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A Correlation of Displacement, Acceleration and Muscle During the Walking Gait of Normal and Above Knee Amputees

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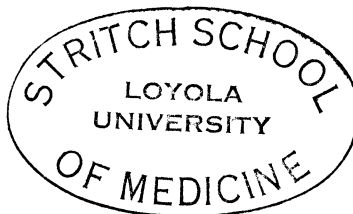


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**A CORRELATION OF DISPLACEMENT, ACCELERATION
AND MUSCLE ACTION DURING THE WALKING
GAIT OF NORMAL INDIVIDUALS AND
ABOVE KNEE AMPUTEES**

By

Albert A. Halls



**A Dissertation Submitted to the Faculty of the Graduate School
of Loyola University in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy**

January

1963

LIFE

Albert A. Hallis was born in Danville, Illinois on January 4, 1928.

He was graduated from Hammond High School, Hammond Indiana, June, 1946. He attended the University of Chicago, Chicago, Illinois and received the degree of Bachelor of Science in June, 1957.

In September 1957, he began his graduate studies at Loyola University and received the degree of Master of Science in June, 1959. He was teaching assistant in the Department of Anatomy 1958-1961.

In June 1956, he was married to Lois Eck and is the father of two children, John, 5, and Peter, 3.

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My sincere thanks is given to all those who made this project possible.

I wish to thank Dr. David S. Jones, Professor of Anatomy, Loyola University who as my advisor, has guided me in this investigation. I am also grateful to Dr. W. T. Liberson, in whose gait laboratory this study was made.

I also wish to thank Mr. H. J. Holmquest, Registered Professional Engineer, who extended his aid and assistance in the engineering aspects involved in this study.

Lastly, to my wife, Lois, I wish to express my deepest love for her encouragement throughout the entire period of my graduate studies. Without her help this investigation would have been more arduous.

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INTRODUCTION

A. Introductory remarks and statement of the problem.

Man has been interested in how he walks for thousands of years. Although walking seems a simple process it is a very complex phenomenon and studying the gait is consequently difficult. Gait is a broad term which is defined in Webster's dictionary as 1. a going; walk; way. 2. manner of walking, running, or moving on foot. 3. Specifically of horses, foot movement etc. This work will be concerned only with the walking aspect of movement on foot. As will be seen in the review of the literature the act of walking is a complexity of activities which can be studied in various ways.

Previous investigators have studied muscle activity by observation and electromyography. Torque (rotational activity) of the pelvis, thigh, leg and foot has been studied. Accelerations and displacement of various parts of the body as well as the duration of the heel and toe contacts and pressures exerted upon the foot while walking have had extensive study. In this work the correlation of the displacement of the trunk and limbs with the acceleration curve

(henceforth called the accelerogram) will be made by means of simultaneous photography. The muscle activity will be recorded electromyographically.

The purpose of this study is to utilize many of the above techniques coupled with a new method of simultaneous photography plus the recording of acceleration directly to correlate muscle activity with displacement and acceleration. It is hoped that this method will lead to a better understanding of the gait of amputees and therefore the possibility of improved prosthetic devices. Correlation of trunk and limb displacement with the acceleration curve (accelerogram) will be made by means of simultaneous photography. The muscle activity will be recorded electromyographically. (EMG).

In walking there are two distinct phases of the gait; one is the swing phase and the other is the stance phase. The stance phase is the period when the foot is in contact with the floor. The swing phase is the period when the foot is off of the floor. There is also a brief period known as the double support when both feet are on the floor. A single step consists of the distance from the heel and floor contact of one foot to that of the

other. The double step consists of the distance between two heel contacts of the same side.

B. REVIEW OF THE LITERATURE

The first recorded observations of the gait are by Aristotle, (in the *Gait of Animals*, Chapter 4, translated by ASL Farquharson).

"Another indication that the right is the source of movement is the way we put our feet forward; all men lead off with the left, and after standing still prefer to put the left foot forward, unless something happens to prevent it. The reason is that their movement comes from the leg they step off, not from the one put forward... And man has the left limbs detached more than any other animal; now the right is naturally both better than the left and separate from it, and so in man the right is more especially the right, more dextrous that is, than in other animals. The right then being differentiated it is only reasonable that in man the left should be moveable, and most detached". Probably this made more sense in the language employed by Aristotle, but it seems to be implying that the impetus which sends the body forward is received from the foot which is behind the center of gravity.

Borelli (1679), cited by Steindler ('53), in De Motu Animalium contributed the following three items to the study of gait and must be considered the pathfinder for all subsequent gait studies. His contributions were 1) a fundamental concept of muscle action, 2) the determination of the center of gravity of the body, and 3) a concept of propulsion and restraint in gait.

The next important report, which marks the beginning of the modern period of investigation of the gait, was the Weber brothers (1836). With only a stop watch with a second hand, a known length of ground and a subject, they investigated the time relationships between the movements of swing and stance and concluded that the leg obeyed the simple laws of the pendulum. They measured the inclination and vertical variations of the back, (the mean inclination of the back from the vertical was 14°), the straightline length of the extremity in different positions, and the oscillation time of the free swinging member with and without clothes. They also observed that the trunk was lower in walking than in standing.

Braune and Fischer (1895) in commenting upon this work, (see

also Steindler '53) states (translating from the German, my own,)... even today it is viewed as undeniable that the trunk in walking assumes a somewhat lower stance toward the floor than in standing and that it will become even lower as we walk faster. What the Weber brothers saw however caused them to draw conclusions which are not immediately realized from the measured results. "In other words they reached conclusions which went beyond the data which they had collected." Continuing with my translation, "thus they had for example no means to ascertain the progress of the movement and change of positions of the leg during the double step... they could only measure the degree of shortening and the length of the leg, the rising and falling of the body, the length of the step..." Therefore, it is remarkable that even though the Weber brothers used such primitive means many of their measurements have been repeated and verified by other investigators.

Marey (1883) in France studied the gait by means of cinemaphotography (cyclography). The subject studied wore a black stockinette on which white stripes were painted over the lateral aspect of the thigh and the edge of the foot. Steinhausen ('30) and Fischer in Tigerstedt's

Physiology (p. 282, figure 30 and p. 283) commented that the photographs were not sharp and hence were of little value for the study of gait. However for some strange reason, Steinhausen and Fischer selected one of Marey's later pictures (1895) to illustrate Marey's results. This picture is not sharp and well defined but the remainder are much more representative of his work. Marey was the first to use this method of studying the gait.

Muybridge (1889) in this country developed a new technique to study the human gait in the nude subject. He set up a battery of cameras. Each camera had a shutter which was actuated by breaking a fine string. The cameras would be placed alongside the planned progression path. The strings would be secured and made taut across the path and the subject in walking would break each string in succession thus actuating each camera. The quality of his photographs are excellent and have never been surpassed or equaled.

Braune and Fischer (1895) studied gait most intensively. They dressed their subjects in black stockinettes but used Geissler tubes instead of white stripes as Marey had done. Geissler tubes serve the

purpose of indicating the position of the body at any moment. These were attached to the black stockinette by means of elastic straps separated from the body by means of thin strips of gutta percha so that the electrical discharge would not be carried through the subject. The experiments were carried out at night because cameras with open lenses were utilized. The subject walking in front of a ruled board with two cameras placed laterally, a third behind the subject and the fourth at an angle of sixty degrees from the path of progression. The tubes were intermittently illuminated by means of an inductorium at the rate of twenty five times per second. The results were a series of lines at different angles on the photographic plate. The gelatin plates were then developed and the measurements of all the angles were carefully done directly on the plates. These angles were then plotted and what resulted was called a displacement curve, or as Braune and Fischer designated it, the progression or path curve. This curve was then differentiated twice and the final curve was the acceleration curve. Actually Braune and Fischer carried out only three experiments, but it took a lifetime to do these three classic

experiments. There are over 5000 measurements reported in their first paper.

Bernstein ('27) cited by Steinhausen ('30) repeated the work of Braune and Fischer, but used small glass bulbs instead of Geissler tubes. These bulbs which were attached to the subject were illuminated intermittently. The individual was photographed with a shutter on a still film. Acceleration data was then computed in the same manner as described by Braune and Fischer. The acceleration curves obtained by Bernstein permitted him to show the acceleration in much greater detail. Another advantage of the method employed by Bernstein was that a shorter amount of time was needed for the analysis.

Liberson ('36) using a piezoelectric quartz was the first to record the accelerations for the gait directly. A block or plate was cut from a quartz crystal perpendicular to one of the faces of the quartz. If this block is then compressed in a plane perpendicular to the edge of the original crystal, but parallel to the face of the crystal, an electrical charge is generated perpendicular to the strain (Henney, '50, Caverly, '52).

Liberson attached a small weight to the quartz and the change of

pressure, as explained above, caused the development of a charge proportional to the pressure exerted. These changes of pressure due to forces of inertia are proportional to accelerations and are reflected in variations of the electric potential picked up from the two opposite faces of the crystal. The amplified potential was recorded by means of an oscillograph. Liberson was able by this method to record accelerations of the body directly. He compared vertical acceleration curves of the trunk obtained by this method with those obtained by Bernstein. "The resemblance is very close, and necessity of differentiating as with Bernstein's curves is eliminated." Liberson further discussed the fixation of the quartz detector to the leg to permit the writing of the "exerted effort either tangentially or radially (angularly) to the portion of the described curve."

Steindler ('53) in an editorial on the history of gait studies reviewed the significant contributions of all investigators since 1679. He concluded by discussing the work of Saunders and Inman and Eberhart on the six determinants of gait. Saunders, Inman, and Eberhart ('53) in the same journal lists the six determinants of gait and discusses them.

The six are pelvic rotation, pelvic tilt, knee flexion in the stance phase, foot and knee mechanisms, and lateral displacement of the pelvis. They also state that accelerometers were used to study gait but "were found to be inferior to methods of graphonumerical differentiation." This latter statement is made probably because, if the gravitational component is not compensated for, as will be shown later, the use of accelerometers for the legs and thighs is not suitable. Force plates were used by Saunders and his group to study the stance phase of the gait, but force plates could not be used to study the swing phase.

Liberson ('57) modified his technique by using strain gauges to record accelerations of the trunk and the extremities. He correlated EMG data with the accelerograms. The method of using a single strain gauge to record accelerations is correct for the vertical accelerations, but is not suitable for the leg or thigh because of the gravitational effects upon the masses during angular displacement. The principles of recording acceleration of the body were used in this study have been further modified.

Marks, Morton and Hirschberg ('58) investigated the hemiplegic

patient electromyographically. Their studies showed that both the paralyzed and the non-paralyzed side were abnormal in function. They stressed the importance, therefore, of re-educating the non-paralyzed side as well as the paralyzed in gait training.

Drillis ('58) reviewed the applications of objective recording methods in investigations and biomechanical analyses of pathological gait. The main emphasis was upon temporal components although there was some discussion of kinetic and kinematic criteria.

Smith et al ('61) by means of an electrobasometer also have investigated the temporal components of gait. Electrobasometer is a term which was introduced by Schwartz ('28) to describe an instrument which he had designed to measure the pressures exerted upon the ground by the foot while walking. Schwartz refined the instrument and has been the most active worker in this phase of gait studies ('32, '33, '34, '35, '36, '37, and '47). Smith ('61) has an elaborate basometer which allows him to record contact of the foot (either shod or unshod) with a plate. He reported that the average contact time of the unshod foot was 0.70seconds, and shod foot 0.67seconds (same subjects). The shoes decreased the contact

time, but the stride time for both shod and unshod feet was an average of 0.40seconds.

A modification of Liberson's original method of utilizing strain gauges in the study was reported at the Panama Congress of Physical Medicine (Liberson, Holmquest and Halls '59). The same method was presented to the American Congress of Physical Medicine ('62).

Cavagna ('61) in Italy, reported that accelerometers constructed of flexible steel plates to which strain gauges are attached could be used to study gait.

MATERIALS AND METHODS

A. General

The overall plan of the study was to have an individual walk over a conductive plate in front of a ruled grid, while being photographed at 64 frames per second, Figure 5. The person walked on the above plate with heel and toe contacts which were connected to signal lamps above the grid indicating heel and toe contacts and departures. The signal lamps were used to show the heel and toe contacts and departures because in the movie the contacts of the various parts of the foot could not be ascertained by inspection of the individual frames. Strain gauges were placed in various places to record vertical and angular acceleration. Electrodes were placed over various muscles to record muscle action. All the wires were run in a cable to an overhead trolley which moved with the individual.

Metal heel and toe contacts were attached to each shoe. Each contact was connected in series with a battery, a coil of a relay and the conductive plate. The coil of the relay was connected in parallel with a galvanometer. When contact was made with the conductive plate a voltage was impressed upon the coil of the relay and the galvanometer. When the relay was thus

actuated a signal lamp was illuminated. The signal lamps were in a box attached to the ruled grid which formed the subject's background while he walked. Simultaneously with the illumination of the lamp, the galvanometer pen was deflected and remained so until the contact was lifted from the floor. (See Appendix I for the circuit).

The subject and his background plus the accelerations of an Offner galvanometer pen was photographed simultaneously. As the subject walked across the plate the strain gauges attached to his body for the purpose of recording acceleration activated the ink writer galvanometer pen. The ink writer galvanometer pen was connected in parallel with the Offner galvanometer pen (hereafter called the camera galvanometer pen). The accelerations of this latter pen could be photographed by means of a lens system to be described later.

After the camera started a foot switch was depressed which simultaneously deflected another galvanometer pen of the Offner apparatus, lighted a lamp in the panel and another in the camera which darkened the edge of the film. This permitted the indexing of the film and the record of the ink writer galvanometer.

In an earlier part of the study, an attempt was made to photograph the entire record while the pens were recording all the data, by means of a mirror placed at a 45° angle in front of half of the lens. The desired result was that the subject would be seen on one half of the frame of the film and the ink recording of the accelerations, as they were being made, would be seen on the other half of the frame of the film. This was not successful because the subject and acceleration record were too far apart to record both through one lens.

Strain gauges (wire) were used for this study because Liberson, (1957) had demonstrated the simplicity of their use for such studies because of their consistency and dependability over long recording sessions. The camera galvanometer pen was connected in parallel with the ink writer galvanometer pen and the former was placed as follows. The shaft of the pen was located in a plane parallel with the direction of the film travel. The shaft of the pen was painted black and the pen was placed in the galvanometer before a thin slit through which light from a reflex flood lamp (150 watts) was being projected. As the pen moved the light beam was interrupted, thus forming on the moving film a continuous

curve of the acceleration. The curve was continuous because no shutter was used and the movement of the film provided the time sweep. The camera galvanometer pen could be connected in parallel with any of the sixteen galvanometers of the Offner apparatus.

Male medical students from the Stritch School of Medicine, male physiotherapists and male amputees from the Veteran's Administration Hospital at Hines, Illinois were used as subjects. Approximately 20 normal subjects and 20 amputees were examined by the method which will be outlined later in this section. Two normal and two amputee individuals were selected for intensive study by simultaneous photography, i. e., photography of the displacement of the subject and his acceleration curve as it was being made. In addition 30 other patients with varying gait pathology were examined but there was not enough in any one category to report in this investigation. The examinations were carried out over a two year period and at various times of the day.

The amputees were all patients from the Veteran's Administration Hospital at Hines, Illinois and were undergoing gait re-education either as in or out patients. The normal subjects ranged in age from 13 to 53

years. (Saunders ('53) has stated that the normal gait pattern is established at the age of 7.) The youngest amputee was 24, while the oldest was 70 years of age.

B. Method of Calibration of the Strain Gauge and Description of the Technique

An amplifier and preamplifier were used to activate the bridge of a strain gauge and amplify the signal to a galvanometer. For readers not familiar with the galvanometer, reference should be made to its evolution (Schweigge, 1821). The strain gauge is a modified Wheatstone Bridge and the readers is referred to Wheatstone (1879); and Aronson ('60) for details.

Initially one gauge was used to determine whether the deflection of the galvanometer could be predicted if the angle of the gauge in respect to a perpendicular line to the earth, were known. A linear relationship was shown to exist which obeyed the mathematical

relationship: $\text{Force} = \text{mass} \times g \times \sin \theta$

Where force equals the total forces acting upon the strain gauges' sensitive element, g equals 980 cm/sec^2 and θ equals the angle of the gauge.

Determination of the effect upon the deflection of the strain gauge is shown in Tables I and II (Appendix II).

In testing the strain gauge a physical pendulum is used. The strain gauge complex, Grass force displacement transducers without springs, is fastened to the pendulum as shown in Figure 1. The strain gauges are shown separately in Figure 2. The gauge is connected to the preamplifier and galvanometer. A voltage is placed upon the bridge, and both arms of the Wheatstone bridge are made equal in resistance and no deflection is obtained at the galvanometer because no current is flowing. This situation obtains when the strain gauge has its longitudinal axis perpendicular to the earth so that its cantilever arm is parallel with the earth (the curvature of the earth is ignored). The strain gauge is rotated to a second position and fixed in that position. This position is with its longitudinal axis parallel with the earth and the cantilever arm perpendicular to the earth. The deflection obtained on the galvanometer will now be adjusted by a calibration control so that a ten millimeter deflection is obtained. If the strain gauge is now placed at any angle, between the two positions, the deflection obtained will be that given in

the formula on page 17. For example, at 30° the sine of the angle is .5000, the masses of the cantilever arms were balanced at zero so that the masses cancel each other. Thus, the deflection will be .500 times 10 (the calibration amplification) or 5 mm. The masses and the force of gravity remain constant in the equation:

$$F \text{ equals } \cos \phi \times g \times m$$

Where F is as previously stated, ϕ (phi) is the angle of rotation to distinguish it from θ (theta) and m is as before.

Once each of the strain gauges were shown to have a linear response, all that remained to do was to arrange the strain gauges in opposition and to connect the outputs of the strain gauges in opposition. The component due to displacement (angular rotation) was eliminated (Consult Appendix III for the details).

It is appropriate at this time to analyze the forces acting upon the strain gauge and to show what information is desired in this study. In the position where θ and ϕ equals zero, there is equal pull by gravity on the masses located on either side of the cantilever beam. If the gravitational forces are equal, then no deflection is recorded by the

galvanometer. However as soon as θ no longer equals zero, a different situation obtains. A component of the force exerted by gravity upon each mass of the strain gauge is at right angles to the cantilever beam. The vector components are shown in Figure 3 and Figure 4. Since it is not desired to introduce the gravitational component into the study the procedure outlined in Appendix III eliminates it.

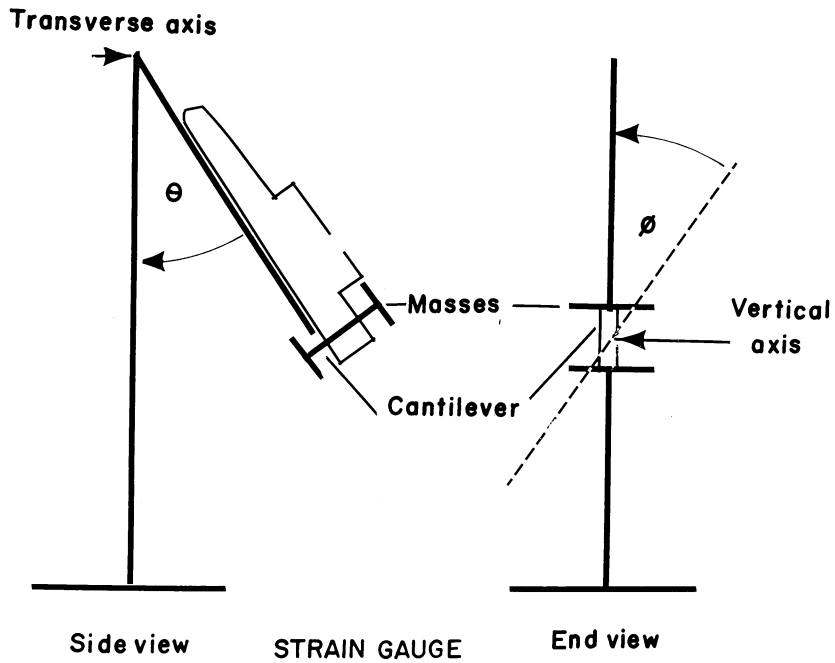
Once the gravitational component force is eliminated from the tracing, what forces remain to cause the deflection of the galvanometer? The force is the inertia of the masses of the cantilever beam times the tangential acceleration of the two masses.

If the dual unit is accelerated linearally, no deflection will be obtained because there will be no difference in the acceleration of the two gauges. The only time the gauges will register a deflection is when the gauges are being accelerated through an angle, for then the force upon the cantilever beam furthest from the point of rotation is greater than upon the cantilever beam closest to the point of rotation. The point may be raised that actually the strain



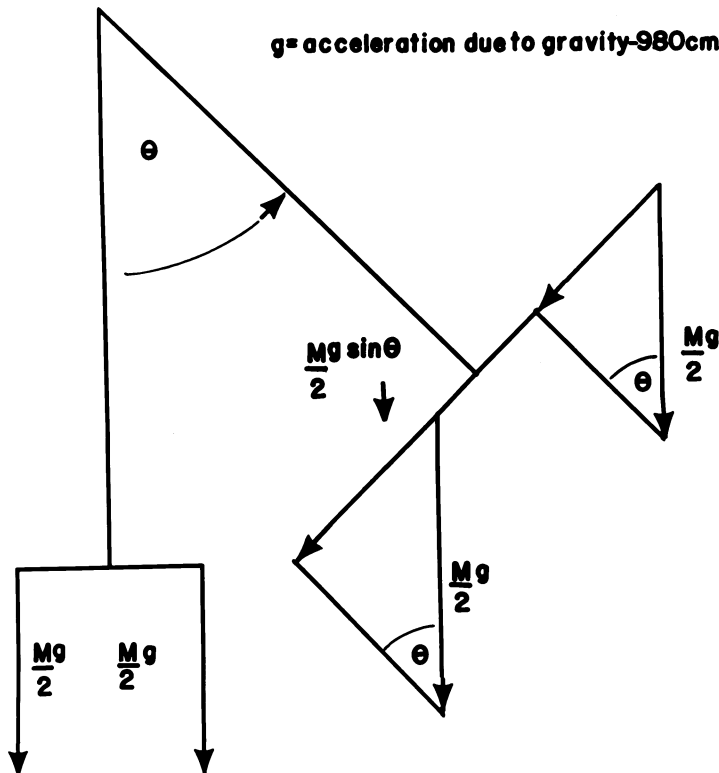
Figure 1

**Strain gauges on a pendulum.
The grid in the background was the one used in the study.**

**Figure 2**

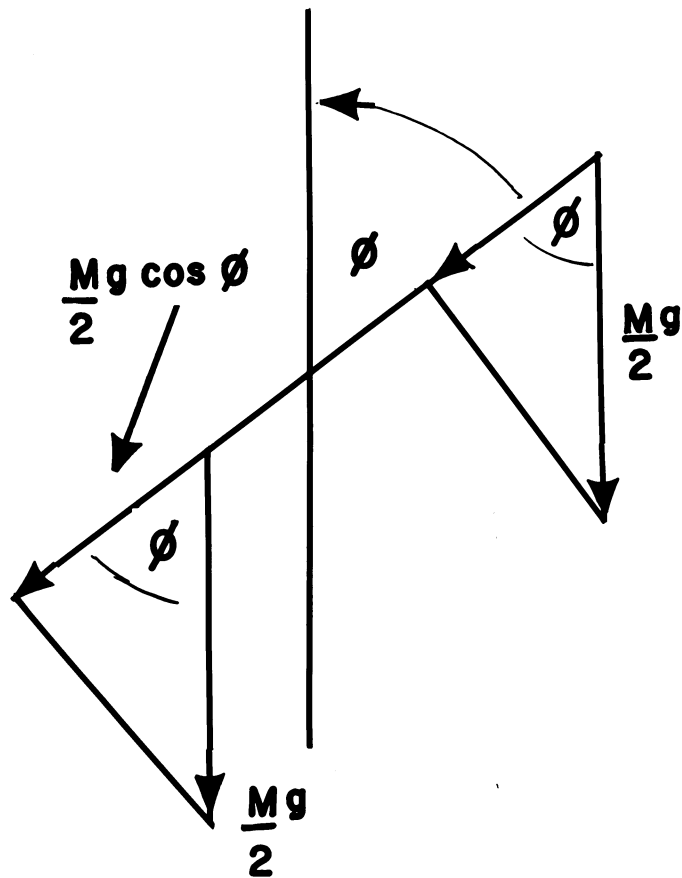
$\frac{Mg}{2}$ = mass on each side of cantilever in grams

g = acceleration due to gravity - 980 cm./cm./sec.



Vector Components Upon Changing Angle θ

Figure 3



Vector Components Upon Changing Angle ϕ

Figure 4

gauge is measuring the tangential acceleration, but tangential acceleration is related to the angular acceleration by the expression:

angular acceleration times the radius of mass₁ equals the tangential acceleration of mass₁

Similarly with mass₂:

angular acceleration times the radius of mass₂ equals the tangential acceleration of mass₂.

Therefore the difference of tangential acceleration is dependent upon the angular acceleration.

C. Optical preparation

A Wollensak high speed WF 14L camera was used to photograph the subject and the accelerogram which was recording the accelerations as previously described. This camera has a special lens built into the camera door which enables one to photograph a moving point such as seen on an oscilloscope tube. The description of the use of this camera will now be given.

One subject, a person, first located with the front lens through a lens finder and by parallax method, is focused on the cross hairs of the finder. In order to use the side lens of the camera, an oscilloscope finder is mandatory (Hays, '55). The second subject,

the camera galvanometer pen, is focused on the ground glass screen of the oscilloscope flinder. If one wishes the image to be to the side without superimposition, then one focuses the image at the upper outer corner of the view flinder (towards the camera galvanometer pen). The f stop is 4.0; camera speed 64 frames per second, Tri X reversal film. The light source, 150 reflex flood lamp, projected through a slit 2 mm wide by 30 mm long focused on a pen tip 1 mm wide at a distance of 19 inches from the focal plane of the lens. In order to make the pen oscillations visible on the film a 1 plus lens was attached to the 2.000 inch side lens of the camera. This enabled the image to be photographed at a closer distance, i. e., without the added lens the subject, the camera galvanometer pen, had to be placed 46 inches from the focal plane of the 2.000 inch lens. Lastly an f 3.2 stop was used for the front lens of the camera with a candle-power source of 13.5 at a distance of 30 feet from the camera. Development of the film was carried out by the tank method in D-11 (for greater contrast) for four and one half minutes.

One frame of the movie accelerogram is shown enlarged in Figures

so that details can be seen. Note the following; the wide beam seen on the left is the light beam from the flood lamp, the black stripe in the center of the light beam is the accelerogram as traced by the camera galvanometer pen as it interrupts the light beam. Also the ruled grid is seen behind the subject.

The reason that a movie accelerogram is used rather than the ink writer accelerogram is that the latter is of short duration and the movie accelerogram allows the stretching out of this curve over a greater distance, and the displacement is shown on every frame; correlation of displacement and acceleration is thus easily made. The film and paper accelerograms are contrasted as follows: 3 cm of paper equals 64 frames or 1.6 feet of film. Expressed in another way, since the paper is running at the rate of 30 mm per second and the film is running at 64 frames per second, there are 2.13 frames for each millimeter of record.

One might think that the paper could be speeded up and thereby if the paper were running at 64 mm per second there would be one frame per millimeter of paper, but such experiments have shown that the

curve becomes so flattened that they are discerned only with great difficulty. Therefore the film allows a reasonable consumption of paper and also allows a temporal expansion of the accelerogram without any additional amplification.

The frequency response of the camera galvanometer pen was tested as follows. A sine wave from a Hewlett Packard generator was introduced onto the ink writer galvanometer when it was connected in parallel with the camera galvanometer. The frequency response of the camera galvanometer pen was then photographed. The frequency was increased from one cycle per second to forty cycles per second, and the results were photographed. The results for six, fifteen and twenty cycles per second are shown in Figure 6.

Further improvement of the camera galvanometer pen could be achieved by using a mirror galvanometer. However the spikes seen on the amputee accelerograms are seen quite well in the movie, and these spikes are in the order of forty cycles per second. It should be noted that the loss of frequency response is in the low frequency rather than in the high frequency range.

D. Procedure for taking a record

The subjects were instructed to walk on a metal plate as naturally as possible, and at the end of walk, at each end of the plate, to turn always towards the camera. This was done to prevent the trolley wires from becoming knotted. The heel and toe contacts were first applied. The heel contact (one half inch wide) is placed in the center of the heel extending the length of the heel and the toe contact is located along the inner aspect of the shoe sole approximately one centimeter from the border of the widest diameter of the shoe and extended to the tip of the shoe. Attachment was secured by means of Weldwood. The shoe was next outlined with white tape, so that a clear definition of the shoe could be seen in the movie.

The electrodes, made of copper and 30 mm in diameter, were then applied to the body. The muscles were palpated and the area overlying the muscle was rubbed with electrode paste until an erythema was produced. The skin was then wiped free of the paste and the electrode with a small amount of paste applied was secured to the area

with an Ace bandage. The ground electrode was applied to the abdomen just under the umbilicus after preparing as described. Electrodes were applied over the gluteus maximus, quadriceps, gastrocnemius, and the tibialis anterior muscles.

A pair of strain gauges, mounted on aluminum strips attached to a fiberboard base, were then fastened to the legs by means of elastic straps. Lastly a chest board was applied in which was inserted the vertical strain gauge properly oriented. All of the leads from the legs and other contacts were then secured to the back of the subject under a wide band holding the chest board to the subject. The subject was then instructed to walk over the metal plate in order to become at ease in the experimental setup. After a final check of all components the paper was set to run at a speed of 30mm per second and a recording was started. During walking the camera motor was started and after allowing a few feet of film to run through the camera, the foot switch was depressed which indexed the film and record as previously described. After the desired portion of the walk had been recorded, the foot switch was opened and the camera was stopped. Therefore, the first and last frames

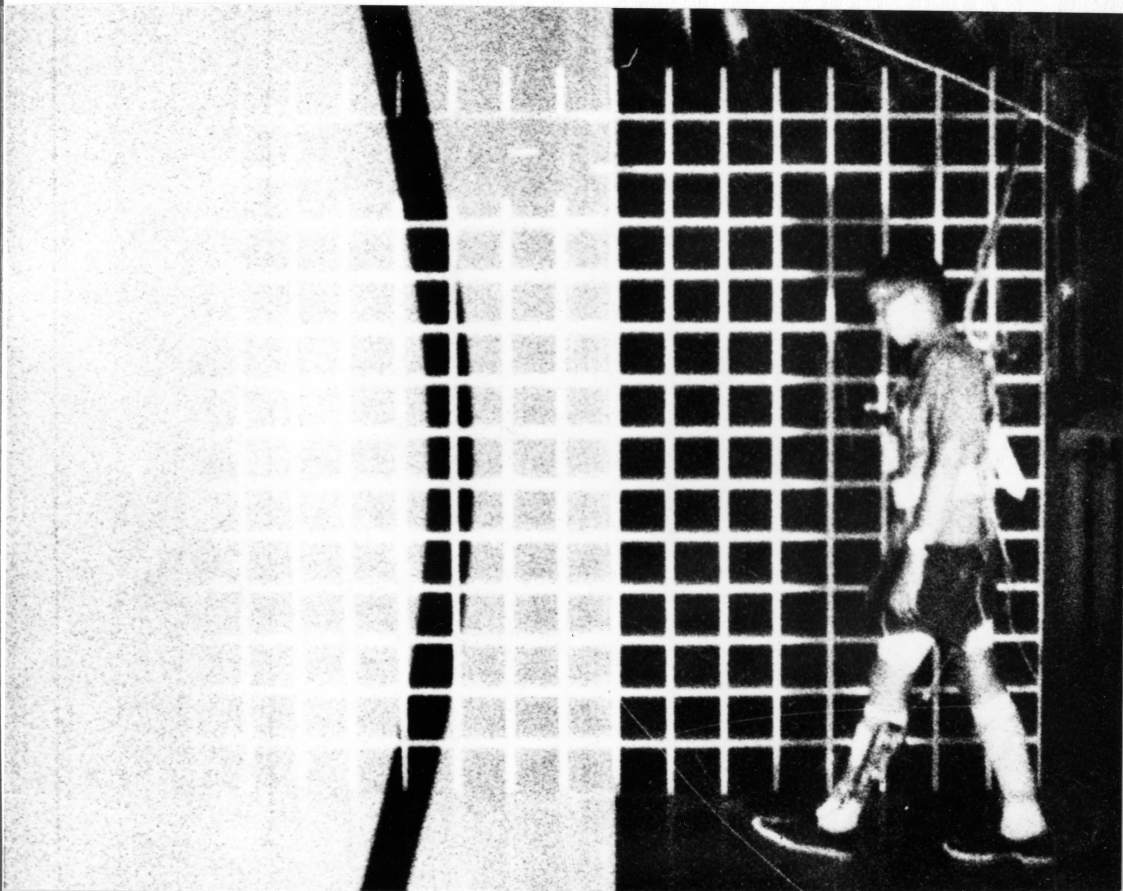
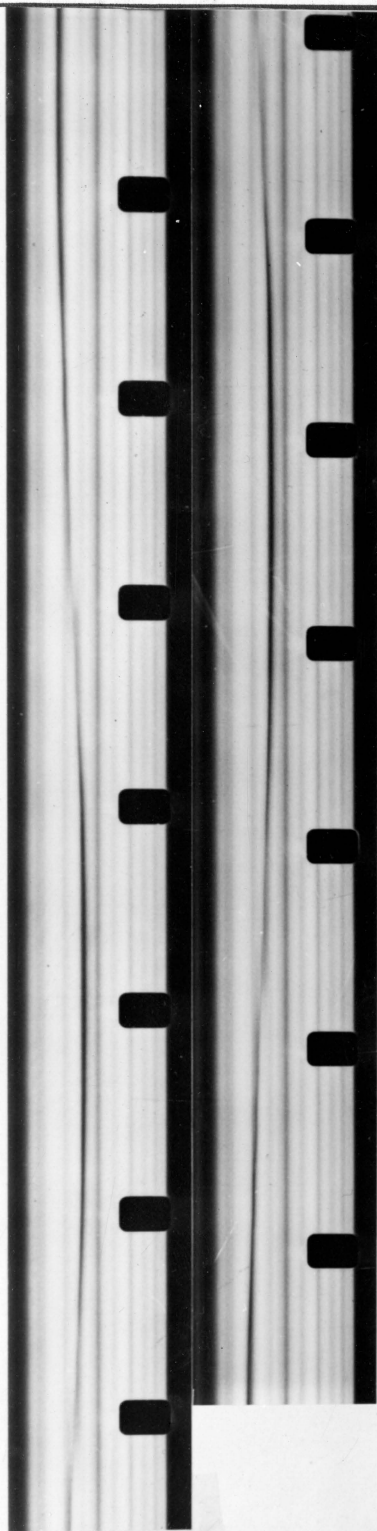


Figure 5

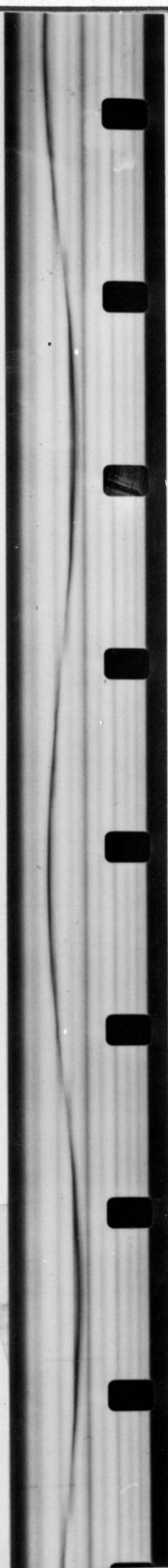
One frame of the movie enlarged to show details. Wide beam on the left is the light from the reflex flood as it is being projected through the narrow slit, solid black line in the wide beam is the accelerogram, signal lamps are above and in front of the subject.

Figure 6

**Strips of film taken from a movie of
the camera galvanometer pen.**



6 cycles per
second



15 cycles per
second



20 cycles per
second

of the film which show the middle signal light operating is the portion which corresponds to the mark by the ink writer galvanometer on the record. Usually 100 feet of film was taken for each subject.

E. Reduction of data:

The film and the indexed oscillographic record are matched. The film is then projected in an ordinary Bell and Howell projector with the clutch inactivated and the drive and takeup pulleys removed so that the movie can be examined manually frame by frame.

The projector is then aligned so that the top and sides of the frame will be projected parallel and perpendicular, respectively, to one square of a ruled one inch graph sheet which served as the screen. The distance of the projector from the graph sheet is placed so that the projected image of the subject's legs will be approximately two inches in height on the paper. The legs were then carefully traced on the graph and the last line of the grid was chosen arbitrarily as the reference line for the accelerogram trace, Figure 5. The trace as noted in Figure 5 covers the six inch square of the grid and again the inner aspect of the trace was chosen for the reference point. After the sequences had been drawn (usually 60 to 80 frames) the zero base line of the movie accelerogram

was then established. The baseline of the written record was found by measurement with a pair of dividers. This measurement was taken as the line drawn by the pen when no current was flowing into the galvanometer. Next the points were found where the accelerogram crossed this baseline. These points were then measured from the time the camera signal activated the galvanometer and computation was done on the basis of 2.13 frames per millimeter of record. This frame where such crossing occurred was then noted on the movie accelerogram and after several such determinations the zero baseline was drawn on the traced movie accelerogram. In order to visualize the deflection of the accelerogram, each point of the traced movie accelerogram was enlarged five times. Lastly the entire enlarged trace for purposes of photography was reduced by one fifth by means of a suspension pantograph. This reduction was carried out so that the trace could fit on two thirty inch joined sheets of ruled one inch graph paper. The figures that corresponded to the important deflections were then placed on the reduced graph and the entire layout with frame numbers and time intervals indicated was reduced by photography to give the figures such as are shown in Figures 12, 13, 14; 15, 17 and 18.

EXPERIMENTAL RESULTS

The vertical accelerogram is characterized by two upward deflections. Figure 7, 8 and 16 show normal vertical accelerograms as described above obtained by ink writer galvanometers. The major deflection (a) as will be shown later in the discussion, occurs during the double support period, Figure 12, 133 and Figure 13, 59. The minor deflection (b) occurs at the termination of the double support, Figure 12, 147 and Figure 13, 75.

The leg accelerogram consists of an initial sinusoidal curve followed by a spike, Figure 7. The initial deflection corresponds with the time of the swing phase Figure 14 (87-99) and Figure 15 (21, 23, 38). The heel contact occurs at 114 Figure 14 and 51 in Figure 15, and initiates the sharp spike.

The accelerogram of the prosthetic leg of the above knee amputee is similar to the normal leg accelerogram described above except during the swing there is a sharp spike. Figures 17, 196 and 18, (72-73) of above knee amputees show these diphasic spikes. They are considered to be due to the locking of the prosthetic knee. Figure 17,

217 also shows additional spikes which occurs after the left prosthetic heel has contacted the floor while Figure 18, 95 shows additional spikes occurring prior to heel contact. These points will be developed later in the discussion.

The gluteus maximus becomes active just prior to heel contact and continues its activity, but with no clearcut termination until after the heel leaves the floor, Figure 16. This action slows down the velocity of the swinging leg and aids in the flexion of the hip joint.

The quadriceps is active during the stance phase and a portion of the swing phase, Figure 9. Its activity during the stance phase is to stabilize the knee joint and its activity during the swing phase is to extend the knee or prevent flexion due to inertia.

The tibialis anterior is active during both the swing and stance phase, Figure 16. Its greatest activity begins just prior to heel contact and persists until heel departure. The activity during the swing is for dorsiflexion of the foot and to prevent the toes from striking the floor as happens in foot drop. The activity just prior to heel contact is to stabilize the ankle, while the activity after heel contact is to prevent the

foot from slapping the floor.

The gastrocnemius contracts immediately after the heel contact and continues until toe departure, Figure 9. Its peak of activity is during the double support phase and so it is the principle muscle responsible for the major deflection of the vertical accelerogram.

The duration of the muscle activity of the normal leg of the amputee versus that of the normal individual is prolonged in the gastrocnemius and quadriceps, Figures 10 and 11.

SUBJECT V.G.

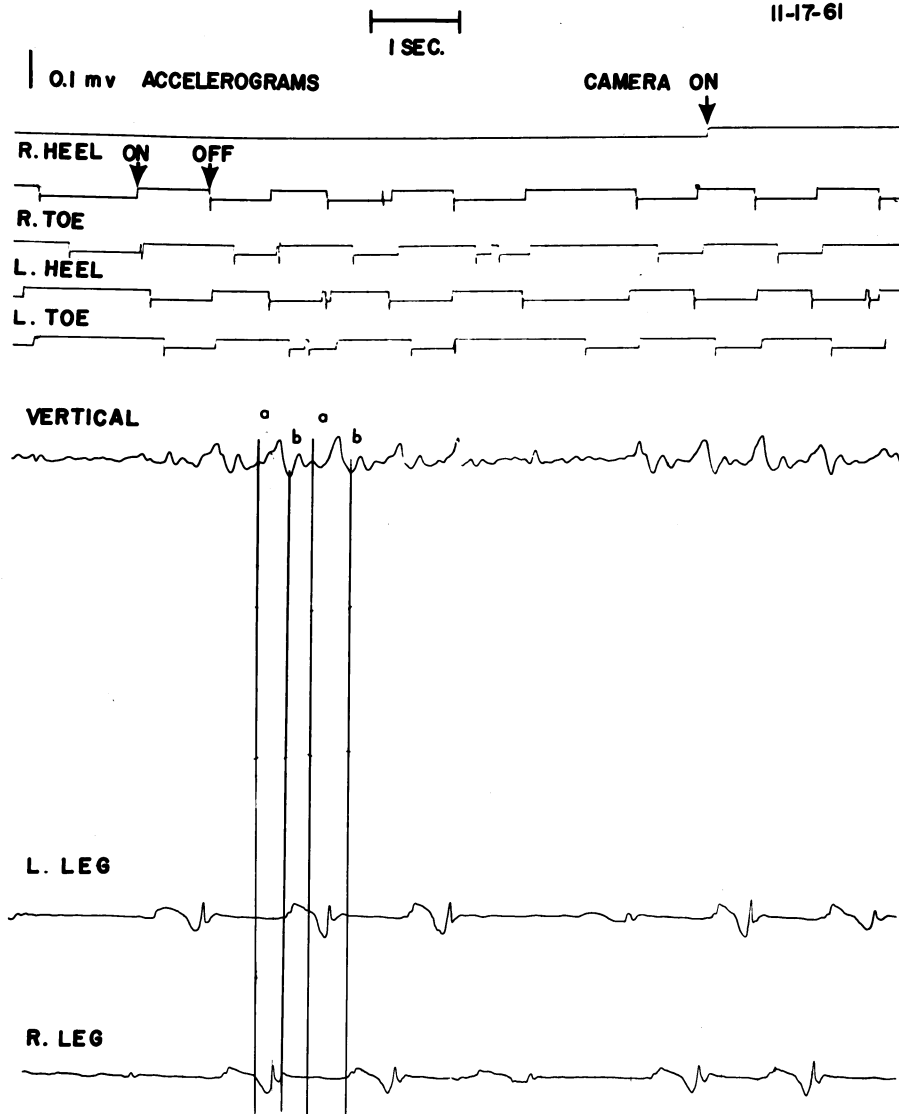
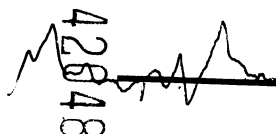


Figure 7

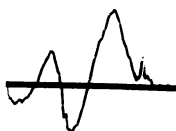
Normal accelerogram
 Graph is read from left to right
 "a" indicates major deflection
 "b" indicates minor deflection

VERTICAL



(R.H.)

—
200ms.



(B.Z.)

Figure 8

Accelerograms as recorded by the galvanometer
ink writers from two normal individuals.
Graphs are to be read from right to left.

8-10-62

SUBJECT R.H.

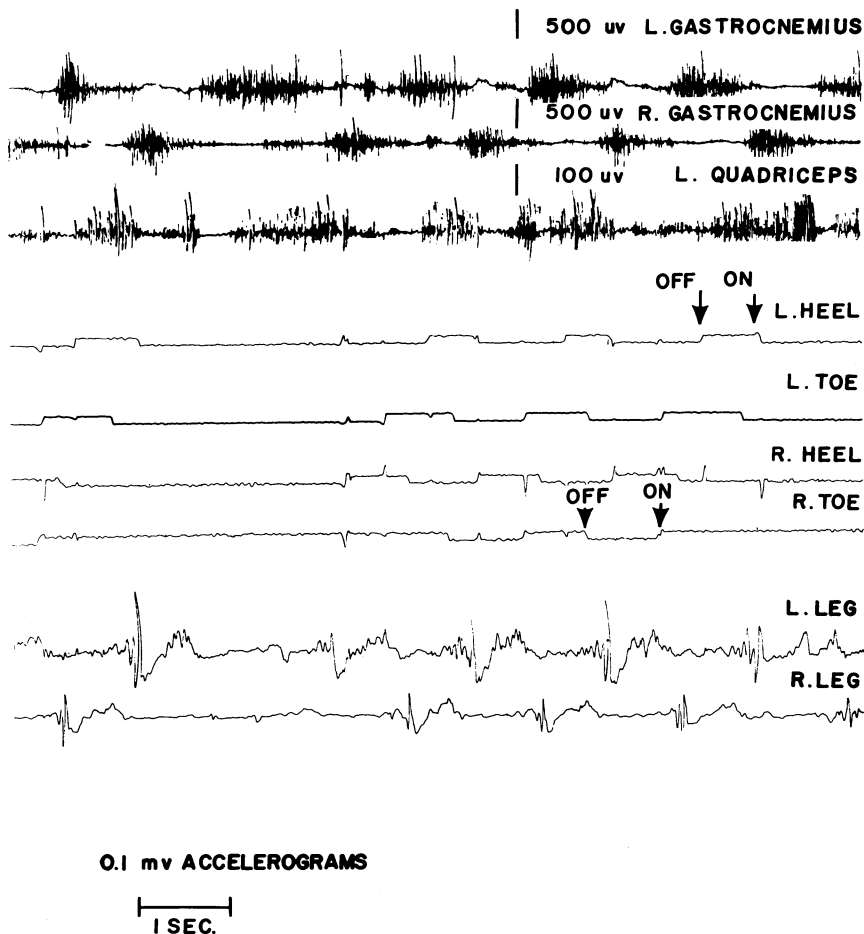


Figure 9

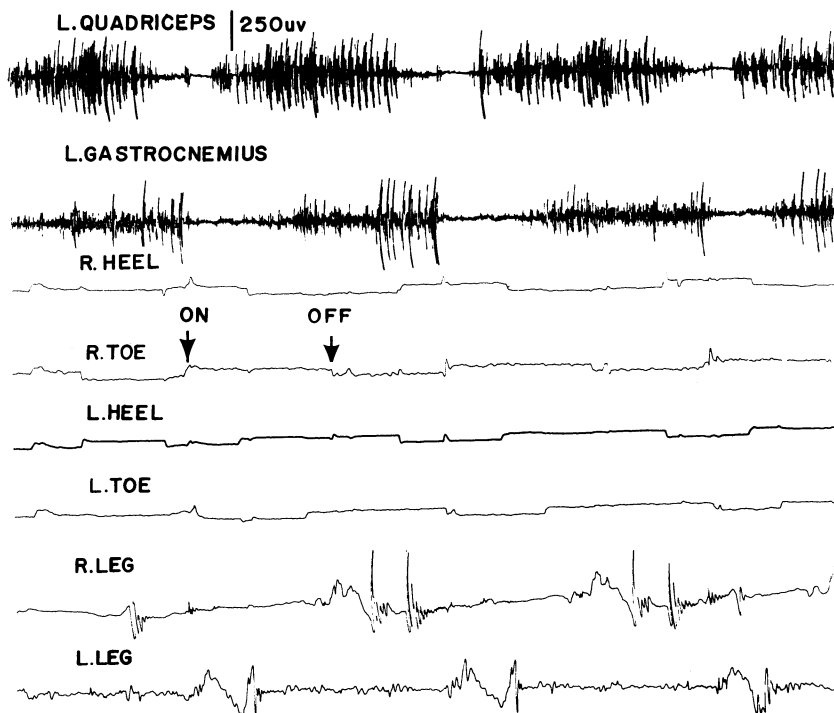
Normal accelerogram and electromyogram
R. leg and L. leg are accelerograms
Graph is read from right to left

SUBJECT L.D.

1 SEC.

8-31-62

01mv. ACCELEROGRAMS

**Figure 10**

Accelerogram and electromyogram of right above knee amputee
R. leg and L. leg are accelerograms
Graph is read from left to right

SUBJECT G.L.

8-31-62

R. QUADRICEPS

R. GASTROCNEMIUS

R. HEEL

L. HEEL

L. TOE

L. LEG

100uv.

1sec.

Figure 11

Accelerogram and electromyogram of left above knee amputee

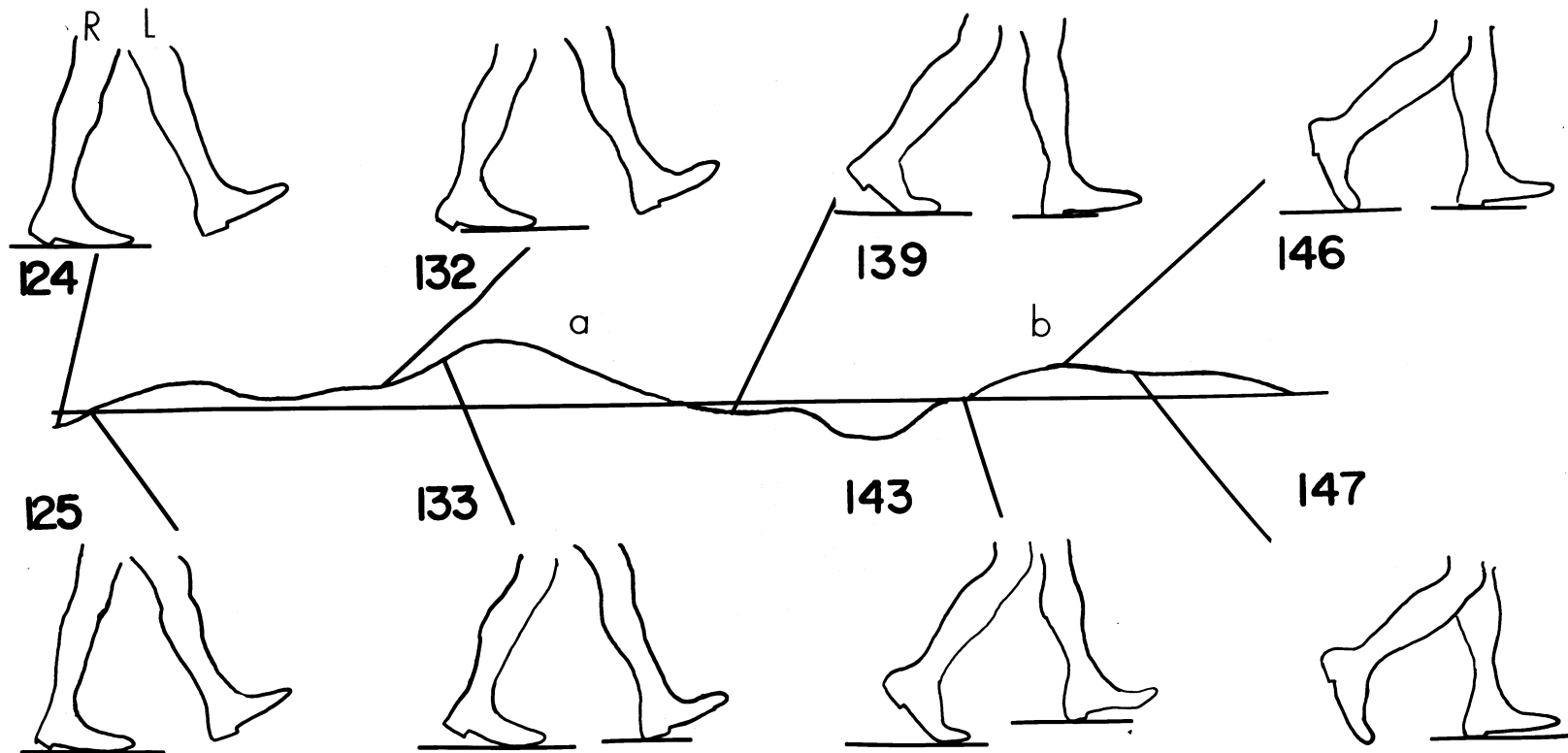
L. leg is an accelerogram

Graph is read from left to right

Figure 12

Vertical accelerogram of a normal subject
Numbers refer to movie film frames
"a" and "b" refer to major and minor
deflections, respectively,
"R" and "L" refer to right and left leg
Lines under the feet represent heel and
toe contacts,
Graph is read from left to right.

VERTICAL NORMAL SUBJECT (R.H.)



100 ms.

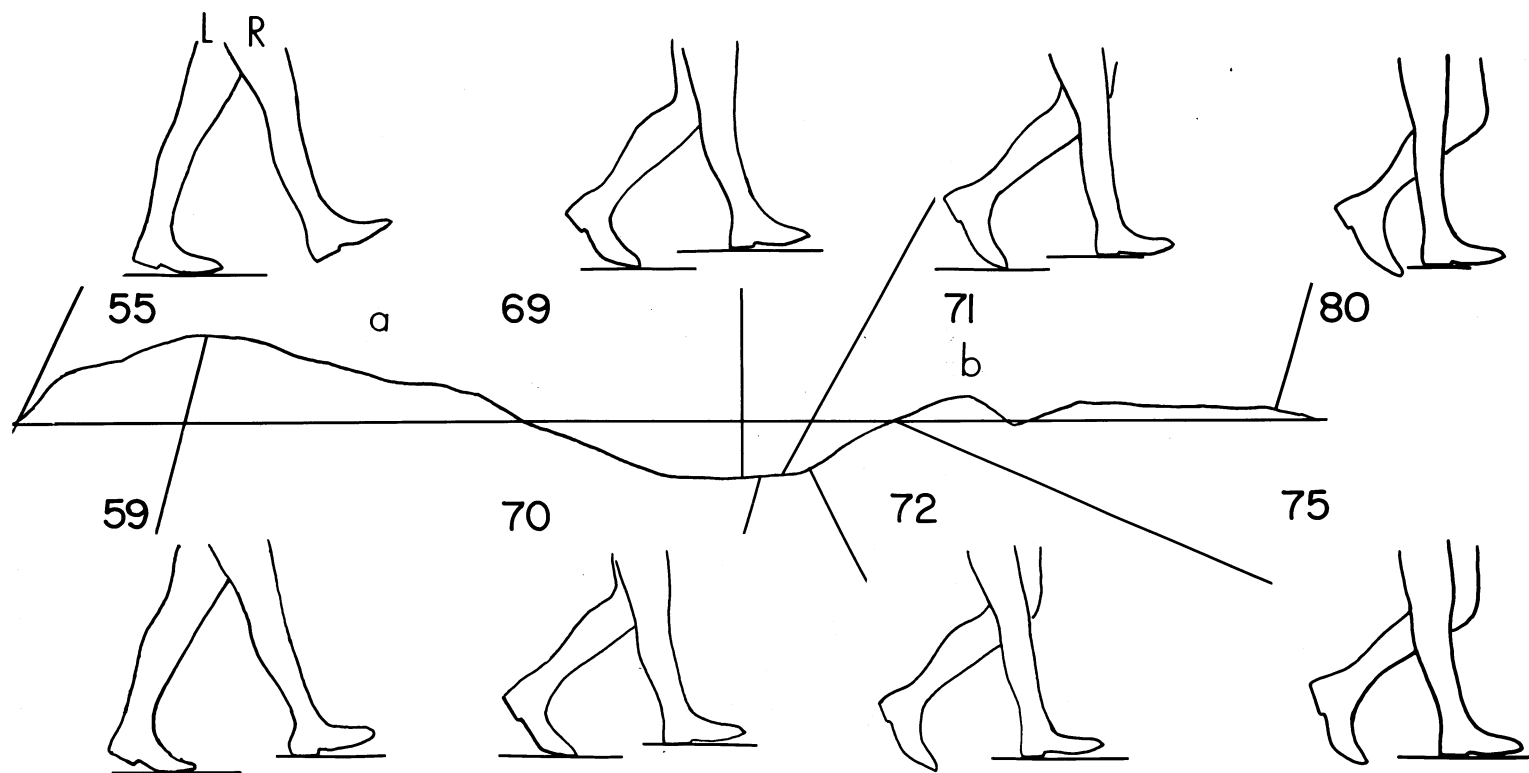
Figure 13

Vertical accelerogram of a normal subject
Numbers refer to movie film frames
"a" and "b" refer to major and minor
deflections, respectively,
"R" and "L" refer to right and left leg
Lines under the feet represent heel and
toe contacts,
Graph is read from left to right.

VERTICAL

NORMAL

SUBJECT (BZ)



100ms.

Figure 14

Leg accelerogram of a normal subject
Lines under feet represent heel and toe contacts
"R" and "L" refer to right and left leg respectively
Graph is read from left to right.

LEG NORMAL SUBJECT (R.H)

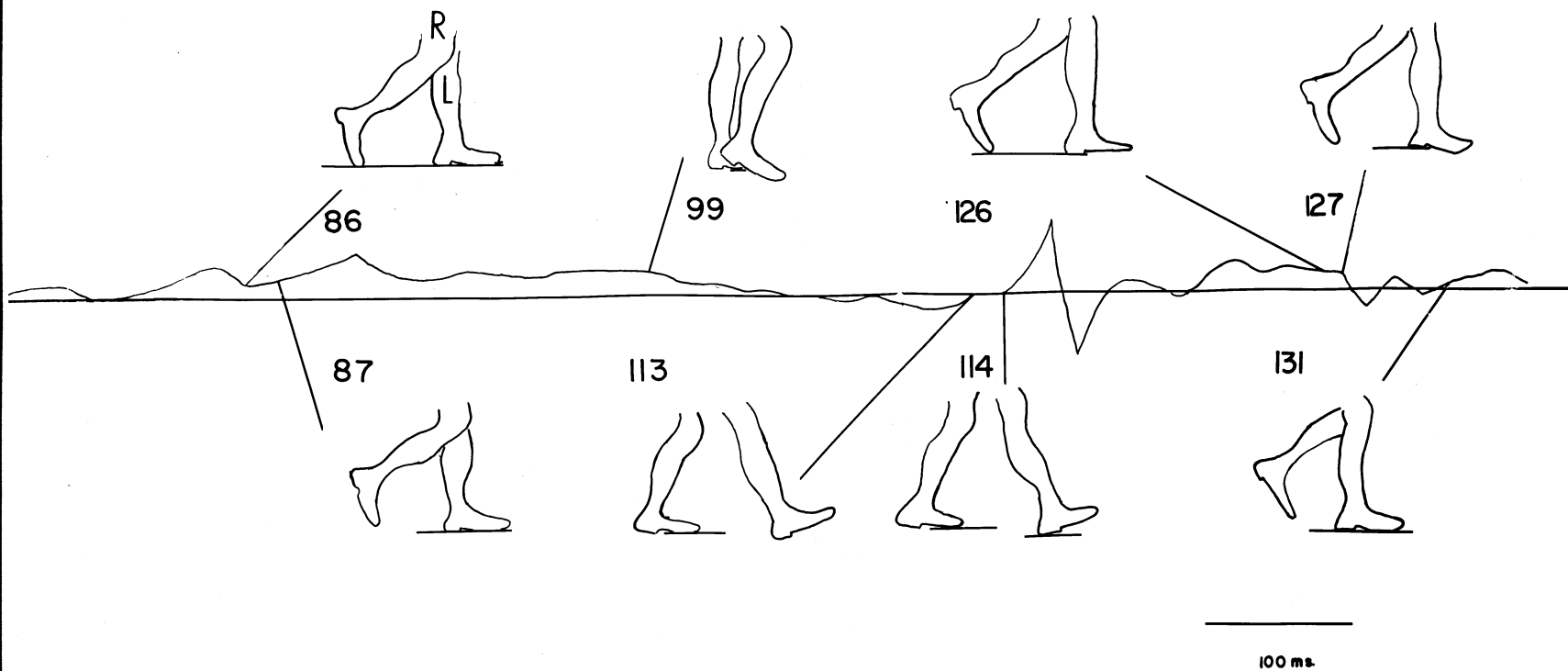
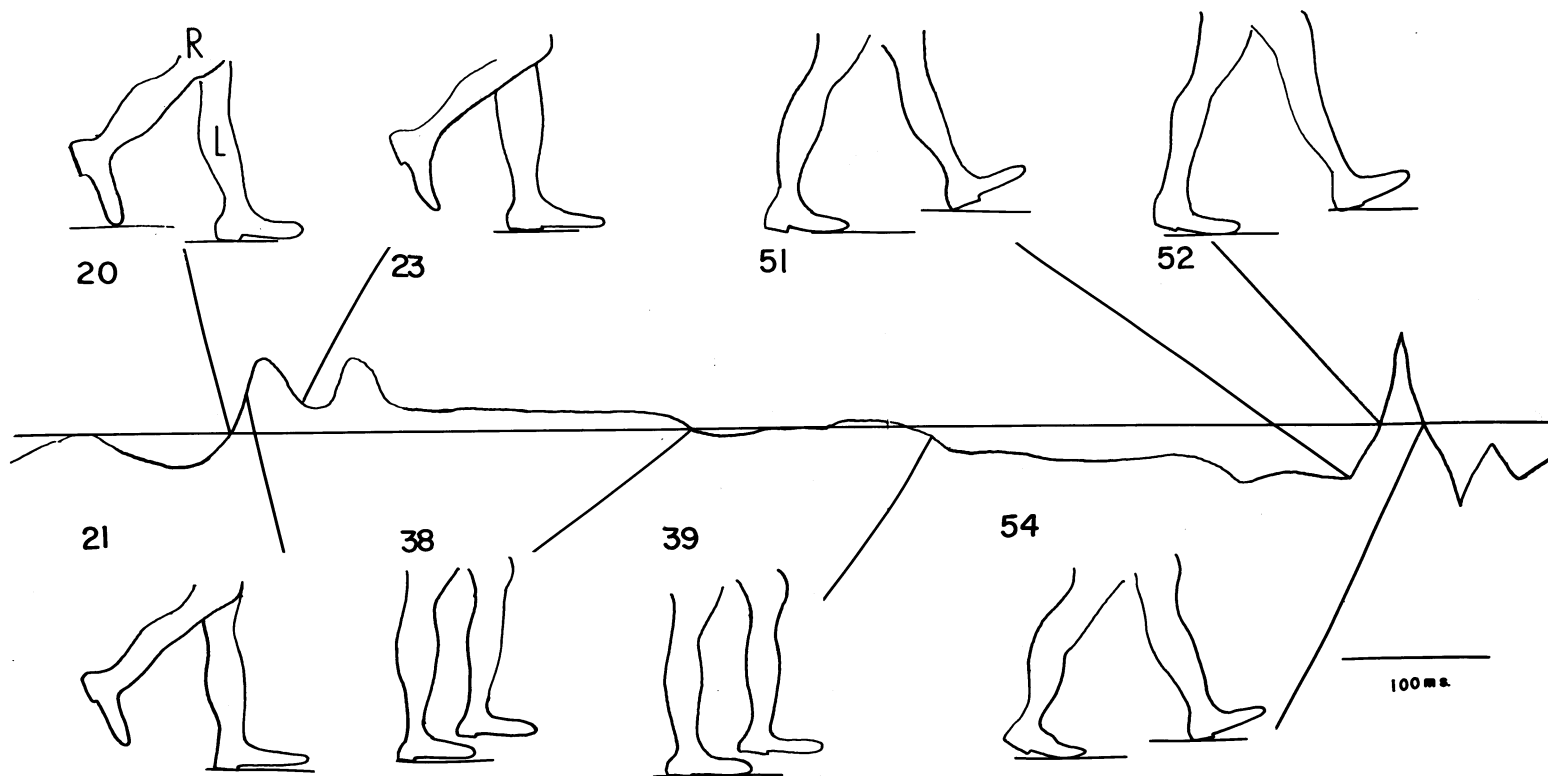


Figure 15

Leg accelerogram of normal subject
Lines under feet represent heel and toe contacts
"R" and "L" refer to right and left leg respectively
Graph is read from left to right.

LEG NORMAL SUBJECT (B.Z.)



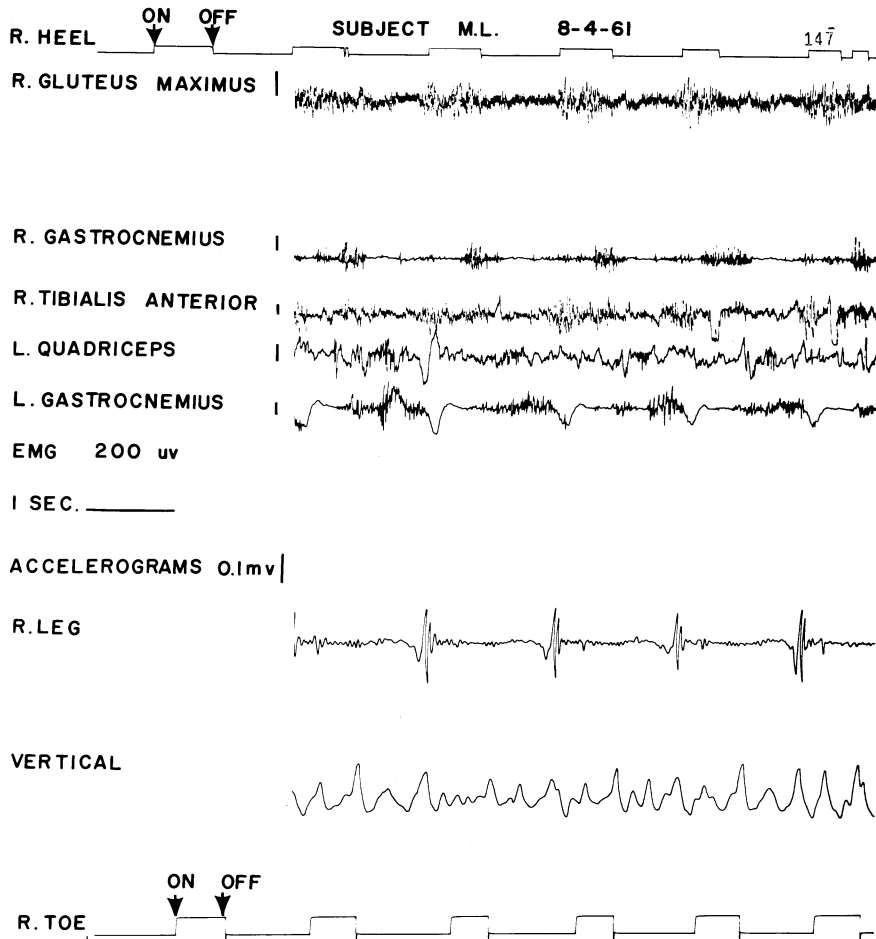


Figure 16

Normal accelerogram and electromyogram
Graph is read from left to right.

Figure 17

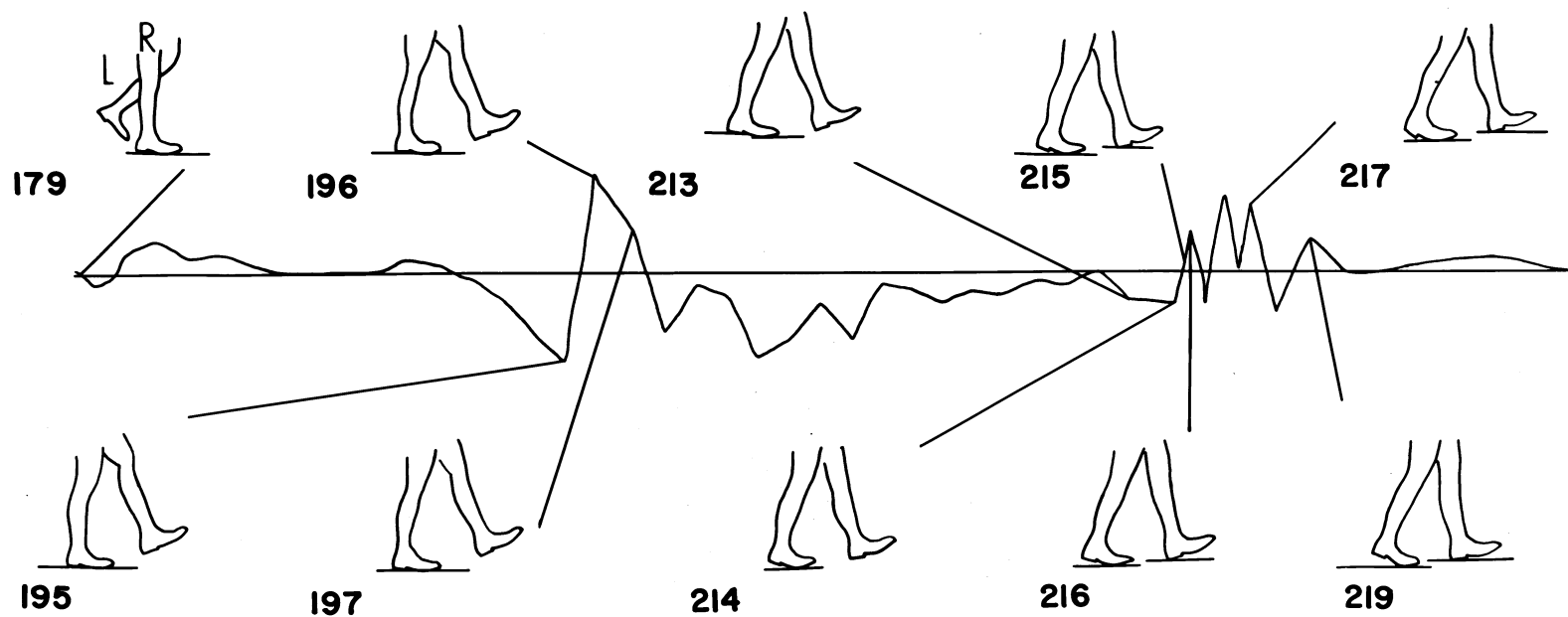
Leg accelerogram of above knee amputee

Lines under feet represent heel and toe contacts

"R" and "L" refer to right and left leg respectively

Graph is read from left to right .

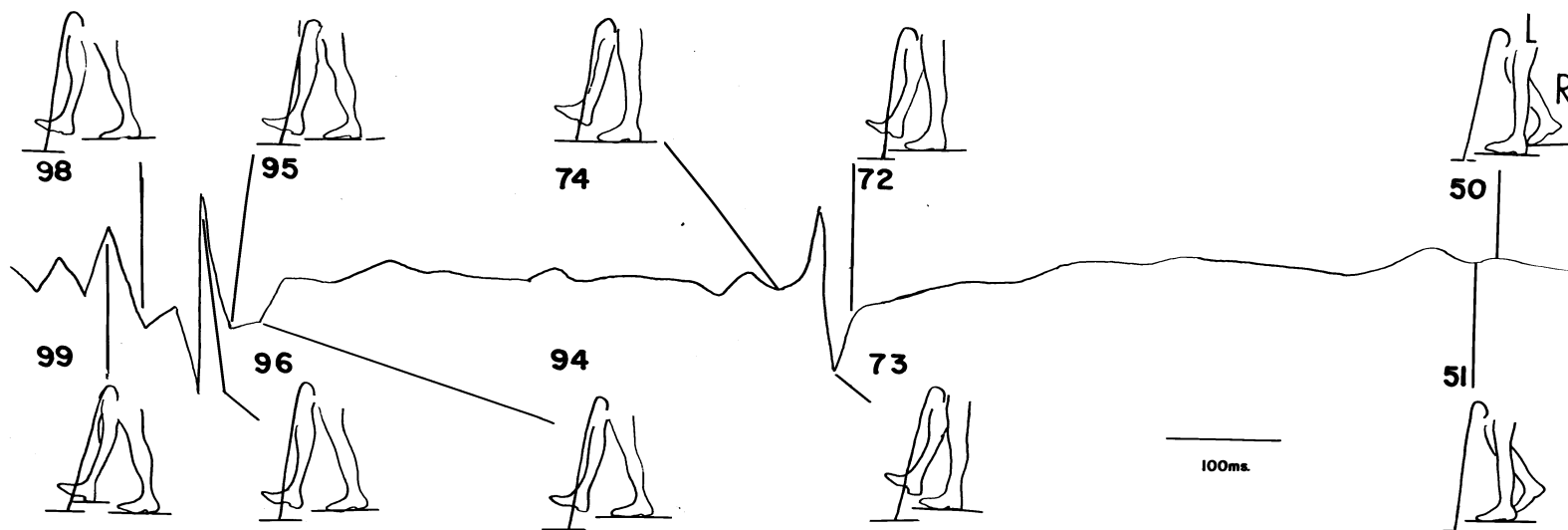
LEFT ABOVE KNEE AMPUTEE SUBJECT (G.L.)



300 ms.

Figure 18
Leg accelerogram of above knee amputee
Lines under feet represent heel and toe contacts
"R" and "L" refer to right and left legs respectively
Graph is read from right to left.

RIGHT ABOVE KNEE AMPUTEE SUBJECT (L.D.)



DISCUSSION

A. Normal vertical accelerogram

The vertical acceleration curve as obtained by wire strain gauges is comparable to that of Braune and Fischer (1895). However their curves are smoother than those shown in this study. The accelerograms of Bernstein are also smooth but show an additional deflection at the peak, Figure 19. Since both accelerograms (those of Braune and Fischer and Bernstein) having been obtained by double differentiation, they would not show the small deflections noted in Figure 7. Liberson (personal communication) states that the vertical accelerogram is identical to that obtained by him using the piezoelectric quartz method. Therefore the curves presented here are believed to be true vertical accelerograms.

In Figures 7, 12, and 13 the vertical accelerogram consists of a major (a) and a minor (b) deflection for each leg. The major deflection occurs at the onset of the double support Figure 12, 133 and Figure 13, 59 and the minor deflection occurs at the end of the double support Figure 12, 147 and Figure 13, 75.

An example will serve to clarify the above and amplify the situation.

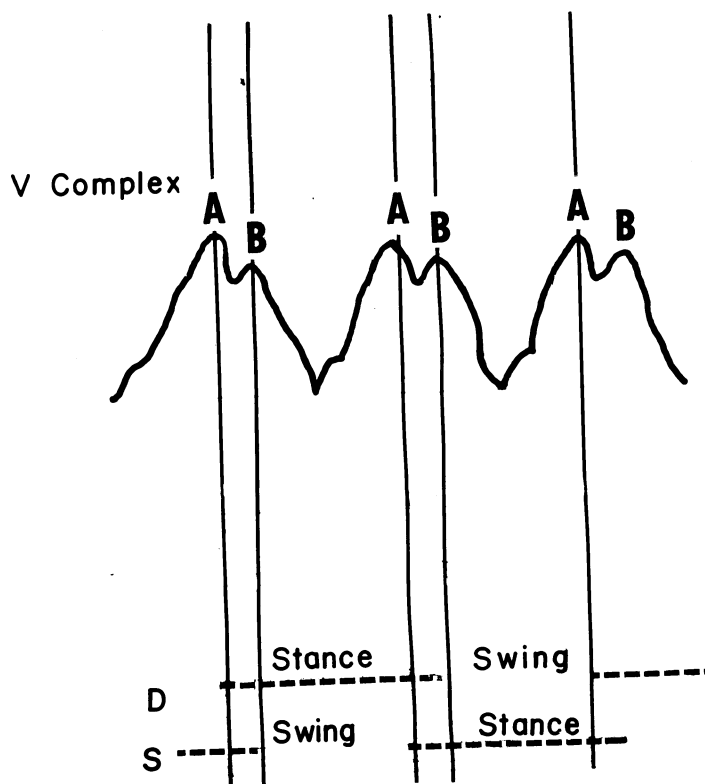


Figure 19

Vertical Accelerogram (Tracing from Bernstein)

V complex refers to Vertical Accelerogram

A, Major and B, Minor Deflections

D and S refers to right and left legs, respectively.

The heel makes contact with the floor and this point coincides with the major deflection, Figures 12 and 13, 133 and 159, respectively. At the time the heel makes contact with the floor the toe of the opposite leg is still in contact with the floor and is pushing the body forward as first noted by Aristotle and the Weber brothers. Therefore the body is in the double support period.

Confirmation of the above is given in Figure 12 (132-143) and Figure 13 (59, 69). The minor deflection coincides with the toe departing from the floor which corresponds in respect to time to the end of the double support, Figure 12 (146-147) and Figure 13 (72-75). In Figure 13, 55 the left leg is in the period of stance and the right leg is in the swing phase. The right then makes contact with the floor(59) and this point coincides in respect to time with the major deflection. The double support then will be in effect during the major deflection (a) and a portion of the minor deflection.

B. Normal leg accelerometer

The normal leg accelerometer is characterized by the initial sinusoidal curve followed by a sharp spike. In Figure, 87¹⁴ and Figure 15, 20 the rising deflection corresponds with the time of the departure

of the foot or the initiation of the swing. At 114 and 51 in Figures 14 and 15 respectively the heel of the swinging leg contacts the floor resulting in the sharp diphasic spike. The descending portion of the sinusoidal curve occurs in the midswing, 39 and (99-113) in Figures 15 and 14 respectively.

The minor deflection of the vertical is correlated with the smooth rising deflection of the leg accelerogram or the sinusoidal portion of the swing. The finding of a sinusoidal acceleration curve in the leg accelerogram would lend support to the Webers (1836) that the leg obeys the laws of the pendulum during the swing.

The large smooth deflection seen in the leg accelerogram corresponds approximately with the minor deflection seen in the vertical accelerogram (See Figure 7). The leg which is responsible for the leg accelerogram is not the leg which causes the deflection seen in the vertical accelerogram. The upward deflection of the vertical accelerogram must necessarily be caused by a leg that is in contact with the floor. The strain gauge, as will be recalled, is mounted for the former accelerogram recording on the chest. Although a swinging leg,

because of the moveable pelvis, may cause some change in the vertical accelerogram, most of the vertical accelerogram must be caused by the stance leg. The swing can be correlated with the vertical accelerogram by observing the heel and toe contacts and departures.

The leg accelerogram is primarily recording the swing phase of the gait because the strain gauge is mounted on the leg and records only angular acceleration. Even though, it is true that the angle of the stance leg is being changed and therefore should register an acceleration, little disturbance of the baseline occurs in the opposite leg because of the slow rate of change. Figures 14 and 15 offer an explanation for the relatively stable baseline. Observe that in Figure 14 (87 to 114) the stance leg does not change its angle very much in respect to a perpendicular line to the floor. Now observe that the change in the angle that occurs in the swinging leg is much more rapid. The time interval, 17 frames or 0.26 second, results in only 15-20 degree change in the stance leg but in the swinging leg the angle changes almost twice as much, for the leg passes through the perpendicular at midswing 99 and by 113 is already 15-20 degrees beyond the perpendicular. Thus the swinging

leg changes 40 degrees while the stance leg does not change more than 15 degrees, in the same length of time. Note in Figure^s 14 and 15 the change in angle is much greater from 87-99 and 21-39 than from 99-113 and 39-51. Therefore since the angle is changing so rapidly in the first position up to midswing there is acceleration up to midswing then the leg begins to decelerate.

C. Muscle Activity

1. Gastrocnemius

The relationship between the two gastrocnemius muscles will be simplified by an illustration. If the toe is on the floor then the leg will soon be behind the center of gravity of the body, Figure 14 (86-126). In Figure 9 the left heel departure corresponds in time with the greatest activity of the left gastrocnemius. The mass of the body is elevated and accelerated by this contraction which produces plantar flexion. The mass will then be shifted to the right leg where the process is repeated. The overlapping action of the gastrocnemius is due to the double support period.

2. Tibialis anterior

The tibialis anterior is active during the stance and the swing phase.

Liberson ('57) has interpreted the constant activity of this muscle as "this muscle seems to be constantly responding to the changing environment seemingly representing the most corticalized muscle of the leg. Thus the feedback structures related to the activity of the tibialis anterior constitute a guiding mechanism for the entire leg." All that can be concluded from this study is that the tibialis anterior is responsible for dorsiflexion of the foot during the swing phase and without this activity, the foot would drag the floor. The second conclusion is that the great burst of activity seen just prior to heel contact is to stabilize the ankle while the activity seen after heel contact is to allow the foot to descend smoothly to the floor.

3. Gluteus maximus

This muscle is particularly active during the stance but the activity begins just prior to heel contact. The activity seen just prior to heel contact has been interpreted by Liberson, ('57). The contraction of the gluteus maximus "brings the swinging leg backwards to the point of heel strike, reversing the overshoot." (Beaver, 1891, '03; Scherb, '27) have stated that the activity of this muscle occurs at the beginning of the

double support, and Inman ('53) has stated that the activity occurs in early stance phase. The records obtained in this study indicate the activity begins prior to heel contact. The interpretation is that the activity of the gluteus maximus is to slow down the velocity of the swinging leg and to aid in the flexion of the hip joint.

4. Quadriceps

The quadriceps begins to contract at the termination of the swing phase and remains in activity during stance phase, Figure 9. Its activity is to stabilize the knee joint during the stance (Inman '53) and to extend the knee at the termination of the swing phase. The conclusion is that its activity during the swing phase is to prevent flexion due to inertia, extend the knee, and during the stance to stabilize the knee joint.

D. Amputee Accelerogram

Since the above knee amputee has lost an important mechanism it would be expected that the leg accelerogram would be different. In the initial portion of the accelerogram the curve appears to be quite normal, Figures 17 and 18, ¹⁷⁹~~237~~ and (50-51) respectively. However during the swing phase the amputee evidently extends his knee resulting in the sharp

deflection seen in Figure 17, 197 and Figure 18 (72-73). Extension of the prosthetic knee is brought about by a device called a "kick strap". This is an elastic band which is attached to the thigh portion of the prosthesis and extends anteriorly over the prosthetic knee. The device prevents hyperflexion as well as aids extension of the prosthetic knee. Some amputees "lock" the knee prior to contacting the floor with the prosthetic heel but not all amputees carry out this maneuver in this manner.

In Figure 18 if the progression of the prosthetic leg in relation to the cane is observed the following points may be noted. At 72-73 the heel is slightly behind the cane but by 74 the heel has advanced considerably. The partial locking of the prosthesis must have occurred between 73 and 74. The heel did not change appreciably between 72 and 73 but one frame later at 74, the edge of the heel has advanced to the edge of the cane. To accomplish this action in such a short time a "locking" of the knee in extension must have occurred and the accelerations seen at 73-74 adds further photographic evidence that such an extension did occur. In 94-98 the heel is progressively further and further behind the cane,

which would lead to the hypothesis that the knee is being "locked" in full extension, but at the same time the foot is being pulled progressively backwards. (See gluteus maximus page 63). This observation is supported by the acceleration curves which show a diphasic spike at 95-96 indicating a completion of the extension of the knee before heel contact at 99.

Figure 17 shows the locking of the prosthetic knee in extension at 195-197. However this represents a broader and smoother extension than seen previously in Figure 18. At 215 the heel contacts the floor. Note now the appearance of three waves. This first wave occurs at 215 and is probably caused by heel contact. However the subject evidently "locks" the knee in full extension after setting the heel on the floor, in contrast to Figure 17 where the complete extension occurred prior to heel contact. Thus if there is only one wave following the heel contact, the interpretation is that the amputee is completing the extension of the knee before heel contact has been made. The waves following heel contact could be artifacts due to an undamped system.

The duration of the muscle activity of the normal leg of the amputee versus that of the normal individual is prolonged in the gastrocnemius

and quadriceps muscles. Comparison of Figure 9 with Figures 10 and 11 shows this prolongation of the electrical activity. One explanation is that the long prosthetic swing causes the stance phase of the normal leg to be prolonged.

CONCLUSIONS

1. The gait may be studied by the use of accelerometers. The method is valid as determined by mathematical computation and experimentally in this study. Confirmation of the acceleration curves is achieved by comparing with the curves of Bernstein and Liberson. Bernstein obtained his curves by double differentiation of the displacement curve.
2. Combining of electromyography and accelerography plus the heel and toe contacts and simultaneous photography of the above allows the simultaneous correlation of displacement acceleration and muscle action.
3. The vertical accelerogram may be divided into a major and a minor deflection. The major deflection occurs at the onset and during the double support. The minor deflection occurs at the end of the double support.
4. The activity of the quadriceps begins prior to heel contact and persists through most of the stance phase. Its activity is interpreted as stabilizing the knee joint during the stance and to extend the knee or prevent flexion due to inertia during the swing.

5. The activity of the tibialis anterior muscle is seen throughout swing and stance. Its activity is interpreted as dorsiflexion during the swing, stabilization of the ankle just prior to heel contact and to allow the foot to descend smoothly to the floor after heel contact.
6. The activity of the gluteus maximus begins just prior to heel contact and lasts until after heel departure. Its activity is probably to check the velocity of the swinging leg and to flex the hip joint during the stance.
7. The use of the dual unit strain gauge ensemble allows the recording of the angular acceleration of the leg. This accelerogram consists of a sinusoidal deflection followed by a spike. The former is correlated with the swing phase while the spike is correlated with the heel contact.
8. The amputee accelerogram differs from the normal accelerogram described above, in that the sinusoidal curve is interrupted by a sharp diphasic spike which is considered to be due to "locking" of the prosthetic knee. The knee appears to be re-locked in final extension after the heel contacts the floor in some amputees and in others the knee is locked before heel contact.

9. A method is now available for the clinician to help him in understanding further what the amputee is doing at any moment of the gait and to perhaps develop better re-education programs.

10. The possibility is open for simultaneous electromyography and displacement during the gait. This would give more accurate explanations of muscle function.

11. The technique of simultaneous photography of displacement and acceleration is new. The technique allows the immediate correlation of these two phenomena without resort to differential calculus. Thus a great economy of time is realized and correlation of displacement acceleration can be secured rapidly for any portion of the body.

12. Practically such information as simultaneous displacement acceleration of the amputee may aid in the development of better prosthesis. For example, removal of the kick strap may lead to the elimination of the sharp diphasic spike seen during the swing. Locking the knee in extension after heel contact may prove to be all that is necessary. Such studies should be made.

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APPENDIX I

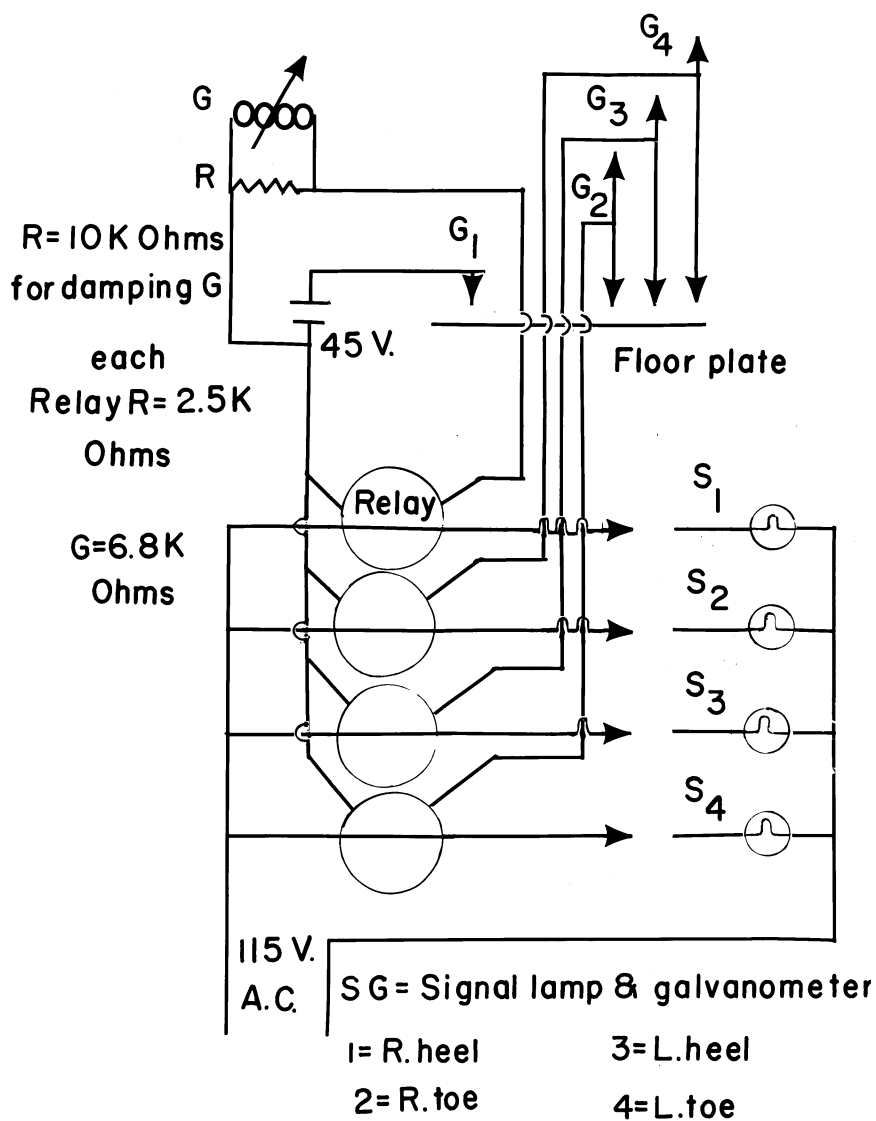


Figure 20

Circuit diagram for relay

APPENDIX II

Table 1

Determination of Effect Upon Deflection of Gravitational Force Upon Strain Gauge for θ when ϕ equals zero.

θ Degrees	$\sin \theta$	D mm deflection	$D/\sin \theta$ (k)
0	0	0	-
30	.500	5	10.00
45	.707	7.1	10.04
60	.866	8.5	9.80
90	1.000	10.0	10.00

Table 2

Determination of Effect Upon Deflection of Gravitational Force Upon Strain Gauge for ϕ when θ equals 90° .

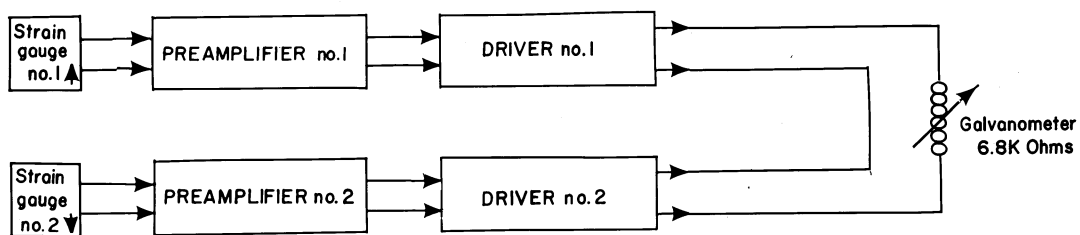
ϕ Degrees	$\cos \phi$	D mm deflection	$D/\cos \phi$ (k)
0	1.00	10.0	10.0
45	.707	7.5	10.60
90	0.000	0	-

APPENDIX III

The procedure that is used to cancel out the deflection due to gravitational components by connecting the two strain gauges in opposition is as follows: (Procedure to be used with Grass Force Displacement Strain Gauges, P5 Amplifiers, P5₁ Preamplifiers and Ink Writer Galvanometers.)

1. Place strain gauges in position so equals zero (critical) and 0 equals zero.
2. Use the circuit as shown in Figure 21; place a milliammeter in series with the circuit.
3. Set "Driver amplifier" (hereafter called the driver), to "cal" position.
 - A. Driver #1 to "up cal"
 - B. Driver #2 to "down cal"
4. Turn off toggle switch to galvanometer of driver #2; Turn on toggle switch to galvanometer of driver #1.
5. Set 1/2 amplitude frequency to 60.
6. Turn on power switch to writer.
7. Adjust the baseline control knob of driver #1 to 0 milliamps (hereafter abbreviated Ma).
8. Note: Monitor on 100, 10 and 1 Ma scales. If the 1 Ma scale is neglected considerable error will be realized at sensitivity selected.
9. Turn on toggle switch to "damping network" of driver #2; Turn off toggle switch to driver #1.
10. Adjust the baseline of Driver #2 to 0 Ma by repeating above steps.
11. Turn on both toggle switches. Repeat steps 4-10. Note: It is very important the rest of the procedure be carried out with both toggle switches left undisturbed, i.e., "on" position.
12. Impress -2000 millivolts (hereafter abbreviated mv) on driver #1. Adjust the driver sensitivity control to give a deflection of 10mm. (12.6 Ma) Repeat this step for driver #2.
13. Impress -200 mv signal of both drivers simultaneously; no residual Ma should be recorded. If so repeat steps 1-13 inclusive.

14. Turn driver polarity switch to "use up". Set sensitivity control to 0.1 mv/cm. Keep driver #2 on "cal down" position.
15. Adjust with millivolt potentiometer of the preamplifier (hereafter abbreviated preamp.) until no current is recorded on preamp. #1.
16. Turn strain gauge through 90°.
17. Adjust "cal adjust" control of preamp. for a 10 mm deflection (12.6 Ma).
18. Return strain gauge to θ equals 0 and ϕ equals 0.
19. Readjust if necessary repeating steps 14-17, as there may be interaction between adjust control and the millivolt potentiometer.
20. Turn driver #2 polarity switch to "down use" and driver #1 to "up cal" position.
21. Repeat steps 15-19 for preamp. and driver #2.
22. Place both strain gauges in position θ equals 0 and ϕ equals 0.
23. Turn both drivers to "use" position.
 - A. Driver #1 to "up use"
 - B. Driver #2 to "down use"
24. The current should be 0 Ma.
25. Turn the strain gauges to 90°.
26. The current should be 0.
27. The strain gauges are now ready to be used to measure angular acceleration.



CIRCUIT FOR CONNECTING STRAIN GAUGES IN OPPOSITION

Figure 21

APPROVAL SHEET

The dissertation submitted by Albert A. Halls has been read and approved by six members of the faculty of the Graduate School.

The final copies have been examined by the director of the dissertation and the signature which appears below verifies the fact that any necessary changes have been incorporated, and that the dissertation is now given final approval with reference to content, form, and mechanical accuracy.

The dissertation is therefore accepted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Date 1-16-63

David S. Jones
Signature of Advisor

**A CORRELATION OF DISPLACEMENT, ACCELERATION
AND MUSCLE ACTION DURING THE WALKING
GAIT OF NORMAL INDIVIDUALS AND
ABOVE KNEE AMPUTEES**

**Abstract
by
Albert A. Halls**

A new method of simultaneous photography of displacement and acceleration of the subject at any moment of the gait is described. Normal and above knee amputee subjects were examined by this method. Twenty normal and twenty above knee amputee subjects were first examined by electromyography and accelerography. The vertical accelerogram was recorded by the use of a wire strain gauge. To eliminate the vector component due to angular rotation the strain gauges were connected in opposition to measure leg acceleration.

Two amputees and two normal subjects were selected from above categories for intensive study of displacement and acceleration by simultaneous photography. Also muscle action was recorded simultaneously with the accelerogram.

The vertical acceleration curve consists of two upward deflections,

a major and a minor. The major deflection occurs at the onset of the double support. The minor deflection occurs at the end of the double support.

The normal leg accelerogram consists of a sinusoidal curve which is terminated by a sharp spike. The sinusoidal curve is correlated with the swing phase of the leg and the spike is correlated with heel contact of that leg.

The major deflection of the vertical accelerogram is correlated with the sharp spike of the leg accelerogram and the minor deflection of the vertical accelerogram is correlated with the sinusoidal curve or the swing phase.

The electromyogram is dynamically analyzed during the gait. The gluteus maximus begins to contract prior to heel contact and its activity continues until after heel departure. Its activity is interpreted as slowing down the velocity of the swinging leg and flexion of the hip joint. The quadriceps begins to contract prior to heel contact and continues through most of the stance phase. Its activity is interpreted as extending the knee or prevention of flexion due to inertia during the

swing and to stabilize the knee joint during the stance. The tibialis anterior contracts during the swing and stance but the greatest burst of activity is seen prior to and after heel contact. Its activity is for dorsiflexion of the foot during the swing to prevent the foot from dragging on the floor; stabilization of the ankle joint just prior to heel contact and to allow the foot to descend smoothly to the floor after heel contact. The gastrocnemius begins its activity at heel contact and continues its activity until toe departure. Its activity is responsible for most of the major deflection. Its activity is interpreted as plantar flexing the foot and thus elevating the mass of the body.

The leg accelerogram of the above knee amputee has a sharp diphasic spike during the swing which is considered to be due to "locking" of the knee in extension. An additional series of spikes occurs in some amputees prior to heel contact while in others these spikes occur after heel contact. It is concluded from the evidence presented by simultaneous photography that in the former group the knee is apparently locked in final extension after heel contact while in the latter group the prosthetic knee is locked prior to heel contact.

The muscle activity of the amputee differs from the normal in that the activity of the gastrocnemius is prolonged. This has been interpreted as a prolongation of the prosthetic swing thus lengthening the time the subject is on one foot.