INTRODUCTION

One of the principal activities of the members of the Biomechanics Laboratory during the past two decades has been the study of human locomotion. A major objective of these studies has been the accumulation of data that might be used in the design and construction of improved prosthetic and orthotic devices. The investigations have included electromyograms of the phasic action of muscles, forceplate recordings of floor reactions in both normal subjects and amputees, recordings of angular displacements and angular accelerations using a variety of techniques, and measurements of metabolic energy expenditures of normal subjects and subjects with various encumbrances, such as loads applied to certain segments of the body or devices to immobilize certain major joints. Amputees wearing various types of protheses have been evaluated by a variety of techniques. Some of the material obtained from these studies has been published in journals, reported at various scientific meetings, or preserved in technical reports with limited distribution.

When the vast amounts of data are reviewed, two facts are evident. First, the major displacements of the hip, knee, and ankle are grossly similar in all people and clearly are the result of our bipedal orthograde type of locomotion. Second, the variations in the less apparent movements are great, for example, in the horizontal rotations of the pelvis, thigh, and shank and the motions of the ankle and intrinsic articulations of the foot.

These latter movements play a major role in determining the unique characteristics of an individual's gait which enable one to recognize a friend walking even at a distance. Furthermore, these individual differences may be of great importance in orthopedic surgery and in the proper prescription of new prosthetic and orthotic devices.

Despite the wide range of anatomic variations which exist and disabilities which may be involved, there is in most individuals a remarkable
ability to integrate any remaining locomotor assets into a relatively smooth-functioning whole. Compensation for disability at a specific joint frequently is possible by modifying the way in which adjacent joints are used. This implies that there must exist between the various articulations certain interrelationships which are complementary or compensatory. A better understanding of these relationships is essential for improved rehabilitation of people with locomotor disabilities.

Any analysis of the compensatory relationships which exist in walking demands simultaneous examination of many variables. Experience has shown that visual examination of walking is not enough; the many interrelated motions of walking are too numerous and occur too quickly for the eye to follow in detail. This realization has underlain all of the locomotion studies of the Biomechanics Laboratory and, in particular, has had a fundamental influence on the current project, in which computers and specialized electromechanical devices are being applied to permit simultaneous measurement of 20 or more relevant variables of walking. Suitably displayed, such measurements can effectively supplement visual impressions and can assist in the diagnosis and treatment of gait disability.

The sections which follow summarize recent progress in instrumentation and biomechanical studies, as well as progress in the design and development projects which provide motivation for the fundamental studies.

**BIOMECHANICAL STUDIES OF HUMAN LOCOMOTION**

1. Instrumented Walkway

*Limitations of Treadmill*

Preliminary studies have shown the importance of considering the whole range of available walking speeds when analyzing gait. These studies have been conducted on a treadmill in order to simplify instrumentation and to avoid the expense and additional complexity of telemetry. It has never been questioned, however, that many types of gait studies cannot be conducted satisfactorily on a treadmill. Although most normal subjects quickly learn to walk comfortably on a treadmill, some never do, and the treadmill cannot even be seriously considered for subjects with serious gait disabilities. Consequently, plans to apply the same, or similar, measurement techniques to the walkway have been underway for some time.

*Wires vs. Telemetry*

The dimensions of the current laboratory allow a walkway approximately 9 m. (29 ft.) long. A longer walkway would be desirable, but this length was judged to be acceptable for the time being. On this relatively
short walkway, direct attachments by wires to instruments on the subject are being used. For those studies which require only a small number of wires, the cable is trailed behind the subject or supported by a passive cable trolley. Any further expansion of gait studies to more complex instrumentation, to longer walkways, or to outdoor environments will be accomplished with the aid of telemetry. Preliminary planning for a 16-channel pulse-code-modulated telemetry system is underway.

Distance Measurements

The principal difficulty in instrumenting a walkway lies in the measurement of the position of the subject along the walkway in order to compute step length, one of the fundamental variables of interest. A closed loop string, such as that used by Drillis (1) in his Tachograph, was considered, but has not been built because of the difficulties involved in allowing the subject to turn around easily and walk the other way. The use of Doppler radar, similar to that used to detect speeding automobiles, offers great promise, but it has been avoided for the present because of the time and expense which would be required for development. The technique which has been selected for initial studies is the common one of positioning two (or more) light beams across the walkway at known distance intervals and detecting interruption of the light beams. A measurement of the time between interruptions allows computation of an average velocity, which together with measured step durations permits computation of average step length. The step durations provide a means for detecting nonuniform progression along the walkway.

The photo-device selected is a commercial unit which contains both infrared light source and detector. This construction simplifies installation because all wiring is on one side of the walkway; only a plastic retro-reflector need be placed on the other side of the walkway. Two pairs of simple tubular supports were built and attached to the floor 4 m. apart. These supports provide simple height adjustments which allow the light beam to be positioned just below the chin of the subject, the level which was judged would provide the smallest errors due to movements of head or limbs. The outputs of the photo-devices have been modified to provide pulses which can be fed directly to the computer.

Conductive Walkway

The walking surface of the walkway consists of a length of conductive rubber conveyer belting. This material is smooth and provides an excellent nonslip walking surface. The conductivity of the rubber is sufficient to allow electrical detection of foot contact.
2. Cyclic Event Markers

Step Events

As mentioned in earlier reports, reliable detection of contacts of the foot with the floor has been the most persistently vexing problem involved in computerizing the measurement of gait. The superposition of successive walking cycles is a valid technique for determining an average, or typical, gait pattern only if successive cycles are superimposed in proper relation to one another. If they are offset, the averaging process unquestionably will confuse, rather than enhance, the data. Consequently, the effective use of computer averaging techniques for locomotion data enhancement is totally dependent on the ability to detect, automatically and reliably, the occurrence of some representative event in the walking cycle. Heel contact usually is the event chosen to define beginnings and endings of steps, but scuffing of the heel, which inevitably occurs part of the time, results in multiple heel contacts which can destroy the precision of cycle time measurements and data averaging.

In view of the absolute requirement for reliable cyclic event markers, events other than heel contact have been considered. The most promising appears to be midswing, defined as that instant when the swinging ankle passes the stance shank. This event has been used by the BioEngineering Unit at the University of Strathclyde in Glasgow in their reduction of cine film data. Midswing can be detected more precisely than heel contact in cine records because it is the period of maximum velocity of the swinging foot, whereas heel contact is a period of low velocity. This feature of midswing which makes it a desirable event marker for cine data also makes it desirable for computerized data acquisition. Unlike heel contact, midswing occurs only once per step and its time of occurrence can be defined with millisecond precision. Techniques are now being examined which may make it feasible to use midswing instead of heel contact to control the acquisition of data by the computer. Foot contact information is still of great interest, of course, but it need not be of such great precision or reliability as before.

Heart Events

In the documentation of gait variables, measurements of metabolic energy expenditure often are of interest. Unfortunately, the available methods of measurement are either very tedious or very expensive. The physiology literature includes a number of experimental reports which suggest that, for an individual, heart rate may be a good indicator of relative energy expenditure (2, 3, 4, 5, 6). Correlation with absolute oxygen consumption is poor, but changes in heart rate generally correlate well with changes in oxygen consumption for the same person.

In view of these encouraging data and the desirability of energy
measurements—even relative energy measurements—for evaluation of devices or procedures, instrumentation has been designed and built which detects the electrocardiogram and produces a computer-compatible output pulse at each heartbeat. These pulses permit the appropriately programed computer to compute and display heart rate. Preliminary results tend to support the literature, although considerable testing will be required before a thorough analysis can be provided of the practical usefulness of heart rate measurements for gait evaluation.

Different heart rate displays are available for different purposes. The computer drives a strip-chart recorder for long-term monitoring (Fig. 1), graphical summaries are obtainable on a Tektronix terminal (Fig. 2), and a numerical summary is included in the standard step-dimension data summary sheet (Fig. 3). The two latter displays were modifications of earlier output formats, and although extensive programing was required for the original plots, the modifications were accomplished quickly. This is a good example of the way careful programing can result in ever-increased versatility of the computer system.

![Figure 1](image-url)
3. Forces and Moments in the Lower Limb

A shank force and moment transducer has been completed, together with its 6-channel portable preamplifier, and tested on an above-knee amputee as shown in Figure 4. The computer data acquisition, data reduction, and automated graphical display give complete results in one day. Selections from these results are in Figures 5 through 8. Good sensitivity and zero stability were obtained for all channels, and cross-sensitivity was small for all channels except axial force, which was influenced to a significant degree by anteroposterior and mediolateral bending moments. Such cross-sensitivity is difficult to avoid in tubular pylon force and moment transducers because strains in the pylon due to bending moments are approximately eight times as large as those due to axial load. Computer corrections for the cross-sensitivity are feasible, but other types of transducer designs are being examined in the hope of
developing a practical and precise transducer which does not require cross-sensitivity corrections.

4. Self-Aligning Goniometry

Electrogoniometry is an appealing technique for measurements of walking, because measurements of relative motions at joints can be obtained directly without the need for subsequent data processing of any kind. Unfortunately, conventional electrogoniometers have been limited in their applications by the fact that their precise application depends upon precise alignment between goniometer axis and anatomic joint axis. At hip, knee, or ankle, precise alignment between a goniometer and the anatomic joint is difficult to determine or maintain, so goniometric measurements are of questionable accuracy at these joints.

<table>
<thead>
<tr>
<th>STEP DIMENSION DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBJ: 24  HT: 164 CM  WT: 73 KG</td>
</tr>
<tr>
<td>NO. OF STEPS: 32  FILE: 2</td>
</tr>
<tr>
<td>LENGTH/FREQ: 424 MM/S</td>
</tr>
<tr>
<td>STEP FREQ: 1786 .621 STEPS/S</td>
</tr>
<tr>
<td>HEART RATE: 983 .15/min  4.22</td>
</tr>
<tr>
<td>VELOCITY: 1237 MM/S  1.12</td>
</tr>
<tr>
<td>STEP LENGTH: 725 MM  1.13</td>
</tr>
<tr>
<td>L: 724 MM  1.24</td>
</tr>
<tr>
<td>R: 726 MM  1.22</td>
</tr>
<tr>
<td>STEP DUR: 586 MS  1.29</td>
</tr>
<tr>
<td>L: 584 MS  1.32</td>
</tr>
<tr>
<td>R: 587 MS  1.21</td>
</tr>
</tbody>
</table>

Figure 3.—Statistical summary of step dimension and other basic data from a typical data-collection run.
FIGURE 4.—Above-knee amputee wearing instrumented Four-Bar Polycentric Knee for force and motion analysis.
Figure 5.—Measured pylon bending moments (1.6 steps/sec.).

Figure 6.—Computed knee and hip moments.
Figure 7.—Measured shank torque.

Figure 8.—Knee moments and angles during swing phase.
To deal with this alignment problem and still retain the advantages of electrogoniometry, mechanical linkages were devised which permitted the angular position between body segments to be measured without any requirement for precise alignment with anatomic joints. These devices, which now are referred to as Self-Aligning Goniometers, were first used in the three-dimensional motion studies reported in 1970.

The original devices were rather complex and heavy, but were very effective, and efforts have continued to develop simpler and more easily applied devices based on the same concepts. The most recent example is the device shown in Figure 9 which measures flexion angles at both hips and both knees of normal or amputee subjects. Further simplifications are planned for this device, and another device is under design for measuring all three angular components of the total motion between shank and shoe. These efforts are directed toward the development of clinically practical gait evaluation devices.

FIGURE 9.—Self-Aligning Goniometers for hip and knee.
5. Data-Control Information

Motion can be defined as a change in position which occurs over a period of time. Consequently, the fundamental variables of motion are time and distance. Locomotion is a specialized type of motion which in humans is accomplished by cyclic sharing of support between the two legs. Any systematic analysis of motion, or of locomotion, necessarily begins with measurements of distance and time. As a result of its cyclic nature, human locomotion is subdivided into basic units of steps and strides. Therefore, measurements of time and distance for each of these cyclic units represent the simplest and most fundamental numerical description of walking which is possible.

Because of the fundamental significance of such measurements in the study of walking, considerable effort has been devoted to the development of reliable techniques for obtaining the measurements and displaying them clearly. The display which has been found to be most satisfactory and useful is a two-dimensional plot of step length versus step frequency. Experience has shown that, for most people, step length and step frequency increase approximately in proportion to one another as walking speed is increased. Furthermore, the same person walking at the same values of step length and step frequency will use the same motion patterns with a surprising degree of repeatability.

These experimental observations have led to the use of the fundamental time and distance measurements as control variables in the collection of kinematic and kinetic data on walking. The variables are always measured, no matter what the primary objective of the experiment may be, and are displayed as shown in Figures 10 and 11. They are not used to control the experiment directly, but to provide a basis for preliminary evaluation and screening of the recorded data. For analysis of a subject’s gait over a range of walking speeds, only those data are considered which were recorded at values of step length and step frequency typical for that subject.
Figure 10.—Typical step dimension plot. Each point represents one step.
Figure 11.—Summary step dimension plot. Each symbol represents an average value for several steps at constant speed.
6. Gait Evaluation

The locomotion laboratory has been developed with the view that documentation of changes in gait is the first step toward improved gait performance evaluation. The first order of priority was instrumentation for the basic time and distance parameters of gait, as described in sections 1 and 2. These data are useful in themselves for gait evaluation, and they are a necessary beginning for any comprehensive description of a particular gait, but they by no means present a complete picture of walking. Many other interrelated variables are involved in walking, including times of stance and swing or of single support and double support, linear and angular motions of the pelvis and trunk in space, and motions of hip, knee, and ankle joints. All of these are combined and correlated to alternately swing the legs forward and continuously support the body against gravity without the impact and jarring which one might expect with such a mode of locomotion.

The next step in developing practical gait evaluation techniques is to select the next most significant variable or variables and provide simple procedures to measure them and display them so that significant relationships are clearly visualized. Practical considerations usually limit the number of related variables to be considered at one time to two; a single graph can easily show relationship between any two variables.

It is not immediately obvious which variables are most significant for purposes of evaluation; only experience will tell for certain. But experience is gained by testing hypotheses, and a strong argument can be offered in support of hip flexion and knee flexion as two very significant variables whose interrelated actions have a great deal to do not only with efficient swinging of the legs forward during swing phase but also with smooth support of the torso during stance phase.

The Self-Aligning Goniometers discussed in section 4 above and shown in Figure 9 provide a practical means for measuring hip and knee flexion angles, and the oscilloscope provides a simple means for displaying the results. Unfortunately, a conventional plot of the two variables against time does not provide the desired clear visualization of relationships between hip and knee flexion. A more suitable display is obtained when the two variables are plotted against each other, with time as a parameter, as shown in Figures 12 and 13. (The still photographs do not properly convey the characteristics of this plot.) It appears without delay on the oscilloscope screen as the subject is walking. Successive cycles are automatically superimposed, clearly conveying an impression of variation from cycle to cycle. Changes in the interaction between hip and knee are characterized by distinct changes in the shape of the closed loop pattern. An oscilloscope camera provides a quick, permanent record which can be placed in the patient's medical records.
ABOVE-KNEE AMPUTEE — SINGLE-AXIS PNEUMATIC KNEE

Height = 182 cm  Weight (with prosthesis) = 91 kg

WALKING ON TREADMILL

NORMAL LEG  PROSTHESIS

101 steps/min
64 cm/step

WALKING ON FLOOR

NORMAL LEG  PROSTHESIS

100 steps/min
63 cm/step

HIP FLEXION

FIGURE 12.—Hip-knee angle diagrams for above-knee amputee wearing single-axis pneumatic knee.
ABOVE-KNEE AMPUTEE — POLYCENTRIC-PNEUMATIC KNEE
Height = 182 cm  Weight (with prosthesis) = 91 kg

WALKING ON TREADMILL
NORMAL LEG  PROSTHESIS

102 steps/min
70 cm/step

WALKING ON FLOOR
NORMAL LEG  PROSTHESIS

98 steps/min
68 cm/step

HIP FLEXION

Figure 13.—Hip-knee angle diagrams for above-knee amputee wearing Four-Bar Polycentric Pneumatic Knee.
1. UC-BL Four-Bar Polycentric Pneumatic Knee

Ten production-prototype models as manufactured by the Hosmer Corporation have been forwarded to the Veterans Administration Prosthetics Center for further testing. A new spherical socket/knee coupling has been added to the basic knee unit. This adjustable coupling allows ±5 deg. rotation adjustment of the socket relative to the knee in flexion/extension and adduction/abduction plus unlimited axial rotation. An instruction manual has been prepared which includes material on biomechanics of linkage knee mechanisms, the pneumatic swing-phase control, and instructions for installation, alignment, and adjustment of the device for the individual amputee.

Ten units have been reserved for amputee testing in the San Francisco Bay Area. Four units have been fitted to date. One active amputee has worn his UC-BL prosthesis for 1 year without malfunction. Some units fitted in the Bay Area also include the UC-BL shank axial-rotation device.

The cosmetic cover continues to be the major unsolved problem and UC-BL staff members are working with Hosmer Corporation in an effort to produce a satisfactory solution. The present cover provides a temporary solution but will require additional development work, particularly in those cases in which the axial rotation unit is added to the basic knee mechanism.

2. UC-BL Shank Axial-Rotation Device

Amputee testing of the axial-rotation device in the San Francisco Bay Area has been very encouraging. Five units are in daily use with two units having been in service for over 1 year without a mechanical malfunction.

Amputee reaction can be described as enthusiastic on the part of the four above-knee wearers. One below-knee amputee with a short stump has experienced some torsional instability when load is carried on a flexed knee with a PTB prosthesis, but he continues to wear the prosthesis.

3. UC-BL Six-Bar Linkage Knee-Disarticulation Prosthesis

An in-depth study of possible six-bar linkage arrangements has been carried out by graduate students as Master of Science research projects. At present six different arrangements have been shown to be kinematically feasible but only two seem to be practical from a prosthetic standpoint.
The unit designated as Prototype 3 has been redesigned to permit a reduction in width by relocation of the swing-phase control cylinder. The redesign uses the body of the swing-control cylinder as the shank structure. The unit has been modified and fitted to an amputee for testing. The function of the unit continues to be excellent.

4. Tube Couplings for Modular Prostheses

The trend toward modular construction of prosthetic legs has led to increasing use of aluminum tubing for the main structural element of the shank. Tubing provides high strength with light weight and is easily cut to length, so it is well suited for use as the shank module, particularly when used with quick-disconnect foot and knee couplings. The foot coupling is the most critical element of a modular shank structure, because practical cosmetic treatment requires a small cross section at this same level, where maximum bending moments are applied during walking.

Following its introduction with the below-knee adjustable leg, tubing of 13/8-in. o.d. and 1/16-in. wall has been used routinely for pylons in prostheses designed at the Biomechanics Laboratory. The choice of this size originally was dictated by a limitation of readily available stock sizes. There never has been any problem of strength with this tubing, but its large size has caused some complaints from prosthetists who encountered difficulty when cosmetic treatment of small ankles was attempted.

In response to the recent suggestion for an international standard pylon tube size of 35 mm. (13/8 in.), a new foot coupling for this smaller tube was designed. In order to minimize the pylon diameter in the ankle region and to retain as much of the strength of the tube as possible, the coupling fits inside the tube and the tube is not split. Strength tests have shown (see Fig. 14) that the new pylon-foot coupling system of 13/8-in. o.d. is actually stronger than the previously used large pylon tube and coupling system of 17/8-in. o.d., despite the 1/2-in. reduction in diameter at the ankle.

EVALUATION AND FURTHER DEVELOPMENT OF NEW DESIGNS FOR BACK BRACES

1. Studies of Spinal Supports

During the past 7 months, the semiflexible body jackets made of laminated polyester resin (4110) with fiber glass reinforcement have been fabricated and tested in four prosthetic-orthotic centers across the country under the auspices of the Committee on Prosthetics Research and Development, National Academy of Sciences—National Research Council. Instructions for fabrication have been prepared and distributed.
Figure 14.—Selected results of laboratory strength tests of modular foot couplings.
Thirty-five patients at the University of California, San Francisco, have worn the device. The results have generally been good. Failures occurred in a few cases, usually because of improper selection of patients, i.e., patients with problems not amenable to improvement by bracing.

A new clinic on problems of low back pain is being set up at UC-SF. Further subjects will be treated with the body jacket, as indicated.

**VARIABLE-HEIGHT-POWERED WHEELCHAIR**

1. General

The interim version of the UC-BL wheelchair was completed to a point at which it was tried by a quadriplegic and a motion picture of activities of daily living was made. By "interim" we mean that this version will not climb curbs, but will fit into an automobile later on. Much enthusiasm was expressed by the quadriplegic after one day of use, in spite of his initial reservations about the need for any of the unique extra features of this wheelchair.\(^a\)

**REFERENCES**


\(^a\) See D. M. Cunningham's article "Variable-Height-Powered Wheelchair for the Quadriplegic Driver," appearing elsewhere in this issue of the Bulletin.