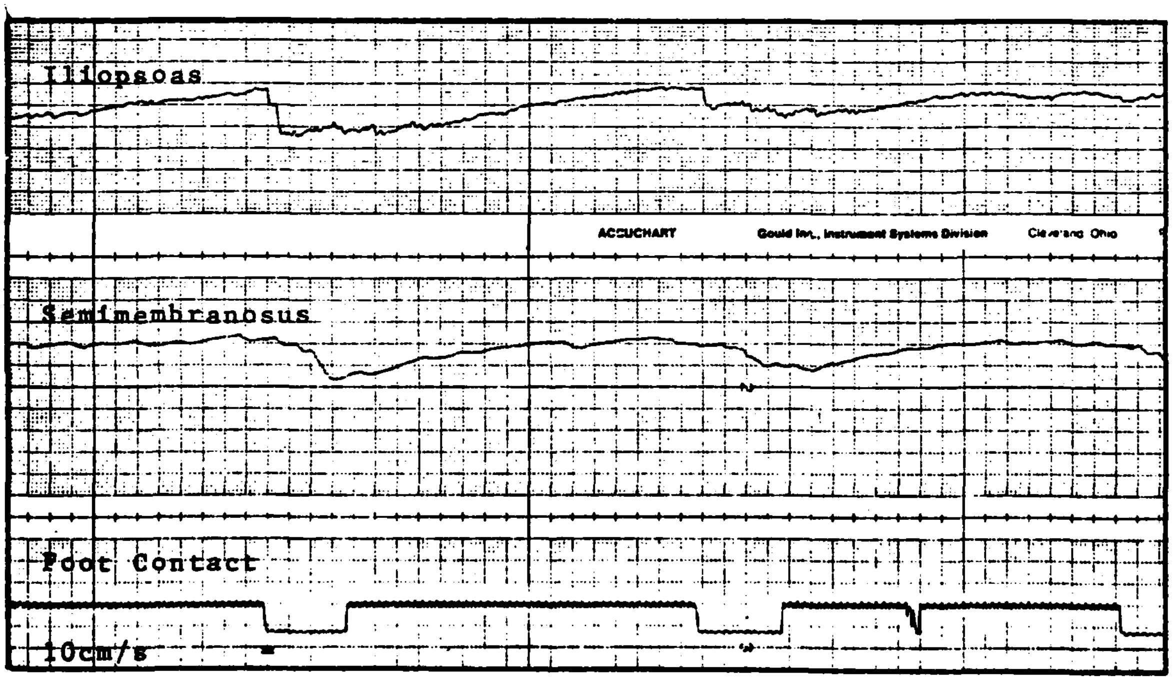


Figure 66A. Expanded View - Indicated In Figure 66

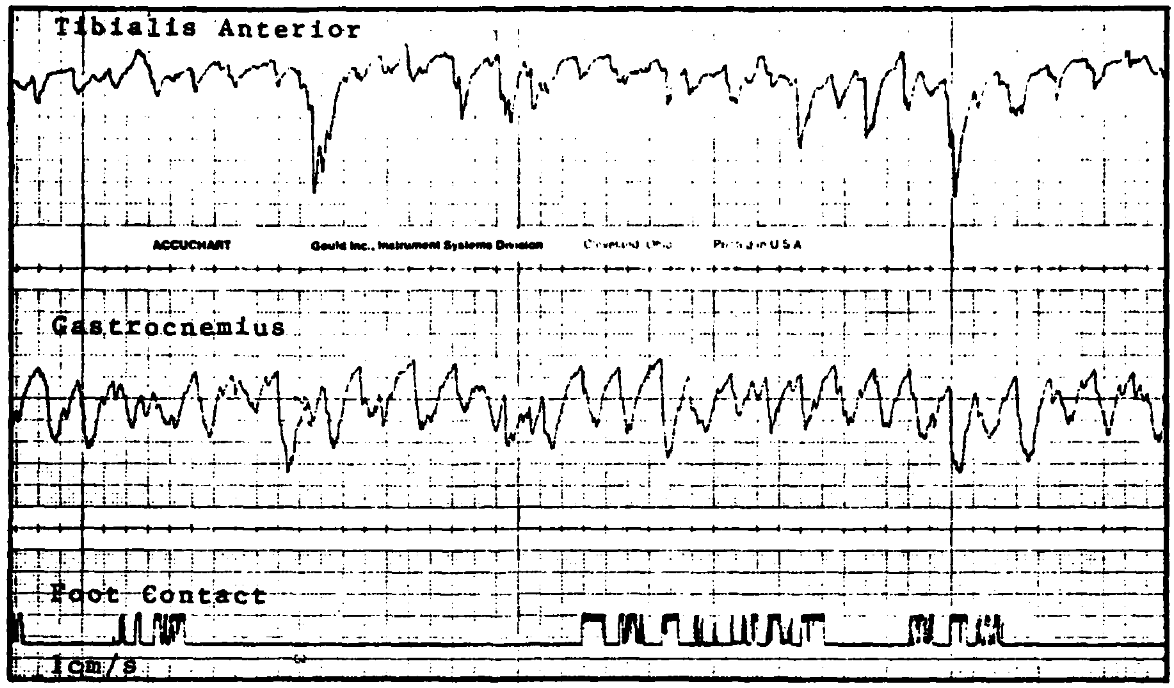


Figure 67. RMS Muscle Activity Data: Tibialis Anterior And Gastrocnemius (0.3m/s)

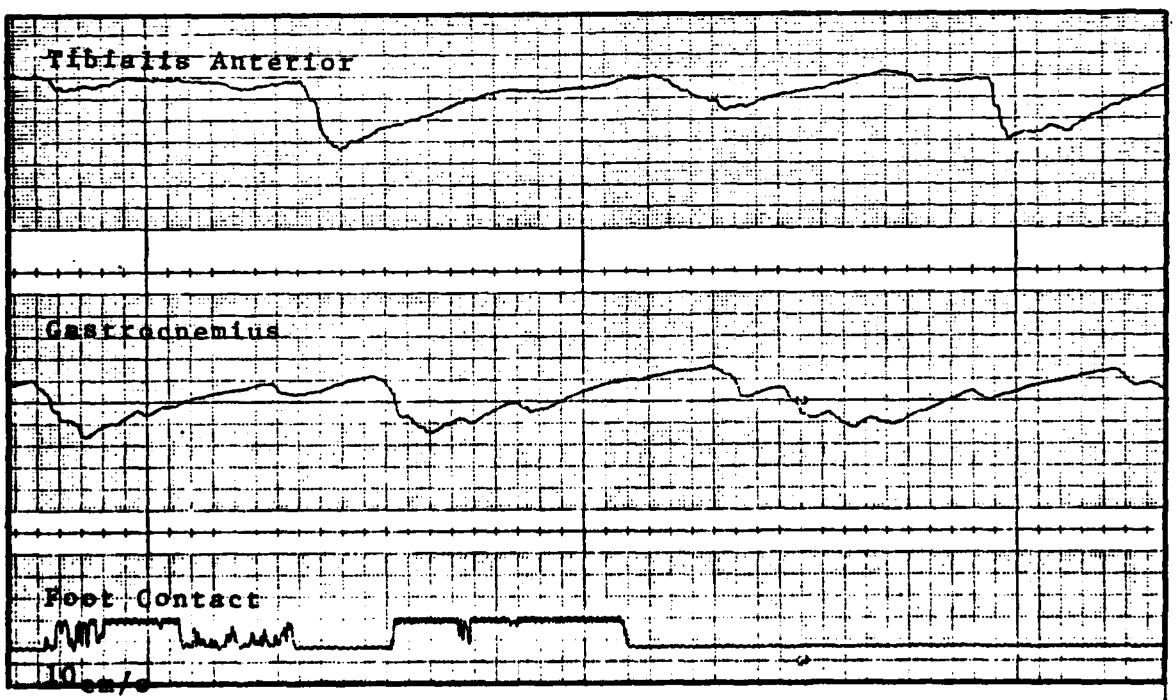


Figure 67A. Expanded View - Indicated in Figure 67

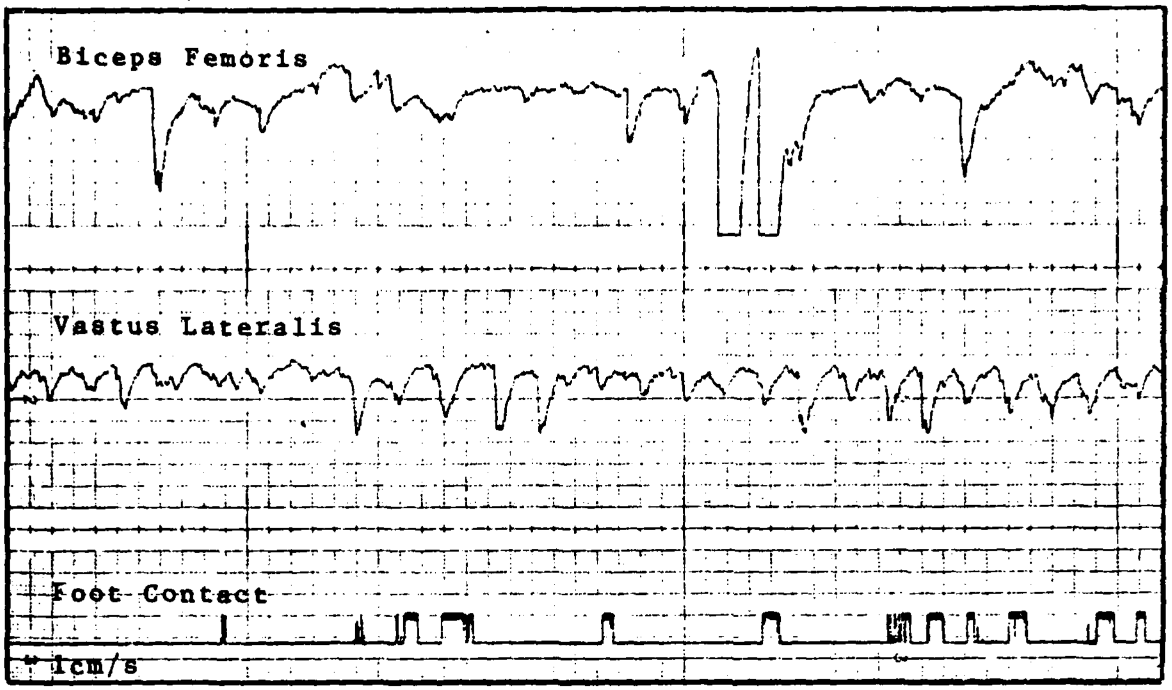


Figure 68. RMS Muscle Activity Data: Biceps Femoris And Vastus Lateralis (0.3m/s)

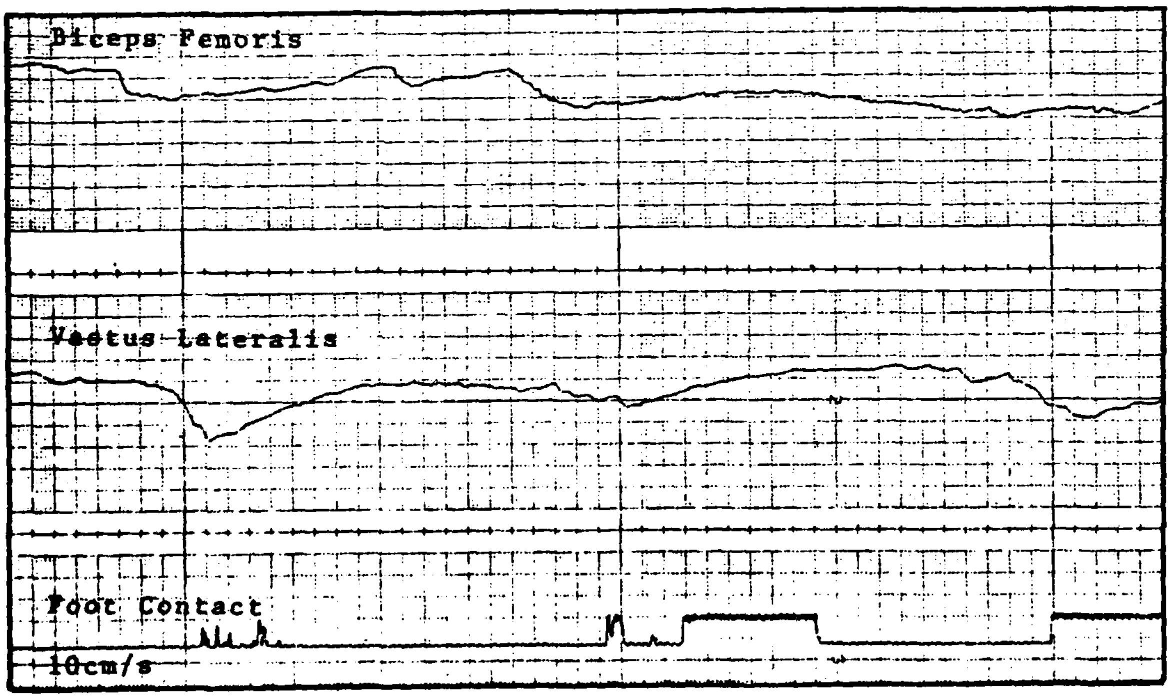


Figure 68A. Expanded View - Indicated in Figure 68

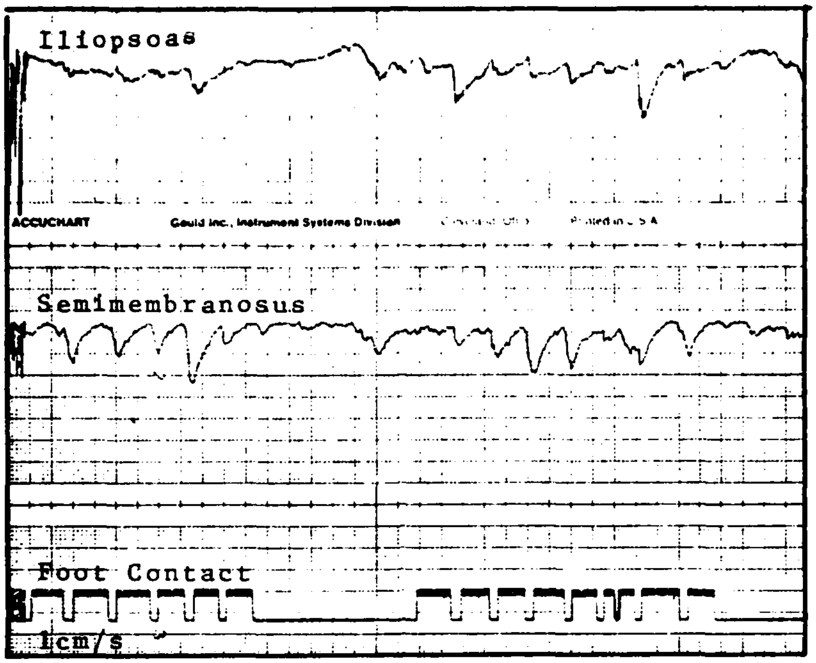


Figure 69. RMS Muscle Activity Data: Iliopsoas And Semimembranosus (0.3m/s)

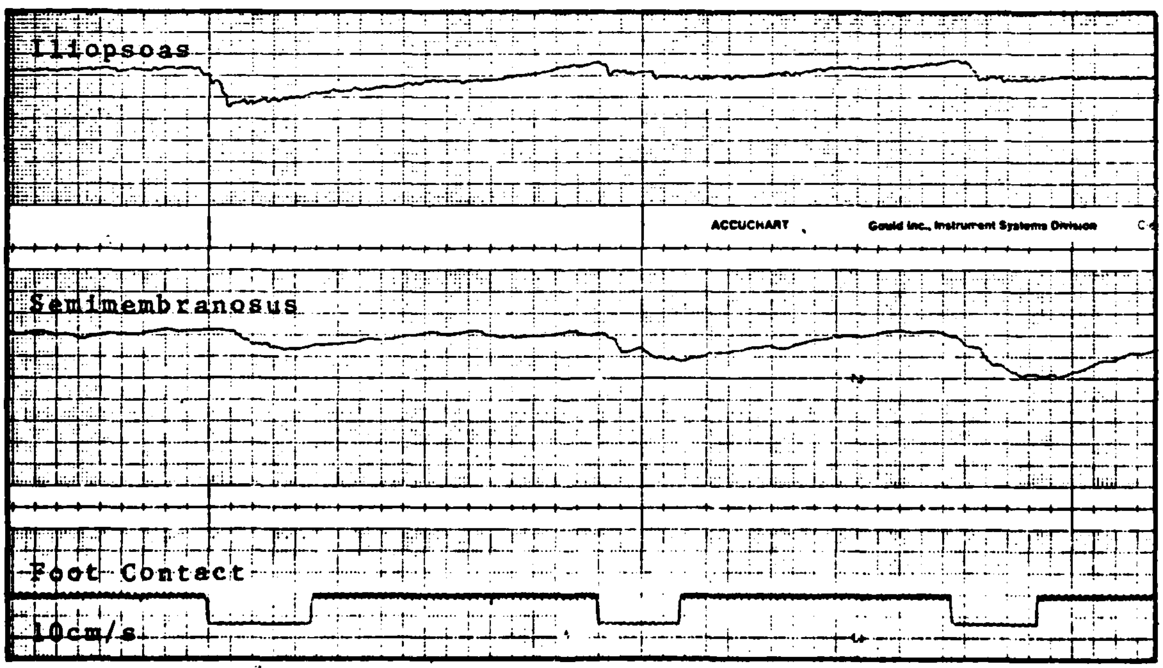


Figure 69A. Expanded View - Indicated in Figure 69

Appendix F

The comparison of data from the support harness (Carroll, 1980) with that of the designed free harness is shown in this section. Using experimental runs of the same speeds the position information for the different harness arrangements and cats is tabulated.

Table VII

Comparison of Gait Cycle in Free Harness and Support Harness (approximately 0.2 m/s).

Time (sec)	Joint Position (degree)					
	Hip		Knee		Ankle	
	Free	Support	Free	Support	Free	Support
0.0	92	84	67	62	73	122
0.1	80	80	63	61	78	138
0.2	70	64	55	52	69	109
0.3	48	56	53	45	60	77
0.4	32	29	54	43	58	77
0.5	20	17	62	49	57	77
0.6	21	17	74	67	63	83
0.7	23	21	84	73	70	89
0.8	27	29	80	73	69	89
0.9	34	37	78	71	66	89
1.0	40	41	76	69	65	85
1.1	47	45	75	69	66	85
1.2	53	52	73	66	65	85
1.3	63	56	71	64	64	85
1.4	72	68	70	63	65	85
1.5	83	76	71	63	65	86
1.6	91	84	70	63	65	88
1.7	92	87	69	63	66	93
1.8	93	94	68	93	66	101
1.9	96	90	67	63	70	111
2.0	92	84	67	62	73	122

Vita

David J. Heichel was born 25 December, 1957 in Butler Pennsylvania. He graduated from High school in Slippery Rock, Pennsylvania in 1976 and attended Grove City College from which he recieved a Bachelor of Science Degree in Electrical Engineering in May 1980. Upon graduation, he received a commission in the USAF through the ROTC program and entered the Air Force Institute of Technology in June 1980.

Permanent address: 898 W. Old 422

Butler, Pennsylvania 16001

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFIT/GE/EE/81D-26
2. GOVT ACCESSION NO.: AD-A115 532
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): FEEDBACK INFORMATION AND ANALYSIS FOR MICROPROCESSOR CONTROLLED MUSCLE STIMULATION
5. TYPE OF REPORT & PERIOD COVERED: MS Thesis
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): David J. Heichel, 2nd Lt, USAF
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Air Force Institute of Technology(AFIT/EN) Wright-Patterson, AFB, OH 45433
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: Wright State University Biomedical Engineering Department Dayton, OH 45435
12. REPORT DATE: December 1981
13. NUMBER OF PAGES: 138
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

15 APR 1982

18. SUPPLEMENTARY NOTES:

Approved for public release; IAW AFR 190-17

~~Frederic C. Lynch, Major,~~ USAF

~~Director of Public Affairs~~

Lynn E. Wolaver

Dean for Research and Professional Development

Air Force Institute of Technology (ATC)

Wright-Patterson AFB, OH 45433

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Feedback Sensors

Gait Cycle

Model

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A cat was fitted with feedback sensors which provided information on joint position and foot force during unrestrained locomotion. A harness outlining the rear leg skeleton of the cat was designed. The harness was worn and supported by the animal. It contained position transducers at the joints and followed the movement of the leg throughout the step cycle. The harness restricted the rotational and lateral movements of the leg. Other feedback sensors were developed to sense foot contact and force. A simple contact switch on the ball of the foot of the cat was

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) used with the feedback harness to show exact foot placement. A force transducer designed to mount on the foot of the cat provided additional feedback from the foot. The cat was walked under different conditions to obtain position data for models of the gait cycle. Hip action with respect to a ground plane was observed for leg motion modeling. The cat was also walked on a treadmill with electromyograph activity recordings for the flexor and extensor group of each loint. This joint provided information to model the activity sequence in the muscles during locomotion. From the tabulated leg position, foot forces, hip motion and muscle activity, a model walk is presented for future microprocessor controlled stimulation experimentation for paralysis.