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Children's Hospital Health Center
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Chairman: Dr. John V. Basmajian
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DISCUSSION OF AFTERNOON PAPERS

Dr. Basmajian: I propose in this final discussion period to have ten or fifteen minutes of directed discussion of an area that has been neglected so far in these discussions, and that is, animal or quadriped locomotion studies, and how they fit into the picture. I hope that the neurophysiologists and the other persons in the group who work with animals will take the leadership in this discussion. Then, I propose that Dr. Akeson and myself try to summarize what has happened during the day and with your help establish some national priorities in locomotion and gait studies. This would be our collected opinions about the needs in the field and some concept of the ways that those needs are being met and how they might be better met in the future. We might also discuss who should have fiscal responsibility for meeting these needs. This may be an impossible task; then again it could be an approach that could be useful at several levels of government, as well as providing some criteria for the Study Section.

Dr. Stein: I would like to make a few brief comments that will give you some idea about current research on animals. One of the things we can do in animal studies that may be useful to people in the human areas, is to study the role of sensory feedback. Over the last couple of years our group, and others in various places around the world, have developed techniques which permit us to look at the sensory fibers not as they are activated in anaesthetized animals but as they function in behaving animals, e.g. animals walking on the treadmill. Within the next few years, basic neurophysiologists will probably be able to provide some information on the normal roles of various sensory fibers.

Another area where some interest is developing is the question of the flexibility of the nervous system; the extent to which retraining might take place if you cut nerves and resuture them in appropriate ways. A related area that has been totally absent from our discussions is biofeedback, and whether it can be of any value in training people who have an inappropriate pattern of activity, to show them their pattern, and ask them if they can do anything about it. A third item that I could mention is an area that is receiving intense effort on the part of basic scientists, namely the heirarchial organization of the motor systems. We have all been brought up on the idea of spinal reflexes, but now neurobiologists can record from the motor cortex and cerebellum with microelectrodes. With these electrodes it is possible to record activity in brain cells during behavior and it is becoming more and more apparent that in addition to the basic spinal reflexes, there are cerebral and cerebellar "reflex" pathways which are affected to a greater or lesser extent, depending on the pathology. In the last couple of years it has been shown, for example, that a "long-loop" pathway involving the motor cortex is affected in Parkinson's disease, and maybe in some other pathological conditions.

Dr. Basmajian: Perhaps Dr. Perry can comment on this.

Dr. Perry: The ability to respond to biofeedback depends on the level of selective control the patient has retained or regained. It certainly is an excellent way of instructing the patient on how he should try to perform compared to how he currently is doing. His ability to respond depends on existance of selective control pathways which let him instruct his muscles appropriately. Voluntary activation of primitive mass action patterns also may yield some gains if the total limb function includes the desired activity without inducing unwanted events as well. Patients who move only by reflex or automaticity will not profit.

Dr. Basmajian: My experience with biofeedback in gait has been limited to training spastic patients to inhibit specific muscles. When you talk about your experience--when a person says "in my experience,"--it means one case (laughter)--but if he says "in my series," he's had two cases, and if he says, "in case after case after case," he's had three patients. So in case after case after case, we have been able to train teenagers who have cerebral palsy with spasticity, to inhibit the spasticity during locomotion. But we have not had long experience in this area and we certainly have not had long experience with some of the smaller muscles. In a few patients with spastic equinus deformity, we could train them to put their heel on the ground.

The possibilities in biofeedback will require a great deal of research. A small fraction of the total population of patients we are concerned with, might benefit from biofeedback training. But it's not going to solve the problems of the majority.

Dr. Houk: I would urge the people who are working in this area to acquaint themselves more fully with the recent, very exciting work that is being conducted on animal locomotion. These studies have revealed some basic principles of motor control in tetrapods that is probably relevant also to the bipedal gait of man, although some of the details may differ, due to the inherent mechanical differences between two-legged and four-legged posture. There are three recent reviews on different aspects of these studies: M.C. Wetzel and D.G. Stuart, Ensemble characteristics of cat locomotion and its neural control, Prog. in Neuroboi, 7:1-98, 1976; J.L. Shik and G.N. Orlovsky, Neurophysiology of locomotor automatism, Physiol. Rev. 56:465-501, 1976; S. Grillner, Locomotion in vertebrates: central mechanisms and reflex interaction. Physiol. Rev. 55:247-304, 1975; and there is a useful book that summarizes a recent symposium on locomotion: R. Herman, S. Grillner, P. Stein and D. Stuart, Neural Control of Locomotion, Plenum Press, New York, 1976. I would also like to call attention to recent developments concerning the mechanisms and function of the stretch reflex in the control of muscle length and tension. I have summarized this latter area in a recent review chapter: J.C. Houk, Participation of reflex mechanis and reaction-like processes in the compensatory adjustments to mechanical disturbances, in Cerebral Motor Control in Man: Long Loop Mechanisms, J.E. Desmedt, ed., Progr. in Clinical Neurophysiol. Vol. 4: Karger, Basel, in press. The chapter by Nashner in the same book also contains information that would be useful to those of you studying gait.

Dr. Basmajian: Jim, there are differences in the biomechanics, but don't you think that the basic neurophysiology is related or evolutionary to the bipedal locomotion of man?

The intermediate animal that we've been studying for some years at the Yerkes Primate Center is the gorilla (and a few chimpanzees, and other apes). We find that there are more similarities than dissimilarities between man and ape when the ape attempts to walk bipedally for reasons such as when you hold up something they want to get above their heads. There are more similarities than dissimilarities in gorilla locomotion on two feet. The dissimilarities would seem to be biomechanical; that is, the gorilla, to stand upright, has difficulty that is based upon its anatomy between the lower thoracic region and the hip joint. But given enough incentive, when he does walk bipedally, there are more resemblances in the electromyography than we had expected. This includes the gluteus maximus muscle which physical anthropologists said for half a century was the limitating factor to preventing the gorilla walking on two feet.

Dr. McMahon: Let me say some words about animal workers in gait. Together with my colleagues, C.R. Taylor and Farish Jenkins of the Biology Department at Harvard, I have been interested in the extent to which running is like the bouncing of a ball. There seems to be the following evidence in support of that analogy.

Firstly, if you look at the frequency of striding during galloping, it is nearly constant in quadrupedal animals. As the animal runs faster, he takes longer steps, but doesn't increase stride frequency. A simple theory which assumes the animal behaves like a hunk of rubber vibrating like a tuning fork can make the correct prediction of stride frequency as a function of animal size, from mice to horses.

Secondly, a new technique we are using shows that the tendons store enormous quantities of energy during a running stride cycle. We tie steel balls inside the achilles tendon (lateral gastrocnemus tendon) and run the animal on a treadmill before a high-speed x-ray machine. The tendon stretches by more than 5 percent while the foot is on the ground. This represents a storage of elastic energy of nearly 40 percent of the energy required to take a stride.

Dr. Basmajian: Tom, that was a lovely dissertation. It raises all sorts of questions. I think you're familiar with the work of Ed Taub on the deafferented monkeys--the amount of residue of behavior--of apparently normal behavior that remains in monkeys who are almost completely deafferented at an early period in life. They manage to walk pretty well and get along quite nicely. We would all assume that such an animal would be like a human being who is denervated in the lower limbs and would be in similar trouble. But the Taub monkeys are not in bad trouble; they can do all sorts of things.

Does the roundtable see as a problem the fact that man's locomotion is practically entirely a learned phenomenon; one that is learned rather late in life compared to most of the quadrupeds you've been referring to, who were born with a genetic pattern of locomotion, and only hours after birth are beginning to imitate their adult counterparts? When I say learn, I mean at a fairly conscious level. A baby learns to walk by imitating what its parents are doing. Then there is a progression over many years in acquiring the adult pattern of locomotion, to the point where it is said, a person's footfall in the corrider can be recognized as that person's signature. In learning this pattern, do we have something that is truly human and different than other animals:

Question: Can man walk like a gorilla?

Dr. Basmajian: It's not easy. My colleague who worked mostly with the gorillas would get down and play with them, and do their kind of locomotion, and he'd become very tired; his back got tired.

Let us now discuss the presentations of Drs. Perry, Murray, and Chao, and the issues that were raised in their papers.

Dr. Rose: To turn to a more general question, that of the characterization of normal gait, one accepts this pattern as an optimum means of locomotion. We have a system however, with different capabilities and different limitations and the question I wish to pose is, why in that case do you accept normal gait as the optimum means of locomotion--in other words, why shouldn't some people limp?

Dr. Basmajian: That's a very good question. Why shouldn't you even attach wheels to their knees and have them roll along? Why do we have to be so anthropocentric in our thinking? Why do we have to have knee joint replacements which are absolute duplicates--except for the embarassing fact that they will not work otherwise. Dave, why don't you give them the San Francisco dicta about what are the limitations of gait? Can you remember the six determinants of gait?

Dr. Sutherland; The six determinants are: pelvic rotation, pelvic tilt, knee flexion in the stance phase, foot and knee mechanisms (4th and 5th determinants), and lateral displacement of the pelvis. A patient with an intact control system can lose one or two determinants and still maintain an even passage of the common center of gravity without rise in energy consumption. Loss of two or more of the determinants makes full compensation impossible. Patient will walk with exaggerated displacement of the common center of gravity and accompanying increasing energy demands.

Dr. Basmajian : A patient who has lost four of the determinants has to decide whether he prefers a wheelchair.

Dr. Stein: One must accept the fact that you have a system which is optimized originally with regard to consumption of energy.

Dr. Simon: Although your statement may be correct, it remains to be proven whether the final goal any individual with a pathological disorder or any treatment program initiated to correct such disorders strives to achieve is an optimization of energy consumption. Someone who has a disability may be incapable of achieving the normal minimal levels of energy expenditure when walking. It is possible that he may be trying to optimize his total energy to the best of his ability. Nevertheless, this attempt is not as good as the normal and clearly may be defined as an impairment. But, it is also to be noted that there are other impairments present. Pain, loss of motion, overall stability, and balance are just some of the other impediments present in an individual's pathological gait. The individual must deal and compensate in some way for all of these if he is to walk. Under such circumstances, it is not clear which factor he "optimizes" or gives priority to. Loss of stability may stop the individual from taking one step. Pain may stop the individual from walking after two or three steps. But, increase energy cost may only stop an individual from walking after some distance is traveled; when further progression becomes extremely fatiguing. The item of acceptability then is the one that achieves maximum forward progression (in distance). Energy expenditure may, therefore, be the significant factor only in the case of normal subjects. Clinically, we are subconsciously aware of this situtation all the time in prescribing different treatments. Braces are used to achieve stability even though they may be increasing energy expenditures. To then relate the situation in normal subjects to that which exists in subjects with pathological disorders may be like mixing apples and oranges. It remains for us to ascertain in each disorder which are the prime factors optimized and how the situation is altered by treatment. The item of the acceptability of the method of progression is significant. Otherwise, the minimum oxygen consumption for all is a motorized wheelchair, and yet we don't choose it. We're mixing apples and oranges, and we do that clinically all the time. We make different optimizations as it were, for different patients, because of their own reactions to their disabilities.

Member: I think there's more to it than that. There's evidence that we do have a good hand on it--the things the patients are happy with when we do optimize them. They do like to have a certain rate of progression; they do like to be able to minimize energies. One can see these things as satisfying. They may be arbitrary, but they certainly solve some of the problems.

Dr. Simon: Certainly, in many cases, either because of the nature of the disease or the treatments available, energy expenditure becomes the rate limiting factor. With oxygen consumption studies, we have an objective method of measuring one aspect of energy expenditure. It is, however, an incomplete measure since it only reflects the aerobic metabolism of the body during walking. Nevertheless, it does provide us with a good indicator in some patients of their walking ability. At certain institutions such as Rancho Los Amigos Hospital where studies of O_2 consumption have been performed, it has been found that once we start increasing our O_2 consumption, we find there is a point at which an adult ceases to walk. Clinically, we are aware of this phenomenon occurring with various disabilities. As young children they may walk but with growth as their body mass increases and energy cost rise, they stop walking.

Dr. Perry: The rate of progression is important for the slower a person goes the longer time he must expend his energy. Hence energy cost per meter becomes a significant functional measure. Further with more severe limb impairment the person cannot exercise sufficiently to develop his energy production system. That is to train heart, lungs, and muscles for oxygen delivery in extraction. With a limited energy production capability a "normal" minute energy cost becomes relatively higher.

Dr. Basmajian: The time, ladies and gentlemen, has come for thinking about some kind of summation, and I would like to suggest that we spend the remaining time discussing the possibility of some national priorities for gait laboratories and gait research, to act as a stimulus for further growth in this area. First, can priorities be set? Is there any way in which we can agree that there are priorities? Is there anyone who has a strong feeling there are no priorities?

Dr. Burstein: We have assembled here people who are deeply interested in the outcome of gait studies, and who have been deeply involved in this area for quite a while. If one can generalize and offer a useful outcome, I would suggest certain things. For example, when we look at gait laboratories and gait studies, I might suggest that we've been developing them using the patient for approximately 30 years. We've reached the stage in development where there is a wide range of instrumentation available, at a wide range of costs, and certain degrees of sophistication, and that we probably, at least in my opinion, should consider developing new instrumentaiton only if we can show that it serves the needs in reaching some goals that are not yet available to us. If you want to talk about a priority, then the development of new conceptual instrumentation should be based on an established need to go over and above the capabilities of existing instrumentation. I'm not talking about number of facilities. That's an entirely different question, but my personal feeling, from the point of view of one involved in instrumentation, is we have more capabilities now than we have uses for it.

Dr. Basmajian: But Al, that's sort of a negative priority.

Dr. Burstein: I didn't get to the positive ones. I just wanted to throw this umbrella idea over the whole area. What about the direct measurement of muscle force? I don't think that one has to worry at this point about developing a kinematic system that can resolve at intervals of let's say, greater than two millimeters. I don't think it is worth the cost, in light of other things we have mentioned. But, if one could measure muscle force, and there's a demonstrated need to do that, because there are clinical questions that have to be answered directly...

Dr. Basmajian: Direct, clearly on-line measure of muscle force...

Dr. Burstein: ...that certainly would be an interesting extension of our instrumentation capability. There possibly are one or two others--and I'm not saying, don't develop them, but I think we should be critical in the expenditure of time and effort at this point. You can become too caught up in the ability to measure things more precisely and more quickly and more rapidly. It doesn't always lead to more progress.

Dr. Basmajian: Can we debate this concept that the state-of-the-art of gait studies in man is now sufficiently developed so that we need not be encouraging major developments--major improvements--in instrumentation?

Members: Pros and cons.

Dr. Basmajian: We agree then that the state-of-the-art in human gait studies is sufficiently advanced so that a major investment to improve upon them is not a top priority. So can we say that reducing the complexity of clinical diagnosis and prognosis, is needed?

Dr. Burstein: I'd put it more strongly than that. I would say right now we have almost no clinically-useful diagnostic tools that can be taken outside of the very heavily-financed research laboratory. There's a complete imbalance between capabilities in a research center...

Member: ...where you may very well do clinical work, but that's not the question. But outside of the heavily endowed research center (with few exceptions) you do not have the capabilities of doing gait analysis/or research.

Dr. Basmajian: What about the need for and understanding of normative data?

Dr. Burstein: Requests to support the procurement of normative data should be evaluated on the basis of individual merit. I think the only thing to establish (in terms of priority) is if somebody sees an area of normative data that is missing and it's related to their clinical interests--then the priority on that is as high as the clinical need or the area of associated investigation. Normative data is necessary in any basic science--especially in the medical and biological sciences. We always talk in terms of studying the abnormal and that inherently implies that we need normative data.

Dr. Perry: All gait laboratories are equipped with multipurpose systems. Many are put together in rather a prototype fashion which requires repeated calibration and adjustment by the staff. For wider application of gait analysis clinically reliable dedicated systems are needed. This should be one objective in improving the development of gait instrumentation. The fact that most gait laboratories are not regularly providing clinical measurements identify that all these laboratories are not set up to do so. Also all laboratories do not measure the same factors. There still needs to be interpretations that will identify which data proves useful guidelines for physicians and therapist.

Dr. Stein: If we say that human gait labs are well set up and well instrumented, then the question is, what are the related studies on animals and when can they begin? In animal studies the idea of looking for general principles, by looking at a broad spectrum of animals, needs to be pursued.

Dr. Childress: Dr. Chao brought up an important point which I should like to emphasize. This is the need for cooperative efforts among the existing gait laboratories. Funds are limited and progress will be slower if the 20-25 laboratories in this area work independently.

We know from such fields as molecular biology and high energy physics that great strides can be made through tightly drawn communication channels. Would an internal sharing of data and information before it is published be beneficial or feasible in this small field?

Dr. Basmajian: That is almost an outcome of the decision that if the state-of-the-art is good, then obviously we move to the situation where we need cooperation. And how do we get that cooperation? Do we have one group acting as a clearing-house? If not necessarily a coordinating center, a clearing-house. And would, for example, NIH accept a grant application for a department to be a clearing-house for information on gait studies? It might not be a very attractive job, but it is a possible way to proceed. Do we then feel that cooperative effort is a high priority, by any technique?

Member: In a meeting with Dr. Fredericksen (Director, NIH) one of the things he pointed out was that in the future we may have work with less in grant funds, and that more cooperation between institutes and between agencies of the government, will have to be developed to best utilize available funds.

Dr. Basmajian: A substantial number of Mickey Milner's list of gait centers are outside the United States, of course, and are doing work as impressive as that which is being done in the U.S. Something could be worked out, surely. So I gather that we see the state-of-the-art as satisfactory for human-based studies in locomotion but that the future emphasis should be on cooperation and sharing. I might ask Dr. Burstein about sharing efforts; he was in a group that tried to get together and standardize techniques some time ago. Did anything ever come out of that as far as gait studies are concerned?

Dr. Burstein: The activity itself was useful. It occurred in 1969 to 1972. The report finally appeared about two years ago. But the activity itself was very useful to all of us in gait, and considerable standardization was achieved. The standardization was probably of secondary value for the fact that during that time we all learned a tremendous amount and were able to keep fully apprised of what was going on. There is, by the way, a publication that is circulated to people doing gait analysis.

I might also mention another whole group who uses gait laboratories but who are not represented here, that is the people involved in athletics. There are probably more of those facilities than now represented on our lists. Their activities are useful; unfortunately, they do have to be supported, but the benefit that you obtain from their work far exceeds support costs.

Dr. Basmajian: Did you have them in your earlier group? Did any of the atheletic researchers...

Dr. Burstein: No.

Dr. Basmajian: Does CPRT sponsor most of their work?

Dr. Burstein: Yes.

Dr. Basmajian: And SRS used to sponsor some things, and the Veterans Administration also is interested. So there are some agencies who have shown interest.

So we're talking about state-of-the-art, not about individual devices. The state-of-the-art is sufficiently developed so that small variations are not as important as they once were and they should be interchangeable; the emphasis should be on interchangeability.

Member: Just on that point could I say that, as more and more people go into the field and need equipment, a lot of time and effort will go into acquiring and standardizing it.

Dr. Buskirk: In the same vein, Simons described the standardization with respect to the techniques for making the measurements--but you also need to standardize terminology. Then if you put these two together, it seems to me that you're going to know whether you're talking about the same measurements.

Dr. Stein: I was wondering whether the other side of the coin of your projection about the state-of-the-art and technology meant that applications for the establishment of a gait lab would be looked upon with disfavor by funding agencies?

Dr. Basmajian: That implication might be read into it by outsiders, but I don't think that really is the inference we should take here. Probably what we've been saying is that if someone comes along and says, "I want $100,000 to improve upon a forceplate" or some such thing, that wouldn't be looked at with great enthusiasm. But if someone decides to conduct research using current methodologies, preferably in an existing lab, that would be looked upon with more favor. But we're not really discussing grant applications at this workshop.

Member: Is any priority being put on human work, rather than animal? Or is research to be judged entirely by the merit of the questions being asked?

Dr. Heiple: There is no question that the Applied Physiology and Orthopedics Study Section has both approved and given high priority scores to meritorious proposals involving animal models, if they looked at important questions in relation to fundamental problems in gait or locomotion.

Dr. Basmajian: I think that the tendancy to consider human gait work came out strongly today. I doubt whether this Study Section can afford to look at it simply because it has to do with human gait, but rather to look at its value and the questions that are being asked. I don't know how to put a priority figure on that. I imagine that's always been one of the NIH's requirements--that the questions being asked are valid. You are suggesting that good questions have priority--I think that's automatic, we expect that.

Dr. Buskirk: Just for our enlightenment here, and since I do not know what is going on in the area, what training activities are available, and how do you set these up, and is there a priority that needs to be established? What's the optimal mix in personnel? I see looking at the programs in the Milner list, that the basic interests appear to be locomotion. That is about the only common feature that you see.

Dr. Basmajian: Good question. Are there some other kinds of priorities, such as training?

It seems to me over the several years that I've watched the growth of gait labs, that half of them result from someone moving to a new institution where he or she has to have a gait lab. They do not seem to spring up otherwise; they are a shift, the result of people leaving and going somewhere else. There's one now, for example, in Waterloo, Canada--it moved from Winnipeg to Waterloo; there's one now at McMaster because Mickey Milner moved to McMaster, and Dave Sutherland moved here, (i.e. San Diego) so there's one here now. Do we need some sort of national priority for training people in this area, or have we reached saturation point even in the number of persons, let alone saturation in the state-of-the-art? There are some 20 such centers now with two, three, or four people at each center. Anybody have any views?

Members: Considerable discussion (not recorded).

Dr. Basmajian: Wayne, would you like to tell us what you have on the blackboard, and what you think is the consensus?

Dr. Akeson: This Workshop has produced a useful compilation of the techniques and facilities which are available for the analysis of gait abnormalities. It is clear that there has been an extensive effort to bring modern technology to bear on the analysis of gait. The variety of sophisticated techniques which have been described offer an ample selection of tools for a study of locomotion disorders. While deficiencies in most of these techniques can be identified, the techniques are adequate for application to most neuro-musculo-skeletal research which requires motion analysis.

The question of research priorities in this field has been raised repeatedly during the Workshop. The most obvious existing need in terms of application of existing technology to clinical analysis, is to develop additional normative data of a variety of types. This effort deserves high priority in the near term for obvious reasons. Coordination between laboratories would reduce any redundancy of this effort.

Another priority which has come up several times during the Workshop is the need for direct measurement of muscle force. This problem does require the development of additional sophisticated instrumentation, an exception to the general statement that the gait laboratories do not require a great deal of more advanced technology for their application to neuro-musculo-skeletal research.

More complex questions arise with respect to the evaluation of results of application of gait analysis in scientific investigation. As Dr. Burstein has pointed out, good scientific questions are being asked by some of the investigators using these laboratories, but many of the laboratories have become bogged down in problems of technology, data management, and redundancy of description. These difficulties are expected to some degree in an era of expanding technology. But they also probably reflect a low order of collaborative effort between the principals: bioengineers and orthopedic surgeons or physiatrists on the one hand and neurophysiologists or neurologists on the other. Dr. Leith has charged during the Workshop, with some justification, that an inordinate gap exists between applied clinical science and basic science which has seriously hampered quality gait laboratory productivity. This is probably the most serious charge which can be leveled at a burgeoning field, and is surely the basis of much of the criticism which has been directed at research utilizing gait analysis in the recent past. It is self evident that critical focus of the scientific method in this complex field in which neurophysiology, neurology, orthopedic surgery, physiatry and engineering overlap requires a multi-disciplinary input, but because of the realities which have been noted, the point must be stated and emphasized. Furthermore, gait analysis is not a discipline, but rather simply a tool which can be used by those interested in malfunction of the neuromuscular control apparatus to obtain specific objective measurements. Gait analysis is but one type of motion analysis which is a necessary element of the data gathering process in projects where there is interest in abnormalities of physical performance. Its effective use requires the effective collaboration of members of each of the scientific disciplines listed above.

Many applications of the locomotion analysis techniques have been suggested today, not only to study control mechanisms, motor activity, and energy expenditure, but also sensory input and response to biofeedback. Applications of gait analysis to animal research is equally appropriate as it is to human locomotion studies and applications from primates through tetrapods have been quoted by Drs. Houk, McMahon and Basmajian which attest to this fact.

As several Workshop members have pointed out, instrumentation already available can provide most of the measurements asked of a locomotion analysis laboratory. The question of the appropriate number of laboratories which should be supported by Federal agencies hinges on specific requirements. Are sound teams of collaborators working together who can develop appropriate hypotheses for testing with this method? The utility of this tool, as others, hinges entirely on the scientific merit of the investigations proposed. Hence, it is folly to attempt to describe the optional number of laboratories or dollar amounts of funding. Rather, one senses a certain amount of urgency about getting on with the appropriate application of the technique rather than further refinement or addition of more complex techniques. If anything, a priority item in locomotion research is the development of techniques simpler to understand, less expensive, less technologically complex and with more discriminating data output which can find application in everyday clinical practice. The elegant refinements from Dr. Perry's laboratory serve as an outstanding example of this approach.

In brief, technology has arrived, but appropriate application has lagged largely through insufficient collaboration between investigators using gait laboratory tools and neurologists or neurophysiologists. Additional collaboration between existing laboratories is also a priority concern which has been emphasized by Dr. Chao and Dr. Childress. Key among near term priorities is closer communication between workers in the field. Improved communications and supplementary meetings of this relatively small group would seem easy to accomplish.

Dr. Basmajian: What remains is to tell you that our time is up, and also to conclude by thanking all of you--especially the guests who came and joined us. We hope that they got as much out of this Workshop as the members of the Study Section obviously did. This session will, I am sure, enable the members of the Study Section to view grant applications with considerably more knowledge and more understanding in the future. Thank you for coming.

JUSTIFICATION OF GONIOMETRIC METHOD AS A MEANS TO EVALUATE JOINT REPLACEMENT PATIENTS

Edmund Y.S. Chao, Ph.D.

ABSTRACT

Accurate measurement of human joint motion is essential to the design and evaluation of internal joint prostheses and artificial limb replacements. triaxial electrogoniometer, instrumented by three miniature precision potentiometers, was developed to fulfill this task. Special linkage was used to attach this apparatus externally to the joint. Three-dimensional angular motion following the classical Eulerian angle definition was measured in real time. The error due to exoskeletal attachment was corrected by the method of 4 x 4 matrix. This technique is now being routinely used on the patients with abnormal hip, knee and ankle joints for objective functional evaluation.

INTRODUCTION

The chronic disease of arthritis and the traumatic inflicted degeneration of human articulating joints have caused severe functional disability for a very large population in this country (1). The loss of manpower and the medical care expenses are incalculable. Following in the wake of the dramatic breakthrough in total hip replacement introduced by Charnley (2)(3), internal joint prosthetic replacement has become the treatment of choice for severely diseased and deformed joints in the human body, particularly in the lower extremities, which includes the hip, knee and ankle joints. A selection of some of the most commonly used internal joint prostheses in the lower extremities is illustrated in Figure 1.

Anatomical and functional integrity of lower extremity joints is essential to human mobility. If any one of the related joints is affected by the disabling disease, the walking pattern will be abnormal, thereby creating substantial functional limitation. Artificial joint replacement is aimed at alleviating this functional impairment and at the same time controlling the pain and correcting the deformity caused by the disease process. Performing objective functional evaluation of these joints in normal subjects will help to establish the standard norm for the joint functions, which can provide the basic design requirements for the prostheses. Such evaluation, if carried out on patients before and after joint replacement, will obtain a quantitative assessment of this new surgical treatment modality. Subsequent design modifications and surgical technique improvements can be implemented to enhance better results.

Traumatic and pathological amputation of the lower leg at various levels requires artificial limb replacement so that the patient can accomplish ambulatory functions, needed in daily activities. The design of artificial limbs requires certain basic guidelines based on measured normal walking data. Evaluation of these artificial devices when they are applied to

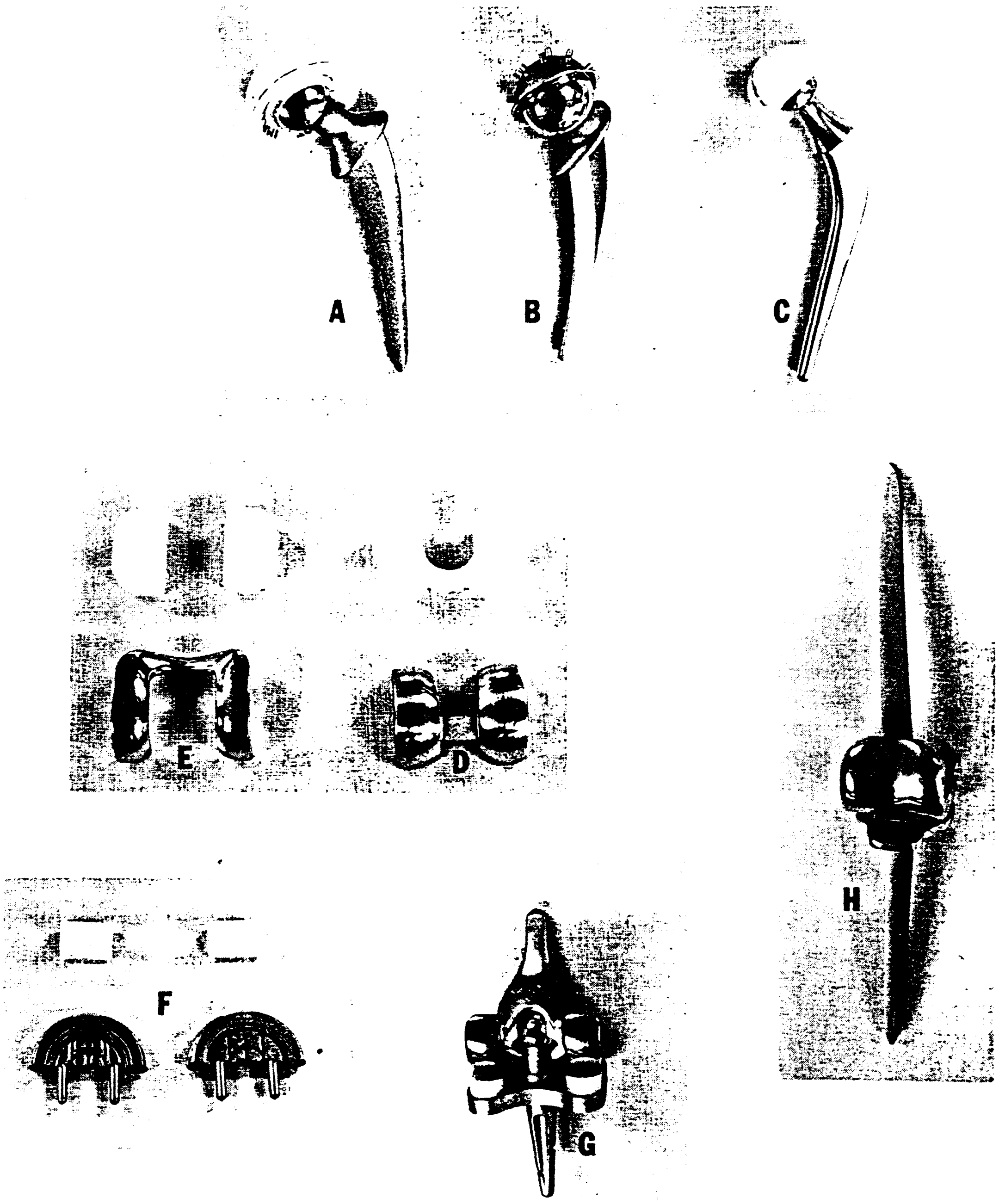

Fig. 1 - Commonly used joint prostheses for the hip and knee. (A) Müller-Charnley Total Hip. (B) McKee-Farrar Total Hip. (C) Charnley Total Hip. (D) Geometric Total Knee. (E) Dual Condylar Knee. (F) Polycentric Total Knee. (G) Spherocentric Knee. (H) Gepar Hinged Knee.

patients also demands certain quantitative means to record the joint motion magnitude and patterns. A reliable and easy-to-use instrument capable of providing accurate joint motion data is therefore warranted.

In recent years, objective functional evaluation has played a significant role in orthopaedic management of patients with musculoskeletal joint diseases. (15)(16)(17). The methodology developed enables one to examine the anatomical integrity and functional status of affected joints in quantitative terms. The reliability of the experimental technique provides new dimension to correlate the exact functional and anatomical abnormalities with clinical examination results. Many important medical and rehabilitative decisions have been influenced by these findings. Such a unique capability offers an opportunity to introduce new disciplines into the field of medicine so that innovative concepts relating to patient care can be developed. This interdisciplinary action would be extremely helpful to many medical problems confronted with unsatisfactory solutions.

Since the correction of joint deformity and restoration of normal function are important factors in judging the success or failure of the treatment of joint disease patients, an objective gait analysis of the hip, knee and ankle motion on a group of subjects before and after joint replacement surgery can accomplish the following objectives.

1. Correlate joint functional deficits and deformities with clinical and biochemical assessment of the disease.

2. Provide an objective means to evaluate the effectiveness of therapeutic and surgical treatments on arthritic patients.

3. Recommend better physical and occupational therapy for patients with systemic involvement so that undesirable usage of joints could be avoided to prevent further deterioration of disease status.

4. Identify critical timing for more aggressive (surgical) treatment for patients in the advanced disease stage to ensure best possible results.

EXPERIMENTAL METHOD AND INSTRUMENT DESIGN

Human lower extremity consists of three major joints; the hip, knee and ankle, as illustrated in Figure 2. The hip joint is basically a ball-and-socket joint possessing three degrees of freedom. The knee joint resembles a hinge joint with one degree of freedom in flexion-extension. However because of the laxity and irregular joint surface geometry, small motion in other planes is also important. The ankle is a more complex joint because of the subtalar structure. If the ankle can be regarded as an ensemble of bony elements providing relative motion between the foot and the tibia, it could be assumed as a modified ball-and-socket joint. As a result, all lower extremity joints could be treated as some sort of ball-and-socket joints capable of producing three-dimensional rotation. In designing the measuring device, this basic requirement is therefore essential.

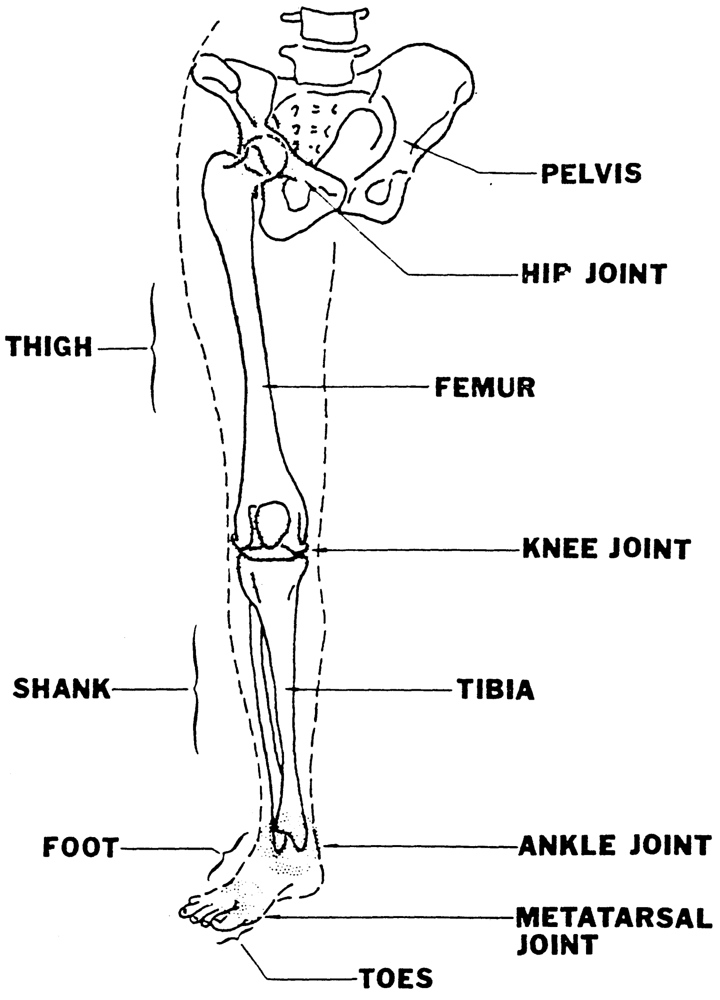

Fig. 2 - Skeletal joint system of human lower extremity.

For the convenience of specifying the direction and sense of joint motion in accordance with clinically acceptable terminology, the following table of definitions is used.

Joint	Angular Motion	Axis	Sense
Hip	Flexion-Extension	Z_H	Ext. (+), Flex. (-)
	Abduction-Adduction	Y_H	Add. (+), Abd. (-)
	Int-Ext. Rotation	Z_H	Int. (+), Ext. (-)
Knee	Flexion-Extension	Z_K	Flex. (+), Ext. (-)
	Abduction-Adduction	Y_K	Add. (+), Abd. (-)
	Int-Ext. Rotation	X_K	Int. (+), Ext. (-)
Ankle	Plantar-Dorsal Flex.	Z_A	Plan. (+), Dors. (-)
	Abduction-Adduction	Y_A	Add. (+), Abd. (-)
	Int-Ext. Rotation	X_A	Int. (+), Ext. (-)

The reference axes and joint motion definitions are depicted in Figure 3 for the hip, knee and ankle joints.

Several techniques have been described in the past to measure lower extremity joint motion in human walking. These include the interrupted light photography method, (4)(5) the TV monitoring method, (6)(7) the accelerometric method, (8)(9) and the electrogoniometric method (10)(11). The photometric and TV methods require tedious data reduction and analysis procedures, thus making them difficult to apply to large patient population. The accelerometric method provides limited information concerning joint kinematics. The use of the electrogoniometric concept presents many advantages, particularly for fast data reduction. It was, therefore, selected for the present application. However, it must be recognized that such an instrument cannot measure the translational components of joint motion, and the joint has to be assumed as a ball-and-socket joint in a gross sense. In reality, the translational motion of lower extremity joints is small, therefore the use of the triaxial goniometer is justified.

The development of the electrogoniometer was first introduced by Karpovich (12) and later used by other investigators. Many modifications have since been introduced for better results. The sophisticated design introduced by Lamoreux (13) is capable of measuring accurate joint motion, but the cumbersome attachments prevent it from being applied to patients. Following the old design used by Johnston, et al, (10) a new version of the electrogoniometer assembly was developed which can be conveniently applied to the hip, knee or ankle joint for on-line, real-time joint motion measurement. Figure 4 depicts this new design which is the most compact and easy-to-use triaxial electrogoniometer assembly available today.

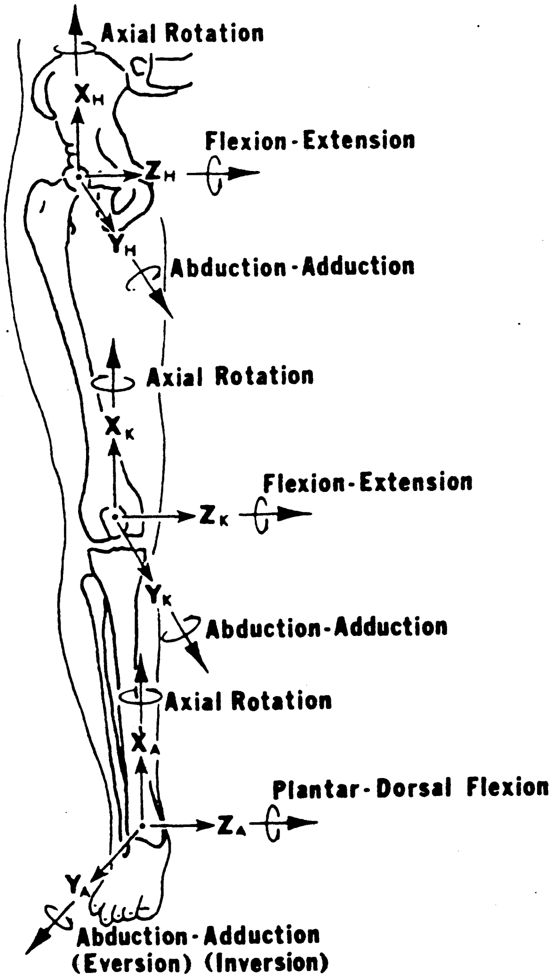

Fig. 3 - Definition of lower extremity joint angular rotation.

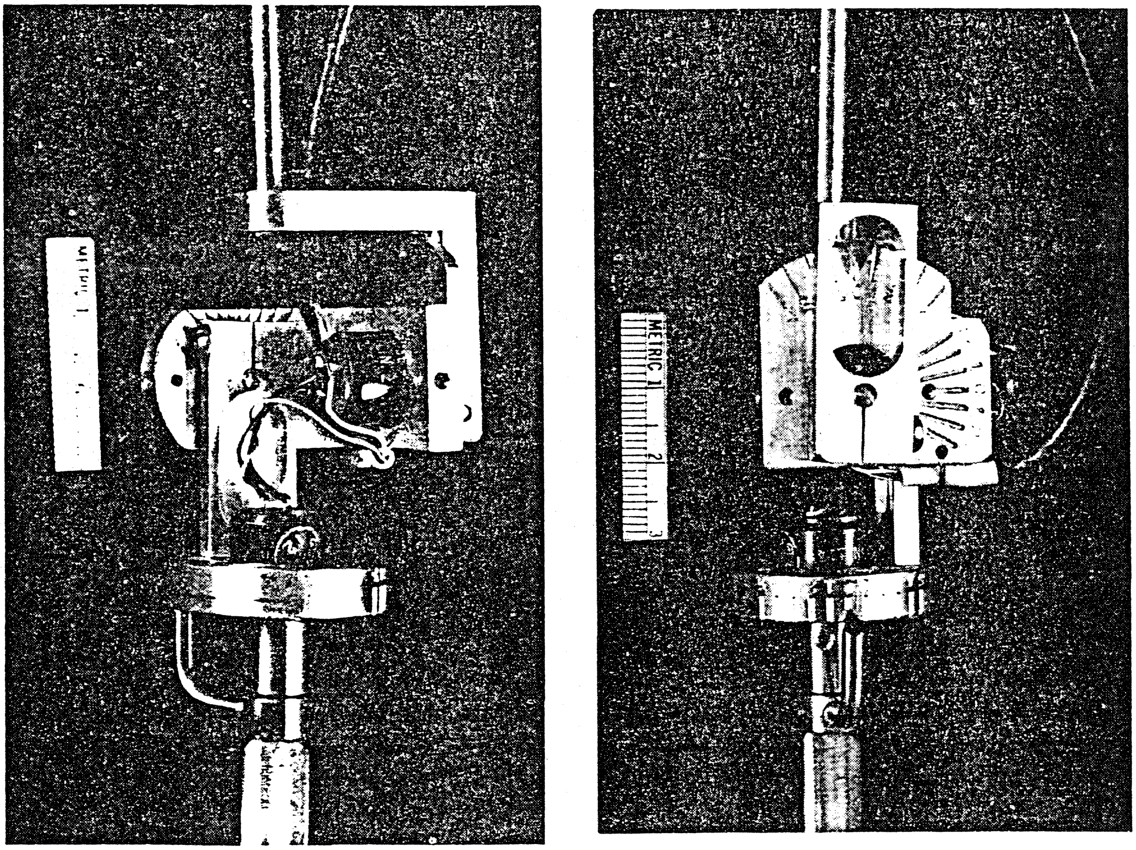

Fig. 4 - Triaxial electromechanical goniometer used to measure three-dimensional rotation of the hip, knee and ankle joints.

The goniometer is constructed by fixing three Duncan miniature potentiometers of the conductive-plastic type (Resolon Pot 1020-556) oriented orthogonally. Each pot has its own axis of rotation capable of measuring the three-dimensional angular motion following the definitions designated in the previous table. Beckman half-bridge pressure/force amplifiers are used for output signal conditioner. High resolution (0.1%) and linearity (1%) signals are plotted on a Beckman/Offener Chart Recorder and stored simultaneously in an Ampex FM 1300 Tape Recorder for later analysis.

Specifically designed attachment devices were used at the hip, knee and ankle area to fasten the goniometer assembly, as seen in Figure 5. The attachment to the proximal segment of the joint forms a set of fixed coordinate systems and the distal attachment constitutes the moving reference The relative angular motion between the fixed and the moving system provides the three-dimensional joint motion based on Eulerian angle definition.

Overhanging track above the walkway, as seen in Figure 6, carries the cables to transmit the signals to the recorders. Foot switches attached to the soles of the shoes (also shown in Figure 5) provide timing marks to identify the important periods of walking during patient experiments. A specially designed walkway is utilized to obtain other pertinent information concerning patient walking characteristics.

The patient is asked to walk back and forth along the walkway for eight to ten times. Two optical switches located at the midsection of the walkway (Figure 7) are used to identify the reliable sector of the gait for subsequent analysis. Step length is recorded by a specially designed apparatus, as shown in Figure 8. Similar tests will be performed for other activities of the lower extremity. All data will be recorded by a Beckman Strip Chart Recorder for verification purposes and transmitted directly to a PDP-1134 Computer for analysis.

Data analysis methods include: (1) statistical correlation, (2) harmon spectrum analysis, and (3) phase-diagram analysis. All clinical and biomech ical data are graded so that a performance index and symmetry index can be obtained to describe the functional performance of the patient studied. The entire experiment requires approximately 45 minutes. Within two hours after the examination, a complete analysis with all pertinent data will be compile for final evaluation on this patient. Such data can then be summarized and presented to the physician in charge. Proper evaluation on the functional status of the patient can then be made.

ERROR ANALYSIS AND CORRECTION

Since the goniometer assembly is attached externally to the joint, the potentiometers may not record the true joint motion. The error between the goniometer readings and the actual joint motion is defined as the cross talk, which has to be quantitated and corrected subsequently, if necessary. If the relative motion between the attachments and the bone beneath the soft

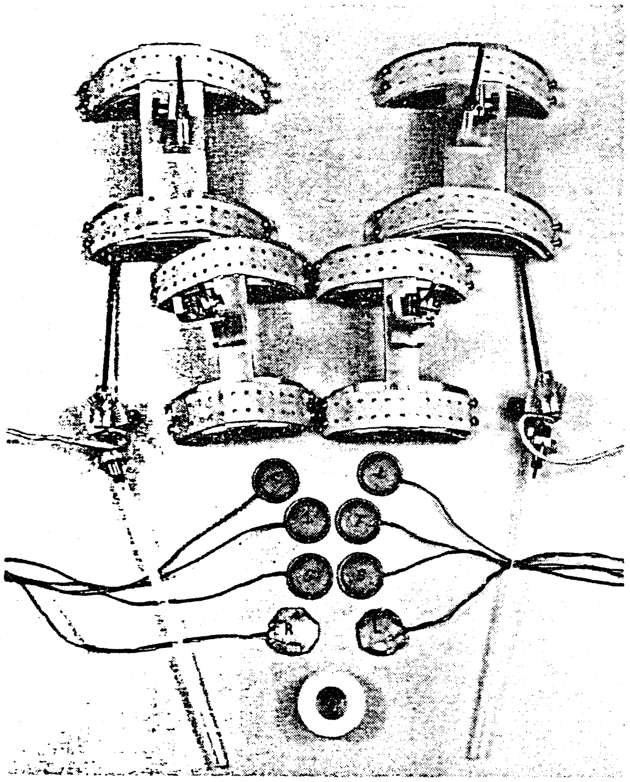

Fig. 5 - Triaxial goniometers, attachment apparatus and foot switch system used for human gait analysis.

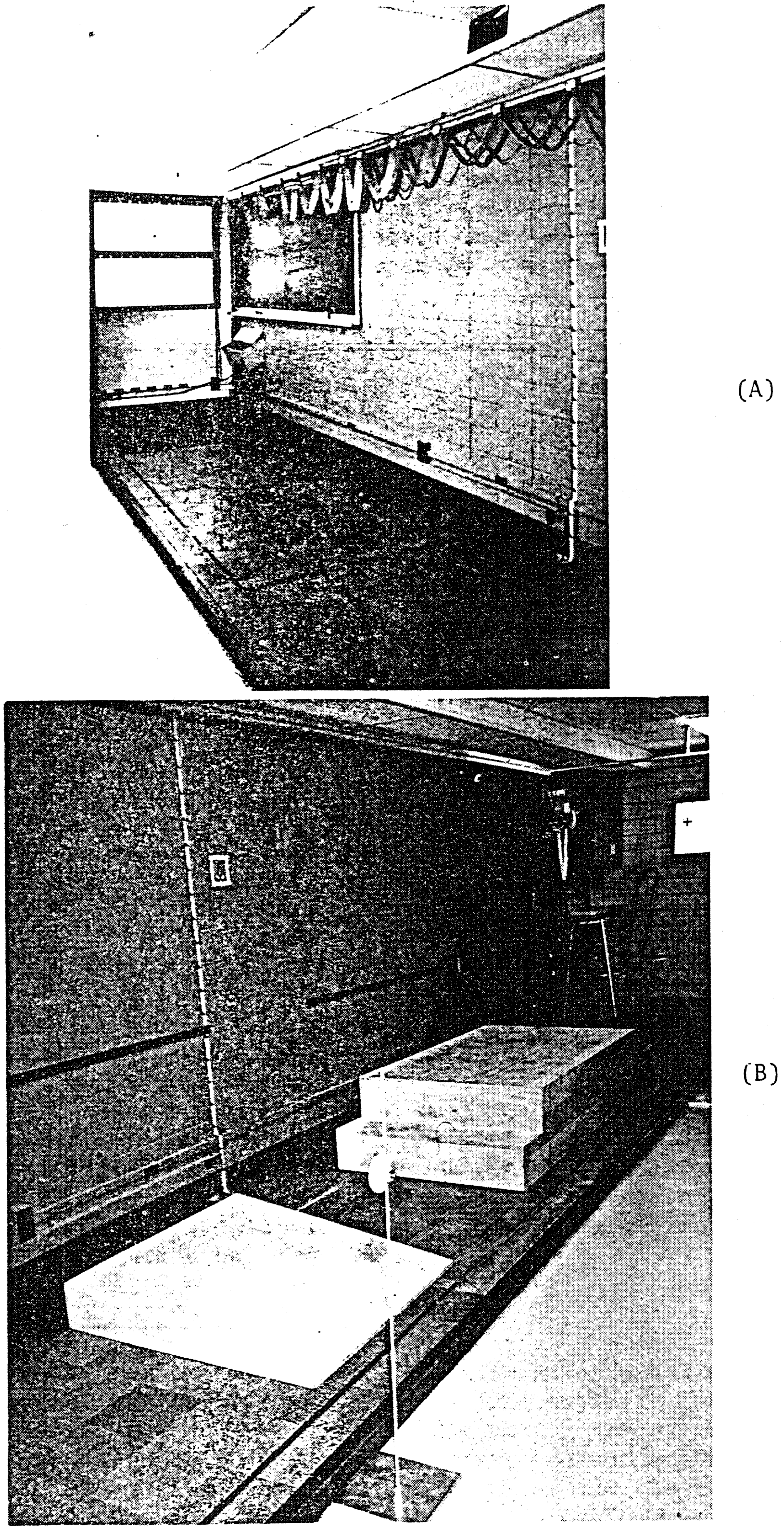

Fig. 6 - Gait laboratory walkway. (A) Overhanging track and force plate used to transmit goniometer data and record foot-floor reactions. (B) Wooden blocks used to simulate various ground slopes and stair conditions.

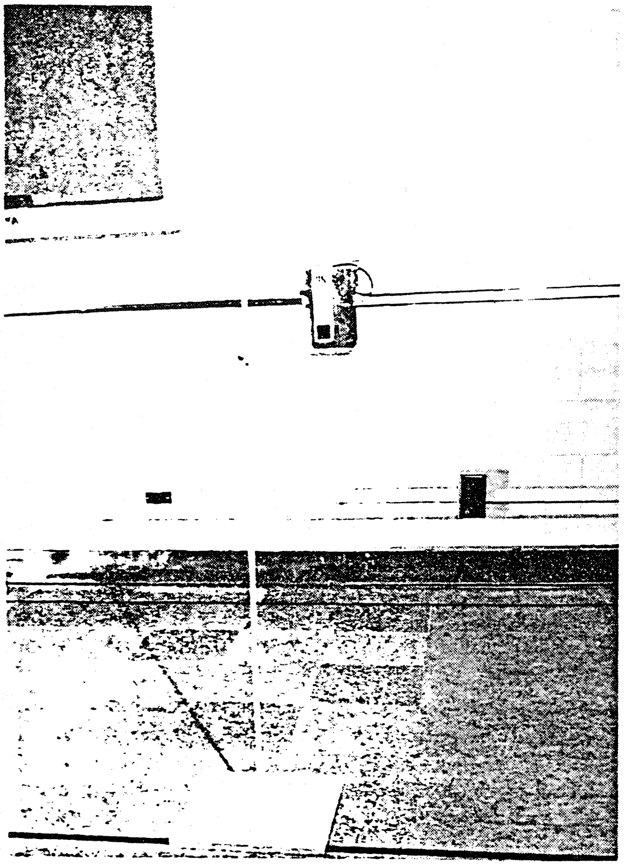

Fig. 7 - Optical switches used to determine gait temporal-distance factors.

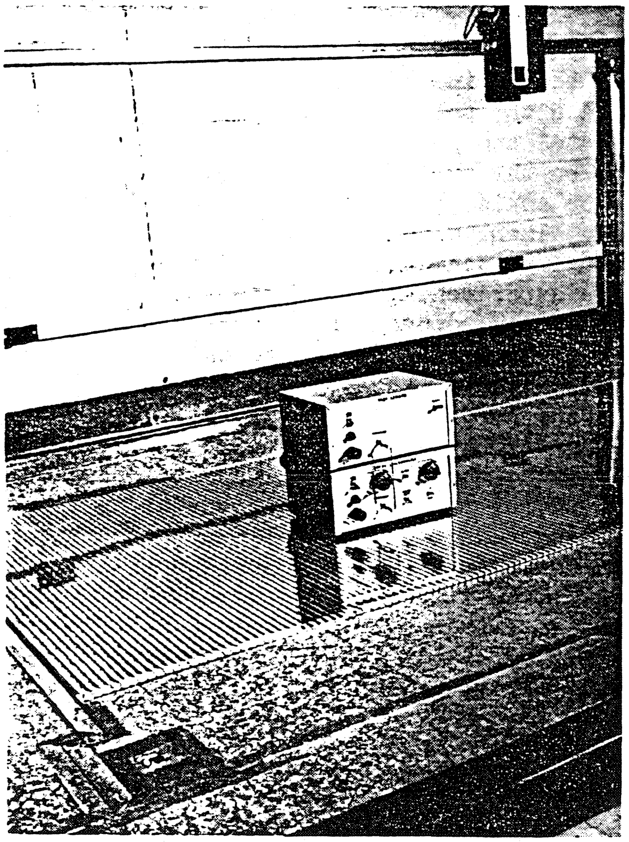

Fig. 8 - Foot conductive strips used to measure step length during gait.

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tissue can be neglected, the goniometer linkage and the skeletal joint system can be modeled as a seven-bar spatial mechanism, as seen in Figure 9. Since two of the seven links are connected by a spherical joint (ball-and-socket), the mechanism has only three degrees of freedom. With the three angular motions recorded by the goniometer pots, the remaining motion of the entire linkage system is uniquely defined. Using the method of 4 x 4 matrix, the ball-and-socket joint (hip, knee or ankle) motion can be determined analytically.

The 4 x 4 matrix method and the way it is applied to correct the goniometer readings has been presented in a previous publication (14). It is, therefore, omitted here. In essence, it applies a linkage loop equation based on the 4 x 4 displacement matrix to determine the spherical joint motio through an iterative process. The true joint motion is first estimated and the error between the calculated and estimated results is minimized until the final results satisfy the linkage loop equation under certain convergence criteria. The differences between the final joint motion data and the potent meter readings are defined as the cross talk, which will be used to assess the reliability of the measurement device.

Corrections were obtained for the hip, knee and ankle joints on subjects undergoing normal walking experiments. Figure 10 illustrates the difference between the goniometer reading and the corrected hip joint flexion-extension during normal walking. Small cross talks were also observed in other components of hip motion. Similar results were found for the knee and ankle joints. However, when motions in planes other than the flexion-extension were large, cross talks became significant and therefore required correction. In order to further verify this correction technique and to develop certain closed-form formula, a special experiment was conducted.

In normal correction process, the actual joint motion cannot be recorded directly since the joint is embedded inside the soft tissue. A special model was thus constructed to simulate the actual set up where two plastic cylinder were used to represent the distal and proximal joint segments. A triaxial goniometer was placed in between the cylinders to make up a ball-and-socket joint similar to a hip, knee or ankle joint, but its angular motion could be measured and recorded exactly. Then, a second electrogoniometer system was attached to the distal and proximal segments in an identical manner as that applied to humans. The entire experimental device is shown in Figure 11. Various experimental tests were then conducted to observe the effect of cross talks. The 4 x 4 matrix method was applied to examine the effectivenes of the correction procedure implemented.

Similar results were found in that the amount of correction was small if flexion-extension remained to be the dominating mode of joint motion. However, if other motions (abduction-adduction and rotation) were significant (greater than 10 degrees), cross talks became significant and thus required correction. An example of the cross talk and the subsequent correction results are shown in Figure 12. The difference between the goniometer readin and joint reading reflects the magnitude of cross talk. After correction, the true joint motion was nearly duplicated, which demonstrates the reliability of the analytical correction technique used. The small variation

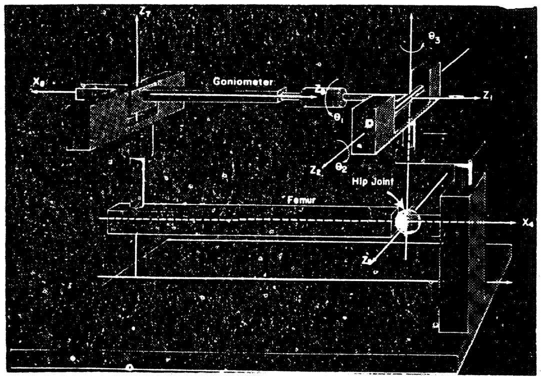


Fig. 9 - The 7-bar, 9 degrees of freedom spatial linkage system used to model the goniometer and lower extremity joints for error (cross talk) correction.

Fig. 10 - Comparison of the goniometer measured and mathematically corrected joint motion in hip flexion-extension.

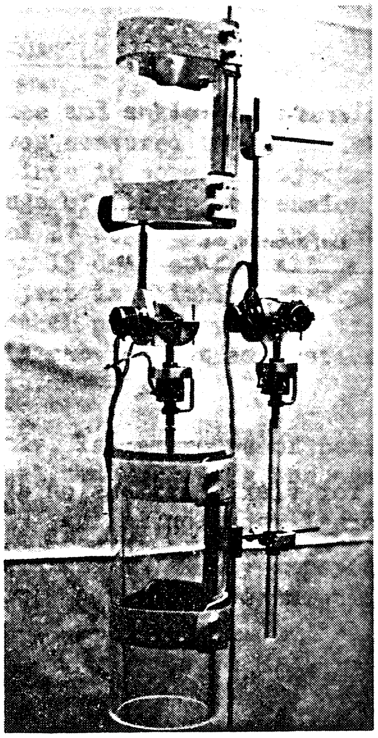


Fig. 11 - The experimental set up used to verify the analytical method of correcting the cross-talk error. The center goniometer system is used to simulate the actual anatomical joint to be measured.

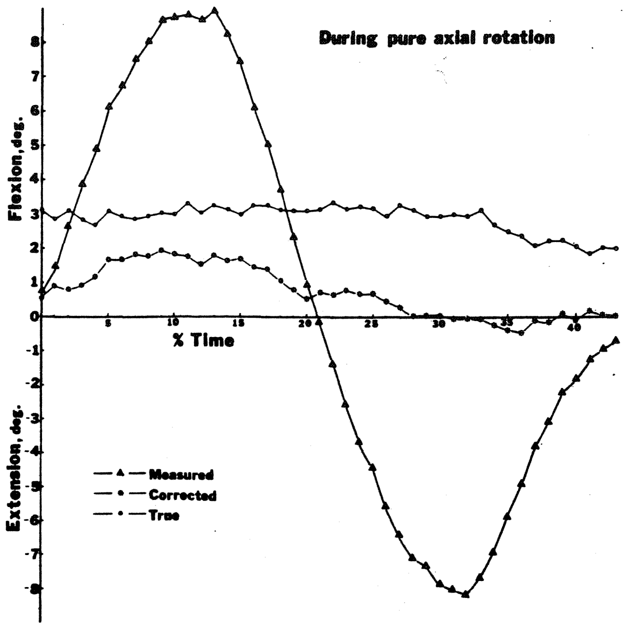


Fig. 12 - Cross talk in flexion-extension due to large axial rotation in the goniometer measurements. The corrected motion closely matches (the difference in magnitude was due to initial off set) the true joint motion measured by the goniometer situated at the joint center of the experimental model shown in Fig. 11.

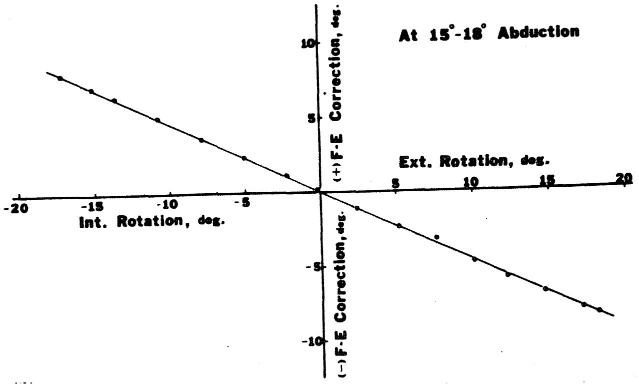


Fig. 13 - Correction relationship for flexion-extension as related to internal-external rotation in the goniometer measurements.

between the true and corrected values was due to the residual placement error. The important feature is to observe the nearly identical patterns exhibited.

The most significant correction is required for the flexion-extension component with large magnitude of internal-external rotation. The magnitude of correction (or the cross talk) on flexion-extension as a function of rotation is plotted in Figure 13, which fits the following linear equation nicely.

$$\phi_{jt} = \phi_{gon} \pm 0.48\ \phi_{gon}$$

where

ϕ_{jt} = flexion-extension occurring at the joint,

ϕ_{gon}= flexion-extension measured by the goniometer, and

ϕ_{gon}= internal-external rotation measured by the goniometer.

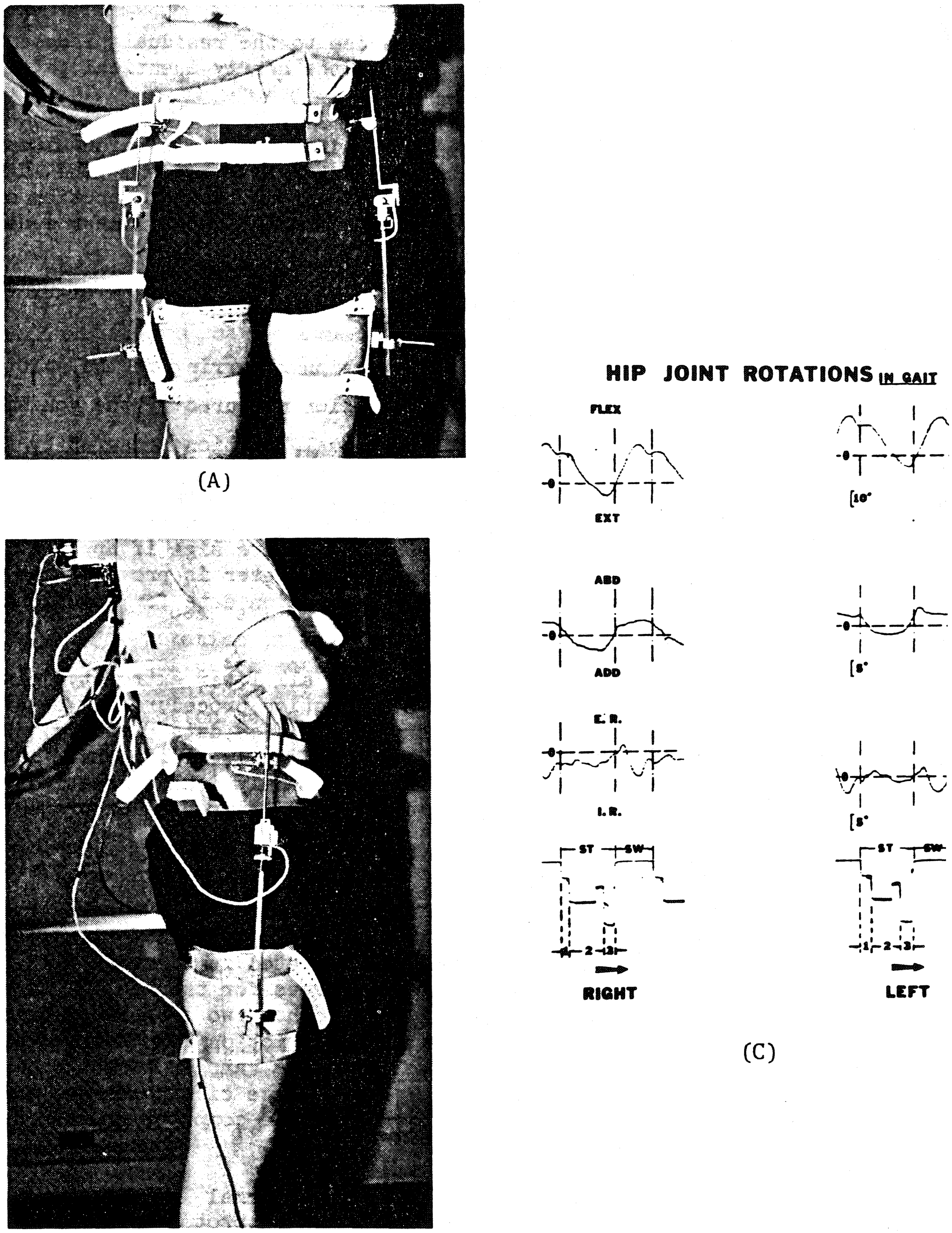
When the rotation is external, positive sign should be used in the above equation and when the rotation is internal, negative sign if applied. From the results of this experiment, the electrogoniometer is proven to be adequate and reliable to measure human joint motion data for functional evaluation purpose.

In normal walking, flexion-extension for all lower extremity joints is always dominant, which implies that the correction procedure may be avoided so that the goniometer pots provide the joint motion data directly. However, in abnormal subjects and in other activities of daily living where leg joints would require an excessive amount of rotation, analytical correction, as presented previously, has to be applied in order to produce accurate results.

PATIENT EVALUATION

Hip, knee and ankle joint motion during walking for a large normal population was measured to establish a data norm. Typical motion patterns for these joints in normal subjects are illustrated in Figures 14,15,16. The mean range of flexion-extension is 55 degrees for the hip, 62 degree for the knee, and 37 degrees for the ankle. The other two components of motion are less than 15 degrees for all joints. These motion components would vary when the subject is climbing stairs, walking on a ramp or side slope and performing other necessary activities. Under these circumstances, analytical correction is carried out automatically within the computer program during data analysis.

Currently, large groups of patients with abnormal lower extremity joints are being analyzed following the same experimental protocol. Those patients who are candidates for total joint replacement will be analyzed postoperatively. These results will be compared with that of the normals for objective functional evaluation. Many important clinical implications concerning the results of such surgical treatment can then be drawn.

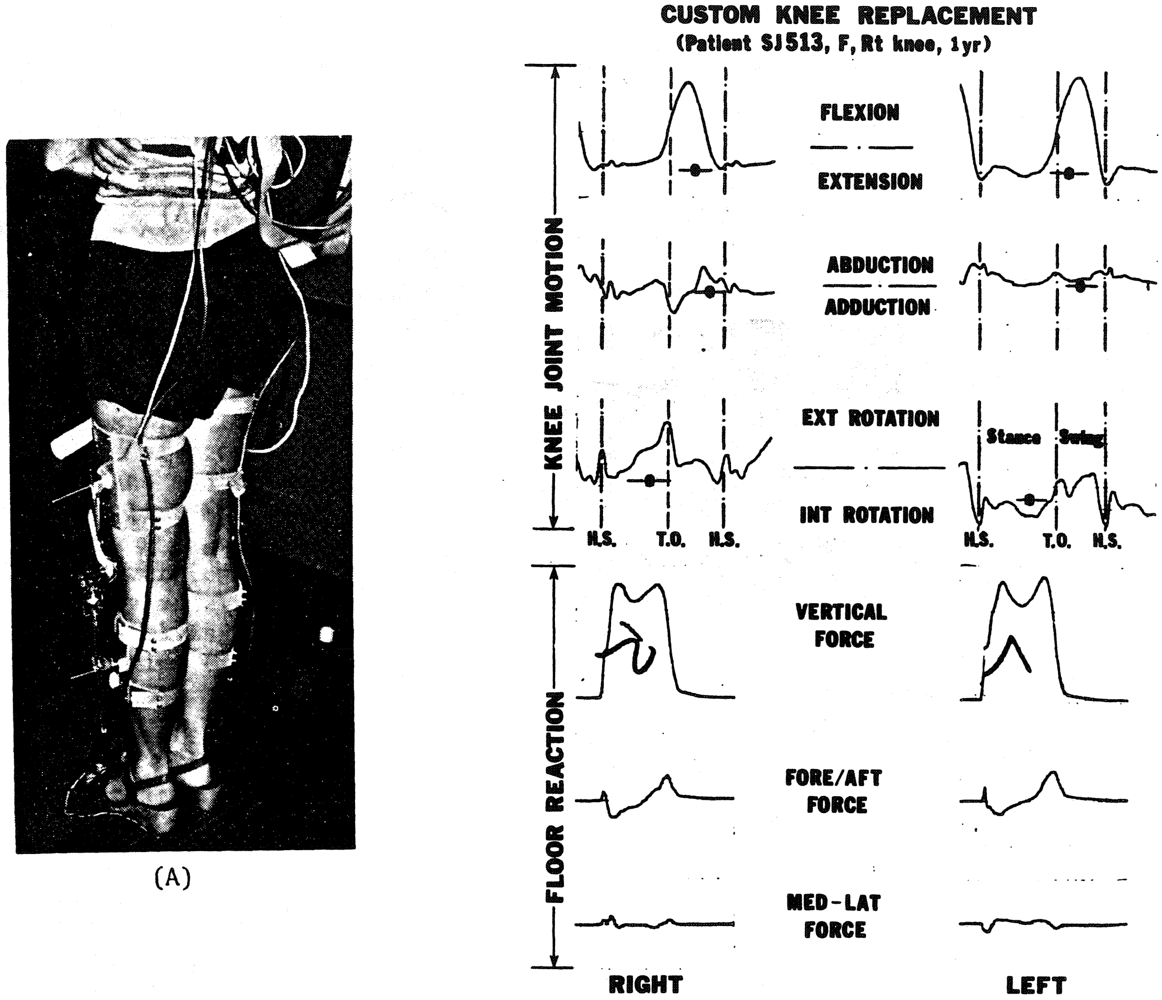


(A)

(B)

(C)

Fig. 14 - (A) Triaxial goniometer installation in the AP view for hip joint motion measurement during gait. (B) Lateral view. (C) Typical tracings of the three-dimensional hip motion measured by the goniometer system.



(A)

(B)

Fig. 15 - Knee joint motion measurement of a patient after segmental and total joint replacement of the right knee due to bone tumor resection. (A) Patient being instrumented to perform gait evaluation. (B) Tracings of the patient's right (replaced) and left (normal) knee motion in normal level walking. The bottom curves represent the foot-floor reaction forces measured by the force plate.

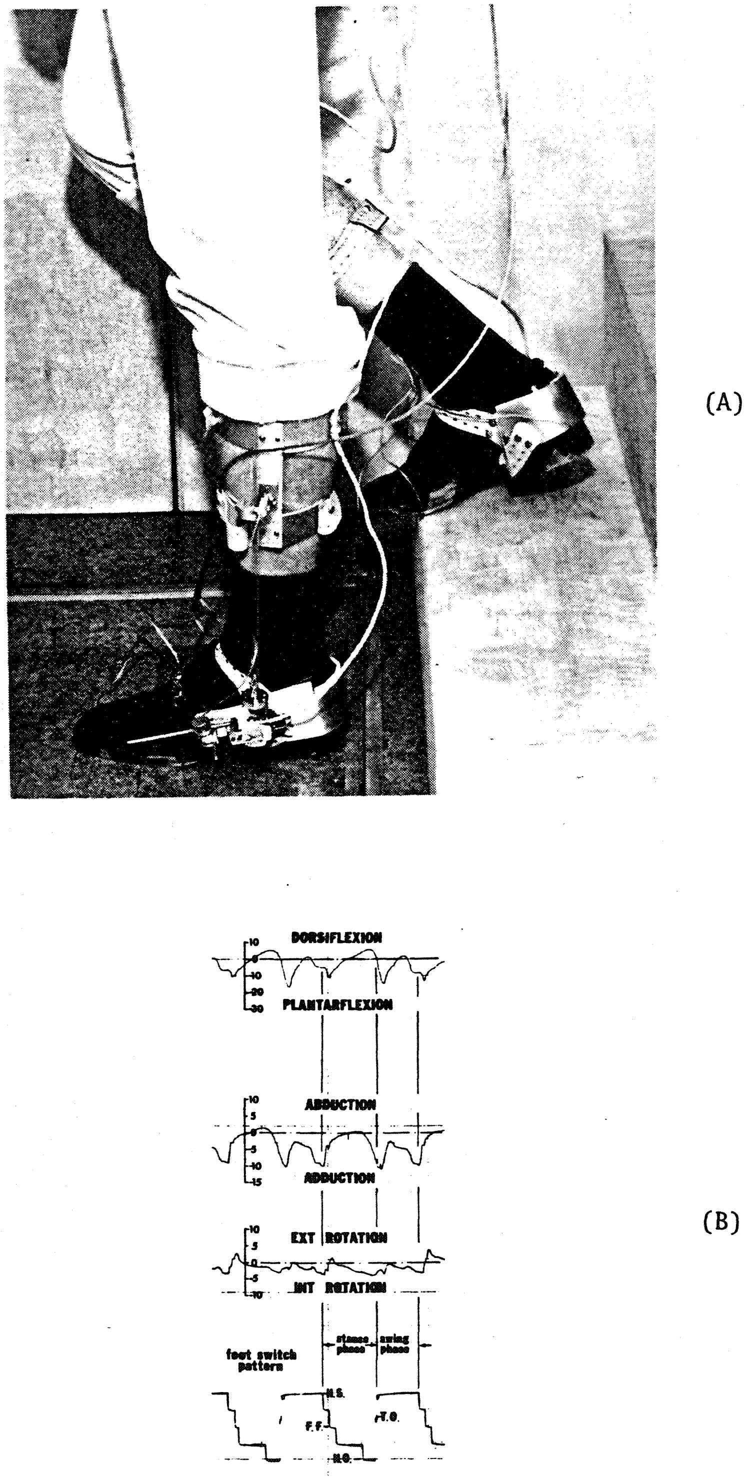


Fig. 16 - Triaxial goniometer system used for ankle joint motion evaluation. (A) Subject performing stair walking. (B) Tracing of the ankle joint motion during level walking.

This technique is also being used to analyze the walking patterns of amputees fitted with different artificial limbs. Quantitative assessments of the patients and the prosthetic devices are being used to establish the basis for artificial limb selection and rehabilitation training guidelines.

Modification of the current electrogoniometer is underway so that the data can be transmitted via telemetry to eliminate cables. Simultaneous measurement of multiple joints on the same extremity is also being investigated. Finally, this design concept has now been adopted to measure upper extremity joints such as the elbow and wrist.

SUMMARY AND CONCLUSIONS

An instrumented device, the electrogoniometer, capable of measuring hip, knee and ankle joint motion during normal walking, has been developed. This instrument is easy to use and reliable. In a large series of normal subjects, the magnitude and pattern of lower extremity joint motion during walking and other activities were established. Patient application is underway for the purpose of providing objective evaluation of the functional effect of joint disease and the results obtained from total joint replacement or artificial limb application.

The error (cross talk) introduced because of the linkage design was corrected by modeling the entire system as a seven-bar spatial linkage system and solving it, based on the method of 4 x 4 matrix. It was found that if flexion-extension of the joint is the principal model of motion, with other components remaining small, such correction is unnecessary since the magnitude of cross talk would be small. However, when axial rotation became large (greater than 10 degrees) analytical correction is necessary, particularly to the magnitude of flexion. This correction was found to be linearly related to the axial rotation; thus making the correction easily implemented.

ACKNOWLEDGEMENT

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NORMATIVE DATA COLLECTION IN ADULTS AND EVALUATION OF HIP AND KNEE PROSTHETIC REPLACEMENTS*

M.P. Murray, Ph.D.

Originally the author's primary interests were to study, in depth, the gait of patients with selected neuro-musculo-skeletal disabilities and to evaluate the effect of various treatment procedures on walking performance. Ranges of variability for the walking patterns of normal subjects were not available, however, and this baseline information was essential for meaningful comparisons of the walking disorders of disabled patients. Accordingly, evaluations of disabled patients were temporarily delayed so that normal baselines could be obtained. The first normative study posed questions which triggered the necessity for additional studies of different aspects of normal gait.

A simple, inexpensive and reliable photographic method to record the simultaneous displacement patterns of walking in two planes of space was developed (Fig. 1). Silver Scotch-Lite targets were fixed to specific anatomic landmarks of the patients, and the patients were photographed as they walked beneath a mirror mounted to the ceiling. The target images which projected in the overhead view and the targets on the medial and lateral aspects of the body were registered on the same film. In our original study we applied this method to establish the ranges of normal variability for the displacement patterns of 16 body segments during free speed walking of 60 normal men, divided equally into five age groups from 20 to 65 years, with equal numbers of men in three height categories from 61 to 74 inches in each age group (1). This study identified the effect of age and height on the free-speed walking patterns, and also assessed the reproducibility of the measurements through repeated trials. A diagram of the experimental design is shown in Figure 2.

The findings from this original study of free speed walking suggested that the walking speed selected by individual men influenced the amplitude of certain movement patterns. Therefore, the next study was undertaken to identify the means by which normal men increase their walking speed (2). We learned that one of the many mechanisms of increasing speed is increasing the amount of transverse pelvis rotation used during walking, as shown in Figure 3. This study provided information which is particularly useful in understanding the deficits in walking speed which are characteristic of a wide variety of disabled patients and which limit the rehabilitation potential and employment possibilities of many patients.

In our original gait study we also noted that several gait components of the men in the 60-year age group differed significantly from those of the younger men, suggesting a "subclinical" presenile walking pattern. The term "subclinical" is used because all of the test subjects had physical

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*These studies were supported in part by grants from the National Institutes of Health.

examinations prior to the gait study and all were normal except for a few who had diminished vibratory sensation. Accordingly, in a separate gait study of 64 normal men divided evenly into eight age groups, the upper age limit was extended to 87 years to determine if the previously suggested presenile patterns were consistent and progressive with advanced age (3). The subjects were of medium or short height. This study demonstrated that the amplitudes of many of the gait components of normal elderly men did indeed differ characteristically from those of normal younger men. For example, walking speed decreased with advanced age, and this decrease resulted more from taking shorter strides than from slower cadences (Fig. 4). This study provided realistic baselines for comparing the disordered gait patterns of disabled men of advanced age.

As we began to record the gait of above-knee amputees and patients with Parkinson's disease, we noted peculiarities in the vertical pathways of the heel and toe and also in their arm swing patterns. Since normal standards for these gait components were not available, these additional normal gait studies were undertaken (4-6).

As our standards became available, we received referrals for gait evaluations of disabled women as well as men. It was necessary, therefore, to establish standards of normality for the gait components of women and to identify the effect of age, height, walking speed and heel heights on their walking patterns (7). We measured pronounced differences in the amplitudes of most of the displacement patterns of women as compared to thos of normal men and also measured pronounced differences in the displacement patterns when the women walked with different heel heights. This comprehensive study provided necessary baselines since many women with orthopaedic or neurological disabilities require shoes with a specific heel height in order to walk comfortably. An example of the effect of heel height on one of the components of walking is shown in Figure 5.

We believe that this series of normative studies has contributed to a deeper understanding of the walking act and that we have established adequate standards of normal variability which can serve as baselines for comparing the gait of disabled men and women in wide ranges of height and age, under various conditions of walking, and with various types of shoes.

Examples of the Application of Normal Standards to Evaluate the Functional Performance of Patients with Hip and Knee Joint Disabilities

Before we started evaluating the effect of different types of total hip replacement on walking performance, we knew it would be prohibitive, if not useless, to analyze all of the gait components we were capable of recording. Accordingly, we expedited two separate studies to give us insight into the most sensitive gait components to be assessed in patients with hip disease. One study identified the common pain-avoidance maneuvers in the gait of patients with hip arthritis,(8) and the other identified the mechanism by which patients with surgical fusion of the hip compensate for absence of hip joint motion during walking (9). In the presence of hip

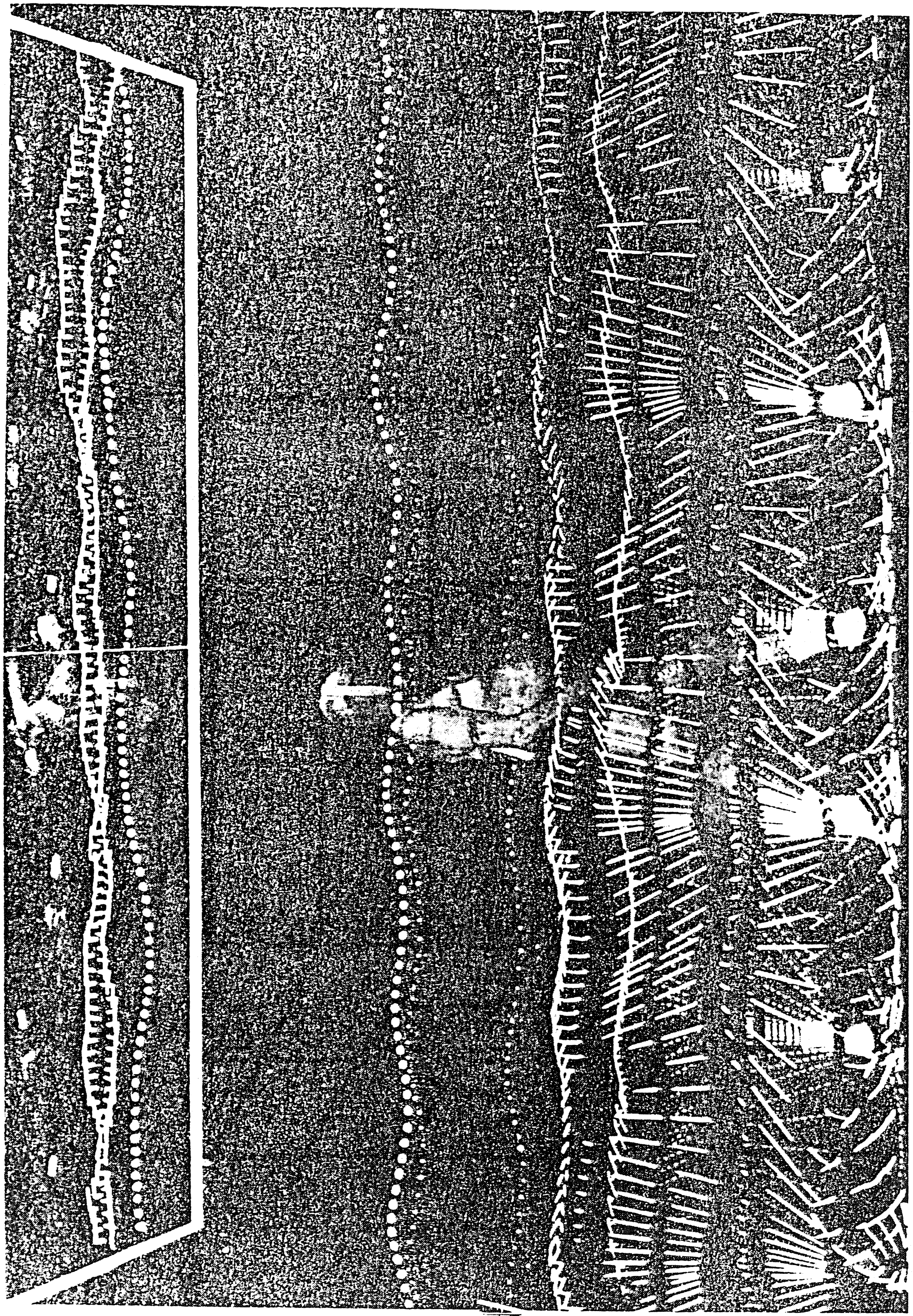


FIGURE 1

FACTORIAL DESIGN

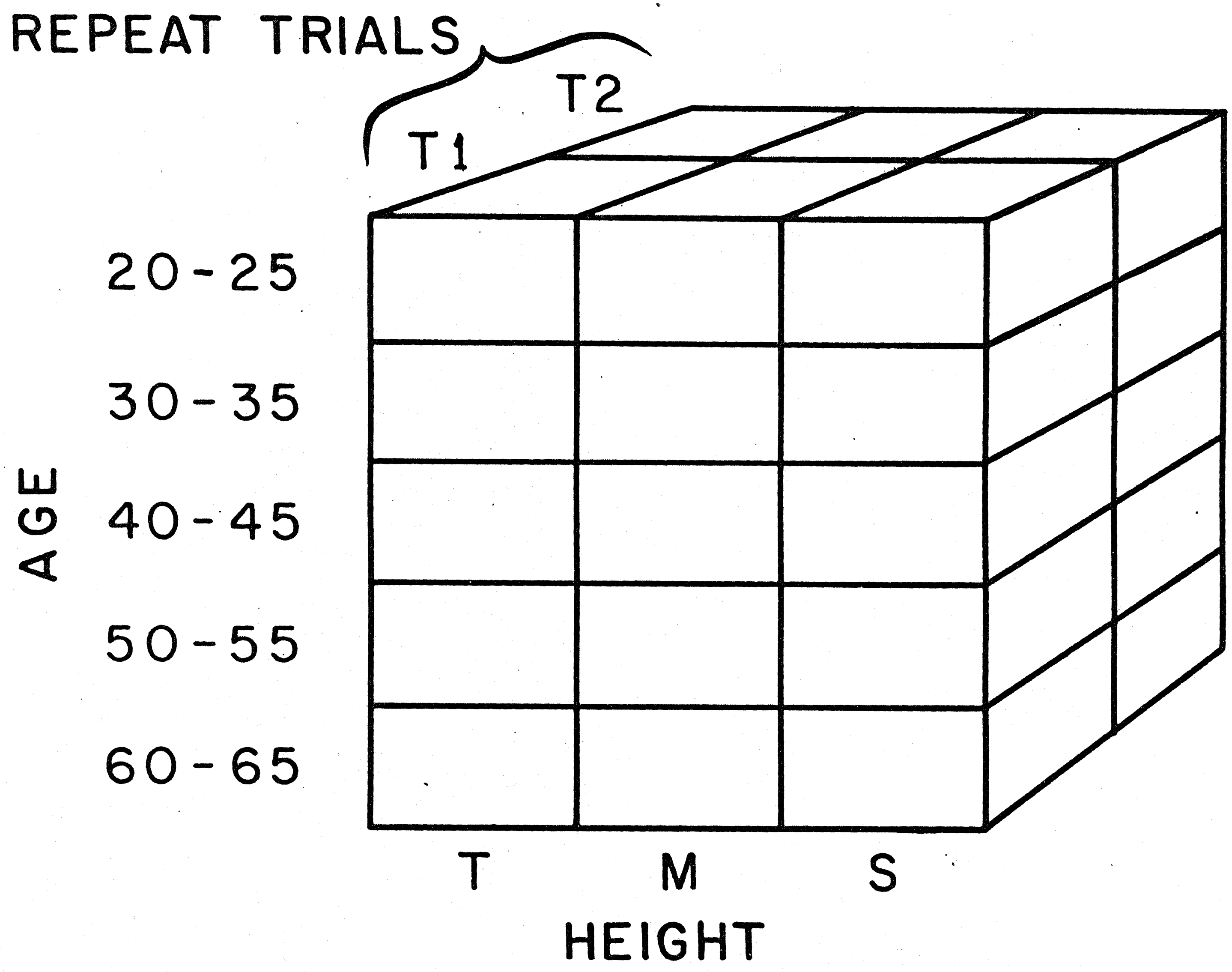
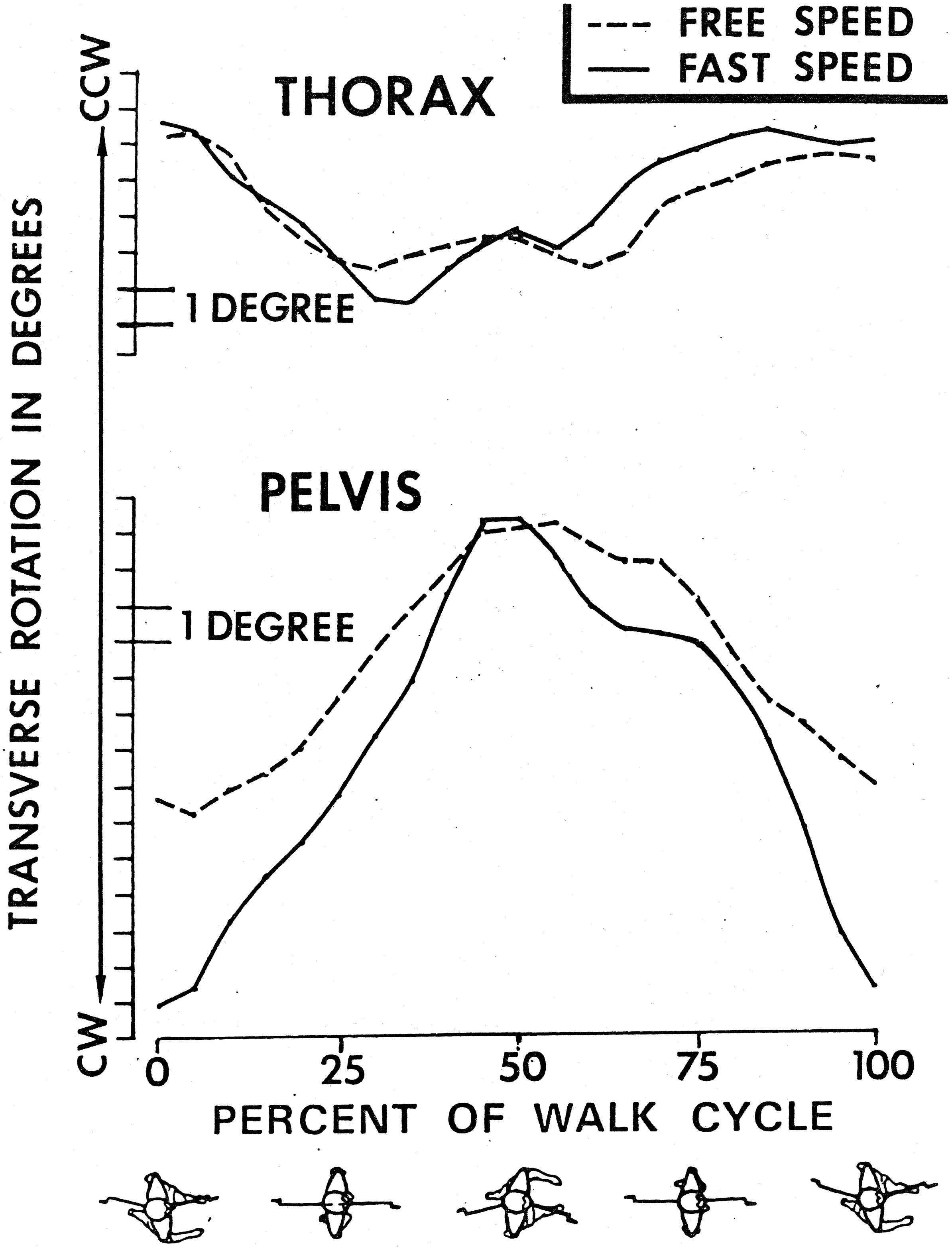
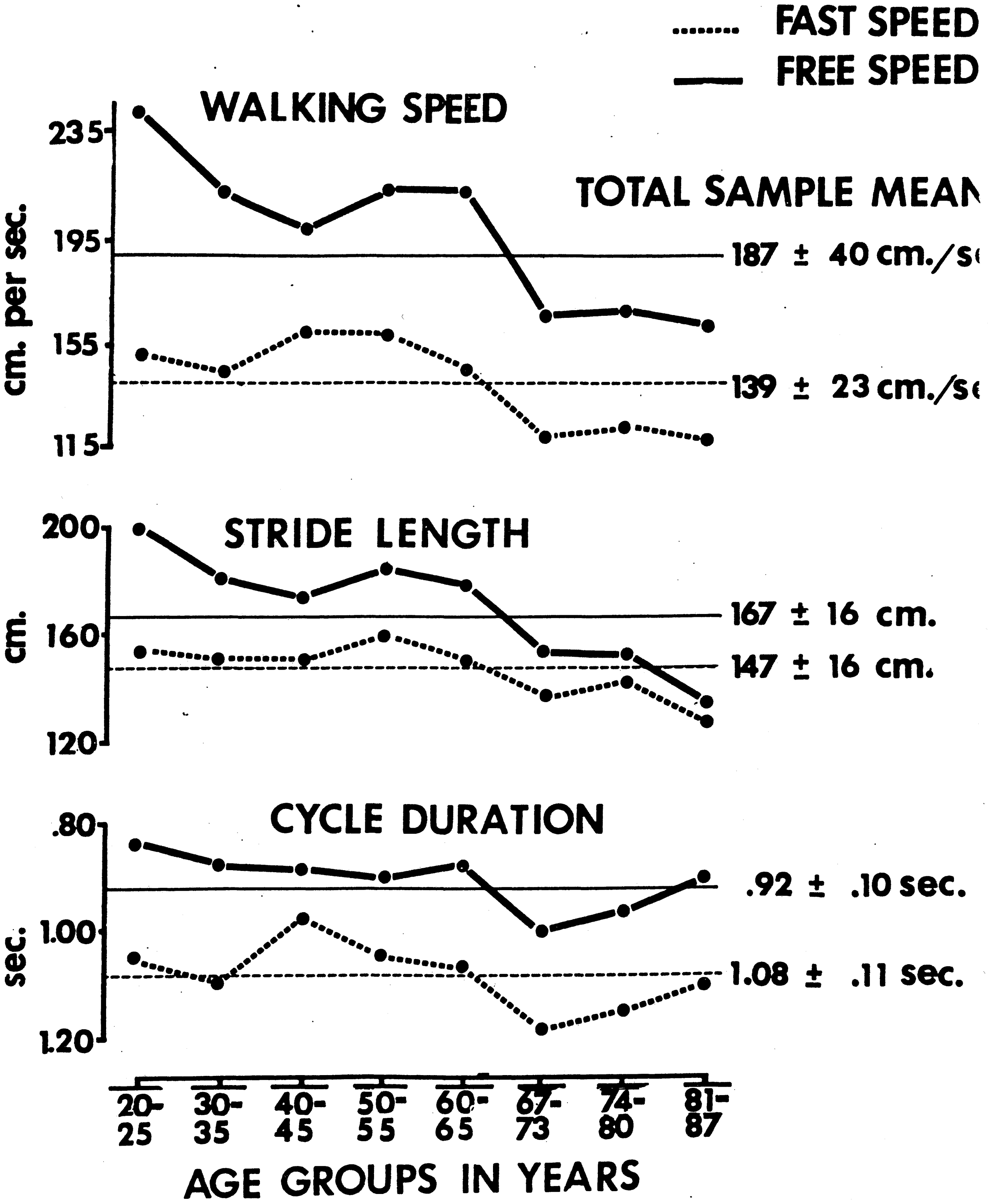


FIGURE 3



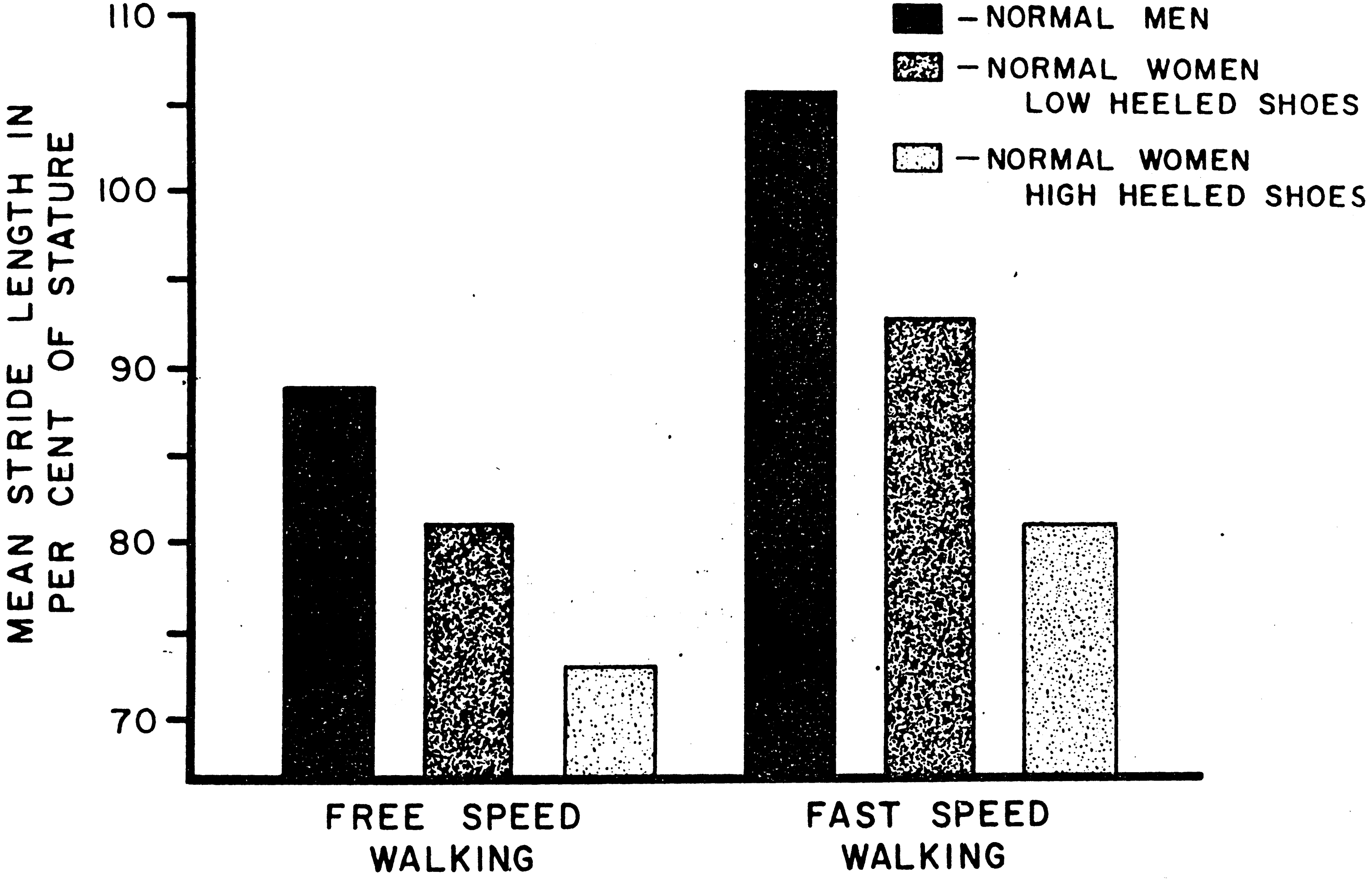
--- FREE SPEED
— FAST SPEED
THORAX
PELVIS
1 DEGREE
1 DEGREE
TRANSVERSE ROTATION IN DEGREES
CCW
CW
0
25
50
75
100
PERCENT OF WALK CYCLE

FIGURE 4



FAST SPEED
FREE SPEED
WALKING SPEED
235
195
155
115
cm. per sec.
TOTAL SAMPLE MEA
187 ± 40 cm./s
139 ± 23 cm./s
STRIDE LENGTH
200
160
120
cm.
167 ± 16 cm.
147 ± 16 cm.
CYCLE DURATION
.80
1.00
1.20
sec.
.92 ± .10 sec.
1.08 ± .11 sec.
20-25
30-35
40-45
50-55
60-65
67-73
74-80
81-87
AGE GROUPS IN YEARS

FIGURE 5


MEAN STRIDE LENGTH IN PER CENT OF STATURE
110
100
90
80
70
FREE SPEED WALKING
FAST SPEED WALKING
■ — NORMAL MEN
▨ — NORMAL WOMEN LOW HEELED SHOES
□ — NORMAL WOMEN HIGH HEELED SHOES

pain, patients show many characteristic gait abnormalities. Their excessive lateral lurching of the head as compared to normal subjects is illustrated in Figure 6. Figure 7 demonstrates another characteristic of patients with hip pain: they use less than normal hip flexion-extension on the painful side during walking, particularly less hip extension. Even though many of the patients had hip flexion contractures before surgery, there was no correlation between the amount of hip extension they had, as measured by standard methods, and the amount of extension they used during walking.

Figure 8 shows clippings of gait photographs of a patient before and after total hip replacement and of a normal woman of similar age and height. Preoperatively, the patient had restricted excursions of the joints of the lower limb, particularly the hip, during walking. Her excessive and irregular lateral lurching of the head can be seen in the overhead mirror, and the side view of the neck target indicates the slow, stop-start type of forward progression before surgery. Postoperatively, it can be seen that she walked faster, had more joint mobility and had smoother forward and lateral motion of the trunk.

Figure 9 shows the average amount of lateral lurching before and six and twenty-four months after surgery for 100 patients with uncomplicated McKee-Farrar total hip replacement. Although the amount of lateral lurching was definitely decreased after surgery, the patient groups did not reach the limits of normal variability by the second postoperative year. The greatest improvement was made during the first six months after surgery, with lesser but continued improvement between the sixth and twenty-fourth postoperative months. These statements apply not only to lateral lurching, but to most of the measurements of walking performance which we made during this study (10).

In contrast, Figure 10 shows examples of declines in functional performance which were measured in this same study in seven patients who had operative or postoperative complications, mainly infection or prosthetic component loosening. Here the declining performance of the patients with complications is compared to the average improvement of the group without complications.

Our normal studies have also been used to provide standards in studies comparing groups with different types of total hip replacement (11). For example, Figure 11 shows the average improvement in the amount of hip flexion-extension used during walking by three groups of men before and six months after different types of hip replacement as compared to normal men. The average measurements were similar for the three groups six months after operation; however, we found that the patients with bilateral disability improved much more than those with unilateral disability in this particular component of function. Whether these trends will persist or change with time is the subject of a future longitudinal study.

Improvement toward a more normal gait has also been measured in patients with Geometric knee replacement (12). Figure 12 shows average patterns of knee flexion-extension throughout the walking cycle for patients before and three, six and twelve months after knee replacement as compared

FIGURE 6

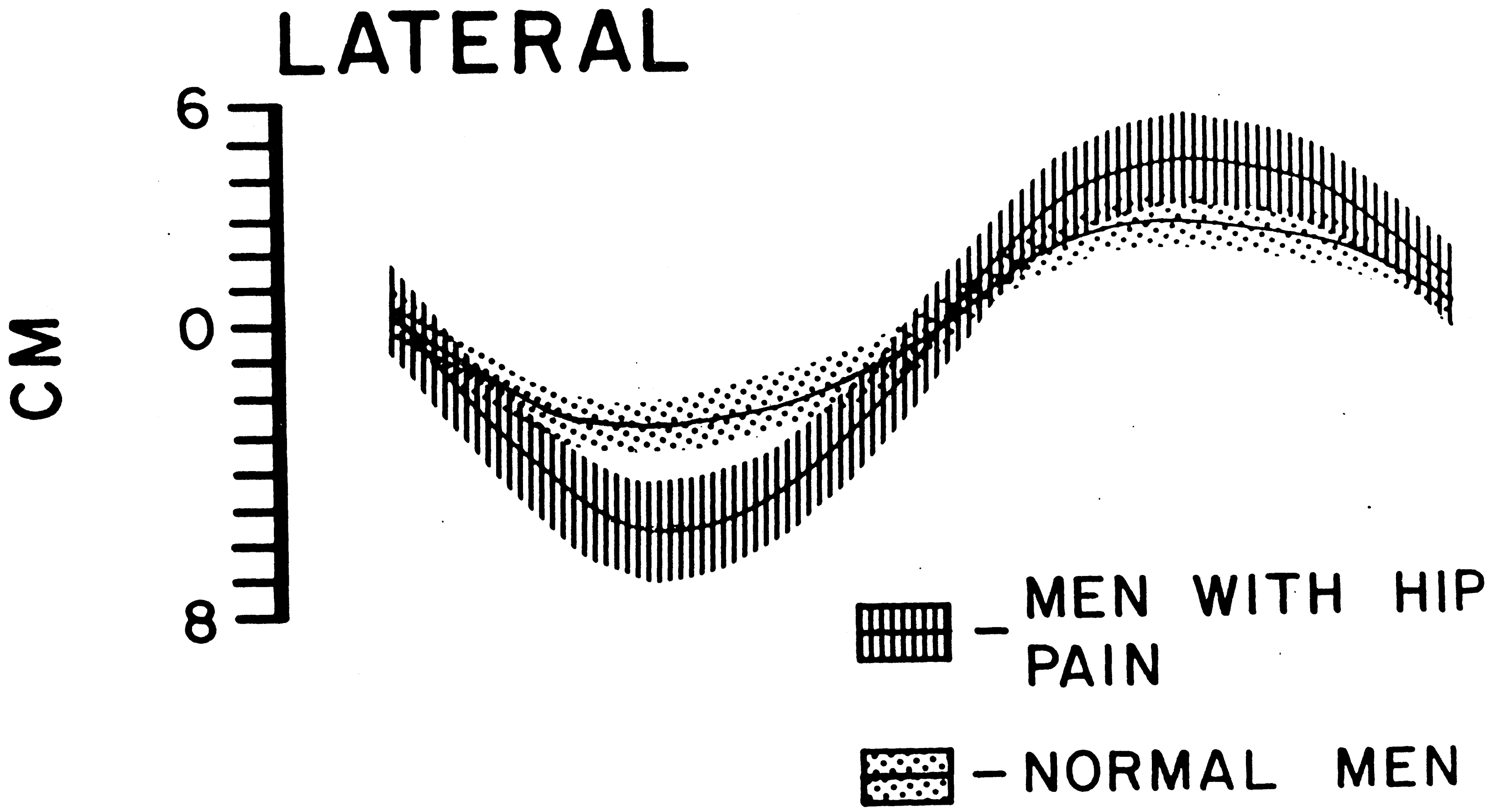
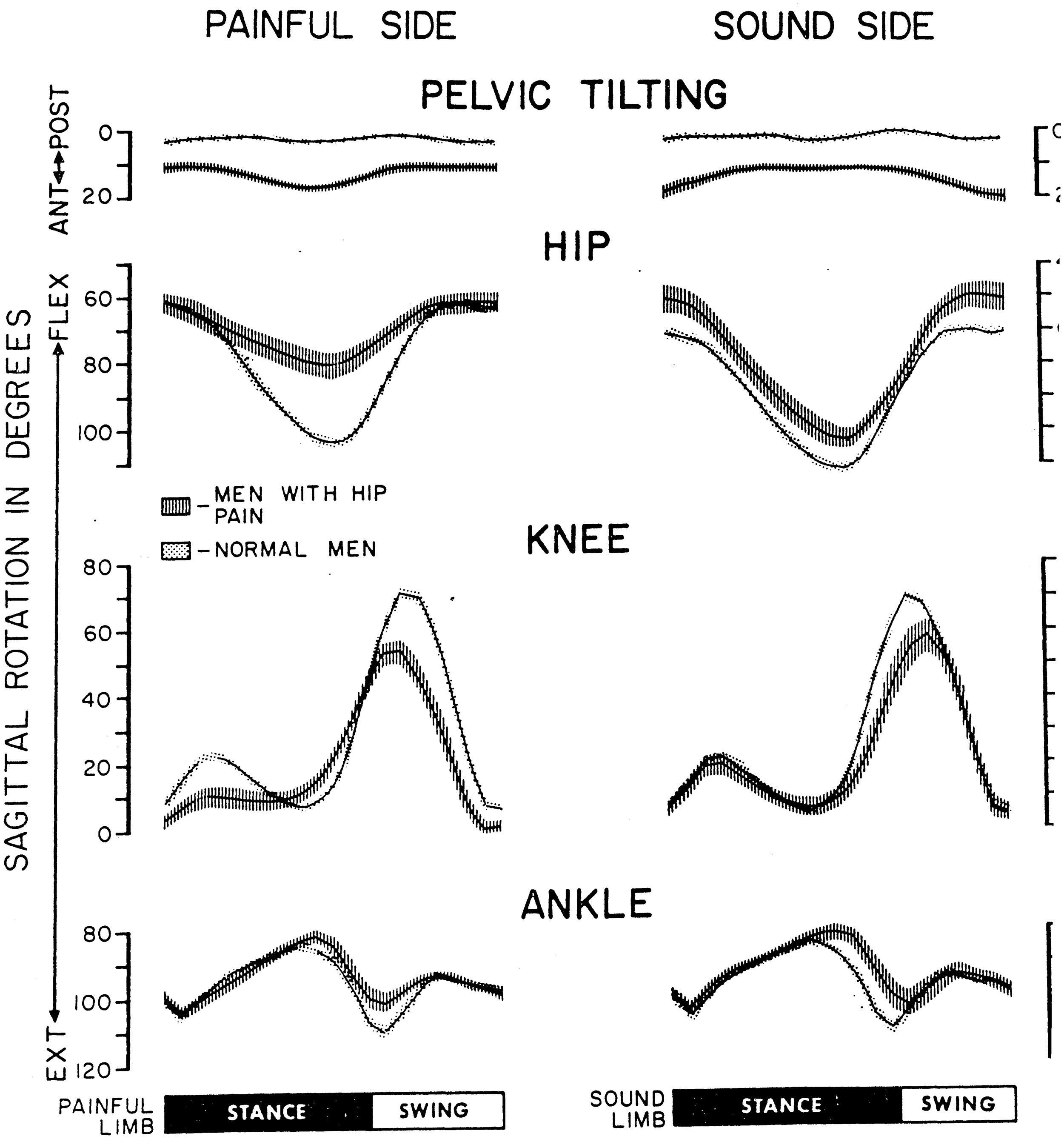
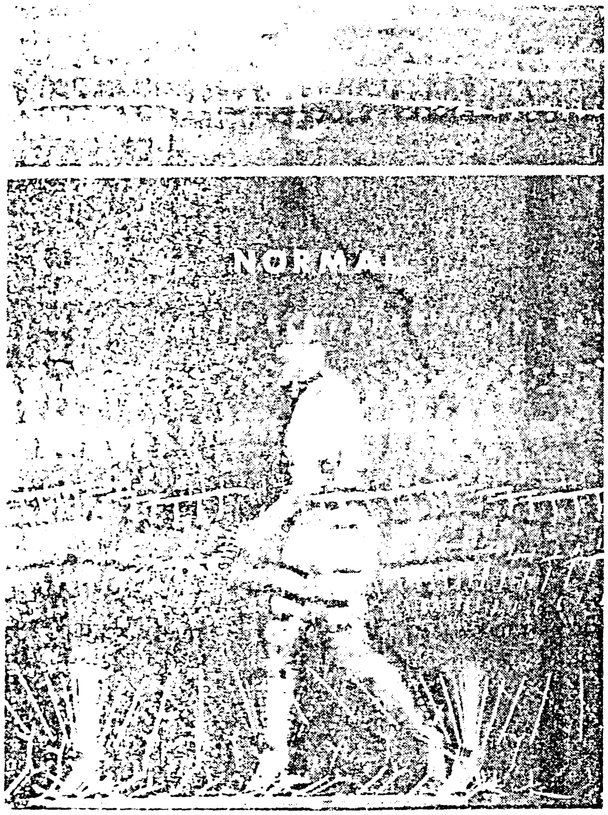


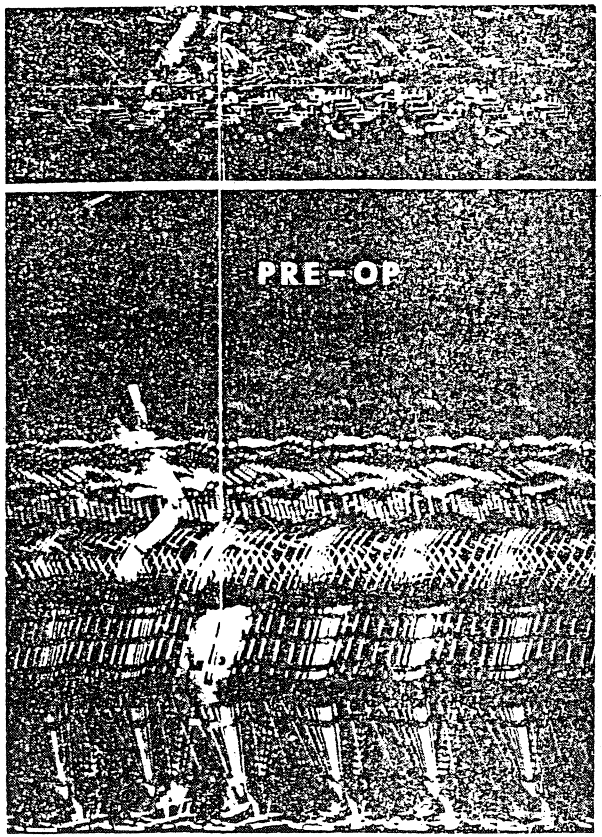
FIGURE 7



PAINFUL SIDE
SOUND SIDE
PELVIC TILTING
ANT↔POST
0
20
HIP
FLEX
60
80
100
SAGITTAL ROTATION IN DEGREES
▥ - MEN WITH HIP PAIN
▩ - NORMAL MEN
KNEE
80
60
40
20
0
ANKLE
80
100
120
EXT
PAINFUL LIMB
STANCE
SWING
SOUND LIMB
STANCE
SWING

[illegible]


NORMAL


PRE-OP

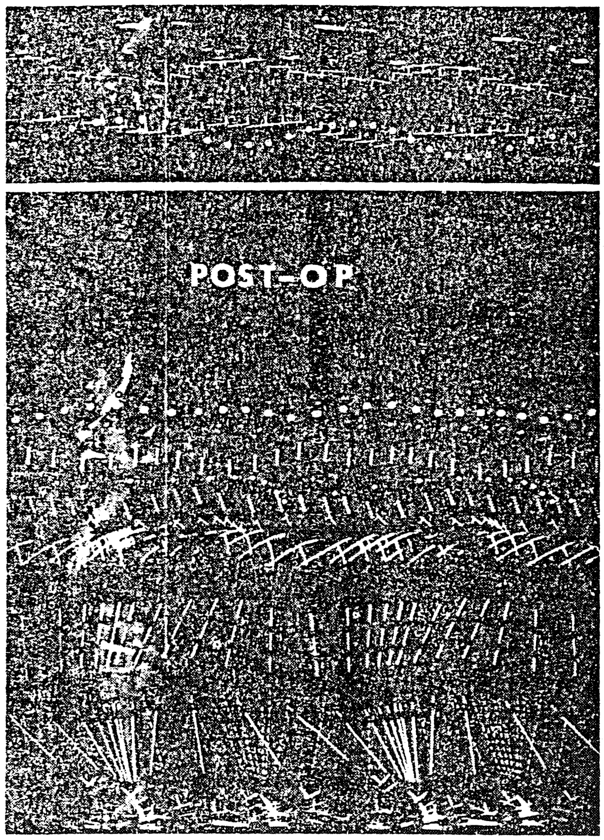

POST-OP

FIGURE 9

LATERAL MOTION OF THE HEAD (CM) *McKEE-FARRAR*

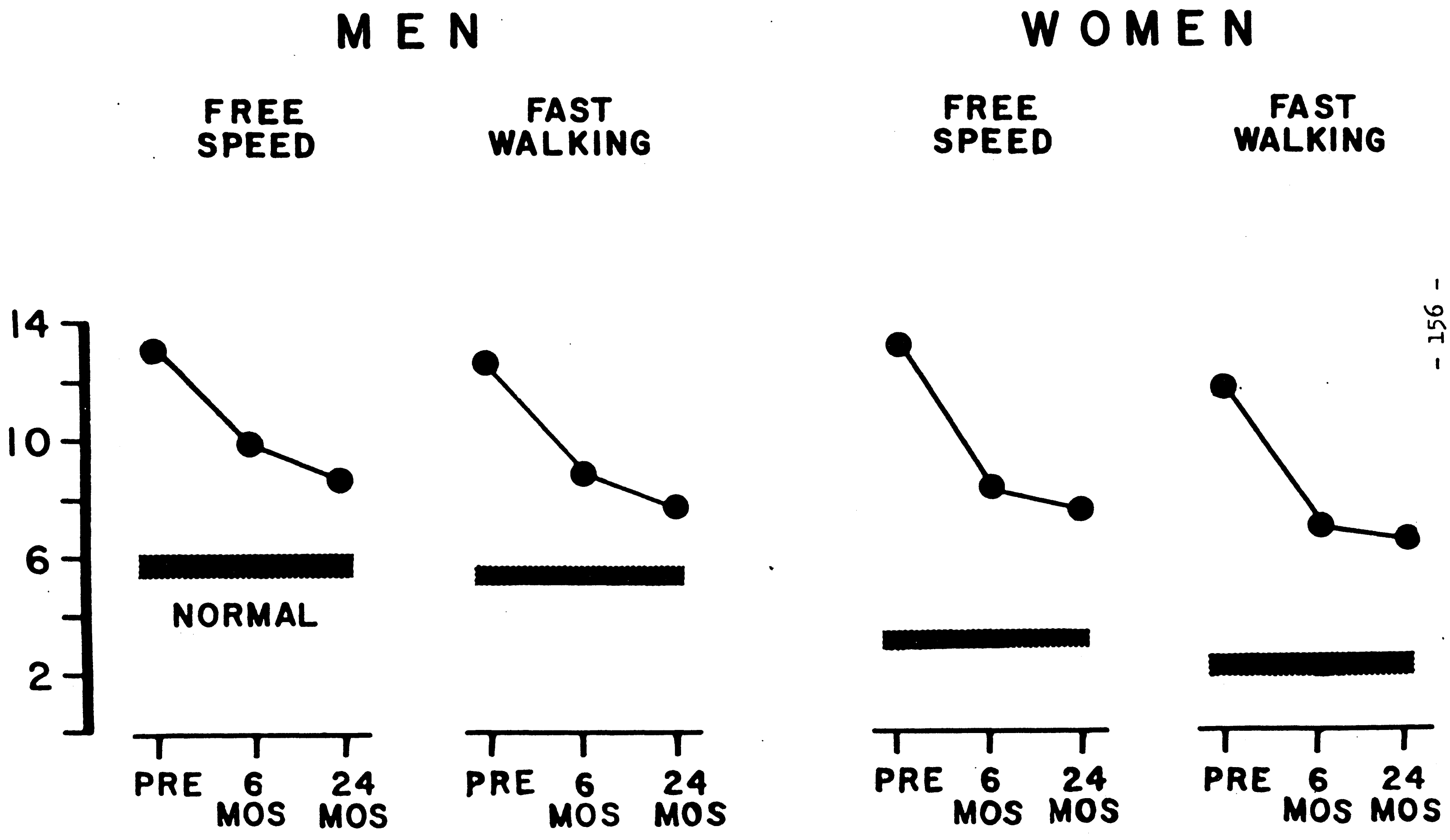


FIGURE 10

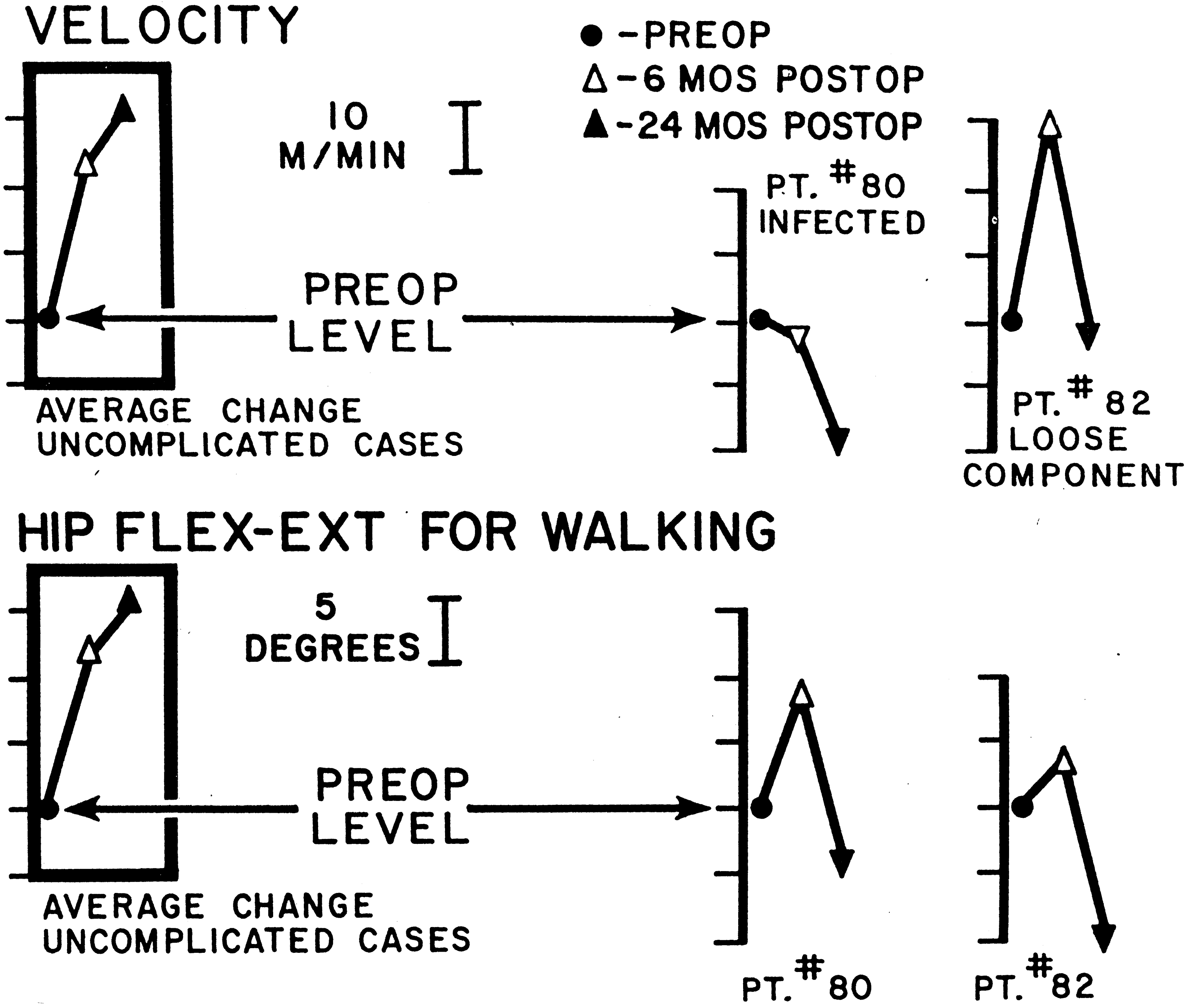

VELOCITY
● -PREOP
Δ -6 MOS POSTOP
▲ -24 MOS POSTOP
10 M/MIN
PREOP LEVEL
AVERAGE CHANGE UNCOMPLICATED CASES
PT. #80 INFECTED
PT. #82 LOOSE COMPONENT
HIP FLEX-EXT FOR WALKING
5 DEGREES
PREOP LEVEL
AVERAGE CHANGE UNCOMPLICATED CASES
PT. #80
PT. #82

FIGURE 11

TOTAL EXCURSION OF HIP FLEXION-EXTENSION

MEN — FREE SPEED WALKING

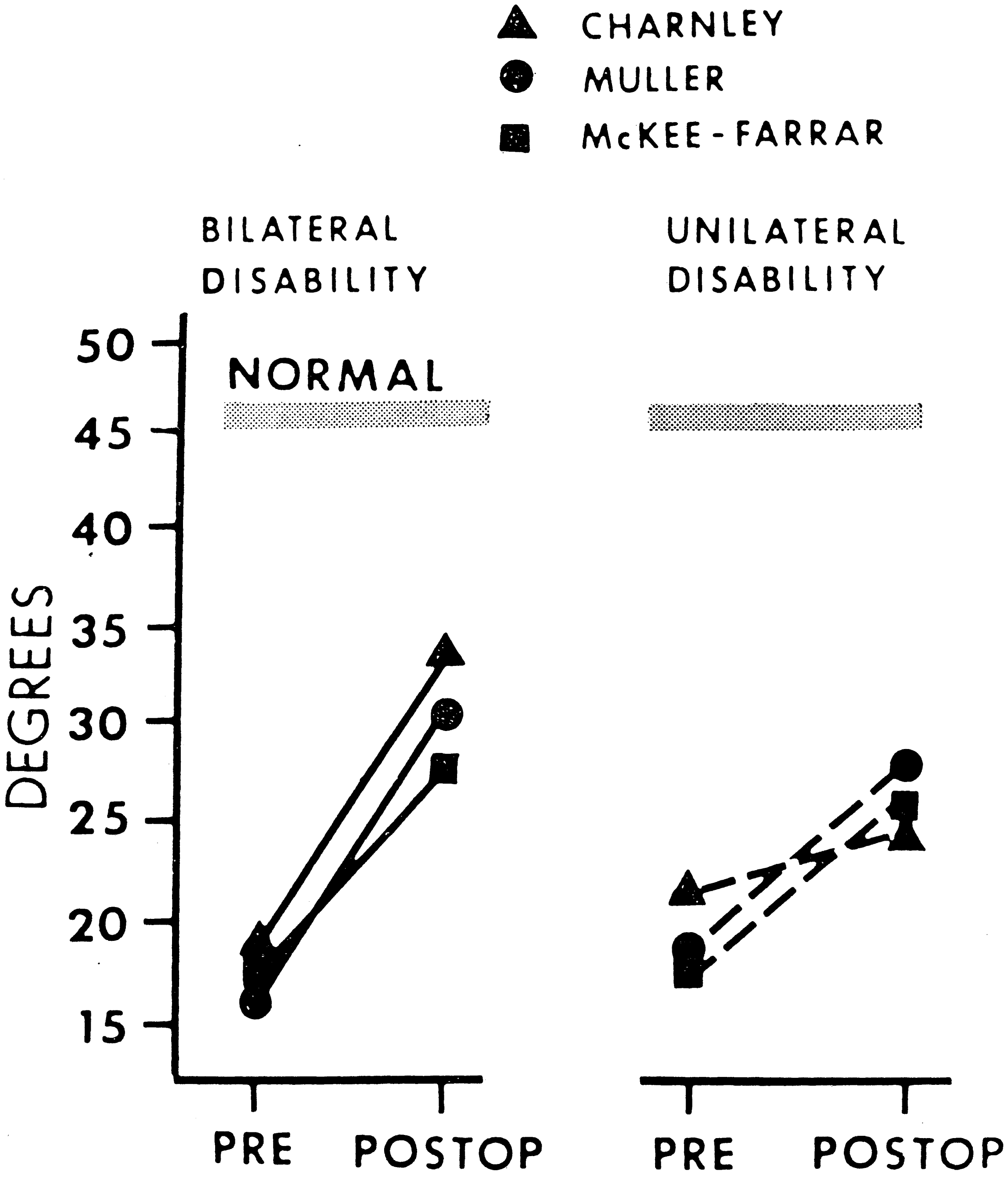
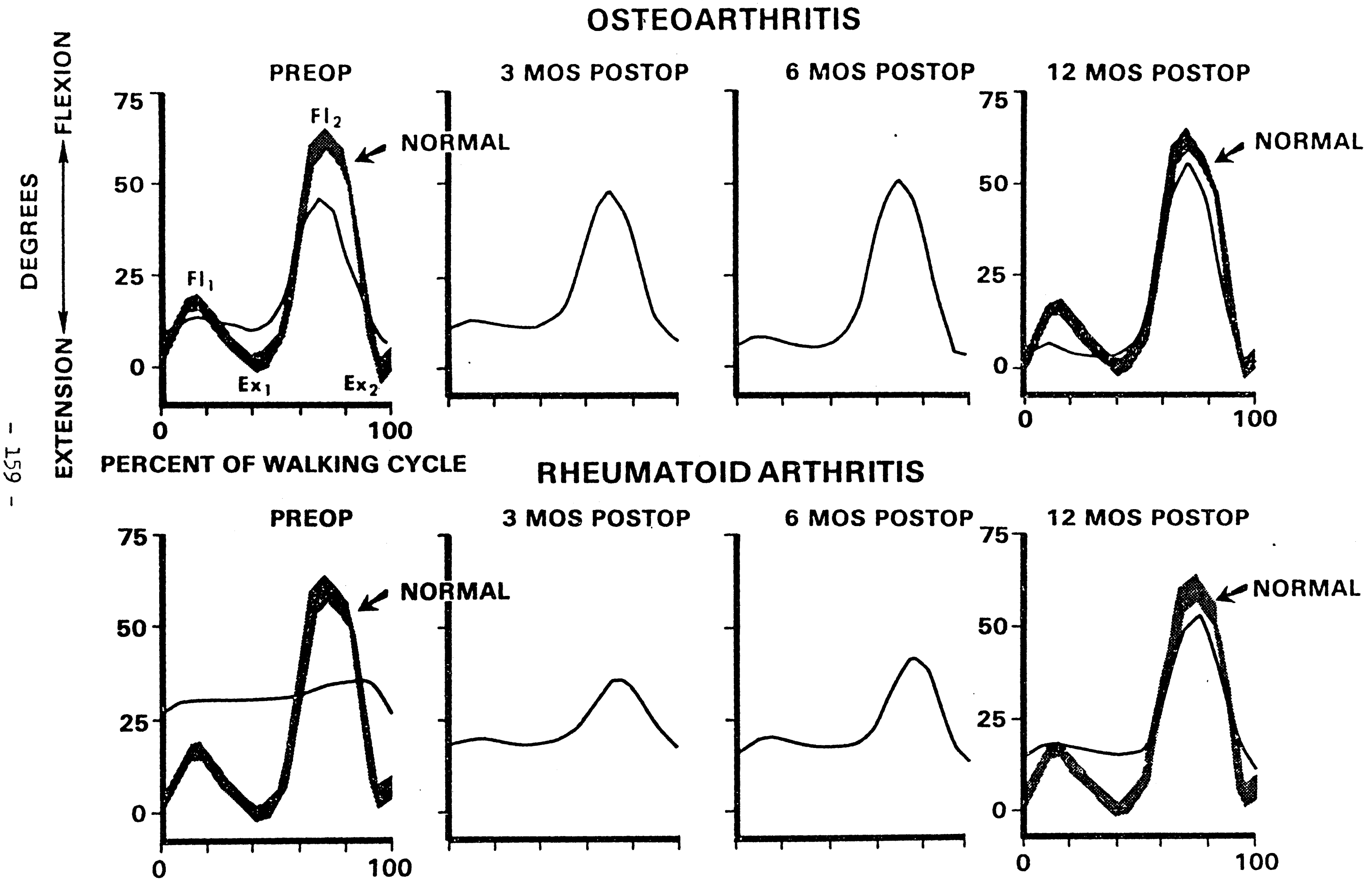


FIGURE 12

KNEE FLEXION-EXTENSION DURING WALKING



to normal. The knee motion of the patient groups was strikingly different from normal before surgery, particularly for the group with rheumatoid arthritis. Although the group with rheumatoid arthritis improved considerably, their average knee pattern was still more abnormal than that of the group with osteoarthritis one year after operation.

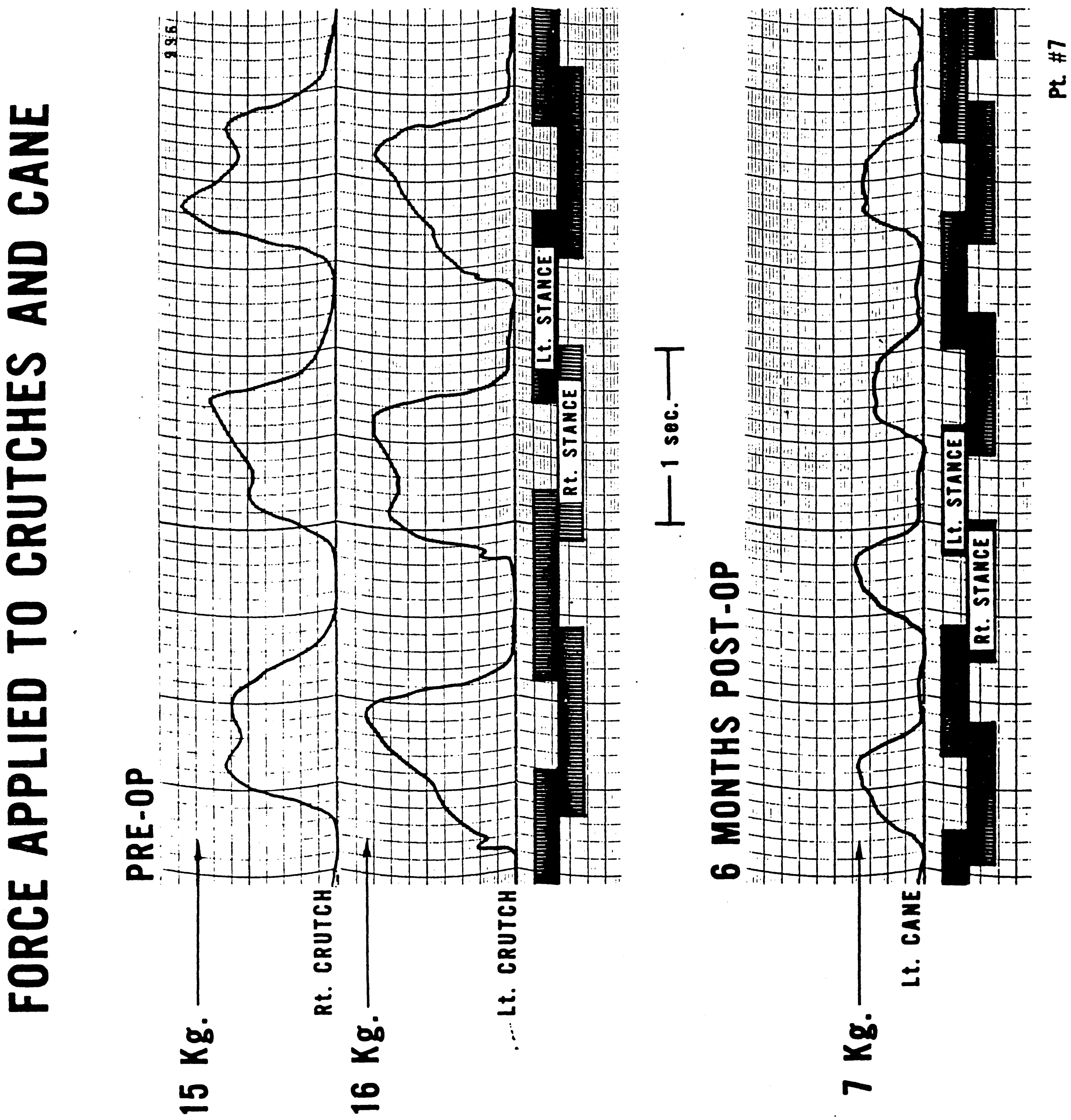
Although this paper was to address itself to gait, it is important to note that we take a multifaceted approach and measure various components of function in the different joint replacement studies. As an example, if the patient uses an assistive device during walking, we monitor the thrust force applied to the canes or crutches simultaneously with foot-floor contact times from our electronic walkway (13-15). Portions of the records of a patient before and after total hip replacement are shown in Figure 13. The dark horizontal bars under the force pattern indicate the durations of the right and left stance phases. For joint replacement studies, we have chosen to report the mean integrated area under the force curve which occurred during the stance phase of the operative limb, and we believe that this provides an additional sensitive measure of change in functional performance.

We also measure strength of particular muscles which span the joint to be replaced. In Figure 14, average gains in strength of the hip adductor muscles from before to six months after surgery are shown for groups of men and women with three different types of hip replacement. The standards for normal subjects were obtained prior to beginning the hip replacement studies (16). While these preliminary findings of differences among the groups are fascinating, they should not be regarded as conclusive since our previous studies have demonstrated that further improvement in functional performance occurs in many patients after the sixth postoperative month.

As a final example, we also measure weight distribution between the feet during one-minute periods of comfortable standing. Figure 15 shows patients with hip and ankle disabilities standing on the platform (17). These platform measurements are also extremely useful in our pre- and postoperative studies of functional performance of patients with hip and knee disabilities.

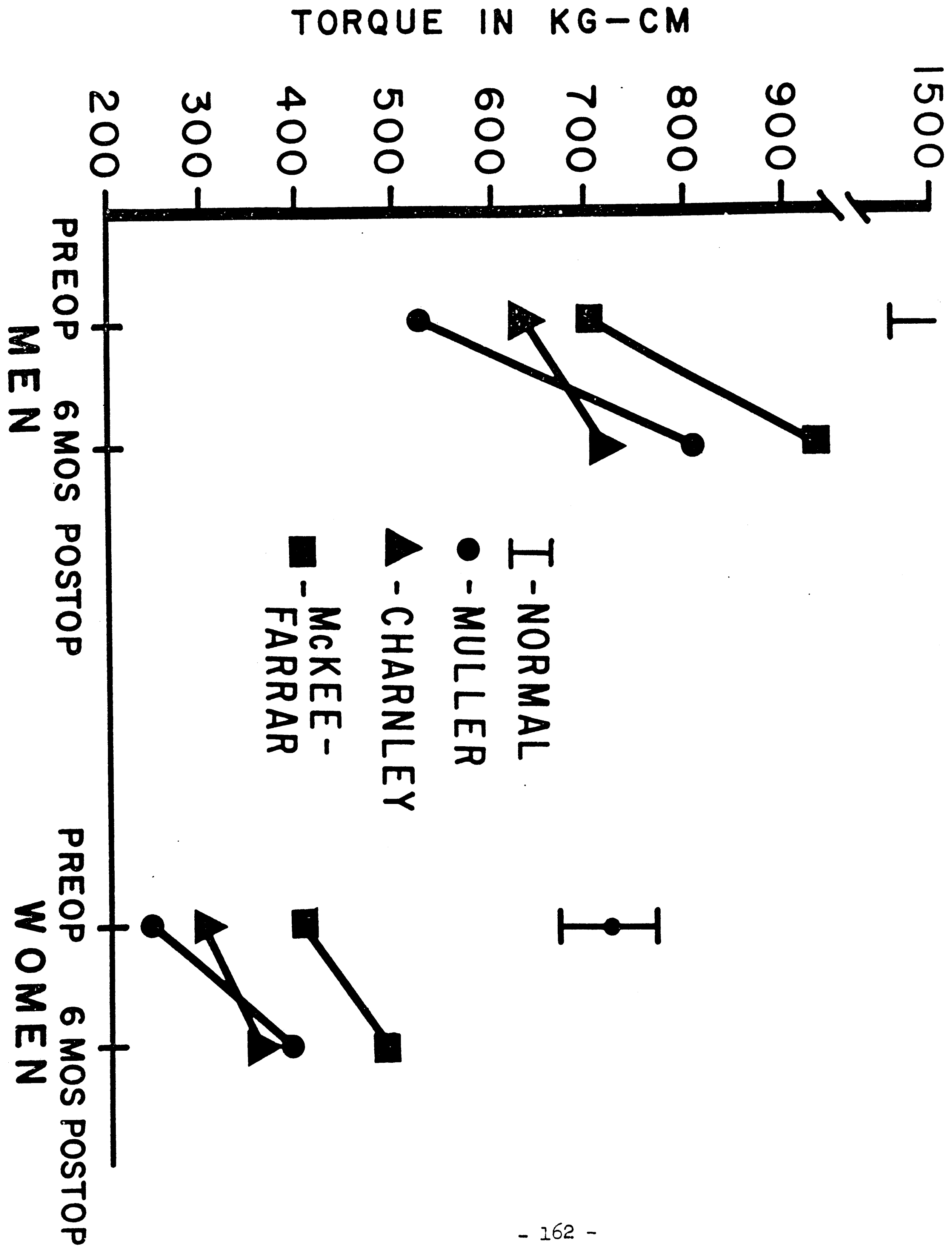
Although patients' subjective impressions are important, they are of little value in a critical evaluation of a given procedure or in comparing the results following different types of procedures. It is hoped that this type of quantitative information will lead to a deeper understanding of the manifestations of the various disease processes and to optimal therapeutic efforts directed toward restoring functional performance.

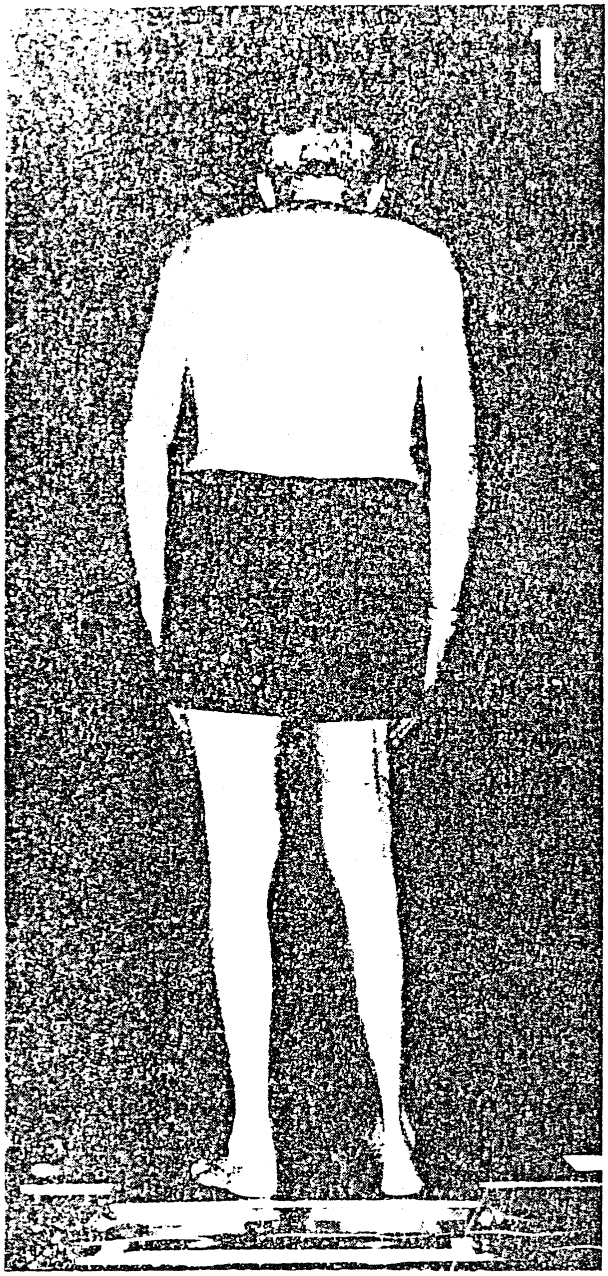
FIGURE 13



FORCE APPLIED TO CRUTCHES AND CANE

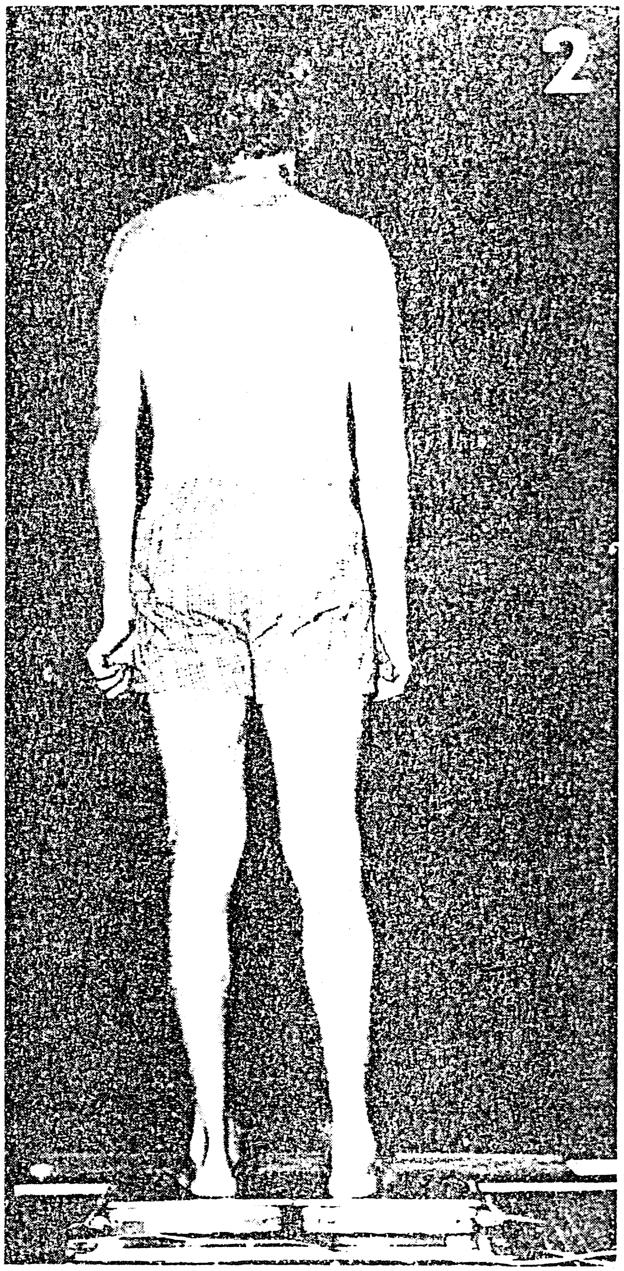
FIGURE 14


TORQUE IN KG-CM
1500
900
800
700
600
500
400
300
200
I - NORMAL
● - MULLER
▲ - CHARNLEY
■ - McKEE-FARRAR
PREOP
6 MOS POSTOP
MEN
PREOP
6 MOS POSTOP
WOMEN



LT.= RT. =
41 kg 28 kg

Solid Union, Rt.
Intertroch. Fracture



LT. = RT. =
46 kg 24 kg

Acute Sprain,
Rt. Ankle

Murray cont.

Figure 12. Mean patterns of knee flexion-extension throughout the walking cycle for patients with rheumatoid and osteoarthritis before and at intervals after Geometric knee replacement. The shaded area represents the mean pattern and two standard errors above and below the mean for normal men of similar age and height.

Figure 13. Polygraph records showing forces a patient applied to axillary crutches before hip replacement and to a cane six months after hip replacement. Foot-floor contact times are indicated by the dark bars below.

Figure 14. Mean maximum isometric torque of the hip adductor muscles before and at six months after surgery for groups of men and women with Muller, Charnley and McKee-Farrar total hip replacement. The dots and vertical bars indicate the means and two standard errors above and below the means for normal men and women.

Figure 15. Photographs of disabled patients on a force platform device as weight distribution was being monitored.

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CLINICAL USE OF GAIT ANALYSIS

Jacquelin Perry, M.D.

Pain deformity, and paralysis may all create difficulties in walking sufficient for the patient to seek medical care. Traditionally the clinical characteristics of physical impairment have been the only means available to physicians and therapists for predicting the functional gains from therapeutic intervention. The wide variety in results, however, indicates there is not a direct relationship between physical impairment and functional loss. A basic reason for this discrepancy is the varying significance of different types of impairment combined with the ability of patients to substitute. Thus the therapeutic world would profit from an objective means of measuring disabled function. Predictions and confirmation of therapeutic effectiveness would be more specifically determined. Gait analysis can do this for limb impairments leading to difficulties in walking.

Rancho Los Amigos Hospital has a large county rehabilitation program. For a research program to survive in this environment, clinical effectiveness had to be demonstrated early. This led to a selection of techniques that could handle large numbers of patients in an effective manner

Four techniques have been emphasized: footswitches, dynamic electromyography, energy cost measurements, and electrogoniometry. Each offers its own type of clinically useful information.

Footswitches provide a simple and direct means of defining a person's basic stride characteristics. While applicable to all patient groups with walking disability these measurements are particularly useful in those with degenerative joint disease. Their physical deterrents are pain and lack of mobility.

METHOD

These data are obtained with contact closing insole footswitches placed in each shoe to identify the swing and stance time, rate of travel, and foot support pattern. As the patient traverses a 10 meter course, the middle 6 meter walk is defined electronically. The electronic data are stored on analog tape for subsequent computer or visual interpretation of a printed record. Video tape also documents both the patient's gross performance and the electronic data.

Location of the switches within the insoles combined with electronic coding displays the normal sequence of foot support as an easily recognized staircase. The steps serially represent heel only support, lateral foot flat (heel and fifth metatarsal), total flat foot (heel, first and fifth metatarsal) and heel off (first and fifth metatarsal). The period of toe contact is a widening of the horizontal bar. No switch activity represents swing. Deviations from this pattern readily identify the patient's variation from normal performance. In addition by relating the swing and stance pattern of the two limbs and the time taken to cover the measured walkway one can calculate seven different stride characteristics. Of these, two have been selected as being clinically the most significant; these are velocity and single limb support time.

Velocity represents the distance a patient can cover per unit of time. It is the product of stride length and cadence. In 90 percent of the patients with hip pathology all three factors tend to change in the same direction thus one can consider velocity representative of all three. Stride length is slightly more reliable as some patients hasten their cadence to accommodate a shortened stride length. Velocity, however, offers the convenience of being readily measurable in any environment where there is a long hall and a stop watch available. These data are used to make several types of clinical decisions. One example is the determination of surgical candidacy in doubtful cases. This woman complained of hip pain after walking five blocks. She had some x-ray changes but appeared to walk well. When tested in the laboratory her initial records were normal, but after walking half a mile around our outside track all three gait values dropped significantly. Her surgeons used these data to confirm her complaints of functional loss, but felt it was insufficient to justify the risk of total joint replacement at that time. One year later (when the surgical program was better established) retesting reaffirmed the patient's endurance disability and surgery was performed with good functional gain.

Single limb support is a more sensitive measure of the patient's limb disability than velocity. It also correlates well with the clinical assessment of walking impairment (by the Harris criteria $r=.76$, for velocity $r=.66$). Single limb support time is that portion of the total stance period during which the other limb is in midair (contralateral swing). During this interval the stance limb is obligated to support the entire body weight and at the same time accept the momentum of the forward traveling trunk. In contrast, the total stance time may represent a large period of double support with both feet on the ground and almost all the weight on the sound limb, hence it is not clinically significant.

The difference in information provided by the velocity and single support time measurements is readily demonstrated by a study that compared the influences of walking aids. It was found that none of the aids, canes, crutches, or walkers change the patient's velocity either pre or postoperatively. Yet these devices significantly altered single limb support duration. Preoperatively canes increased the patient's single limb support 10 percent, with crutches the gain was 30 percent, and 120 percent by walkers.

The footswitch analysis of 150 patients showed that the functional gains from total hip joint replacement varied with the balance between pathology and surgery performed. All the patients with unilateral hip disease (105) and, therefore, a single joint replacement showed improvement unless there was a medical complication. They averaged a 24 percent improvement in velocity and 23 percent in single limb support time. Twenty-five percent showed less than representative gains and these were found to have unrecognized disease in the other hip. In the patients with bilateral joint disease the gains varied both with the degree of their impairment and whether one or both hips were replaced. All the patients with bilateral joint replacement experienced good improvement, at least a 50 percent in both velocity and single support time. If, however, only one of the two painful hips was replaced with a new joint, fewer patients improved their single limb support capability though modest gains in velocity were seen. A logical explanation for this difference is that the mobilities gained with the artificial joint improved stride length but the limited capability of the other hip continued to restrict walking endurance and vigor. Consequently the muscles could not strengthen enough to give good single limb support. These data convinced the surgeon that early bilateral hip replacement was clinically important. As a result we no longer see this semi-improved patient.

Stride characteristics also have helped us evaluate some aspects of surgical techniques. For instance, the most complete exposure of the hip joint is gained by a lateral approach that includes dividing the greater trochanter. The latter technique makes it possible to lift the abductor muscles out of the way. While heavy wires are used to reattach this bony segment, healing has been difficult to obtain since patients now have gotten up and walked in the immediate postoperative period. The question has been whether or not x-ray changes of incomplete union and broken wires were significant of functional loss. The stride characteristics demonstrated that both velocity and single limb support were good if no complications arose, whereas single limb support was poor if there were non-union of the greater trochanter or pain from the wires or calcifications. This information has encouraged surgeons to be more selective as to when they use this approach, reserving it only for those situations where the potential complications would be justified.

A common means of relieving a contracted adducted posture of the hip joint is to divide the abductor tendon. This has always been considered a very innocuous procedure because in the paralytic it commonly improves their ability to walk. However, measurement of the stride characteristics in the patient with total joint replacement demonstrated that both velocity and single limb support time averaged less than was found in those who did not have this procedure. Hence it is not totally inconsequential and will be done more selectively. The reason probably is that the patient substitutes for weak hip abductors with a lateral trunk lean. This pulls on the adductor area, which following its release, is less strong than previously.

Having demonstrated that measurements of patient's velocity and single limb support time have clinical value, a second project undertaken by our staff was make them measurable in any clinical environment with a hallway at least 35 feet in length. This effort focused on developing a portable footswitch system. Basically, it consists of a memory unit and calculator. The memory packet worn at the patient's waist stores the footswitch data generated as the patient walks. These data are then translated into velocity and right and left single stance times at the end of the run by the calculator. Lights set at the end of the measured walkway triggers a switch to active the system. This equipment is now being used routinely in our total joint and amputee clinics. It is gradually being made available to other centers.

Perry cont.

Electrogoniometry is a convenient way to measure joint motion during walking. Its clinical value is readily demonstrated by the findings in patients with total knee replacement. In our laboratory we use a parallelogram type single axis goniometer to record the relative ranges and rates of flexion/extension occurring during walking. Customarily physicians judge the joint mobility by measuring the passive range of motion. Patients with severe knee degeneration usually walk with a relatively stiff knee. Improved motion is thus a significant gain from the total joint replacement. Surgeons, however, have been disappointed by the finding that following total joint replacement the average passive range is not significantly greater than it was pre-operatively (78° vs 82°) even though the patients appeared to walk better. By measuring the knee motion during walking it became evident that the range of motion used during swing was more than doubled over that employed pre-operatively (49° vs 22°). The difference in results is one of timing. During walking the knee must be flexed rapidly whereas the passive range of motion is obtained slowly. Swollen painful tissues will not change their length with sufficient speed to meet functional demands. In normal gait the knee reaches the needed 70° by flexing 300° per second whereas in pre-operative patients this rate was only 10° per second, forcing them to walk more slowly and with a relatively stiff knee.

ENERGY COST

The amputee population probably best presents the clinical gains that can be accomplished with this technique. One limitation, however, is the fact that a person must reach a steady aerobic state in order to make the measurements valid. This requires the patient to walk approximately three minutes to reach his measurable condition and then continue another two minutes for adequate gas samples to be obtained. The patient's physiological tolerance of this effort is identified by simultaneously recording their heart rate and respiratory rate. At the same time, work is indicated by recording the patient's velocity using a heel switch. To have the patients walk in their customary manner, a sixty meter concrete track is used with all the data being telemetered into the laboratory.

Gas is collected in a light plastic bag and analyzed at the end of the test. The amount of energy consumed is indicated by the amount of oxygen extracted from the air. This extent of oxygen consumption may be related to three base lines: time, distance walked, and maximum energy production capability. Energy cost per minute expressed as milliters per kilogram body weight per minute is the most common measure. This is an index of the person's immediate physiological experience. All the amputees except the youngest and huskiest, i.e. traumatic below-knee patients have a minute oxygen consumption slightly less than normal. They averaged 12 vs 13 ml/kg/min while the traumatic BK used 15 ml/kg/min. This latter value, however, did not represent excessive use but good physical conditioning. They were able to expend this much energy (and hence walk faster) while using only the normal 35 percent of their aerobic capacity (i.e. the maximum minute oxygen exchange possible). All the other patient groups stayed within the normal limit except the diabetic above knee amputees who required 63 percent of their aerobic capacity in contrast to the normal 43 percent for their aged group.

Heart rate confirmed this indicated level of stress. It was close to the normal 104 for all the patients except the same diabetic group with the above knee amputations. Age proved to be the significant differential with the diabetic patients averaging 60 years and the traumatic amputee groups only 30 years. This difference in age was reflected in the patient's velocity. Hence both age and amputation were functional determinants.

Correlation of energy cost per minute and gait velocity gives the energy cost per meter traveled. This is a very significant functional measure because the object in limb management is to allow the person to travel the distances necessary for self-care, vocational, or advocational pursuits. Both the two traumatic groups (AK and BK) and the two elderly diabetic populations who had retained their knee joint (BK and Syme) had an average penalty of approximately 50 percent above the normal requirements. However, the diabetic above knee patient showed a much greater deficit. Theirs was more than double that of the normal requirement (220 percent). These data very clearly identify why gait training has been universally successful with most patients, yet so ineffective for the elderly (diabetic or vascular) patients with above knee amputations. Their failure to become ambulatory commonly has been blamed on lack of motivation. It is now well documented by the energy cost studies that the degree of exertion necessary for these persons to accomplish an effective gait is almost physiologically intolerable. The clinical response to these data has been a more intense drive by our surgeons to preserve the knee, even to accept slower healing rates because the social outcome is so different. A second clinical response has been more realistic planning for those elderly patients who must have an above knee amputation. Their preference to walk with crutches rather than prostheses is now accepted by the clinical staff. For comparable energy cost values both the traumatic and diabetic above knee amputees walk faster with crutches (and no prosthesis) than when wearing their prosthesis. Such is not true in those patients who have retained their knee. In addition, heart rate in all patients depending on their arms for walking was high regardless of their limb capabilities. This rate, however, did not exceed that which elderly, above-knee patients experienced in the attempt to walk with a prosthesis. Thus with no increase in energy they could experience a faster gait and therefore be more effective. The rationale of this finding is supported by other energy cost studies which show that upper limb function is 30 percent less efficient than lower limb function.

Another question investigated by energy cost measurement was the significance of carpeted surfaces in comparison to concrete. In patients minute energy cost was increased 25 percent while their velocity was decreased 30 percent by the carpet. Comparable values were obtained for normal persons using a wheelchair. As a result, the oxygen uptake per meter increased 37 percent for normals and 56 percent for patients. This indicates that in areas where disabled patients walk or push wheelchairs carpet should be avoided so that the patient can function most easily.

DYNAMIC ELECTROMYOGRAPHY

The objective definition of muscle action during walking in patients with hemiplegic, cerebral palsy, and head trauma has been a particularly rewarding clinical contribution. Muscle action with these pathologies is a mixture of voluntary control, stretch reactions, and primitive patterning. As a result, performance cannot accurately be predicted by static testing despite many years of effort to do so. For example, the "prone rectus test" was designed to differentiate excess tightness (contracture or spasticity) in the rectus from that in the hip flexors. It depends on the anatomical fact that the rectus femoris muscle crosses both the hip and knee where as the other relate to the knee. For the test the patient is prone with limb extended. If the hip flexes as the examine passively flexes the knee, it is assumed that there is tightness of the rectus muscle and this muscle should be surgically released to improve the patient's gait. Dynamic EMG has demonstrated that the major hip flexor also may equally react to this test and thus the desired differentiation will not result. Similar ambiguity has been demonstrated in the majority of the other stretch tests.

To overcome this limitation our laboratory has been using wire (50 μ) electrodes inserted in the significant muscles to identify thier activity during walking. The phases of gait are determined with the insole footswitches differentiating swing and stance. Telemetry transmits the signal to the recording equipment where permanent storage is by both video and an tape. A printed record provides the immediate source for visual qualitati analysis.

Management of the cerebral palsied child's flexible varsus (internall twisted) hindfoot demonstrates the value of EMG over customary clinical testing. When a foot twists in during walking but is manually correctable when standing, it is due to excessive or inappropriate muscle activity. Surgical correction focuses on the two primary foot inverters: the tibial anterior which is normally active during swing to pick-up the foot and the tibialis posterior which contributes to foot stability during stance. Thr variations in normal muscle function has been identified by dynamic electr myography in the cerebral palsy child. One type is the tibialis posterior changing its phase from stance to swing so that it functions at the same time as tibialis anterior. This makes available a muscle that can be move anterior to pull up the lateral side of the foot at the same time the tibialis anterior is raising the medial side. The results postoperative has been good correction with a balanced foot. Postoperative EMG studies have confirmed that the muscles continue their same pattern of action. Clinical type two consists of persistent tibialis posterior activity in all phases of gait. The surgical management of this problem has been to release the tendon so that the muscle no longer can create an adverse pull In this way the other muscles are allowed to function in an uninhibited no fashion. The third situation is to have the tibialis anterior display continuous activity throughout both phases of gait. The foot is balanced by splitting this muscle's tendon and putting half of it laterally so that the continuous activity is now balanced with equal pull on both the medial and lateral side of the foot. All three of these procedures are common throughout the country but rather than being selected on a muscle activity basis, operations have a geographical distribution depending on which one procedure has been most effective in the senior surgeon's hand. Through dynamic electromyography, we have been able to match the surgical choice to the individual patient's muscle pattern and therefore have consistently good results in all patients rather than having to accept many undesirable outcomes. The same type of analysis has been done for the reverse deformity of valgus foot or the internal rotated hip.

Thus in summary, several examples of the way gait analysis have been used to make surgical decisions have been discussed. Preliminary experience confirms that these same analytical techniques also provide objective means for determining the relative effectiveness of different orthosis or physical therapy techniques.

Both instrumentation and testing techniques still require considerable development. Reliability, patient convenience, universality of measurement, and proper results are the goals. Some functions still do not yield to ready measurement. Equipment is bulky: it has the unreliability of prototypes, and requires considerable staff involvement for operation. Data analysis remains time consuming, either because of staff involvement or the lack of routine on-line (or immediate) computer processing. The research aura must be transformed into the production demands of routine patient care if clinical staffs are to profit from the assistance objective gait analysis can provide.

DISCUSSION OF MORNING PAPERS

Dr. Basmajian: Let's start the discussion by addressing any questions that you have for the speakers.

Dr. Kelly: I'd like to direct my question to Dr. Sutherland. Number one, if you're going to do this sort of analysis, can you combine it with evaluations of the muscular involvement?

Dr. Basmajian: I think all three speakers (Milner, Simon, Sutherland) can answer this question after David leads off.

Dr. Sutherland: We do simultaneous electromyography along with movement measurements and force plate recording. We use surface and internal electrodes and our attention is directed primarily to obtaining the off and on time of selected muscles. There is a great value to knowing the timing of muscle contraction as it relates to the events of gait, but I think that we cannot rely upon the electromyograms as we now do them to give us quantitative information about the force of muscle contraction. As you know, Dr. Perry is doing work on quantitation of the electromyograms utilizing a computer program to measure the area under the curves of the muscle action potentials. We are investigating the relationship of intramuscular pressure to muscle tension and are currently testing a miniature solid state pressure transducer which can be inserted percutaneously into the muscles. But even if we do develop a satisfactory method of assessing muscle tension, there are still many problems. The absence of action potentials during the performance of a movement is good evidence that the muscle is not contributing to the movement, but the presence of action potential or recordable tension in the muscle only tells us that this muscle is activated during the time that movement occurs and possibly the degree of activity or tension. To obtain the full picture we must have knowledge of all the other muscles that might affect the movement and inertial and gravity forces which affect the movement must also be considered.

Dr. Basmajian: Thank you. Are there any other comments along this line? Those of you who have seen and heard Paul Brand lately perhaps know that he is emphasizing muscle bulk in evaluating its potential usefulness in muscle transfers. He shows slides of practically every muscle in the body laid out to show their variation in size, the characteristic of the direction of fibers of the muscle, and the potential usefulness of this in determining the force that the muscle would exert--or at least the force that muscle would exert at a particular joint.

These are very contentious issues. It is true that electromyography is relatable to force, and yet the problem has arisen repeatedly that forces have been measured only in an isometric fashion; all that tells us is that this muscle is bigger than that muscle. These are facts we have known anyway. So the ability of gait laboratories to come up with a diagnosis of the contribution that a muscle is making to a particular action in normal or abnormal gait, is going to be very, very difficult.

Dr. Burstein: Let me ask a question. There are several gait laboratories now in existence that have devoted considerable time to measuring parameters from which they can calculate muscle force during various activities. There are several calculation schemes that look very promising, the University of Iowa, for example has developed an interesting optimization method. It now becomes a matter for the investigator to put together a clever test in which he can then evaluate the capability of the performance of a particular muscle or muscle groups. For example, if he is to do a transplant on a particular muscle, then he would have to require the patient to perform a task utilizing that particular muscle. The experimental and analytical techniques do exist but are not being employed. One reason that nobody is dealing with it, to my knowledge, is that nobody's trying to evaluate performance by imposing a particular path. Most of us are interested in the problems of walking, running, climbing up and down stairs. But we haven't progressed far enough in terms of the sophistication of our experiments, not necessarily in terms of the sophistication of our measuring technique, or in terms of the accuracy of the data we collect.

Dr. Basmajian: Dr. Burstein, are there two ways then of approaching the problem? Is the first gait recording, and the other, biomechanical and electromyographic techniques, divorced from the gait training?

Dr. Burstein: Yes, there really are two ways. When Dr. Milner spoke, he showed us a table of information. I would like to bring up one point: i.e. the concept of linear force in joints. He emphasized it; he talked about forces in bones, forces in joints, forces in muscles. These forces aren't measured in any of those laboratories; they are all calculated. We do have the capability of calculating them; they are a mathematical imprint. Some special assumptions have to be made of course, but we have ways of verifying these assumptions and we are turning out some reasonable numbers. The "direct measurements" are EMG or muscle pressure, those phenomena related to muscle activity in functions that we're trying to relate to the occurrence of the force, or to the magnitude of the force. The EMG signal is obviously responsible for producing the force. On the other hand, the internal muscle pressure is a direct result of the force. Those are different kinds of measurements, and we hope that we can get direct transducer measurements that have a straight line output/force relationship. This development is in the future. The approaches we already have, do have the capability of quantitating the force.

Dr. Basmajian: Ed Chao, do you have a comment to make on that?

Dr. Chao: Direct and indirect verifications of theoretically calculated joint and muscle forces are possible. The use of instrumented joint prostheses to monitor the joint contact force and compare it with the theoretically predicted force would be classified as a direct verification method. There are other direct methods too. These methods include measuring hand flexor tendon tension using strain gauges in patients undergoing carpal tunnel release under local anesthesia; using muscle force transducers or applying strain gauges to bone in experimental animals and measuring intramuscular pressure to relate to contractive force. However, these direct methods lack reliability, repeatability, and they are impractical for human use. The instrumented prosthesis has yet to produce any realistic results. Using animals as models requires a separate mathematical analysis, since the structure and behavior of animals would be different from that of man. These problems lead to the need of an indirect method to verify the analytical results.

The use of quantitative EMG to correlate with the theoretically determined force can serve as an effective qualitative verification provided that the function involved will be primarily isometric. The literature in the past has documented that there is certain correlation between muscle force and its rectified and integrated EMG. If the externally applied force during isometric function is increased incrementally, then the subsequent increase in measured EMG response should provide certain qualitative verification. However, if the function involves joint motion then the muscle contraction force will be difficult to correlate with integrated EMG since muscles will have different functional lengths and their fiber response will be different.

In talking about verification, one important aspect has to be remembered. The advantage of analyzing biomechanical systems through theoretical modeling is not to achieve a precise description of the realistic biological system. In fact, it is nearly impossible to do so. However, the main goal of doing so is to provide a reliable trend so that results on a comparative basis can be objectively assessed. Through such analysis, upper and lower bounds of results can also be established which will be extremely useful in providing safety limits and minimum requirements of therapeutic treatments in joint disease patients. In this case, an exact experimental verification is not necessary.

Dr. Basmajian: Jacqueline Perry wants to speak next.

Dr. Perry: The EMG represents the intensity of the signal stimulating a muscle to contract. There now is good evidence this is proportional to the intensity of the muscle's contraction, i.e. its level of activity. Hence we can identify when and how much a muscle is working but not its resulting force. To learn the percent of intensity the muscle is working from the EMG signal, one must have a base line test relating EMG to measure maximum effort. There are several variables alerting this relationship, however. (1) The fact that shortening contractions accomplishes 30 percent less force than isometric or eccentric (yielding) types of activity. (2) Velocity of contraction reduces the muscle efficiency. (3) The three muscle fiber types have different capabilities of exhibiting force and different endurance tolerances. Hence to determine the force from an EMG requires a very complex mathematical model of which several factors still need more definition.

Dr. Basmajian: Jacqueline's remarks lead to a neurophysiological consideration. Before I call on Dick Stein, I might mention that underlying all this is the fact that active muscles may be playing no efficiency role--that is, muscles in children may be acting, but no demonstrable role can be assigned to them in the achievement of a movement through space. This has been shown over and over by electromyographic studies of youngsters in whom there is an excessive activity in muscles that are unrelated to what we would consider to be a useful achievement. This is part of the pattern of growth; there is an excessive activity which is almost spastic in some babies, and this continues late into childhood, as late as junior high school age. And no one can assign any particular use to it. Czechoslovakian investigators have shown that when you ask a child to extend his knee while sitting on the edge of a table, for example, that the adductors of the hip joint act very, very strongly; but with growth this gradually disappears. By the time they are adults, or young adults, they are no longer using those muscles in extending the knee or in walking.

So you will find that there are EMG activities that cannot be related to purposeful movement, and this is all related to the maturation of the central nervous system and its control mechanisms. Dave Sutherland showed us slides of a number of graphs that he provides to surgeons, with an explanation of what they all mean. He has brought this work to the practical level, so that the surgeon, looking at the gait analysis can make judgments which are superior, we hope, to simply looking at the patient walk.

Dr. Simon, would you like to comment?

Dr. Simon: Dr. Sutherland, Dr. Perry, and Ms. Murray are notable in their achievements in illustrating not only how certain measureable parameters of gait can be clinically useful, but in presenting them in a form that is easily understood. There remains a considerable body of measureable or calculable information, whose value in assessing a variety of gait disorders is yet to be determined. In the past when they have been obtained, quantities such as angular and limb segment velocities, accelerations and energies, and joint forces, have all been considered to be important and useful. But these instances have been few. We are now in a favorable position to present these parameters in a clinically palatable form, and apply them to a wide variety of pathological disorders. I think some of our attention should be focused on doing this and ascertain in what instances information so derived is inherently useful and in what instance it is of more importance than simpler quantities.

Dr. Basmajian: I'd like to draw Dr. Houk into this conversation now.

Dr. Houk: I'm impressed by the technology that is being used to record many important variables, but I would like to question the use to which this technology is being put. I don't think enough thought has been given to the design of experiments that are capable of revealing important principles and concepts concerning the mechanisms by which gait and posture is controlled by the central nervous system.

Dr. Basmajian: Al Burstein has a further comment.

Dr. Burstein: We've had some pretty good descriptions of some of the major gait labs in the country. We then went into what I consider the major topic, first, the desire for normative data, and second, the need for scientific experiments. Then we started getting into the topic of how one uses these tools in terms of clinical diagnosis. I think we've bounced back and forth, and, in my mind, I think we have to keep these topics separated. One seeks a collection of normative data as a scientific data base from which you can either do scientific experiments or develop new clinical diagnoses. One does a scientific experiment only if you have a hypotheses to test. But I think that if we keep going through the cycle as to what constitutes an experiment, what constitutes diagnosis, and where are we in the state of the art of instrumentation and normative development, we are going to become very confused.

What can we do in the gait laboratories? Obviously we can observe the limb. But we also have the capabilities of going within the limb, of looking at, for example, different stage of activity--basic activities. This tells us that they're part of the problem, different muscle forces being applied. We can diagnose specifically what the detailed differences are, and these are reflected grossly in the fact that what we have is an output--a limb motion. We must always remember of course, that we have an equilibrium system--we push it off equilibrium in one way, it tries to come back, and depending on how hard we push it, it may not come all the way back.

I also think that we can address ourselves to what kinds of serious scientific experiments can be performed in a gait laboratory. I think that's very germane. But you must pose a question. If you want to get right down to it you can write a proposal which says, I have a question that needs answering; it is justified on clinical grounds. I have to use a gait facility in order to obtain the information that will answer the question.

Question: Are serious experiments being done?

Dr. Burstein: Yes, I have spent some time talking to people who have gait laboratories and asked them what kinds of experiments they were doing. There are a good number that I would consider good scientific experiments.

Dr. Basmajian: I've introduced a simple hypothesis in recent years which everybody has ignored; that is, that human gait on a flat surface--walking gait--is bicycling--and has many of the characteristics of simple bicycle riding. I also think that footfall is really a portion of the circle of the wheel--a very large wheel in the case of human gait, that's rolling along in a two-wheel fashion. I would welcome anybody testing that hypotheses: I don't know how to do it myself. It's a concept rather than a hypothesis, perhaps. And remember, when we talk about locomotion, that walking on a surface is only a small portion of the capability of the human anatomy to move across the ground. There are many other aspects of gait--both human and vertebrate, that we have not addressed in the discussion so far.

Dr. Childress: Two or three statements have been made about the usefulness of optimal control theory in understanding gait. I should like to caution against being overly optimistic about the value of optimal control solutions. Experimentalists and theorists working on joint motion have been forced to consider optimal control because they have an indeterminate problem; many more forces are developed by the musculature than are actually needed. The question then is what pattern of forces is developed in these muscles.

One approach to solving this problem is to assume the pattern used by the body is one which actually tries to minimize some performance index. However, this of itself is a problem because the performance index (if there is one) is unknown. Therefore, the procedure is to select some logical performance indices and see if the solutions agree in any way with those expected.

This is the crux of my thought. The forces must still be measured to show that an assumed performance index is indeed correct. Consequently, optimal control tends to avoid the problem of verification. If the forces must be measured to verify theoretical results why not emphasize the development of instrumentation to measure muscle forces. Then we would obtain the information desired and even a good approximation to the performance index could be determined by solving the inverse optimal control problem.

Even muscle measurements may not be sufficient because a very complex system is being studied. Each person may solve the problem of walking in a slightly different way, even though gait may be generally similar in different people.

Dr. Basmajian: Before concluding the morning session, perhaps we ought to come back to the question of costs, although we're not here to establish norms for the nation. What is the outlook for support in the immediate future for the kinds of research that are needed and the total cost to at least achieve these goals satisfactorily? Dr. Milner, you had an estimate--do you want to expand on that estimate? What would an adequate center cost?

Dr. Milner: Approximately $100,000 for equipment alone. Depending on the nature of the study undertaken, pertinent staff skills would have to be provided. Also amortization of equipment must be accounted for realistically.

Dr. Heiple: I think that cost is one question we have to address. The economic cost benefit rate does enter a Study Section's considerations, along with the scientific merit of a project. The cost benefit is often reflected in the priority score. We all make some kind of value judgment related to the expensiveness of propositions, as opposed to subjective judgment of the value of the data to be obtained to scientific knowledge, or possible clinical usefulness. I do not think that we're going to arrive at any qualitative answer to this today. If we simply refine our understanding of what the problems are that are being raised, and the kind of questions that need to be answered, I think it will have been worthwhile.

Dr. Childress: Dr. Milner has indicated his list of gait laboratories is not exhaustive. As we have several people here who are well acquainted with this field it would perhaps be appropriate to attempt to complete the list. Two gait labs in Boston are not listed ant there is another at Presbyterian St. Luke's Hospital in Chicago. Are there others?

Audience: Vanderbilt has one.

Audience: There is one at Cornell.

Dr. Basmajian: Would you glance at the list. Are there other centers that are not listed in the Table? That is not a large additional number. It should be possible to add that to the table before it's published.

Dr. Akeson: It will be important for participants to review the gait lab listing and to fill in any gaps. One of the purposes for this conference was to survey the existing facilities, and it is important that the list be comprehensive.

I would like to echo the comments of Dr. Heiple and Dr. Burstein with respect to the need to assess the scientific merit of the product of gait laboratories. Questions of need with respect to normative data gathering, effectiveness of construction of hypotheses, and suitability of experimental design are central to this workshop and will be addressed recurrently today. Cost effectiveness of this research will also be an obvious concern.

Dr. Basmajian: Biomechanic labs. Have they contributed something that's real, that justifies cost?

Dr. Leith: With the courage of the non-combatant, I would like to comment. I don't think I've ever seen the situation where the gap between applied clinical science and the basic sciences, was broader than I've heard this morning. I think Jim Houk and Tom McMahon have been perhaps excessively gentle in saying what I think they're trying to get across, which is that the field appears to be dominated by clinicians who have pressing practical problems to solve, but don't know quite how to go about it. And they haven't been talking enough to the Houks or McMahon's; and so the productive approach i.e. the research approach, is not being pursued. Until the gait people start talking more to the basic scientists they simply aren't going to have the productive research results that are needed.

Dr. Basmajian: Do you include the bioengineers with the clinicians, or with the basic scientists? Sometimes it's hard to tell.

We'll let Dr. Burstein have the last word before we go to lunch.

Dr. Burstein: In a meeting held last year, through the efforts of Ed Chao, some very important results were presented and I think really started a merger of clinicians and engineers and the basic scientists from the point of view of some very good analyses of joint function relating to certain surgical problems. But there's another whole area that we don't see clearly, and I want to leave you with a word on that. That is the contribution to the design aspect of some of these new plans that are being developed.

THE VALUE OF NORMATIVE DATA IN GAIT ANALYSIS

David H. Sutherland, M.D.

The term pathological gait has little meaning divorced from normal gait. The significance of the measurements carried out in gait laboratories depends upon, (a) the accuracy of these measurements, (b) the existence of reliable normal controls and, last but not least, proper understanding of the human control system and the muscle forces producing movement. In the development of reliable control standards the largest holes in our knowledge are in the very young and the very old.

Our movement measurement system using three dimensional triangulation measurements from movie film was first presented in 1967 in a scientific exhibit at the American Academy of Orthopedic Surgeons annual meeting. Since that time we have added many additional measurements, and data reduction time has been greatly reduced. At this time an average study generates twelve angular joint rotations for each lower extremity, five force curves, four to eight electromyograms and twenty linear measurements.

To verify the repeatability of the measurement system used in the gait laboratory; two different observers read the same walk cycle two times each. The results of this test appear in the graphs (Figs. 1 & 2). The circle and square are the results from the first observer and the triangle and asterisk are the measurements of the second observer.

I am going to show some preliminary results from our studies of normal children one to seven years of age, then present summaries of gait studies of three children with pathological gait. These normal and pathological studies are presented to show our dependence upon normative data for any description of pathological gait and to emphasize the great need at this time for more complete normal control data.

NORMAL GAIT

Case Study - C.S.

This normal one year old girl walks in a staccato manner (Fig. 3). The walking cadence is rapid, but the steps are very short. Walking velocity is approximately one half that of an average adult. The elbows are maintained in flexion and reciprocal arm movements are not yet present. In the frontal plane a wide base of support can be observed. Foot strike occurs without initial heel strike.

General Measurements

	Right	Left
Opp. toe off (% cycle)	12	16
Opp. foot strike (% cycle)	50	48
Single stance (% cycle)	38	32
Toe off (% cycle)	66	61
Step length (cm)	21	21
Stride length (cm)	42	42
Cycle time (sec)	.7	.7
Cadence (steps/min)	171	171
Walking velocity (cm/sec)	60	60
(m/min)	36	36

By comparison with a composite of normal adult controls there is increased swing phase hip (Fig. 4B) and knee Flexion (Fig. 4C). Plantar flexion is present at foot strike, and there is impaired dorsiflexion in early swing phase (Fig. 4D). There is excessive external rotation of pelvis (Fig. 4E), femur (Fig. 4F), tibia (Fig. 4G), and foot (Fig. 4H) in both stance and swing phase.

All of these variations from mature gait are normal initial adaptations to the demands of independent walking.

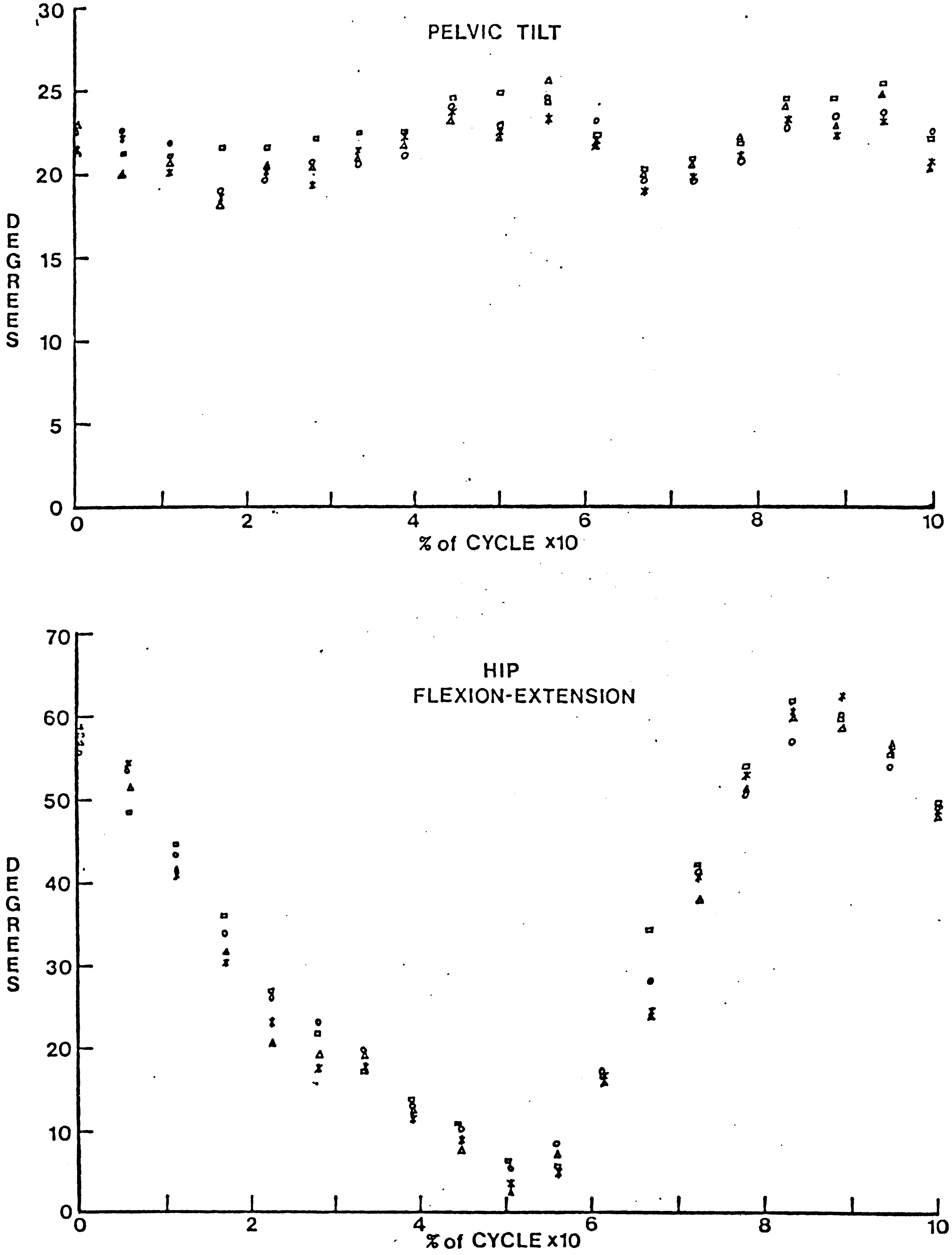
Case Study - R.K.

This normal three year old male demonstrates nearly mature gait (Fig. 5). Reciprocal arm movements are present. The dynamic base of support is normal. By comparison with the normal one year old girl, cadence is slower and walking velocity is greater. Limitation of step length still prevents achievement of mature gait walking velocity.

General Measurements

	Right	Left
Opp. toe off (% cycle)	18	17
Opp. foot strike (% cycle)	52	49
Single stance (% cycle)	34	32
Toe off (% cycle)	68	67
Step length (cm)	29	32
Strike length (cm)	61	61
Cycle time (sec)	.76	.76
Cadence (steps/min)	158	158
Walking velocity (cm/sec)	80	80
(m/min)	48	48

Fig. 1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25
20
15
10
5
0
0
2
4
6
8
10
% of CYCLE x10
HIP
FLEXION-EXTENSION
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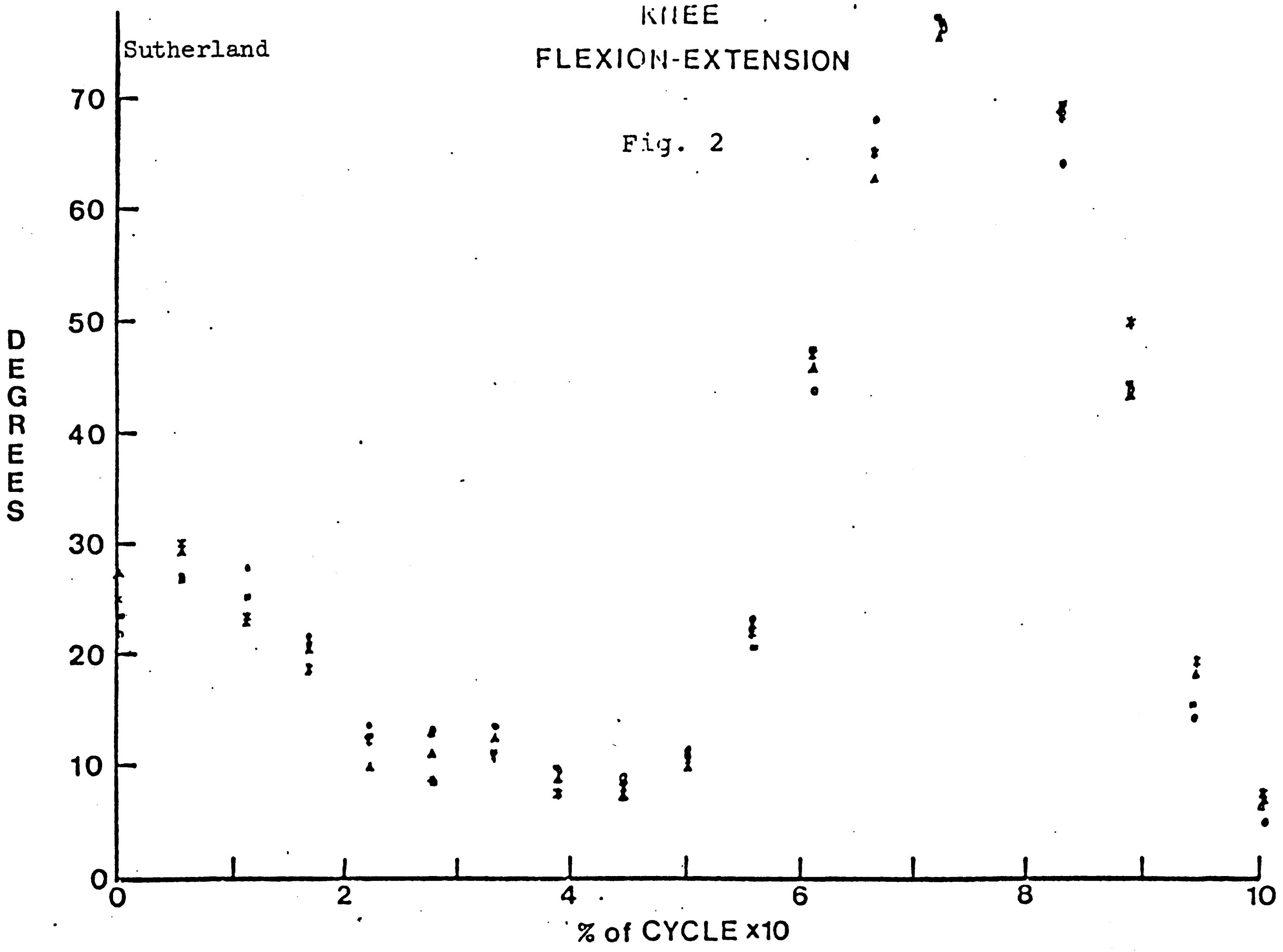
KNEE
FLEXION-EXTENSION
Sutherland
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Fig. 2

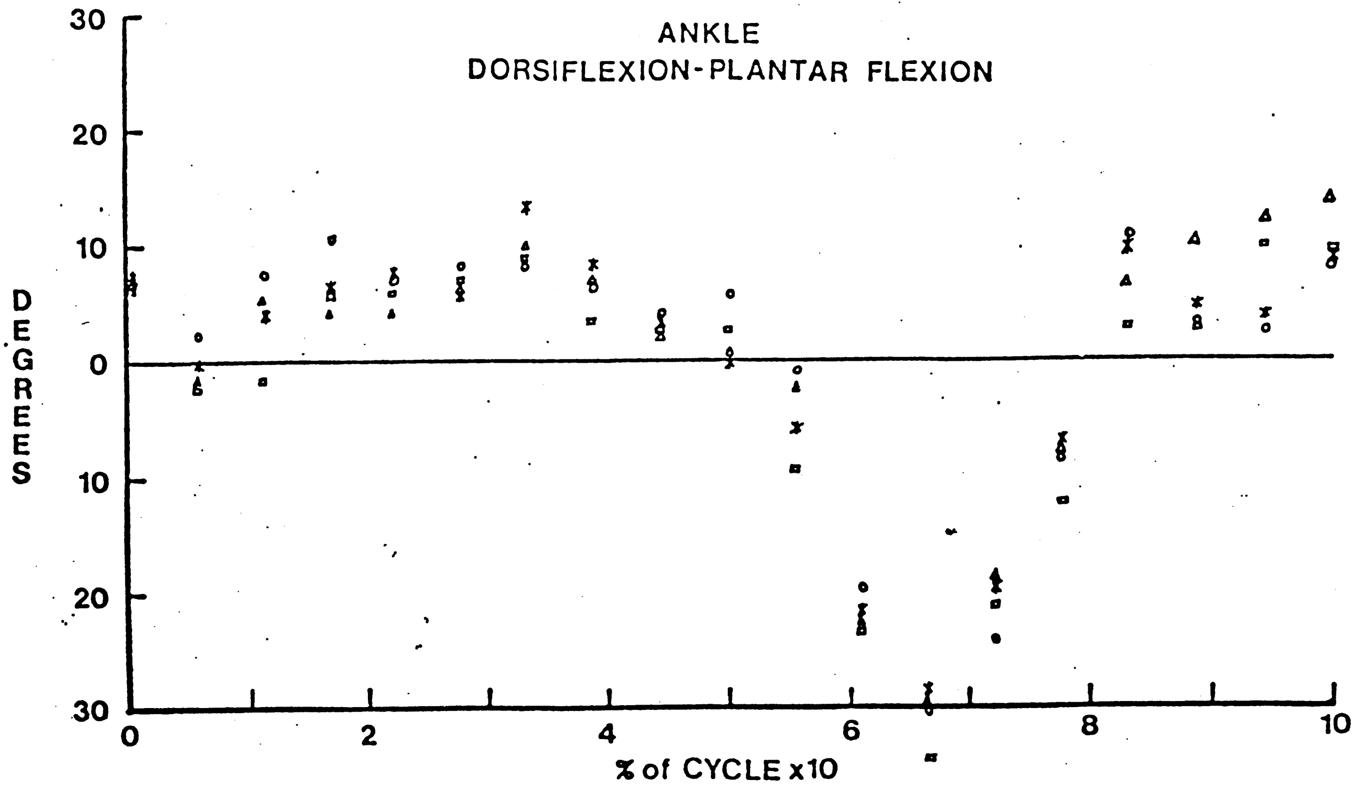
ANKLE
DORSIFLEXION-PLANTAR FLEXION
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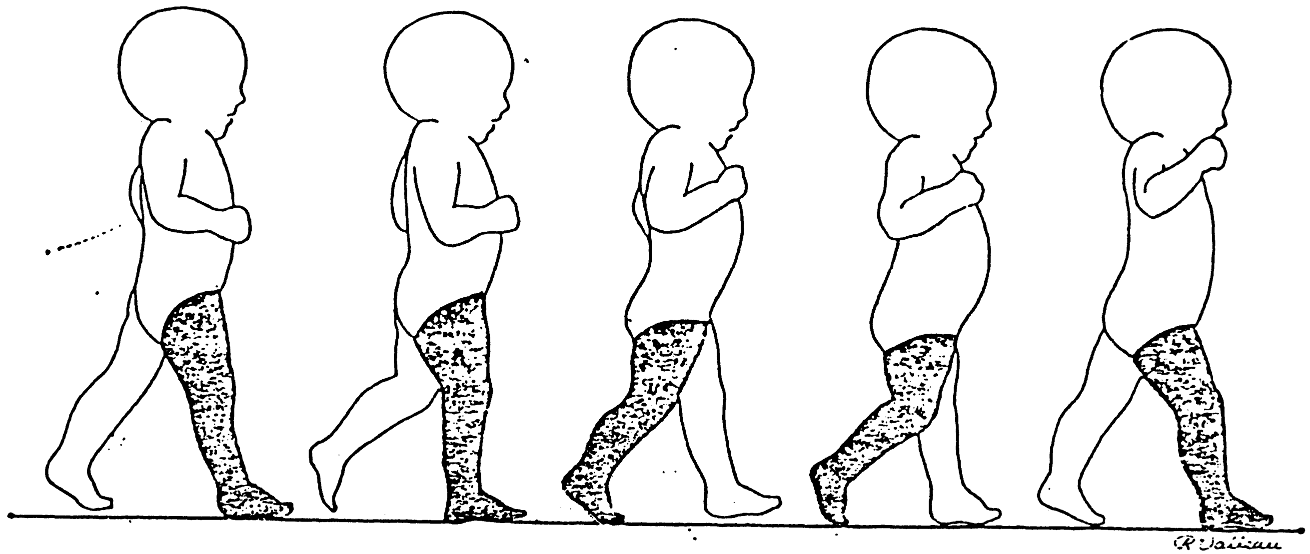
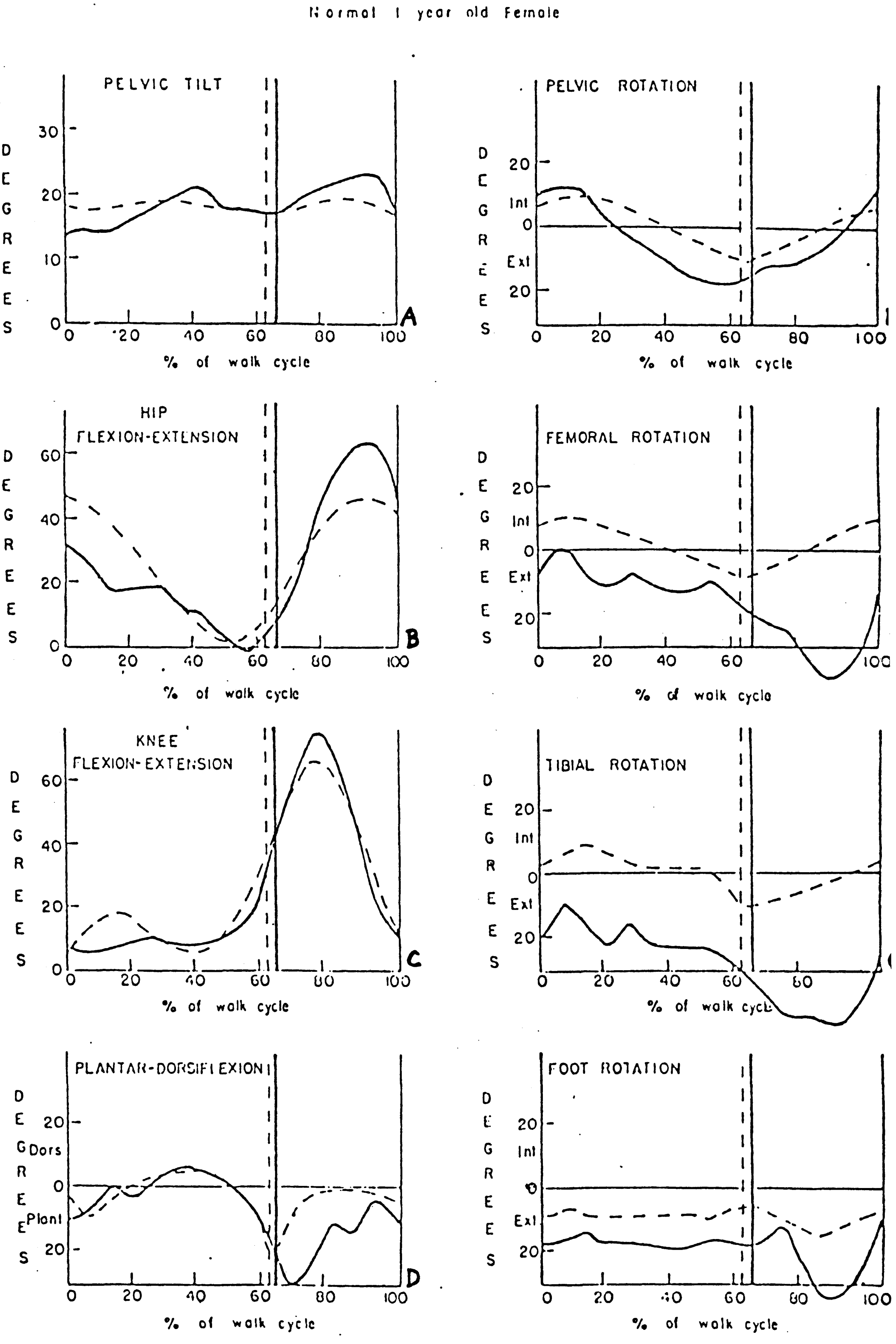
Fig. 3



NORMAL 1 YEAR OLD

Note the flexed elbows, absent arm swing, plantar flexion at foot strike and increased shoulder sway in this one year old girl.

Fig. 4
Joint Angular Rotations



A. Slightly increased sagittal plane pelvic oscillation in this normal one year old girl.

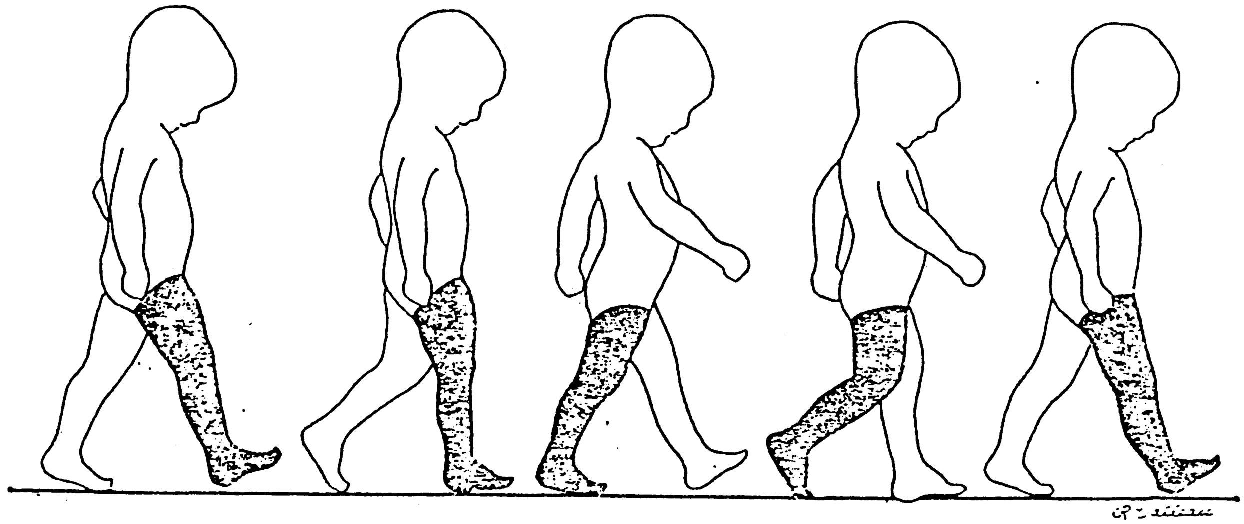
B. Increased swing phase hip flexion.

C. Extended knee throughout stance.

D. Plantar flexion at foot strike and drop foot in swing.

E to H. Exaggerated external rotation of pelvis, femur, tibia and foot.

Fig. 5



NORMAL 3 YEAR OLD

Synchronous arm swing, heel strike and apparent trunk stability are indicators of considerable gait maturity in this three year old boy.

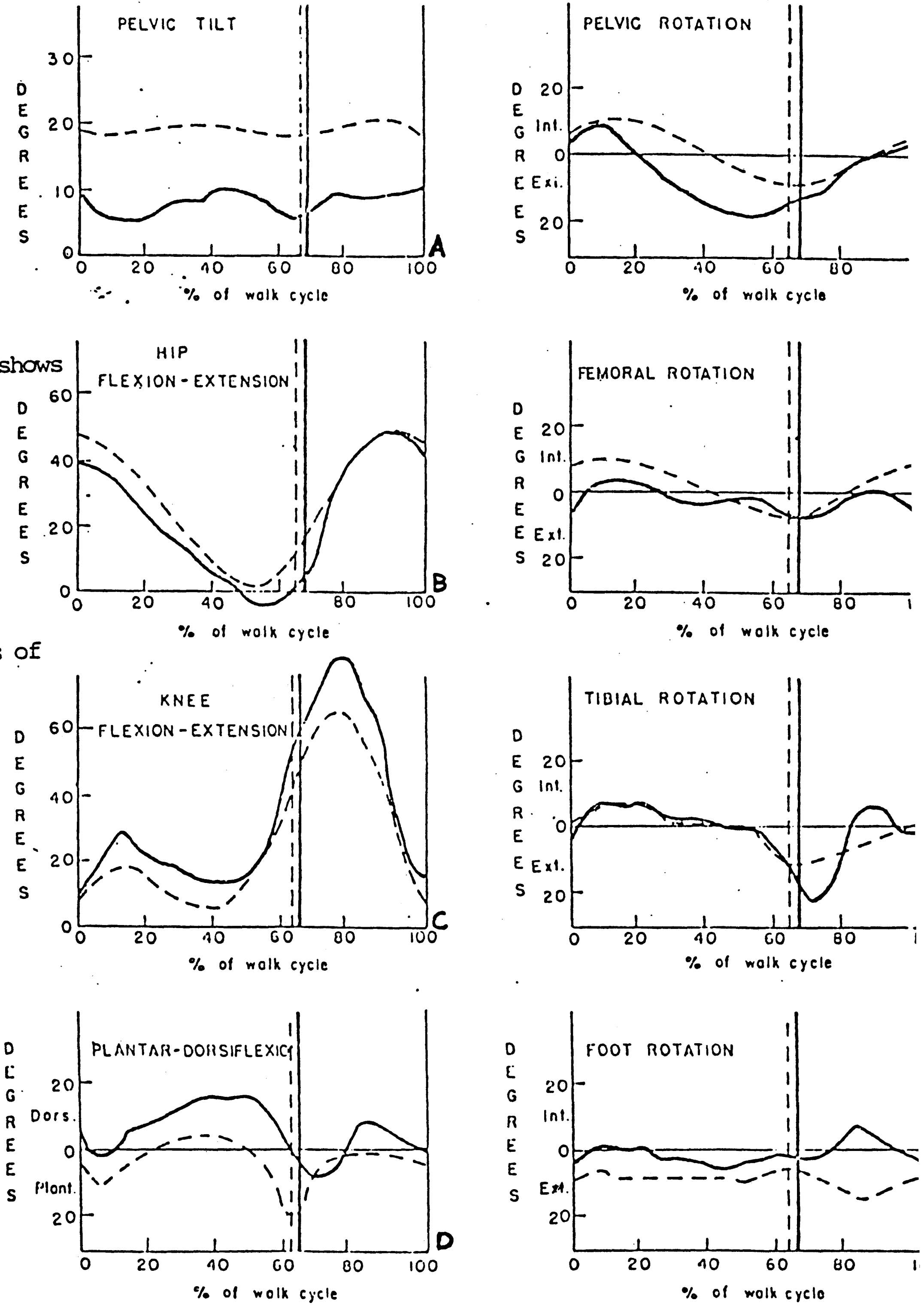
Joint Angular Rotations

Fig. 6

A. to D.
The sagittal plane joint angular rotations of this three year old male are comparable to normal young adult controls.

E. Pelvic rotation shows mild exaggeration of stance phase external rotation.

F to H.
With the exception of some irregularities of foot and tibial rotations in swing phase, femoral tibial foot rotations are similar to young adult controls.



Normal 3 year old Male

While hip and knee angular rotations are very similar to a composite of normal adults (Fig. 6B and 6C), ankle dorsiflexion in stance phase is increased (Fig. 6D). Fully mature gait will be present when better control of ankle musculature brings about the normal plantar flexor activity necessary to facilitate step length. Also Fig. 7.

Case Study A.E.

This six year old normal girl walks with a mature gait pattern (Fig. 8). Walking velocity, step length, and cadence are appropriately related.

General Measurements

	Right	Left
Opp. toe off (% cycle)	10	11
Opp. foot strike (% cycle)	49	52
Single stance (% cycle)	39	40
Toe off (% cycle)	60	63
Step length (cm)	49	49
Stride length (cm)	98	98
Cycle time (sec)	.7	.7
Cadence (steps/min)	171	171
Walking velocity (cm/sec)	140	140
(m/min)	84	84

The increase in pelvic rotation (Fig. 9E) is attributable to rapid free speed cadence. First peak vertical force and mid stance valley (Fig. 9I) are also increased for the same reason. The rapid cadence also is responsible for increases in fore-aft (Fig. 9J) and lateral shear (Fig. 9K). Electromyography reveals normal phasic activity of the vastus medialis, vastus lateralis, gluteus maximus, gastrosoleus, medial and lateral hamstring and anterior compartment muscle groups. Also Fig. 10.

The gait of this child differs in no significant qualitative manner from that of a young adult.

On February 28, 1977, studies of 112 normal children between one and seven years of age had been performed. Data reduction was complete on 92 of these individual studies.

Fourier analysis

THE MODEL

f (t) is some function of gait, such as ankle D/P, at point t of the walking cycle. We fit the model

$$f(t) = \alpha_0 + \sum_{j=1}^{6} \left[{}_j\cos\frac{2\pi}{T} t + \beta_j \sin\frac{2\pi j}{T} t \right]$$

by least squares. In this model α_0 is an overall constant, and T is the total number of observations (equally spaced). Always T is between 16 and 22, usually between 18 and 20.

Force Plate Curves

Fig 7

Normal 3 year old Male

Vertical force, fore-aft shear and medial-lateral shear duplicate adult control values. The curves are terminated at the asterisk because of opposite foot strike on the plate.

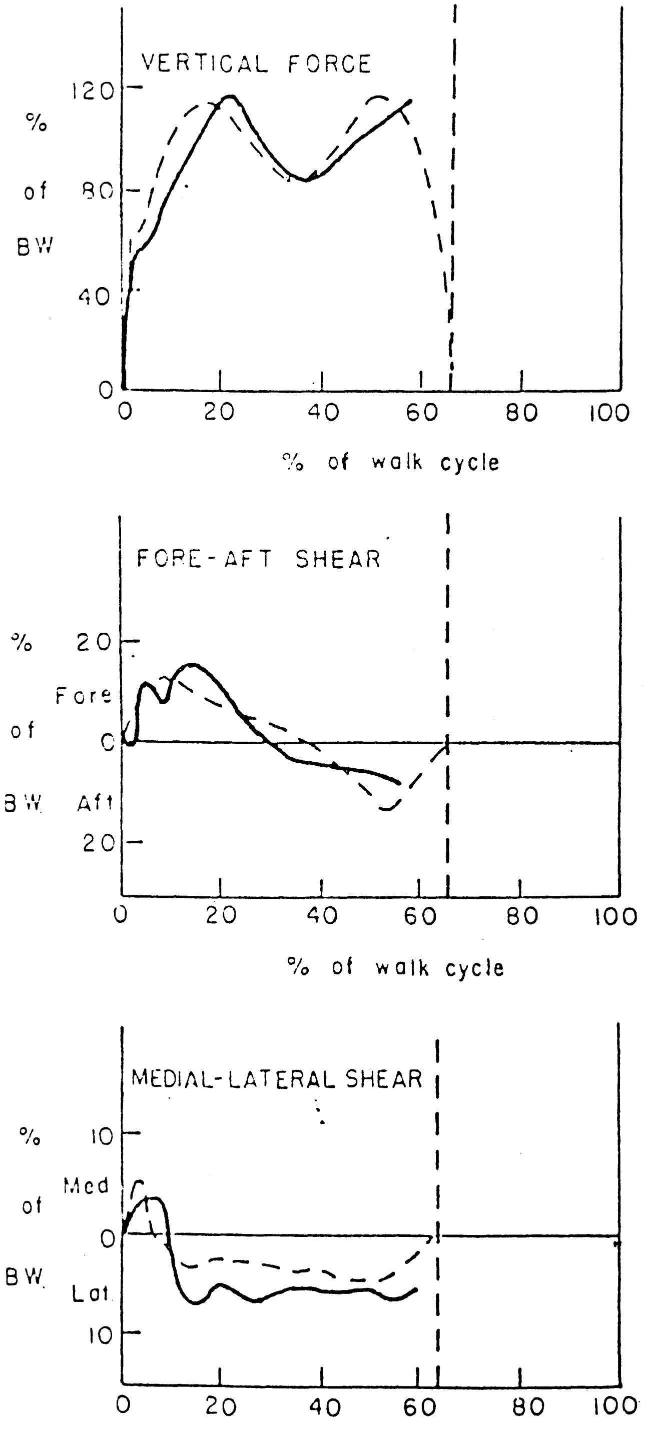
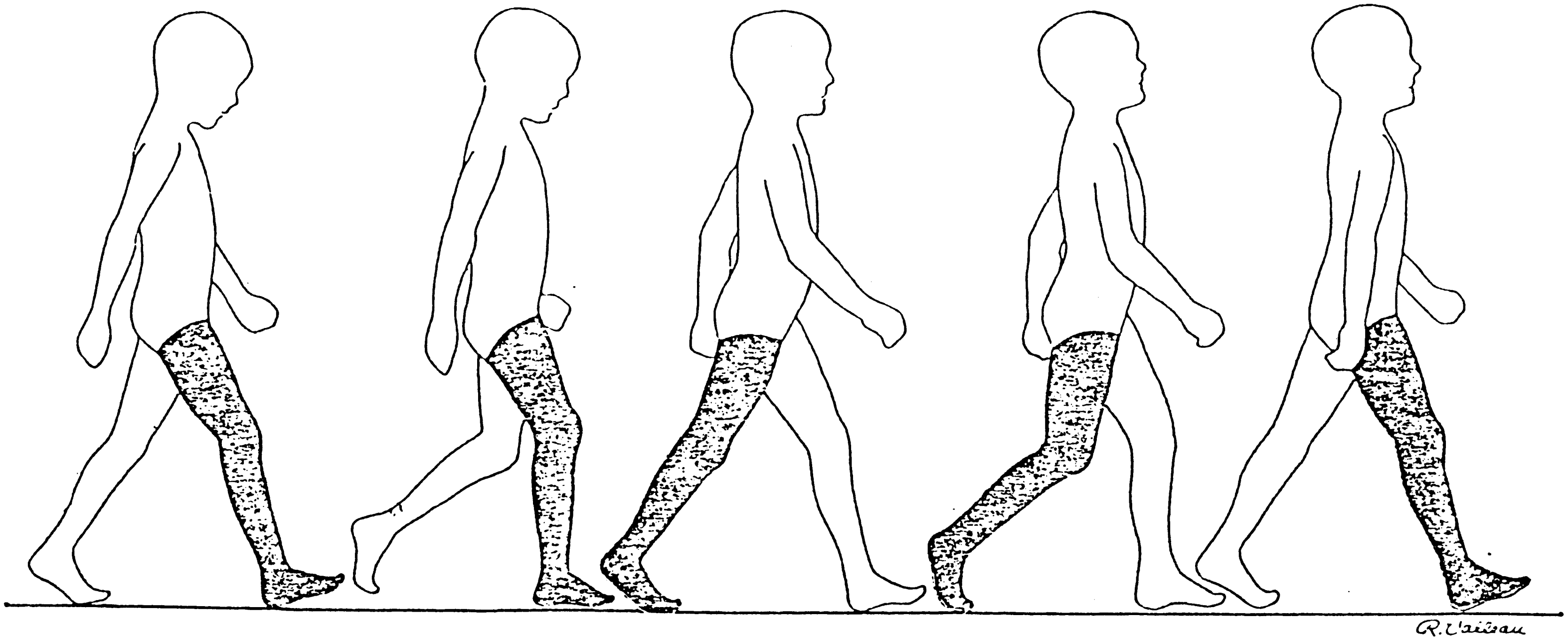


Fig. 8



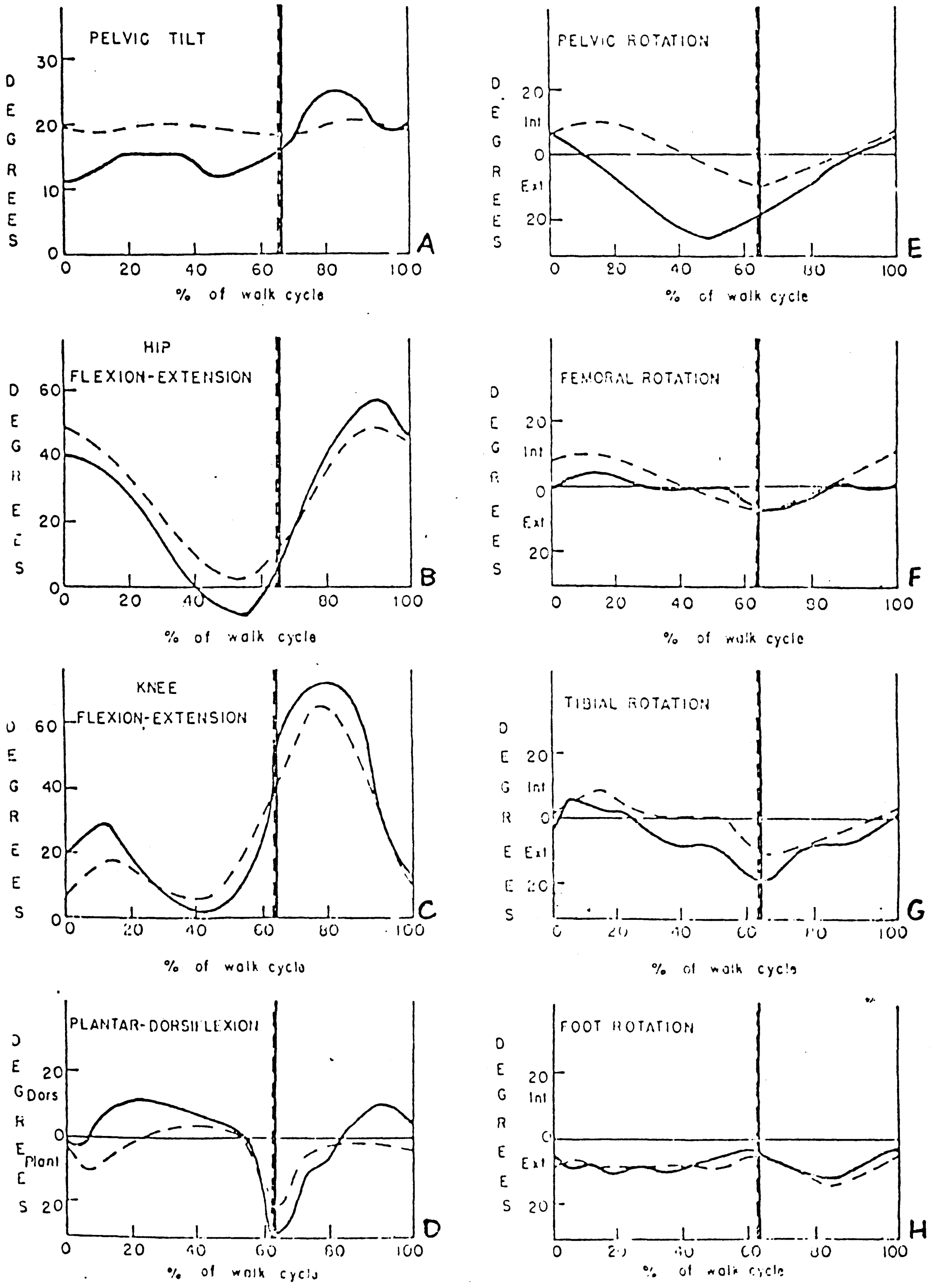
NORMAL 6 YEAR OLD

The gait pattern of this six year old girl resembles very closely that of a young adult.

Joint Angular Rotations

Fig. 9

Normal 6 year old Female



A to D. The sagittal plane joint angular rotations of this six year old girl differ in no significant manner from a composite of curves for young adult controls.

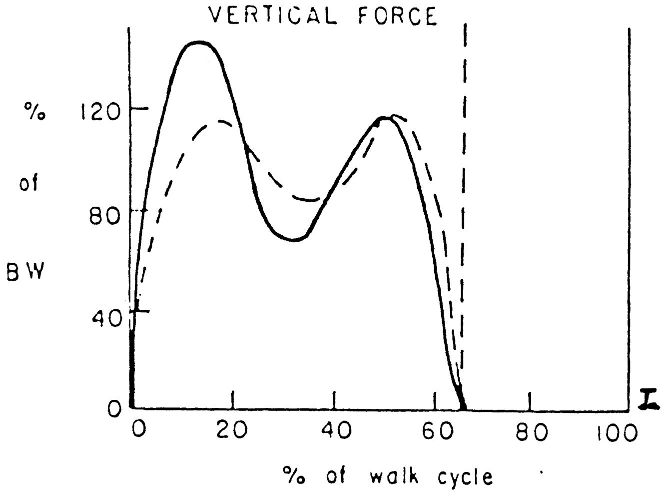
E. Pelvic rotation is increased by high cadence and increased walking velocity.

F to H.
Femoral, tibial and foot rotations are normal.

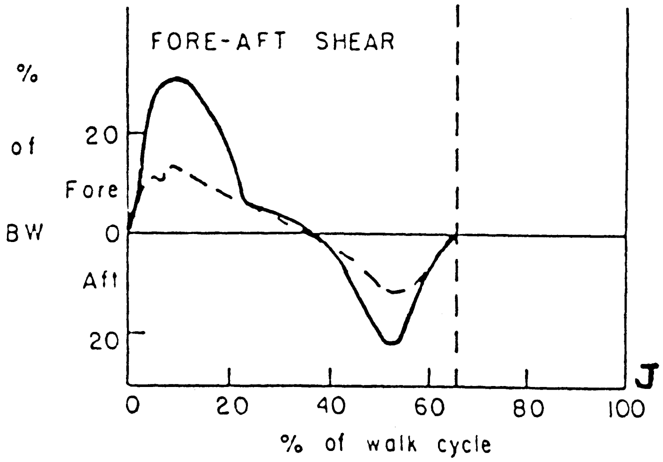
Force Plate Curves

Fig. 10

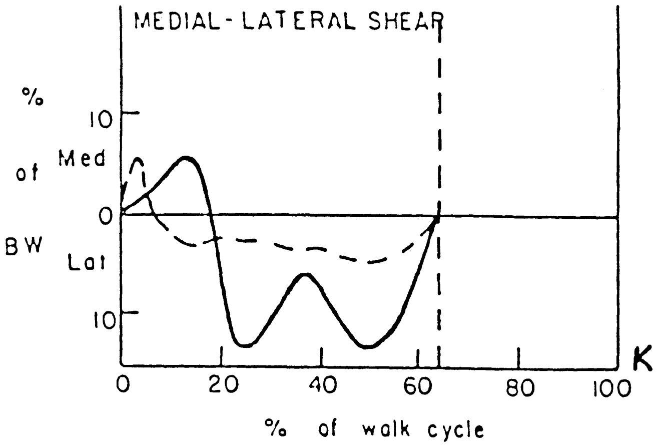
Normal 6 year old female



I. Vertical force first peak and mid stance valley are increased due to rapid cadence and walking velocity.



J. Fore-aft shear are increased for the same reason.



K. Lateral shear is increased because of rapid cadence and walking velocity.

Sutherland cont.

The ankle plantar flexion/dorsiflexion curves of 32 children demonstrates a complex curve pattern with multiple coefficients significantly different from 0 at the 5 percent level. Somewhat to our surprise 22 of 32 children demonstrated heel strike. (Fig. 11) Slope at zero negative denotes the presence of heel strike, and only 10 of the 32 children demonstrated absent heel strike.

In this relatively small group there was not a significant correlation of heel strike with age. We believe that the explanation for this observation, which appears to be at variance with the findings of previous authors, lies in the 50 frame/second camera rate utilized in our studies. Most of the previous authors utilized a sampling rate which we believe to be too slow to demonstrate a very brief heel strike. It appears from our early data that our initial hypothesis regarding the importance of heel strike as an indicator of the achievement of mature gait is disproved. By contrast with the ankle dorsiflexion/plantar flexion curve, the knee flexion/extension curve reveals a much smaller number of relatively important coefficients and a higher explanatory power of the largest coefficient. (Fig. 12). The knee curve also appeared to have less variation in the children than the ankle plantar flexion/dorsiflexion curve. From our preliminary results it appears likely that the angular rotations in the sagittal plane in very small children differ only slightly from adult curve patterns. It appears that the development of adequate step length and walking velocity may correlate much more closely with overall gait maturity than angular rotations at individual joints.

The surprising similarity of angular rotations between very small children and adults has led us to critically examine other measurements such as step length and the factors influencing it. Walking velocity, age and pelvic rotation are significant variables affecting step length, however, pelvic rotation has a negative correlation with step length. An equation including these variables can be constructed which explains 90 percent of the variability in step length.

$$\text{Step Length} = 5.3203 + (2.9446)\,(\text{Age}) + (.1561)\,\left(\overset{\text{Walking}}{\text{Velocity}}\right) + (.1788)\,\left(\overset{\text{Pelvic}}{\text{Rotation}}\right)$$

It is well known that the step factor, which is defined as the step length divided by leg length, increases from age one to four years. Scrutton (12) describes a mean step length at one year of 10 inches, at two years of 11.5 inches, at three years of 13 inches, 4 years at 15 inches. Various explanations have been given for this very rapid increase in step length. Improvement in balance during single limb support is one possible explanation. Improvement in strength and control at the ankle relating to the cephalocaudal progression of myelinization is a second explanation. A third explanation is that pelvic rotation increases with age and promotes greater step length. From our preliminary studies we believe this explanation to be incorrect.

The second major new area of investigation is the determination of sagittal plane torque in the lower extremity joints. Normalized comparative torques in the two to three year age range when compared with the 4 to 7 year old children appears to show a predominance of hip flexion torque with limited hip extension torque. The numbers are small and many more studies will be drawn. We also found in the ankle torque determinations a trend toward

Sutherland cont.

Fig. 11

ANKLE D/P
(32 Children)

Cell #	Age	# Coefficients Significantly Different from 0 at 5% Level		Relatively Important Coefficients**	Slope at 0 - implies heel strike***	*
1748	1	8	(averages)	B_1,B_2,B_3	- 9.28	22
4724	1	3	5.5	B_1	-12.42	65
4340	1-1/2	2	2	a_2	- 1.77	60
1652	2	0	2.5		- 1.14	24
2996	2	5		B_1,B_2	- .55	43
2708	2-1/2	7		B_1,B_2	- 2.89	34
5012	2-1/2	3	4.25	B_1	+ 4.68	57
3284	2-1/2	3		B_1,B_2	-10.53	50
1940	2-1/2	4		B_1	- .35	48
4532	3	6		a_1,a_2,B_1,B_2	+ 1.89	26
3476	3	5	5	B_2	+ 4.34	49
3572	3	2		B_1,B_2	- 4.49	51
2324	3	8		a_2	- .97	36
4820	3	5		B_1,B_2	- 7.40	54
4244	3	4		B_2	+ 1.41	41
4916	4	3	3.67	a_2,B_2	- 3.47	35
1844	4	5		B_1	+ 1.29	33
3188	4	3		B_2	+ 2.72	53
2132	5	1		B_2	-11.62	65
3860	5	4	3.17	a_2,B_2	+ 1.06	39
5108	5	4		a_2,B_1,B_2	- 1.06	39
2900	5	2		B_2	+ 1.84	56
4148	5	2		B_1,B_2	- 3.75	46
4628	5	6		B_1	+ 2.57	49
4436	6	5		B_2,B_3	- 1.90	43
4052	6	6	4.75	a_1,a_2,a_3,B_1,B_2	- 3.90	21
2516	6	4		B_1,B_2	+ 2.50	46
1556	6	4		B_1,B_2	- 6.09	41
2612	7	9		B_1	- 5.72	52
2804	7	6	5	B_1,B_2	- .19	37
3956	7	4		B_1,B_2	- .73	50
1460	7	1		B_2	- .35	65

*Explanatory power of largest coefficient (in%)

**B_1 was significant 20 times; B_2 was significant 23 times

***Heel strike for 22 children
None for 10 children

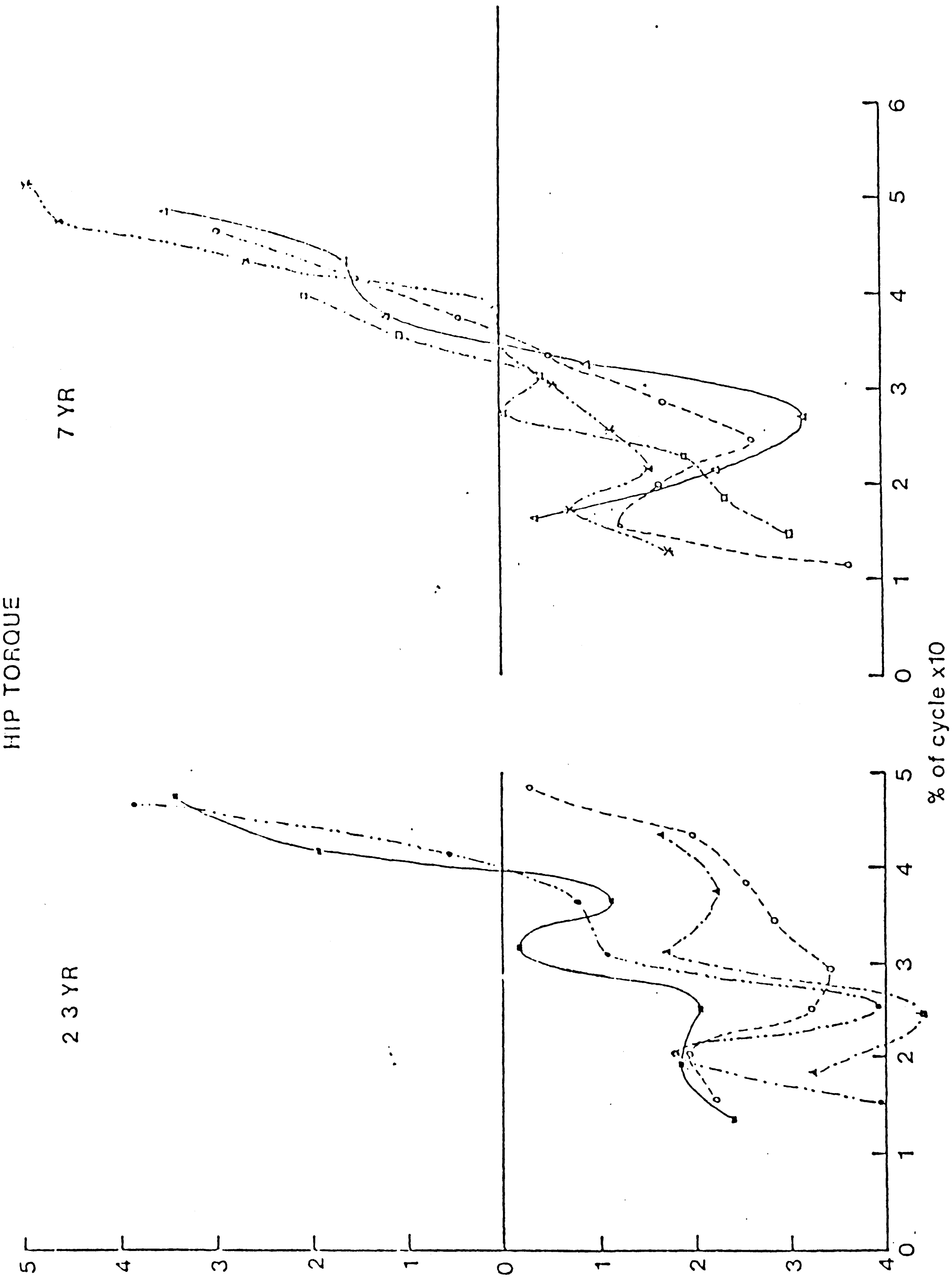
Sutherland cont.

Fig. 12 KNEE F/E (Rt.)

Cell #	Age	# Coefficients Significantly Different from 0 at 5% level	Relatively Important Coefficients	Explanatory Power of Largest Coefficient (%)
1748	1	7	B_1	64
4724	1	4	B_1	63
4340	1-1/2	5	B_1	67
1652	2	3	B_1	59
2996	2	3	B_1	50
2708	2-1/2	6	B_1	57
5012	2-1/2	5	a_2,B_1	45
3284	2-1/2	6	B_1	66
1940	2-1/2	5	a_2	56
4532	3	3	B_1	62
3476	3	5	B_1	69
3572	3	5	B_1	60
2324	3	3	a_2	58
4820	3	5	a_2,B_1	53
4244	3	9	a_2,B_1	43
4916	4	5	a_2,B_1	51
1844	4	5	B_1	60
3188	4	4	B_1	57
2132	5	5	B_1	62
3860	5	3	a_2,B_1	50
5108	5	3	a_2,B_1	56
2900	5	8	B_1	59
4148	5	6	B_1	57
4628	5	4	B_1	63
4436	6	5	B_1	62
4052	6	5	B_1	66
2516	6	4	a_2,B_1	52
1556	6	7	B_1	58
2612	7	5	a_2,B_1	54
2804	7	4	B_1	74
3956	7	7	B_1	66
1460	7	5	a_2,B_1	41

Fig. 13

HIP TORQUE



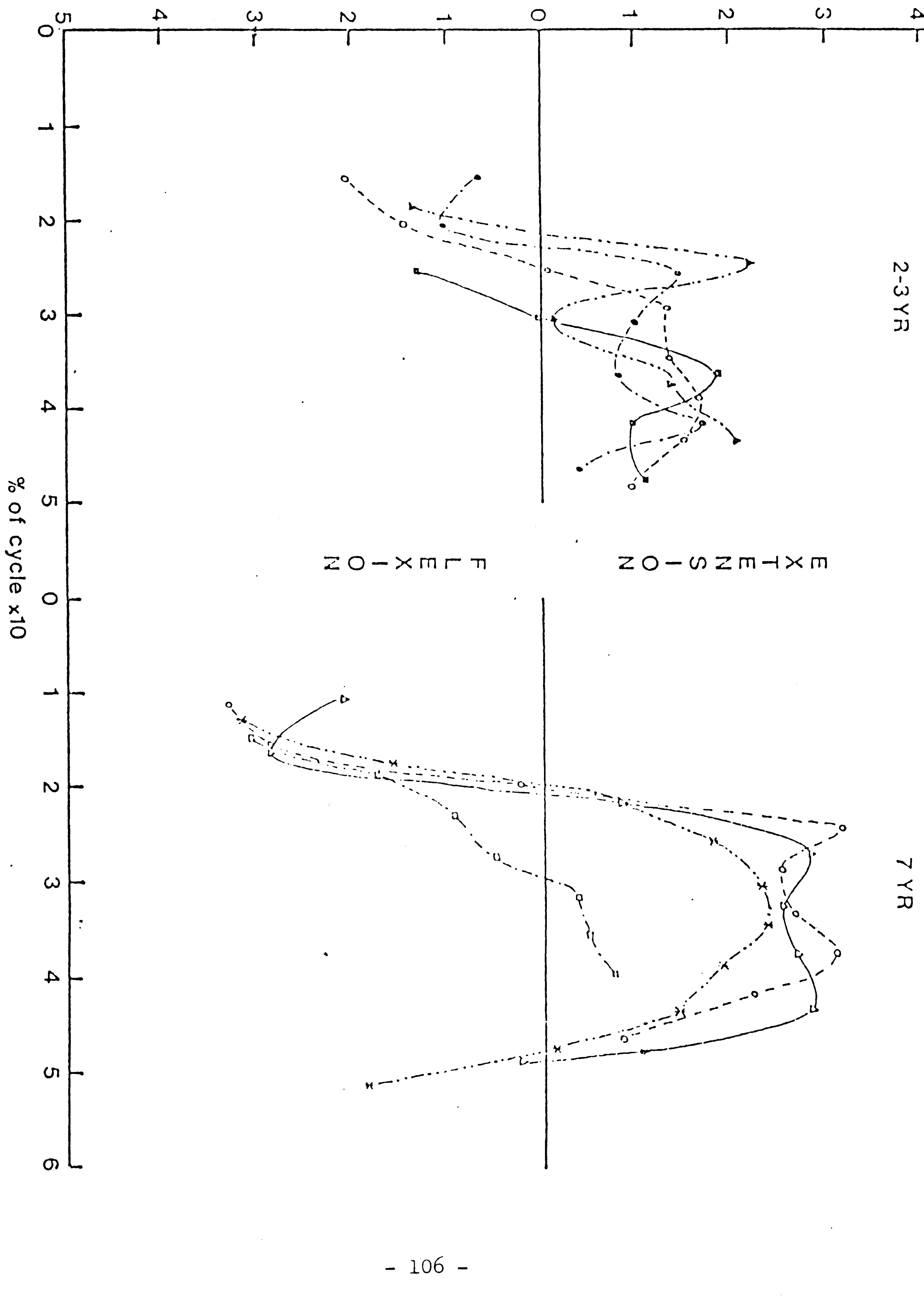


Fig. 14

KNEE TORQUE

greater variation in the younger age group. This would appear to correlate with the restricted step length, and it may be explained by the cephalocaudal myelinization sequence (10 and 15).

Initial results of electromyography suggest a definite trend toward stance phase prolongation of the gluteus maximus and hamstring muscles. A predominance of hip flexion torque would necessitate compensatory hip extensor muscle firing. Again, this is a preliminary observation and will require greater numbers for statistical significance. Also see Figs. 13, 14 and 15.

CALCANEAL LIMP

Case Study - F.F.

This thirteen year old male had polio at age one year with primary residual paralysis of the left gastrocnemius and soleus muscles (grade 0) (Fig. 16).

tibialis posterior	4
flexor hallucis longus	4
flexor digitorium longus	4
extensor digitorium longus	4
peroneus longus	5
peroneus brevis	5

In spite of extreme plantar flexor weakness, he is a community ambulator and is brace free. His "calcaneal limp" is quite obvious and progressive calcaneal deformity has been documented.

General Measurements

	Right	Left
Single stance phase (% cycle)	38	36
Step length (cm)	40	61
Cadence (steps/min)	126	
Walking velocity (cm/sec)	106	

Primary Abnormality

The primary movement abnormality is apparent in the graph of left ankle plantar flexion/dorsiflexion (Fig. 17H). Because muscle strength is lacking to decelerate forward rotation of the tibia on the talus (15, 17), ankle dorsiflexion increases to 40 degrees. No ankle plantar flexion occurs until after toe off. Opposite step length as compared with ipsilateral limb is reduced 35%. Reduction in opposite step length, increased double support time and reduced walking velocity are common in this disorder.

Compensatory Mechanisms

Since poliomyelitis leaves the control system intact, compensatory mechanisms are at work to smooth the gait and minimize energy consumption. In the ipsilateral limb, electromyography revealed premature phasic activity in the tibialis posterior, peroneus longus and peroneus brevis. In the contralateral limb, first peak of the vertical force curve is exaggerated (Fig. 18I). Fore and aft shear are also increased (Fig. 18J).

Surgical treatment has subsequently been carried out to correct the calcaneus deformity and to improve the limp. A Beak triple arthrodesis (14) with a generous subtalar wedge was performed to increase the calcaneal lever arm (Fig. 19B). This was followed in several months by transfer of the peroneus longus and tibialis anterior to the os calcis. Followup studies are not yet available.

GLUTEUS MAXIMUS AND QUADRICEPS WEAKNESS

Case Study - M.J.

This eight year old male has Duchenne muscular dystrophy (Figs. 20, 21). At the time of this study he walks with moderate difficulty, and without effective intervention his walking ability can be expected to end in two years or less. Mild abduction contractures are noted of both hips and 10 degree ankle equinus contractures are present. The muscle ratings are:

gluteus maximus, right 2, left 2
quadriceps, right 2+, left 2
gastrosoleus, right 4+, left 4+

General Measurements

	Right	Left
Opposite toe off (% of cycle)	15	15
Opposite foot strike (% of cycle)	50	50
Single stance (% of cycle)	35	35
Step length (cm)	37	39
Cycle time (per sec)	1.3	1.3
Cadence (steps/min)	92	
Walking velocity (cm/sec)	58	

Primary Abnormality

While there is generalized muscle weakness the proximal muscles of the extremities and the trunk muscles show the earliest and greatest involvement. Weakness of the gluteus maximus and quadriceps muscles are responsible in large part for the gait abnormalities.

Compensatory Changes

In the sagittal plane the most striking abnormality is a peculiar lordosis accompanied by posterior alignment of the arms behind the trunk. Weakness of the gluteus maximus necessitates maintenance of the saggittal plane force vector $\overline{R}$ through or near the hip joint center (Fig. 21). This is accomplished by arching of the back and posterior arm positioning. Weakness of the quadriceps muscle is compensated for by movement of the force vector line in front of the knee joint producing knee extension (Fig. 21). This is accomplished by overactivity of the ankle plantar flexors and by prolonged phasic stance phase activity of the quadriceps muscle. Evidence for these compensatory changes is seen in: 1) the graph of ankle plantar flexion/dorsiflexion showing plantar flexion at foot strike (Fig. 21D), 2) in the graph of knee flexion/extension showing extended knee position throughout stance (Fig. 21C), 3) in the center of pressure diagram showing concentration of pressure in the metatarsal head region (Fig. 22L). As long as the center of rotation of the hip, knee and ankle can be held close to the force vector line, he will continue ambulation. When contractures prevent satisfactory alignment, walking will become impractical. Extension of ambulation for three to four years can usually be achieved by contracture release, lower extremity long leg braces and by a vigorous physical therapy program.

While satisfactory compensatory mechanisms were apparent when this study was performed, walking became more labored and contractures of the hips were noted three months later. The patient is now awaiting surgical release of contractures and immediate reambulation in casts and braces. In addition to the prevention of scoliosis, continued ambulation provides profound functional and psychological benefits for the patient. Also see Figs. 23-27.

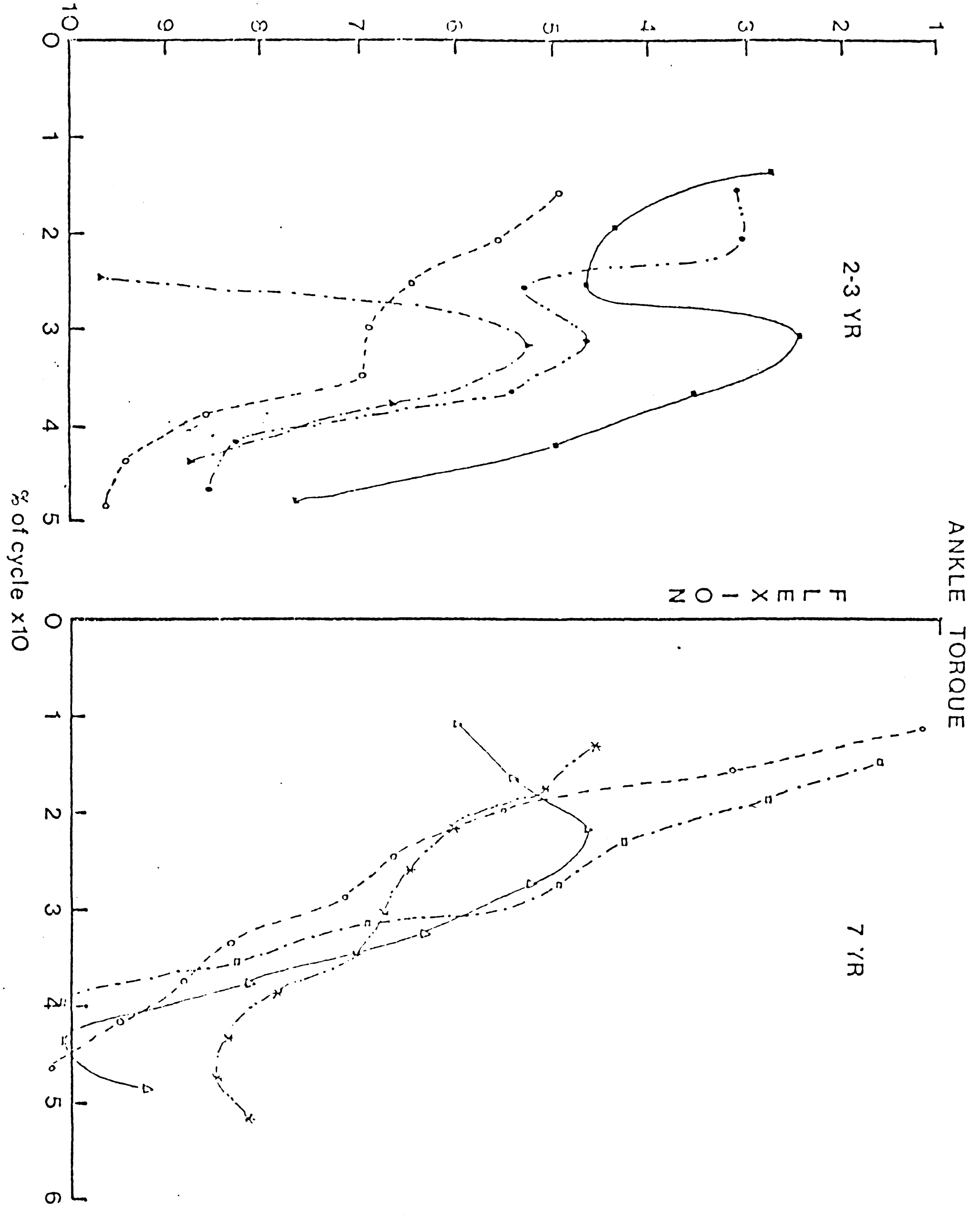
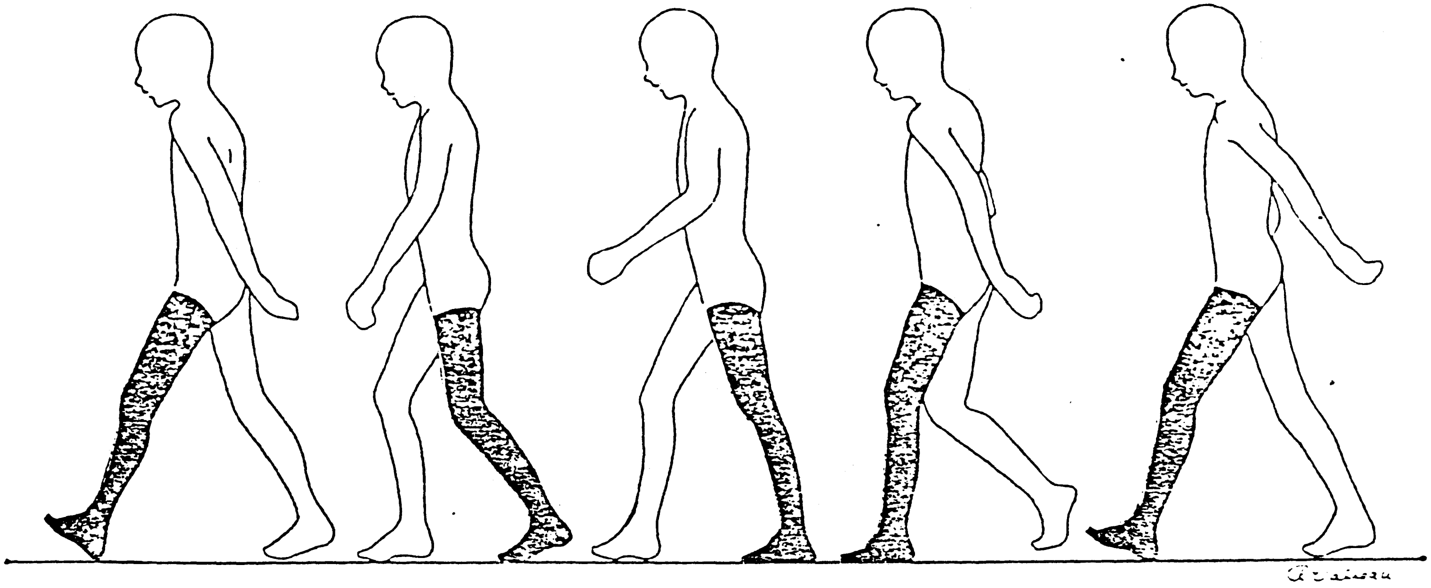

ANKLE TORQUE
FLEXION
2-3 YR
7 YR
% of cycle x10
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
0
1
2
3
4
5
6

Fig. 15

Fig. 16

Poliomyelitis



CALCANEAL LIMP

Poliomyelitis at age one year caused permanent paralysis of the left gastrocnemius and soleus muscles. Note increased ankle dorsiflexion in stance phase. Opposite step length is reduced.

CALCANEAL LIMP

RIGHT SIDE

Fig. 17

Poliomyelitis

LEFT SIDE

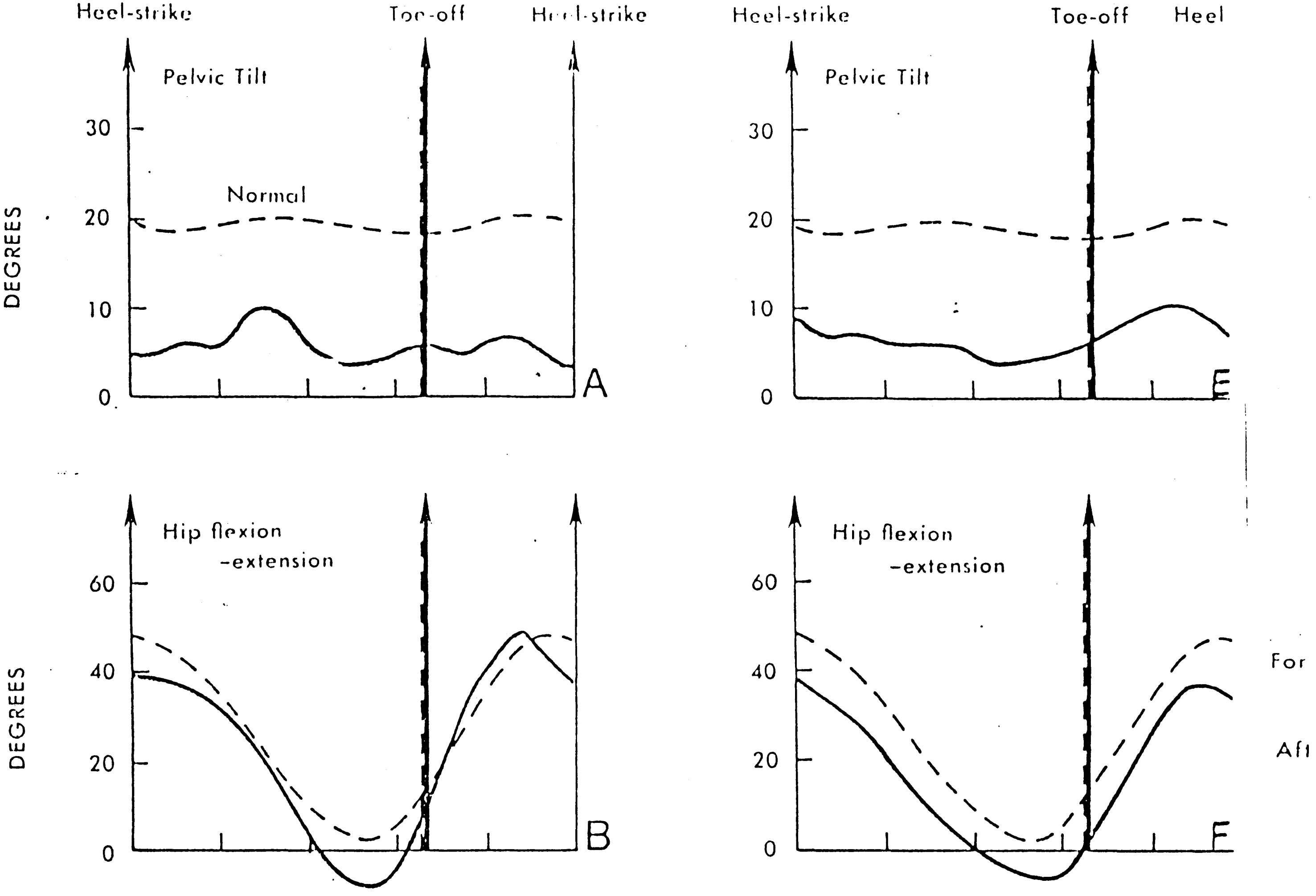
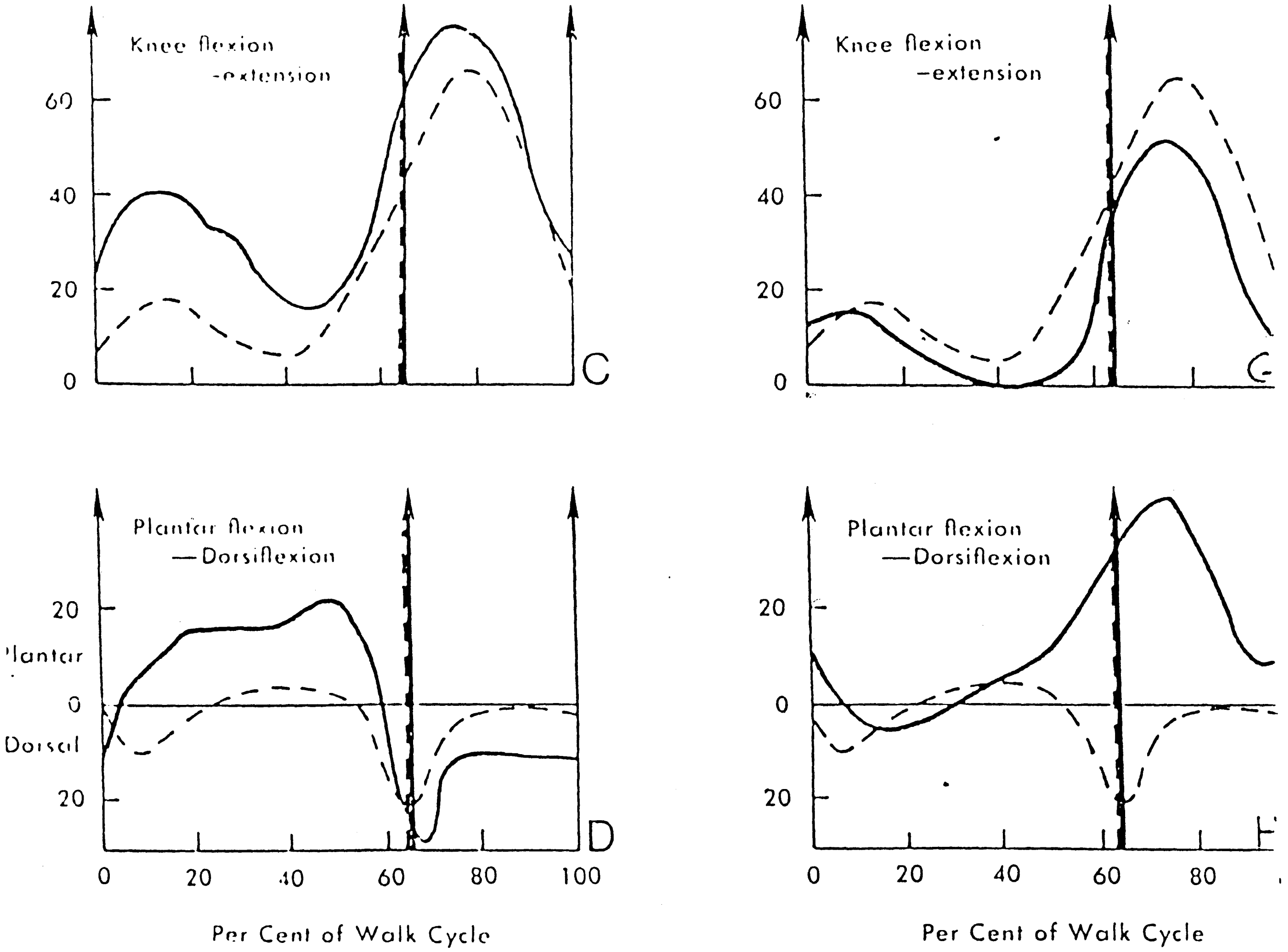


Fig. 17 cont.



A to D. Increased knee and ankle flexion in stance phase in the contralateral limb may be compensatory or due to mild polio paresis of the right leg. No functional problems relating to this limb were noted.

E to H. The primary movement abnormality is excessive stance phase ankle dorsiflexion. Note the absence of reversal until after toe off H.

Fig. 18

Force Pla:e Curves

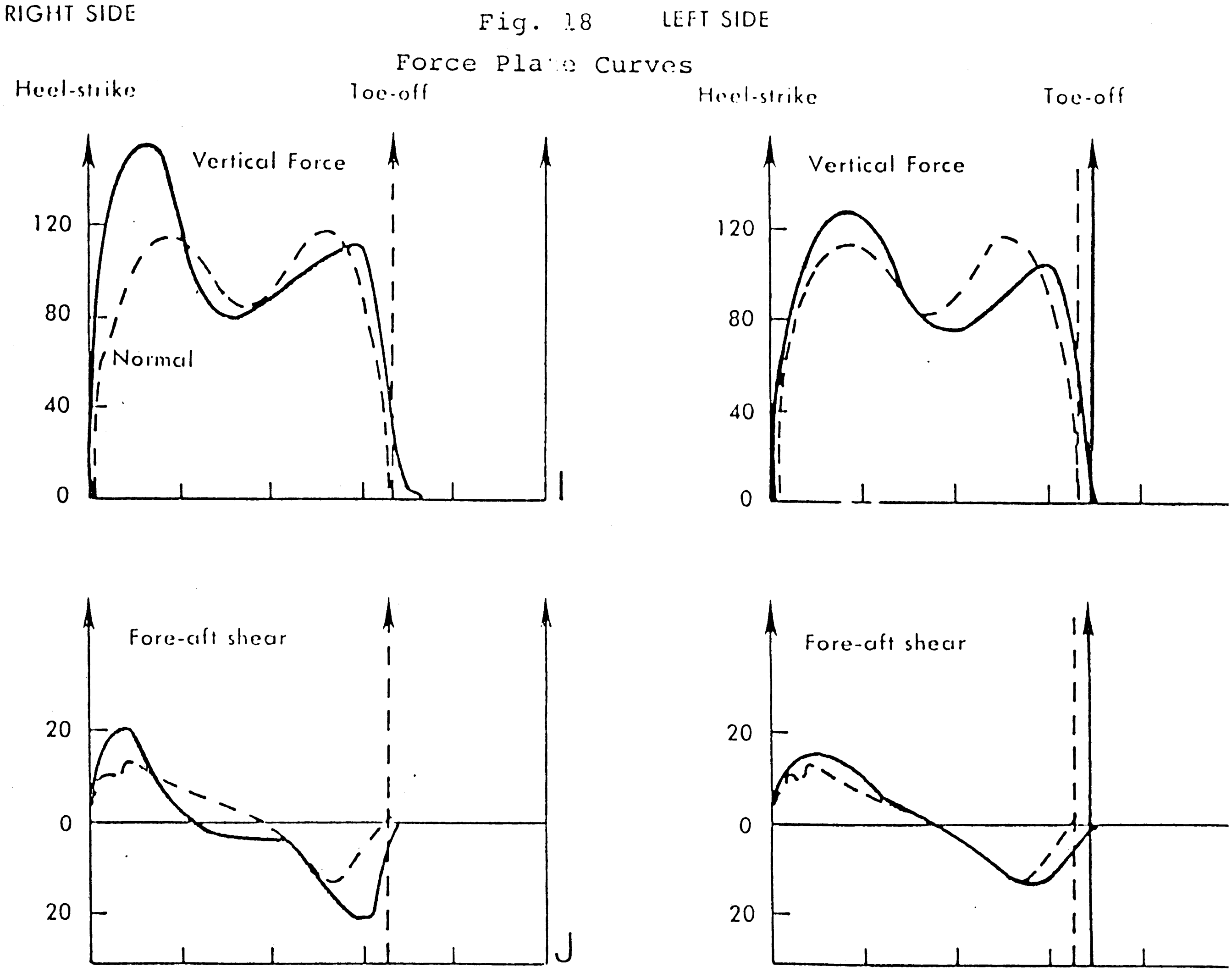
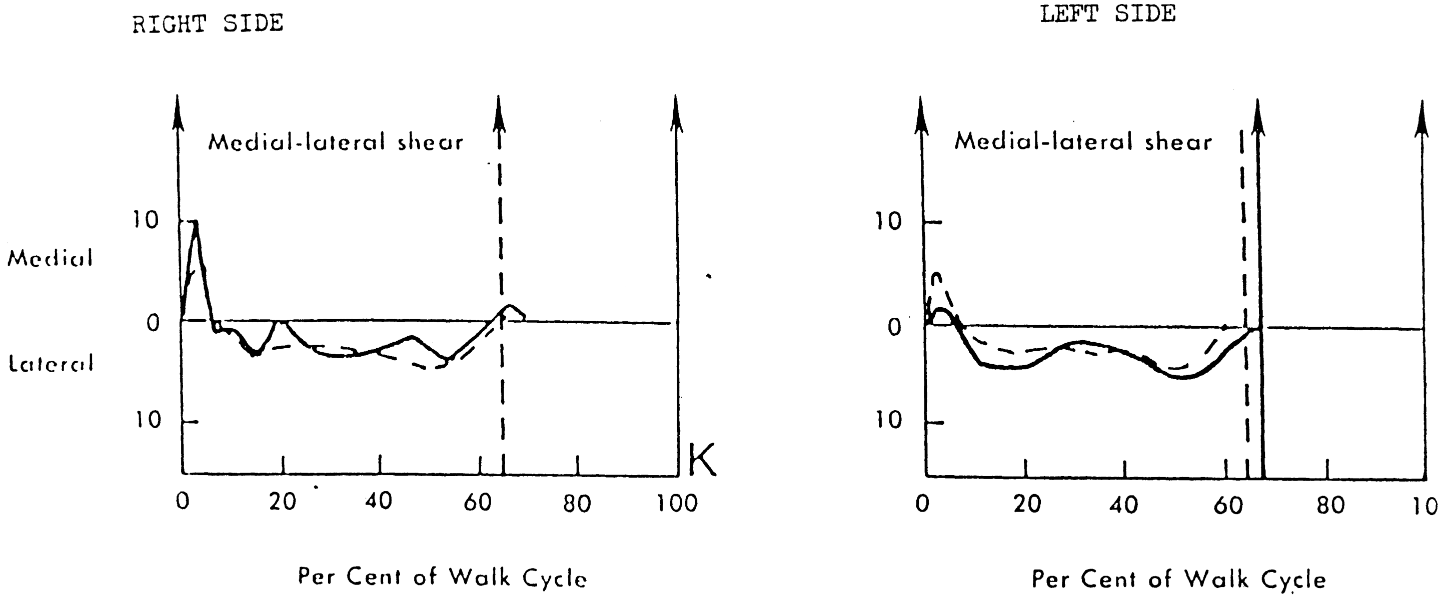


Fig. 18 cont.



I. On the contralateral side there is compensatory increase in first peak vertical force.

J. There is also compensatory increase of fore-aft shear.

K. There is some increase in medial-lateral shear.

L. On the side of gastrocnemius and soleus paralysis second peak vertical force is diminished. Such a reduction occurs regularly with experimental tibial nerve block to simulate calcaneus gait. (18)

M to N. Fore-aft shear and medial-lateral shear are normal.

[illegible]

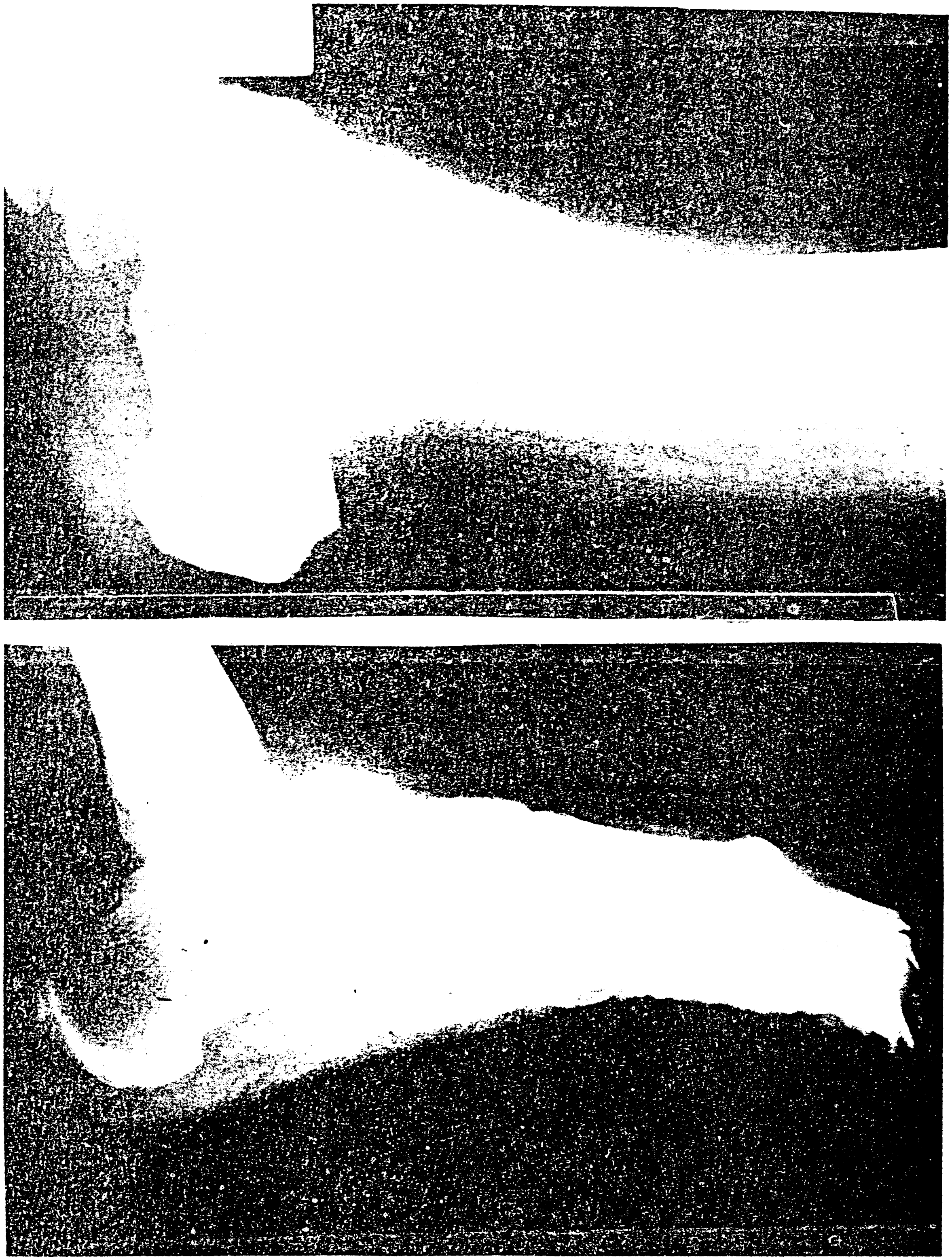


Figure 19. Poliomyelitis - Calcaneal Deformity (title)

Legend

Preoperative A and Postoperative B lateral roentgenograms of the foot seven months following triple arthrodesis for calcaneal deformity and limp. Transfers of the tendons of the peroneus longus and tibialis anterior to the os calcis were the last stage of the surgical treatment plan.

Figure 20. Duchenne Muscular Dystrophy (title)

Legend

The dynamic posture in single support of an eight year old male with Duchenne dystrophy is contrasted with a seven year old normal male. Note the arched back and posterior arm position in the patient w_i_th dystrophy. The line of application of the floor reaction force $\overline{R}$ remains close to the hip joint center and in front of the knee joint center in the patient with dystrophy. Quadriceps and gluteus maximus weakness together produce the characteristic gait.

Fig. 20

Duchenne Muscular Dystrophy

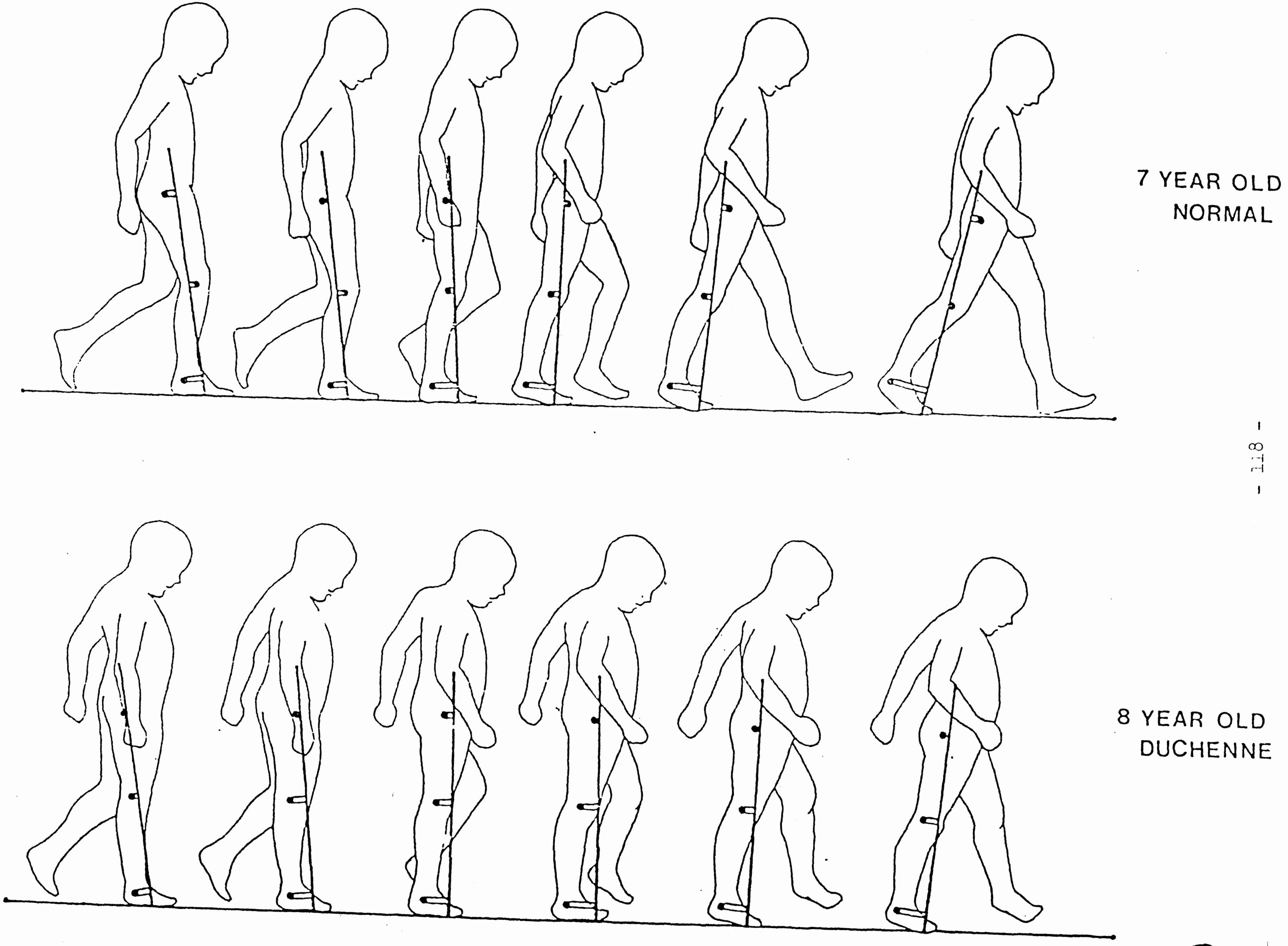
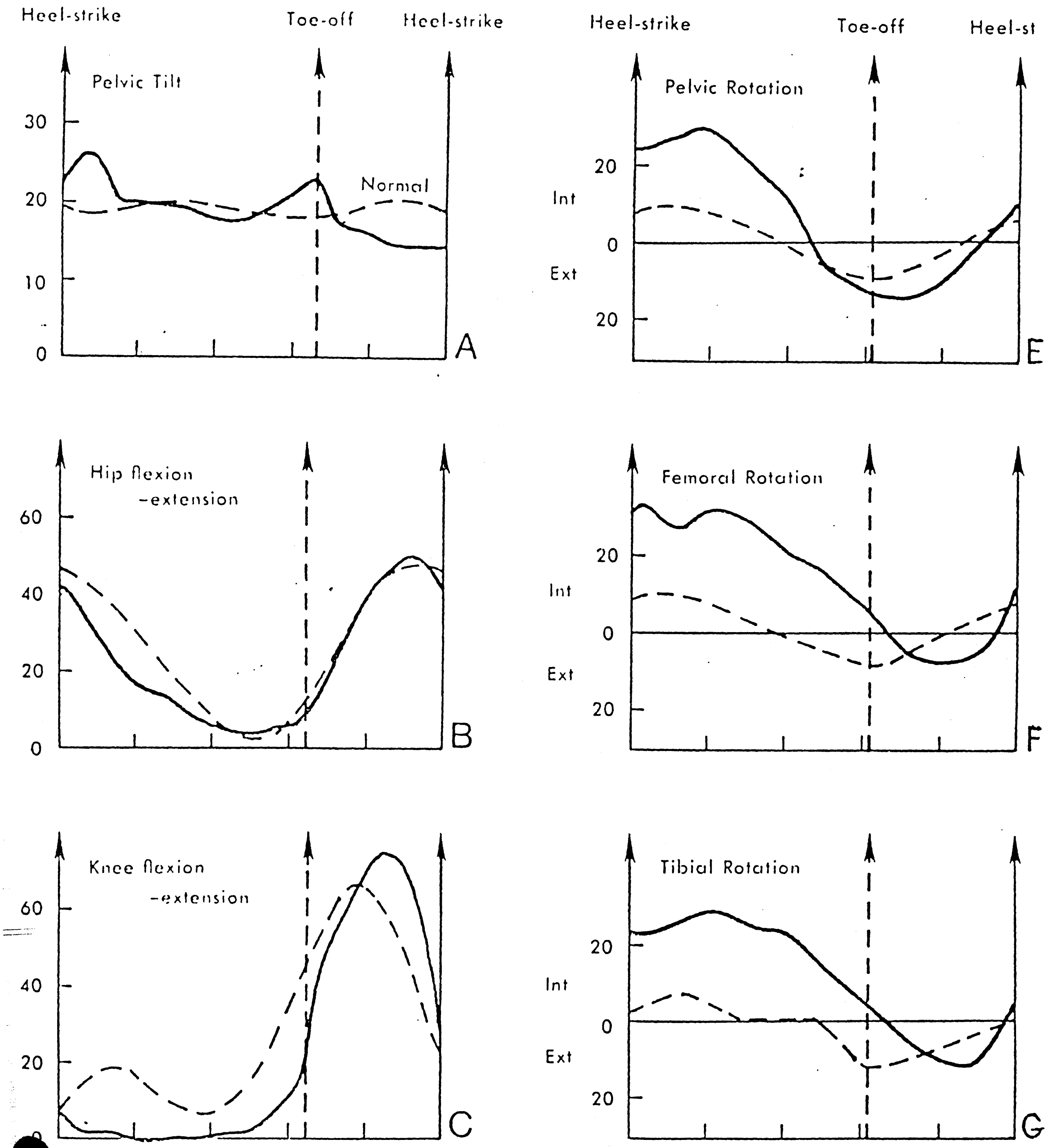


Fig. 21

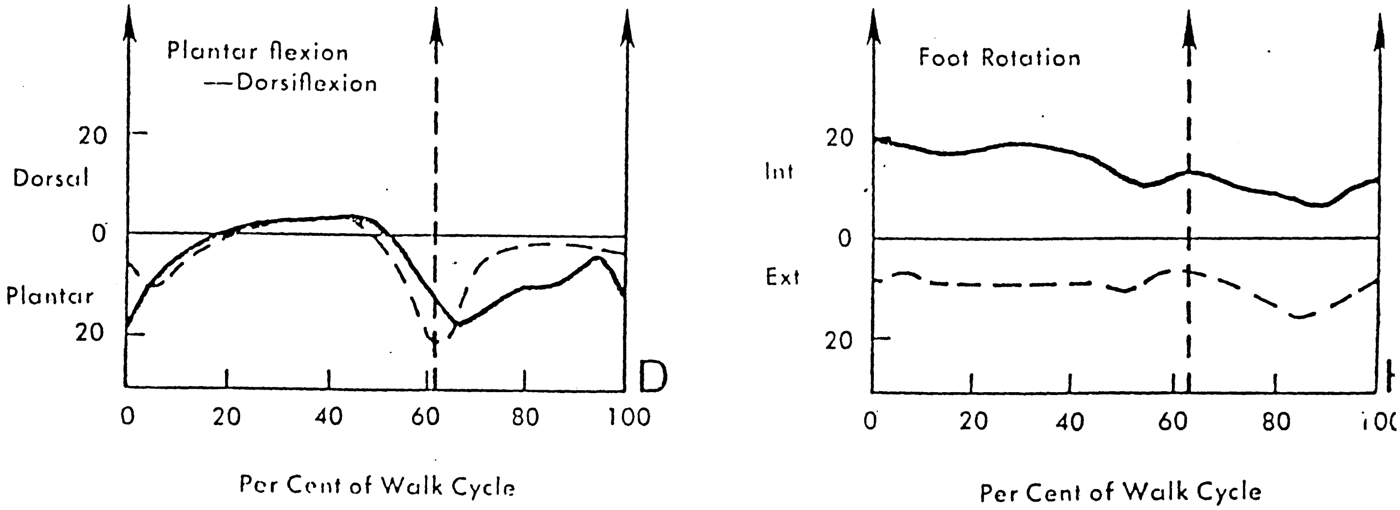
Duchenne Muscular Dystrophy - Joint Angular Rotations

LEFT SIDE



Sutherland

Fig. 21 cont.



Sagittal and transverse plane joint angular rotations of eight year old male with Duchenne dystrophy.

A. While excessive anterior pelvic tilt is common in later ambulatory stage of this disease, this has not yet occurred.

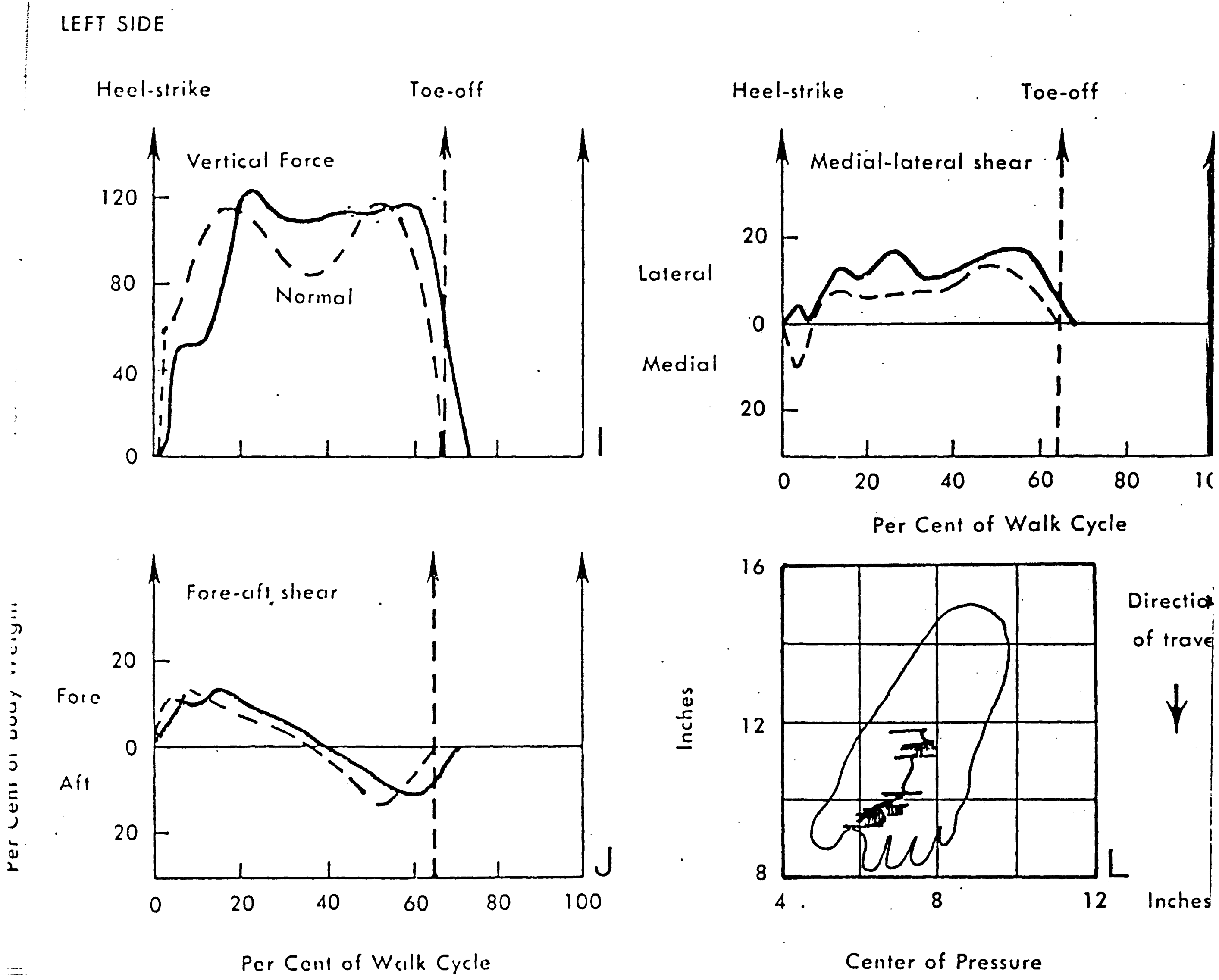
C. Full knee extension is present throught stance.

D. Note increased plantar flexion at heel strike and drop foot in swing.

E to H. Stance phase internal rotations of pelvis, femur, tibia and foot are increased.

Fig. 22

Duchenne Muscular Dystrophy - Force Plate Curves



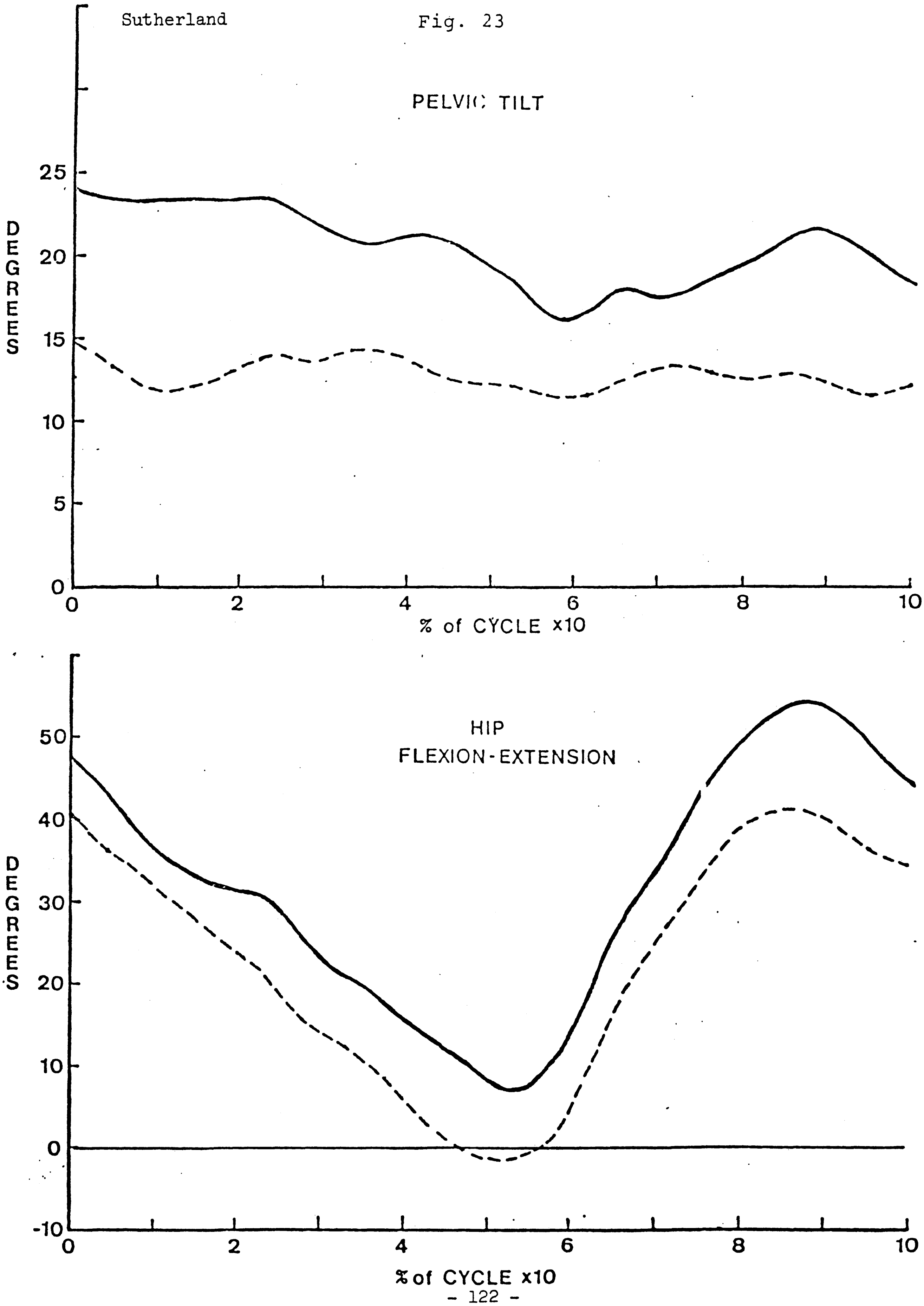
I. Vertical force mid stance valley is absent.

J. Fore-aft shear is normal.

K. Medial shear is missing.

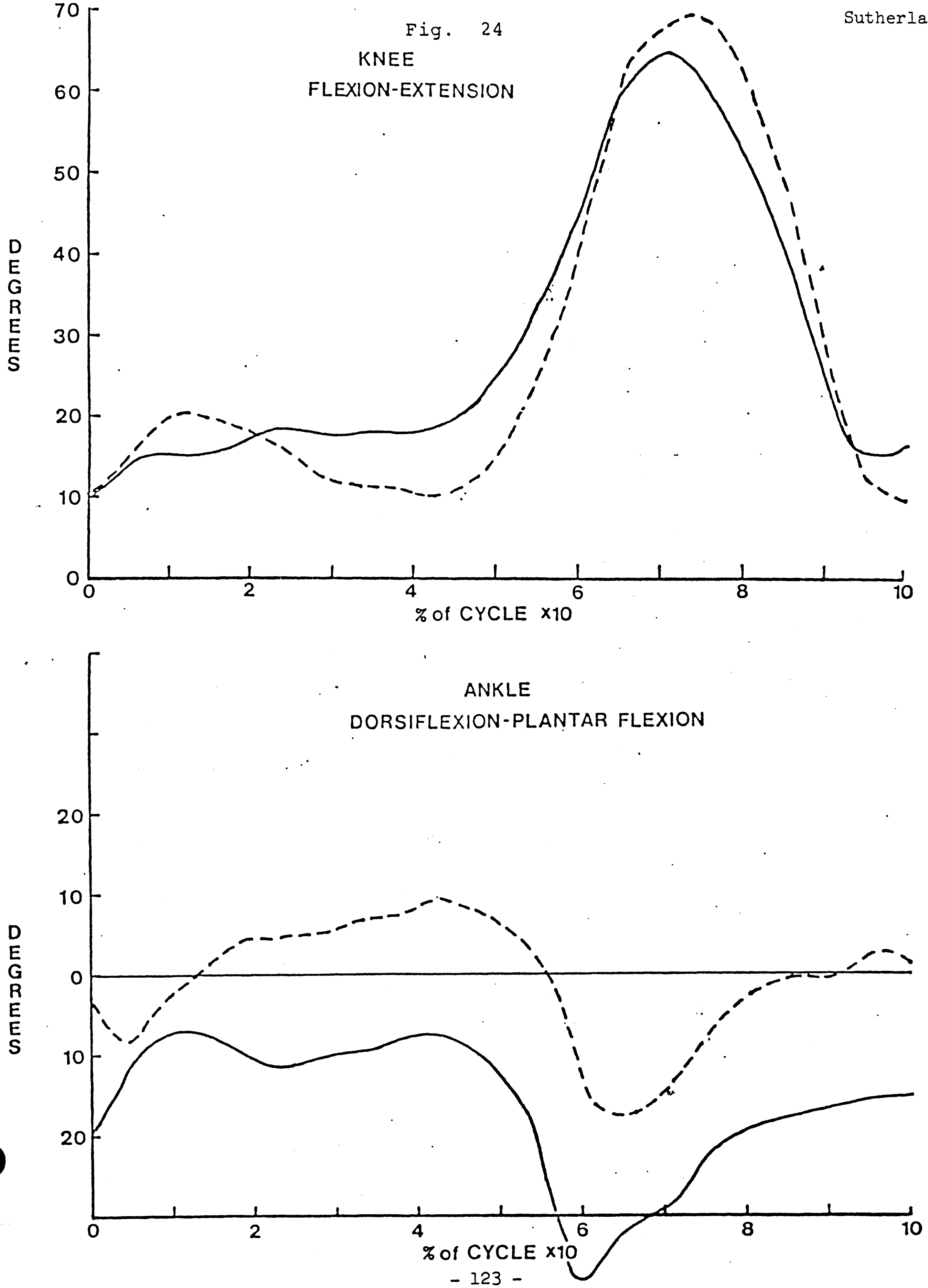
L. Center of pressure concentration is in the forefoot due to equinus contracture and to compensatory overactivity of the plantar flexors.

Sutherland Fig. 23



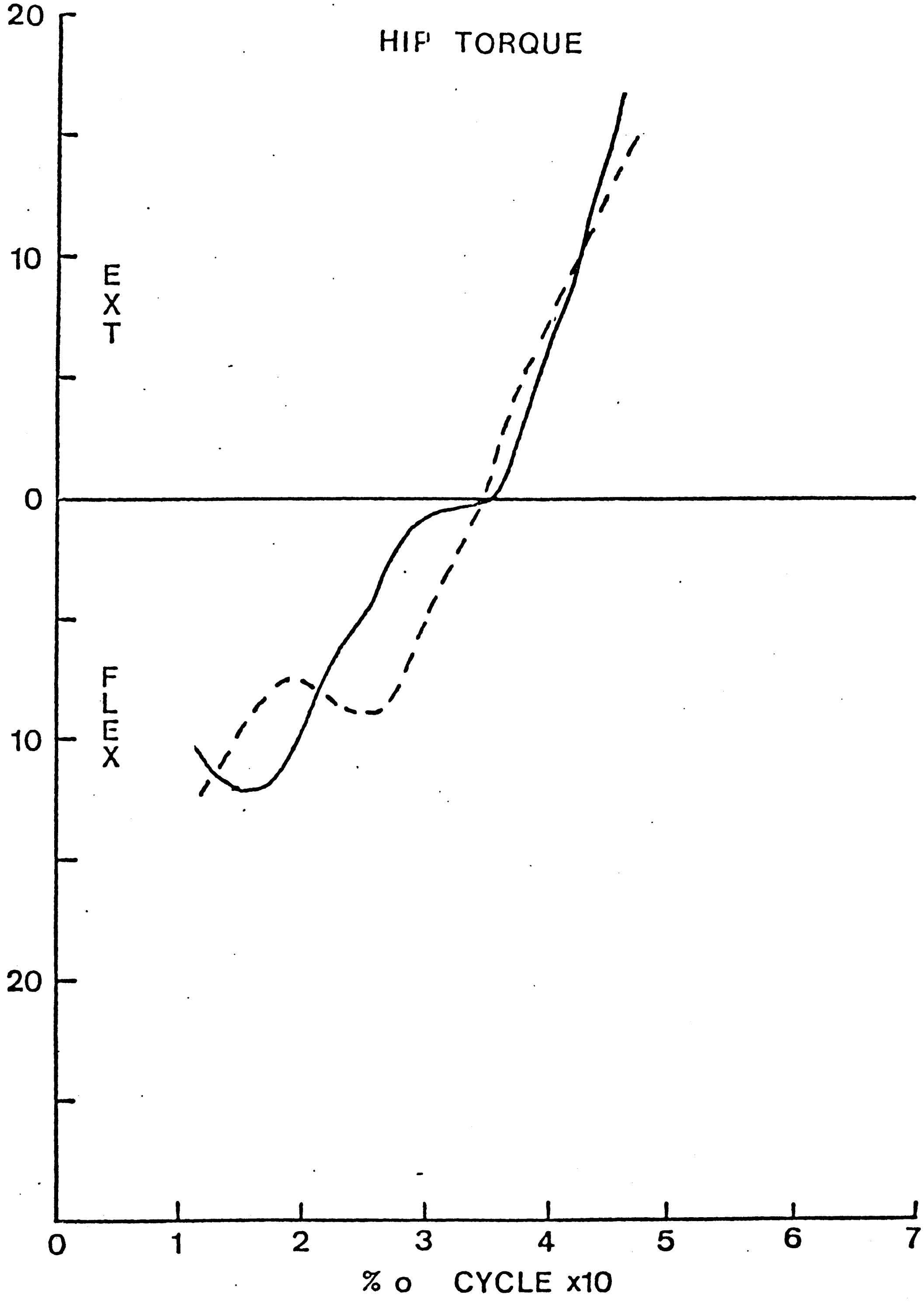
Sutherland

Fig. 24



Sutherland

Fig. 25



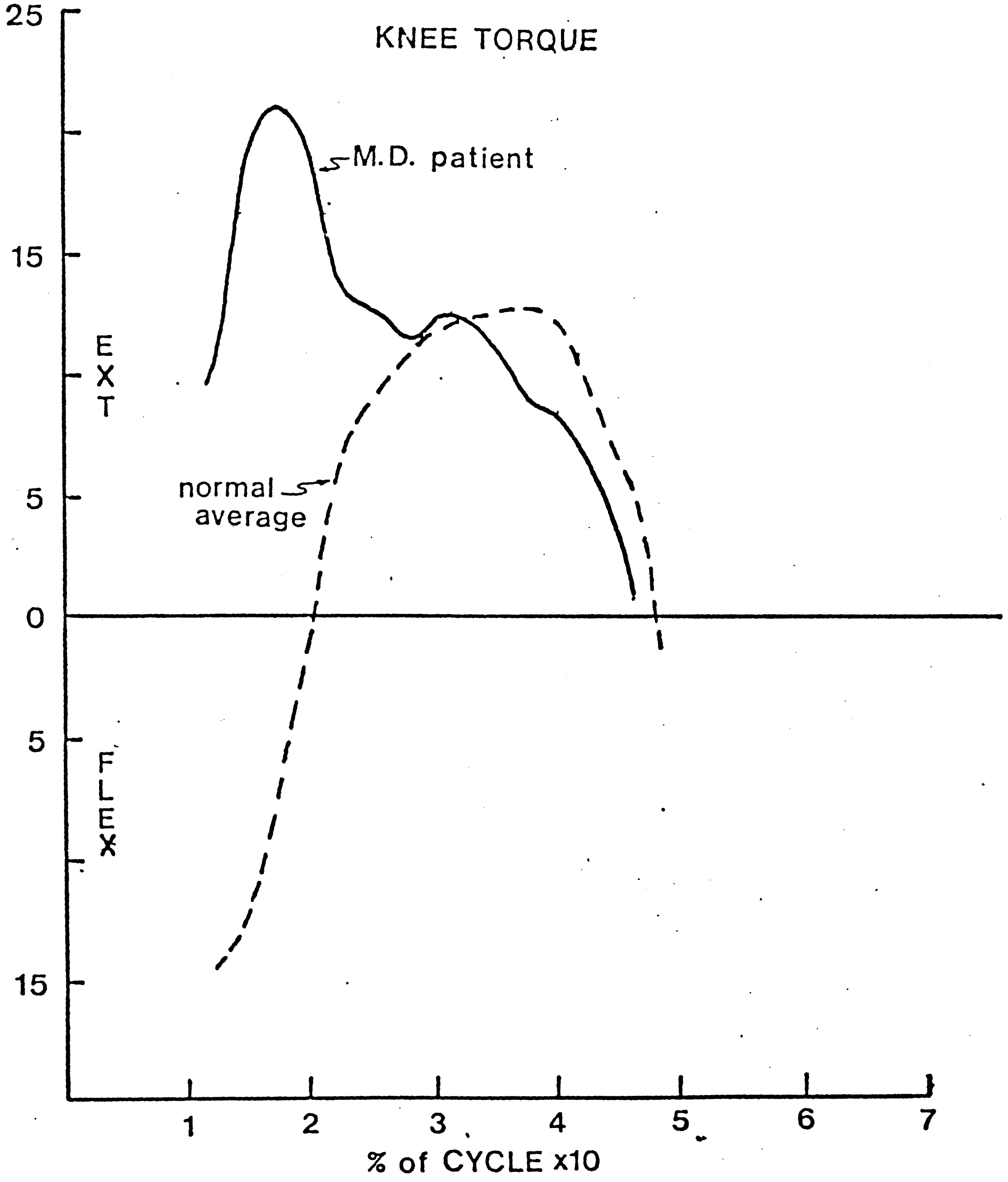
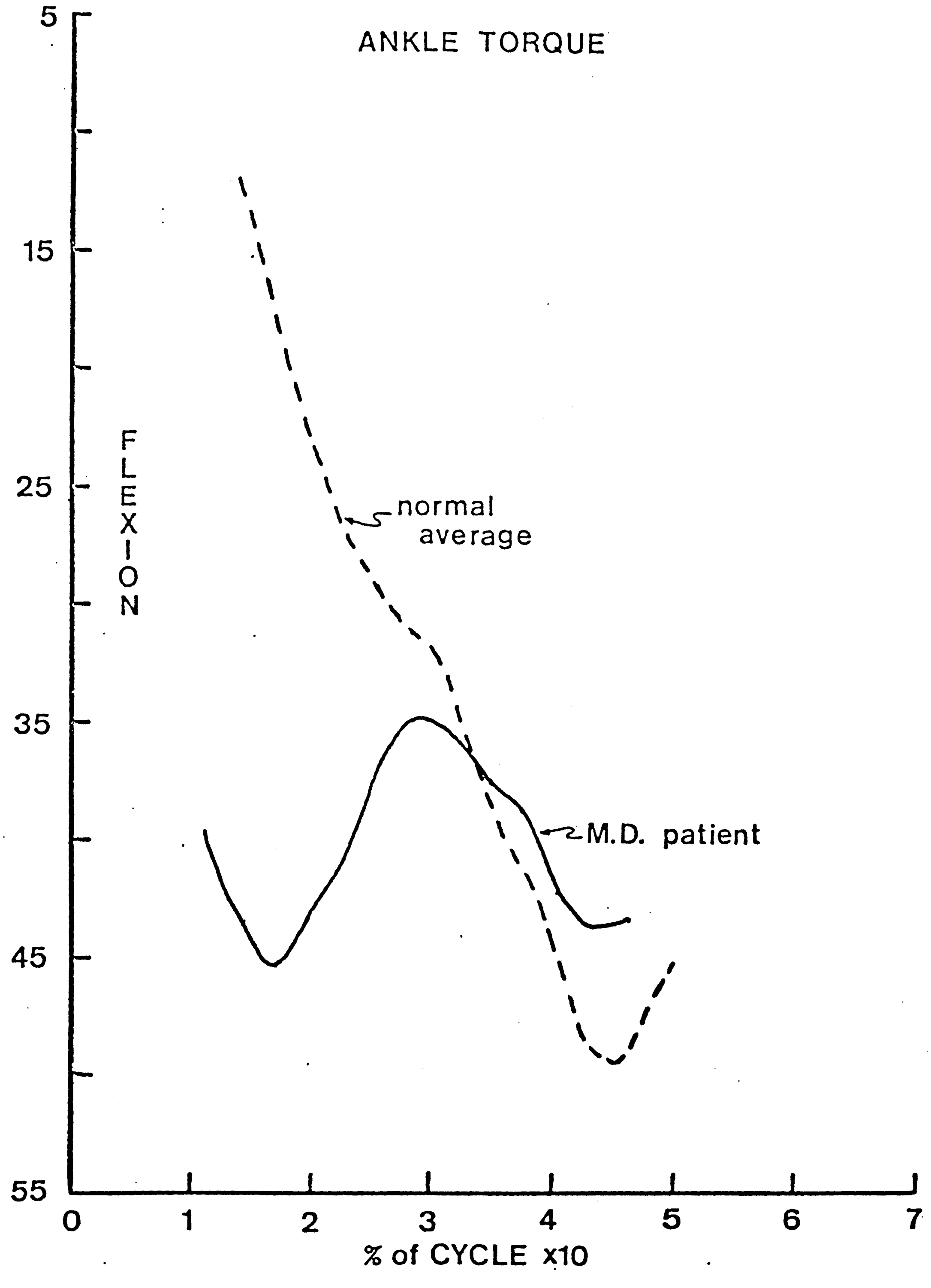

KNEE TORQUE
M.D. patient
normal average
25
15
5
0
5
15
EXT
FLEX
1
2
3
4
5
6
7
% of CYCLE x10

Fig. 27


ANKLE TORQUE
FLEXION
5
15
25
35
45
55
0
1
2
3
4
5
6
7
% of CYCLE x10
normal average
M.D. patient

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TECHNIQUES IN GAIT RESEARCH

AND MANAGEMENT OF DATA

Sheldon R. Simon, M.D.

INTRODUCTION

It is natural for humans to have an interest in the way they walk. For one thing it is fundamental to the performance of their everyday activities. For another, it is so complex as to be of interest to a wide variety of disciplines in medicine and science. Finally, both because it is so fundamental and yet so complex, the performance of walking can easily be altered by diseases that affect any one of a number of organ systems, e.g., muscular, skeletal, cardiovascular--and the correction or substitution of this impaired state becomes a matter of upmost practical concern. The need for studying gait, therefore, needs no further defense. However, the manner in which it is studied and the types of information sought, still remain open to debate.

The process of walking involves a complex set of movements primarily of the two lower limb systems, secondarily of the two upper limbs, while balance is maintained in the trunk, which contains most of the load. The control and coordination of these movements involves the neurological system, with force being produced as a complex interaction of the body masses' inertia and weight, active muscle contractions, and passive muscle, tendonous, and ligamentous elements. The resulting movements are limited by the geometry of the joints located between the individual segments and the position and resistance of the external environment (neglecting wind resistance; in everyday situations this becomes the floor or the ground).

For over a century numerous attempts have been made to measure various components of this function objectively, but until recently these have been hampered by the ease, speed, and "naturalness" with which walking could be done. With the advent of modern electronic and computer technology many of the major stumbling blocks have been overcome. It is the purpose of this report to describe the basic principles and some of the most popular methods by which measurements are currently being made and the data so obtained, handled.

KINEMATICS

Modern techniques of gait analysis involve the measurement of both kinetic and kinematic elements. With regard to the kinematic elements a variety of techniques exist to obtain limb segment displacement data. In general the techniques may be divided into three types: (a) visual, (b) optoelectronic, and (c) electronic.

(a) Visual

Perhaps the oldest form still in use, and the most common procedure involves some visual method. (1) Here a camera records the light "emitted" from the various segments of the individual while walking. If the entire cycle is recorded on a single plate it is called a photograph or cyclogram. The latter term refers to the condition when, instead of the reflected light, visualization is made by specific light bulbs located at designated points on the body. This method was first used by the physiologist, Marey (2), and was adopted by many German and American investigators in the early 1900's. By either method, although no data are lost, information regarding the relative displacement of points or limb segments so marked is difficult to discern. For this reason, time must be marked in some way on the photograph. Perhaps one of the easiest ways is to place a rotation shutter in front of the camera. This method is called a chronocyclogram or chronophotograph. A second method is to record the data in a given instance in time on separate photographic plates. Muybridge (3) in the late 1800's first used this method to record the locomotion of horses, by having trip wires in the horses path that triggered a series of cameras. Marey (4) (1885) devised a "photographic gun" which could shoot twelve sequential pictures per second when triggered. Resolution was fairly good as each exposure was 1/720 of a second. This method may be considered the predecessor of cinephotography. Marey actually developed his gun prior to his use of chronophotograph, but abandoned it because of the limited number of pictures he could take within any given time period. Though by the 1920's cinephotography had improved, it did not offer a frequency range considered fast enough for accurately depicting human movements (Bernstein, 51). Although rapidly rotating shutters used in cyclograms could achieve this frequency, at the desired speeds the position of individual points was difficult to decipher. For this reason Bernstein combined a rapidly rotating shutter with a slowly moving film to distinguish points in a trajectory at frequencies of up to six hundred per second. This technique (Kymocyclography) is rarely, if ever, used today and in general has been replaced by cinephotography (6). Cinephotography in its present state has the advantage of using ambiant light, does not require the subject to wear or use any specific equipment, and can "shoot" a sequential series of pictures several hundred to a thousand times per second. It also offers good resolution, the ability to see an entire limb segment or segments, and provides a wide and adjustable range of field depths. It has the disadvantage of a film record, which is expensive and not reusable, and only able to be viewed after a time period for developing.

To overcome some of these disadvantages the subject can be photographed on videotape using a TV scanner. Visualization and recording are made from a phosphoric screen where the image is illuminated every 1/60th of a second (520 horizontal lines are sequentially scanned). The disadvantage of this method at least until now, has been its resolution. The lines "float", not maintaining a fixed position with regard to a reference, and the number of lines are "relatively" few. These disadvantages promise to be corrected in the near future with further advances in TV technology.

In all of the methods so far described, the desired temporal recording of events has been made by alterations in the receiving equipment. Sequential "pictures" can also be obtained if interrupted light is used.

The simplest method would be by flashing lights, i.e., a strobe. In its current technology it offers the disadvantage of having to be produced in a darkened room and can interfere with the subject's ability to walk--producing "atypical" gait. This is especially true if the subject being studied has gait abnormalities stemming from neurological disorders, but can be circumvented if the interrupted light source is directly on the subject. Such a method was originally used by Braune and Fisher (1895-1904) (7) with flashing tubes controlled by a spark inductor with frequencies up to approximately 100 per second. This method may be considered the precursor of the modern "SELspot" (Selective Spot Recognition System) (1,8), which has frequencies obtainable from fifteen "mini-LCV" (small light emitting diodes) of 322 times per second. In its current form it requires a large cable to follow the patient or requires the patient to carry a 400-500 gram transmitter pack. The latter method, although acceptable for adults, is not acceptable for small children. Additional details of this method are described below.

The displacement of an object in space, i.e. changes in all three spatial coordinates of the object, requires observation from no fewer than two points of view. All of the above methods afford this option and have been incorporated into the system ever since the first measurements were made. Braune and Fisher utilized four cameras, while Bernstein used fewer cameras but reflecting mirror placed more than one view on a recorded image. If additional "cameras" are employed some means of synchronizing the images obtained from each must also be incorporated. Depending on the type of "camera" and the frequency with which the movements are recorded, various devices have been added either as part of the recorded data or incorporated into the recording equipment. The methods and accuracy of each are beyond the scope of this survey. Suffice to say that this is not a significant limitation to the accuracy of the techniques developed.

Except for the SELspot system, in all the visual methods herein presented, the data recorded is not in a form suitable for kinematic analysis. Further processing (analytic photogrammetry) must be performed.

Perhaps the greatest progress in the study of locomotion in the past ten years has been in this area. The advent of modern electronic and computer technology has made it possible to perform this task more rapidly than was previously done by hand. With new techniques, processing has been translated from a chore requiring days, to one performed in hours or minutes. It promises, in the near future, processing within seconds. The field of analytic photogrammetry for industrial and military purposes has developed elaborate techniques with almost unlimited capabilities. Although these techniques are fully automatic and can easily scan cine film in rapid order, they are not in use for the evaluation of human locomotion, primarily because they are prohibitively expensive. Other techniques designed specifically for and by researchers working in human locomotion, have been developed for this reason. Perhaps the most popular method currently being used is some form of a semiautomatic system using a sonic digitizer. This consists of a series of small sonic receivers organized in linear arrangement along two mutually perpendicular arms of the frame. A "sound sensitive gridspace" is thus formed into which is placed the "pictures" to be "measured." These pictures can be a cyclogram or graph, a cine photogram, or SELspot data. The unit operator then specified the location of the point whose cordinates are to be recorded by touching the spot on the projected or actual film image with a sound emitting cursor. Resolution is thus very accurate, as the limitations to the system are the photographic lens used to photograph the image originally, the size of the original photograph as it is being projected on the gridspace, and the size of the individual gridsquares. To give an example, the current method used at the Gait Analysis Laboratory at Boston Children's Hospital Medical Center, utilizes 3-16 mm Photosonic cameras*, having 12.5mm and 25mm lens, located eight and ten meters from the subject, a Vanguard Motion Analyzer** as a projector unit (images of about 15x15 inches), and a GRAF-PEN Sonic Digitizer*** consisting of a frame which establishes a grid over an area 2500x2500. With such a system, resolution of approximately 1mm can be obtained. As they are currently being used, most digitizers are under computer control and various schemes of data recording incorporate both hardware and software components. The type of system developed depends on the needs of the investigator and the degree of human-machine interaction desired.

(b) Optoelectronic Devices

The incorporation of electronic-computer processing devices with visual systems can be considered, in the strict sense of the word, optoelectronic methods. This method in one form or another is the most widely used system for obtaining and processing displacement data today. Its advantages are the merits of each system component and as such depend on an individual laboratory's needs. A system can be put together in a variety of ways. It has the disadvantage, however, of being only semiautomatic; it still requires man hours to obtain data and does not have the ability to acquire these data in "real-time." An example of such a system in the author's laboratory, where this process requires one half to one day of film developing and an additional one hour to computerize one gait cycle (which consists of recording twenty anatomical areas from three filmed projected images). This is the most rapid time period that this system is capable of reaching at the present time (9).

In order to eliminate the man-hours still spent in digitizing and to obtain real-time data, "truer" optoelectronic systems have been developed (10, 11). In one type a videotape is replayed onto a tungsten phosphorant grid screen. Only large reflective markers (semicircular ping pong balls) are sufficiently bright when so projected to illuminate the screen. The screen is transformed into matrix, stored in the computer memory. In this matrix the bright markers have the value of one, while the dark ones have the value of zero. The screen can be

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* Photo-Sonics, Inc., Burbank, Ca.

** Vanguard Instrument Corp., Melville, New York

*** Science Accessories Corp., Southport, CT.

scanned sequentially from left to right, top to bottom, and sufficient time to record the coordinates of the illuminated points before the subsequent data-points are produced. Each scan then becomes a frame. Its disadvantages include difficult calibration, low resolution, large software (memory) programs and "limited" sampling frequencies. Another type of optoelectronic device utilizes infrared light emitting diodes, placed on the subject and viewed by receiving cameras whose photographic plate is a voltage grid. Each light source is pulsed in rapid sequential fashion so that the grid sees only one spot at a time. Outputs in two directions are analog voltages. For automatic processing appropriate rapid computer software and analog to digital signal converters are needed to identify each spot as a landmark and assign a fixed number of spots to a frame. With appropriate standardization, the true (parallex free) rectalinear coordinates of each spot can be obtained and the same spot found on several cameras can be combined to produce its true position in space. The SELspot system*, incorporating all of these features, can take up to fifteen spots 322 times per second, but in its current model has several disadvantages. Resolution is two to three times less than that of previously mentioned optical methods. Although the voltage grid has a resolution of 1000x1000, this is not well utilized as the limiting factor appears to be in the LED's and ten bit words produced in the analogue to digital conversion. Field range and paralex correction appear limited by camera lens. In addition the LED's appear to produce extraneous points from reflections created by them on the floor. This makes it difficult to use the LED's on positions lower in height than the knee. Similar in principle but somewhat different in detail, is CODA (Cartesion Opto-electronic Programmic Anthropometer). Little information is currently available on this system (12).

Rather than have light emitted from the patient, an alternative approach is to have the light produced elsewhere and allow sensors on the patient to pick up the light. Knowing the angle of incidence, the sensors position in space could be determined. This principle is currently incorporated in the POLGON (Polarized Light Goniometer)**(12, 13) A projector emits a diverging beam of polarized light. This is directed toward sensors located on the walking subject. "Each sensor consists of a pair of photocells mounted behind polarizing gilters," the "plane of polarization within the sensors are set at right angles to each other." A polarizing filter placed in front of the projected light is rotated at a rate of 8000 r.p.m., making the sampling rate 133 H_z. "The time phase relationship between the signal from the reference source and limb mounted sensors is used to provide concurrent outputs of voltage analogs of the angular orientation of each of the sensors." Resolution is better than .2 degrees. The minimum distance from walkway to projector is four meters, and the maximum is ten meters. The principal drawback

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* Selective Electronic Co., S-43121, Molndal, Sweden

** Crane Electronics STD, Warwickshire CV93PJ, U.K.

appears to be the system's ability to assess only the angular orientation of a limb segment in space, and the limited number of sensors it can process.

(c) Electronic Devices

In an effort to produce real-time low cost data, other electronic devices have been produced. In principle sound waves can be used in the same manner as light waves, but to-date sound waves have had only a limited application in the measurement of limb displacements. It has been used to a limited extent to measure angular displacements, as has the polarized light goniometer. In single joint analysis, i.e., measuring the relative displacement between the adjacent limbs, perhaps the most popular method currently employed uses electric goniometers. Such devices will be dealt with in greater detail in another section of this Workshop (by an author more familiar with it than the present author). Suffice to say, like all the electronic devices it offers many advantages but has the disadvantages of being encumbering to the patient, subject to considerable vibrational and cross-talk errors, and in its present state does not provide spatial positioning information.

CRITERIA FOR SELECTION OF DISPLACEMENT DATA ACQUISITION SYSTEMS

Although no one system is ideal, it is obvious from the above descriptions that a variety of good data acquisition systems are presently available to obtain desired displacement information during walking. With any system, trade-offs between advantages and disadvantages must be made, but with few exceptions, all currently used systems provide the opportunity to study gait with greater ease than hitherto. The criteria for the selection of a system will depend on the type of information desired, the subject population to be examined, and the overall purposes for which the examination is performed.

If multisegment analysis is desired one must be concerned with a large amount of input information while maintaining appropriate identification of each area, and determining each segment's relationship in space. If the entire body is to be examined, no fewer than fifteen body segments must in some way be monitored. Hands and assistive devices crossing the paths of motion of the lower limbs, or one side of the body crossing in front of the other side, must in some way be dealt with. If single joint analysis is desired, the problems created are much fewer in magnitude and easier to solve. Table I lists some of the methods presently employed in each situation. The subject population under study will further limit the choices available. For subjects with pathological disorders, the type of disorder or assistive device necessary for walking, become important factors to consider. Visual disturbances can distort the gait pattern if good lighting is not provided. Neuromuscular or skeletal-joint disorders involving the use of braces or orthoses, can prevent the donning of certain types of apparel. The examination of children mandates the use of comfortable surroundings, minimal time in patient preparation, and minimal equipment encumbering the body. All these factors become of greater importance of the measurement of other parameters, such as muscle function (with EMG), is also to be performed. Finally objective assessment of the gait characteristics of the subjects examined in a clinical research setting is far different than the assessment made to assist the clinican in his everyday work i.e., as a clinical nonresearch tool. In the former case, patient loads are apt to be smaller, greater accuracy in the data is apt to be demanded, and the absolute magnitude of the parameters measured is likely required. In the latter case, real-time information, speed of patient preparation and handling, reliability and longevity of equipment, reproducibility of selected landmarks over longer time periods, and relative values of the parameters selected (rather than the absolute values) are more significant criteria in technique selection.

Regardless of which technique is chosen, a certain degree of inherent error will always be present. The only aspects of the limb segments that are rigid masses are the bones; yet all present day techniques utilize various landmarks located on the external covering of the segment, the skin. As such, noise superimposed on the true information is produced in the actual measurement. This noise is due to movements created in the skin by vibrations transmitted from deeper inertial accelerations of the tissue mass, by vibrations transmitted along its surface when the foot impacts the floor and by movements of the underlying tendons and contracting muscles loosely attached to it on its inner surface. The smaller the soft tissue mass below the skin, and the slower the speed of gait, the less the noise. It is for this reason that most techniques utilize landmarks over joint surfaces and data collected from patients who walk slowly may be better than data collected from those who walk at normal speeds.

A number of techniques have become available to filter out the true signal from the noise (14, 15, 16). These are based on the principle that such signals occur with speeds slower than that produced by noise. The utilization of these techniques is dependent upon the recording of the data at a speed faster than either type of movement. For gait, researchers examining the question feel that sampling frequencies of fifty times per second, or greater, are more than adequate (14, 17, 19). The specific technique employed to filter the true signal will depend on the information desired and from which area of the body such information is obtained. If quantitative information, such as velocities and accelerations, is to be derived from displacement data, some smoothing technique is needed (18, 19). The need to perform such a procedure will also then influence the basic measuring methodology.

KINETICS

In addition to determining the kinematics of the subject while walking, valuable information can be gained from examining the kinetics of the system as well. To do this for each body segment is unfortunately a more difficult task than determining their respective movements. The techniques utilized in assessing the kinetics of the system can be divided into those that can be performed directly (measurable quantities) and those that can be indirectly determined by calculation.

Neglecting wind resistance, total external force applied to the body is manifested in the foot-floor interaction. This can be measured with the use of a force plate set in the floor, or perhaps even placed inside a shoe. The former method was suggested as a useful device as early as 1930 (2) and theoretically calculated by Braune and Fisher as early as the turn of the century. Force plates currently being used can determine the three mutual orthogonal components of the foot-floor reaction force vector (vertical fore-aft, medial-lateral) the torque in the horizontal plane as well as the center of pressure of the foot in any instant. If force plates are transparent, the contacting area of the foot with the floor can be assessed; hence pressure distribution at any given instant can be determined. Two plates currently available have this potential.* As in the motion-analyzer systems, some inherent error is present in this apparatus as well. Pure vertical load applied to the plate will register forces in the horizontal plane with a magnitude of 1-3 percent, depending on the type of plate used. This crosstalk between mutually perpendicular directions seems small in magnitude, but it must be noted that the fore-aft forces during gait maximally reach approximately 20 percent of the vertical load but medial-lateral forces are only about 5 percent of the vertical load. A second error arises from motion of the plate when struck. The plate will ring (resonance) like a tuning fork, and hence creates signals of forces which for all practical purposes must be considered noise. This is present at heelstrike and for about the first 10 percent of the cycle thereafter. Originally designed plates had a resonant frequency of 35 H_z which was close to that of the body's motions: however present day plates using piezoelectric transducers and more modern strain gauges have resonant frequencies at 100-200 H_z, greatly reducing their contribution to the noise signal. A new strain guage plate (recently acquired in our laboratory**) has resonant frequencies of close to 500 H_z; the only high frequency impulses created by the body present in walking is therefore found to be a one to two m.sec. impulse occurring at heelstrike. Frequencies of up to 100 H_z are present in the recordings of the cycle. For practical purposes, therefore, this implies that hardware or software low pass filters with a cutoff frequency of 125 H_z, and with sampling frequencies of the signal of 500 m.sec., may be used to eliminate noise. This procedure is currently being used in most gait laboratories. With such sampling procedures high demands are placed on data storage over short periods of time, since five to seven channels must be sampled at this rate.

Though force plates in shoes hold interesting promise, to date no practical design that is reasonably noise free, and has minimal crosstalk, has been developed. Two major theoretical limitations to further development using shoes, would be the necessity for each laboratory to have a number of these present in different sizes, and the necessity of having

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* Kistler Instruments Ag, CH-8408, Winterthur, Switzerland

** Biomechanical Research Systems, 1751 Santa Cruz Ave., Santa Clara, CA.

a backup system to determine the foot's orientation in space and position relative to the floor.

The forces acting on each limb segment can directly be measured by the use of accelerometers, if mass, mass center and inertial properties are known. A number of investigators have recently been exploring this technique. Small accelerometer packages of three, six or nine units have been used to insure avoidance of directionality problems (21, 22, 23, 24, 25). Although small in size they would need to be fixed to the skin where a minimal amount of underlying soft tissue is present, in order to avoid considerable noise problems. Its position in space must be independently determined if it is to be used to calculate velocities and displacements by integration. To date accelerometers have not found wide popularity in areas of the body other than the tibia, sacrum, head and shoulders (26, 27, 28).

Forces about joints as well as energy expenditures of various limb segments can be calculated either from accelerometers and/or from a combination of data derived from motion displacement and force plate data (29, 30, 31, 32, 33, 34, 35, 35, 37, 38). The determination of this parameter, for one or many joints, requires such extensive calculations that it is only feasible with computers.

Ideally one would like to perform intra-vital measurements of forces occurring in the muscle, tendons, ligaments, and bone. To date the closest that modern techniques have come to this goal, have been strain guage recordings of a femoral prosthetic replacement (39), nail-plate insertion into the proximal femor for internal fixation of a fracture (40), Harrington Rod implantation for internal fixation during scoliosis correction and spinal fusion (41), and direct recordings of strain guages placed on the human tibia. In only the first instant and the last two have recordings been made during gait. With the common treatment modality of total joint replacement as a standard part of the orthopaedic armamentarium, it is possible to obtain a greater knowledge of the forces present around certain joints during gait with the use of small electronic packages such as pressure recorders and telemetry devices. To date, however, none have been implanted (44).

Since muscles are the force actuators of the body, the forces that they create during walking are of prime interest to investigators in this field. This measurement has totally alluded any reasonable approach partly because of the anatomical and physiological properties of the system. To date the only property of this organ system that can be ascertained is the depolarization of the sarcomere membrane of individual motor units. (EMG of motor action potentials). To examine the voltage changes occurring during this physiological phenomenon, electromyography is used. For a review of this subject, the reader is referred to the excellent book by Basmajian (45). However, in the study of gait, two basic techniques have been standardly used and for the sake of completeness should be mentioned here.

The first is the use of extremely fine wire, intramuscular electrodes (46). The pair of electrodes consists of 106 mm. diameter wires, insulated with a polyurethane coating over the entire length. The wires are threaded through an injection cannula of 27 guage, the loop used to insert it is cut, the wire ends are deinsulated over the last two mm. of their length and are then bent around the end of the cannula. After the wires and cannula are sterilized they are inserted into the desired muscle and the cannula withdrawn (47). The second technique employs the use of a pair of electrodes, approximately one quarter of an inch in diameter, placed on the skin (surface electrodes) over the bellies of the desired muscle groups. Wire electrodes because of their small exposed ends and direct contact with the muscle are able to register voltage changes of only five or six motor units within a given muscle. The advantage of this is the assurance of obtaining only the signal from a single muscle and offering the ability to easily judge the intensity of the muscle contraction. These advantages are only in the eyes of the beholder, as the same factors are considered by others to be disadvantages. Since the intensity of muscle contraction involves an increase in the number of motor units acting as well as an increase in the firing rate of each individual unit, a more representative measurement could be obtained from surface EMG's. This factor may be even more significant if certain diseases utilize one type of contractility behavior over another, or have created non-uniformity in the action of the motor units. Surface EMG's offer the additional advantage of being a painless procedure. However, they have the disadvantage of not being able to evaluate deep seated muscles and the unfortunate disadvantage of, at times, picking up activity from adjacent, unwanted muscles. Because the power spectrum of surface EMG's has been found to be lower than that of needle EMG's, it offers lower digital sampling frequencies, if so desired, which are on the order of 500-1000 H_z rather than the 1000-2000 H_z for needle EMG's. In both cases some form of high-pass filtering in the hardware or software is necessary, as noise created by motion artifacts and electrical signals in the room environment where the gait studies are held are commonly found. No uniform standard for the cutoff frequency has been established, but has been usually considered to be between 20-60 H_z.

Any assessment of the EMG signal beyond an indication of the phasic on-off activity of the muscle is difficult to do. To obtain some idea of the intensity of the contraction, further processing of the signal needs to be performed. A variety of techniques and parameters have been used (45); all can be performed via hardware apparatus or via computer software processing. Processing the data in one form or another prior to storage is preferred. However, this limits what can be done and prevents any further processing in the future. It must be emphasized that although modern electronics and data processing systems permit elaborate means of processing EMG signals, such methods only provide a manner of determining the <u>electrical</u> intensity of the contraction. The exact relationship between this and the intensity of the force observed, even in normal muscle, is not at all clear and is even less so when pathological disorders affect these muscles. This appears to be true in both the magnitude and phasic timing of the two parameters.

OTHER TECHNIQUES OF DATA ACQUISITION

A review of modern data acquisition systems would not be complete without mentioning the devices that have been produced to measure a limited but very significant number of parameters of gait. Various laboratories have developed electronic hardware to rapidly and easily determine gait velocity. In addition the timing of the individual phases of the gait cycle has been found to be a valuable clinical parameter and can easily be ascertained with new devices measuring merely the foot-floor contacting times (48).

DATA STORAGE, PROCESSING AND DISPLAY

Concomitant with the explosion in the development of modern techniques of gait analysis, electron technology and computer science have provided the means by which such information can more rapidly and more easily be stored, processed and displayed. The availability of such devices in the area of gait analysis has perhaps been the major reason why interest in this field of applied research and clinical assessment has expanded so rapidly in the last decade. The expanding capability of relatively low cost, mini-computers has made hitherto arduous procedures of data processing become a thing of the past. In earlier research, computers were merely used as in-stage processors, reserved for extremely detailed and complex calculations. Computers are now being used in every step of gait analysis, from data acquisition, to storage, to processing, to displaying. Not only have they significantly reduced the time required to obtain information from gait analysis, but in certain cases without them the techniques developed would not be possible. The speed in handling large volumes of information, from many inputs and outputs, allows easy integration of the many kinetic and kinematic parameters of gait. Table 2 lists the various ways in which information can presently be stored and displayed. Which system is to be used is dependent upon each laboratory's priority of: (a) amount of information to be stored or displayed per patient, (b) need for rapid access to such information, and (c) cost effectiveness per patient. A great deal of effort has been expended in establishing computer-based systems and sub-systems. With the use of such devices and methods, the variety of pathological disorders examined can be expanded, as more patients can be examined per day. EMG, force plate, and motion data "raw" form can be rapidly displayed in Marey's simplistic, but very informative diagrams, but containing more information that Marey ever thought possible. Such diagrams were Elftman's and Bernstein's qualitative representation of the dynamic state of walking. Using such diagram communication between various medical and scientific disciplines is assured. Calculations of velocities accelerations, forces, energies and power are not only possible, within short periods of times, but can be combined with other parameters of gait, such as muscle activity, to provide a greater understanding of the gait process and answer indepth questions (34, 49). In short, the modern techniques of gait analysis and and the currently employed methods of data handling have altered the emphasis of work in this field, from that of developing techniques of acquiring data to determining the ways in which it can assist the researcher and clinician in performing their job.

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TABLE I

Single Joint Analyses

- Polarized Light Goniometers
- Ultrasonic "Goniometers"
- Electrogoniometers

MultiSegment Analysis

- Stroboscopic Photography
    - single plate
    - low speed film
- Cinematography
    - isolated
    - projected image measurement
- Scanning Chronocyclograph
- TV Picture Analysis
- "Selspot"

TABLE II

<u>Storage Systems</u>

- Analog Type
    - 7, 14, 28 Tracks
    - FM or AM
- Computer Discs
    - Plain
    - Floppy
    - Multiplatter
- Digital Tape
    - "DEC" Tape
    - Cassette Tape
- Memory
    - Semiconductor
    - Core
    - CCD (Charge Couple Device)
    - Bubble

<u>Output Devices</u>

- Storage Oscilloscope
- X-Y Plotter
- Graphics Terminal
- Line Printer
    - Mechanical
    - Electrostatic
- Video Monitors

AREA

UNITED KINGDOM

EUROPE

I. BIRMINGHAM, ENGLAND

ADDRESS
Biomechanics Laboratory
Physical Education Department
University of Birmingham
P.O. Box 363
Birminghan B15 2TT, England

Researcher: A. Howard Payne

I. EQUIPMENT

Biomechanical.

Runway: Total length 100.0 m +
Run-in: up to 100 m — Effective length 2.0 M — Run-out 10.0 m
Force plate — Accelerometer
Cine — Video

Physiological.

nil

II. PARAMETERS

Both limbs recorded singly or simultaneously
Motions: Linear: Stride length, cadence, velocity
Forces: Ground Reaction: Vertical, AP and ML shear, center of pressure

Processing - Manual, Motion Analyzer, Computer

Range: Largest forces in sporting activities
Experimental error: ± 5%
Time: Force plate: instant
Film: 7-10 days

III. PHILOSOPHY

This laboratory is concerned with biomechanics in sport. It has gait analysis capabilities. The Force Platform Group includes many researchers in gait. A document "A Catalogue of Force Platforms" and a periodic Newsletter can be obtained from the director.

II. GLASGOW, SCOTLAND

ADDRESS

oengineering Unit
University of Strathclyde
Wolfson Center
106 Rottenrow
Glasgow G4 0NW, Scotland

Directors: John P. Paul, Ph.D.
John Hughes

Deputy: N. Berme, Ph.D.

I. EQUIPMENT

Biomechanical.

Walkway: Total length 17.0 m
Run-in 7.0 m   Effective length 3.0 m   Run-out 7.0 m
Force plate   Pylon dynamometers
Cine   Video

Physiological.

EMG surface electrode   Cardiac rate

II. PARAMETERS

Recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
  Spatial Relations: Joints and segments
  Angular: Hip, knee, ankle and foot in three planes
Forces: Ground Reaction: Vertical, AP and ML shear, center of pressure
  Joints: Compression, tension, shear in hip, knee, and ankle
  Bones: Compression, tension, shear in pelvis, femure, tibula and fibula
  Muscular Tension: In major groups only
Physiological: EMG

Processing - Manual, Motion Analyzer, Computer, and Analog Computer
Combined Computer/Television/Force Platform/Dynamometer System
Immediate playback of digital record.

Sampling rate: 30-200 Hz
Time: 1-3 days

III. PHILOSOPHY

The assessment and evaluation of the normal and the disabled must involve the basic mechanisms whose function is impaired - i.e. muscular force, joint loading.

IV. PROJECTS

This well-established unit is involved in a multiplicity of research projects as follows: (a) Evaluation of modular systems of construction for below-knee prostheses. (b) Development of a kneeless, telescopic, energy storing leg for above knee amputees. (c) Development and evaluation of prostheses

Glasgow cont.

for through-knee amputation. (d) Biomechanical matching of prostheses and patient at above-knee amputation level. (e) Assessment and development of materials and techniques for fitting of prostheses and orthoses. (f) Development and evaluation of prostheses for hip disarticulation patients. (g) Assessment of characteristics of patient/orthosis at lower limb level. (h) Assessment of proprioception and position awareness in normal and pathological patients. (i) Assessment of biomechanical function of endo prostheses for hip and knee joints. (j) Development of a television computer system for analysis of human locomotion. (k) Biomechanical studies of the shoulder, elbow and finger joints. (l) Studies of the kinematics of the head, arms and trunk in normal and pathological gait. (m) Development of a telemetry system for physiological measurement to assess amputee performance. (n) Evaluation of supracondylar suspension techniques on PTB below-knee prostheses. (o) Evaluation of a cosmetic below-knee orthosis fabricated in polypropylene. (p) Development of an on-line PDP 12 signal processing facility for studies in human biomechanics, tissue mechanics and the assessment of cardiac function. (q) Long term ambulatory physiological surveillance. (r) Physiological cost of ambulation in the disabled.

III. LONDON, ENGLAND

ADDRESS

Biomechanical Research and Development Unit
Department of Health and Social Security
Roehampton Lane
London SW 15, England

Director: Prof. R.M. Davies

Deputy: R.B. Lawrence

I. EQUIPMENT

Biomechanical.

Walkway: Total length 13.0 m
Run-in 4.0 m Effective length 5.0 m Run-out 4.0 m
Force plate Foot switch Elgons Accelerometer
Foot print records
Cine Strobe Video

Physiological.

EMG surface electrodes

II. PARAMETERS

Limbs recorded singly or simultaneoulsy
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: All joints in three planes
Forces: Angular Moments: Hip, knee, and ankle in sagittal and transverse planes
Ground Reaction: Vertical, AP and ML shear, center of pressure
Physiological: EMG

Processing:

Varied

IV. MANCHESTER, ENGLAND

ADDRESS
Biomechanics Laboratory
Department of Mechanical Engineering
University of Manchester Institute of
Science and Technology
P.O. Box No. 88
Sackville Street
Manchester M60 1QD, England

Director: Ronald D. McLeish

I. EQUIPMENT

Biomechanical.

Walkway: Total length 6.5 m
Run-in 1.5 m   Effective length 3.0 m   Run-out 2.0 m
Force plate   Foot switch
Cine

Physiological.

nil

II. PARAMETERS

Both limbs recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity
Spatial Relations: Joints and body segments
Angular: All joints in sagittal plane; hip, knee, ankle in coronal plane; foot in transverse plane
Forces: Angular Moments: All joints - all planes in stance only
Ground Reaction: Vertical, AP and ML shear, center of pressure
Joints: All - compression, tension, and shear
Bones: Nil
Muscular Tension: Major groups only

Processing - Manual for cine, Computer for force plate

Sampling rate: Up to 3,000 Hz; normal 100 Hz
Experimental error: ± 5%
Time: Force plate: 4 hours
Cine: 5 days

V. OXFORD, ENGLAND

DDRESS

xford Orthopaedic Engineering Center	Director: Dr. J.W. Morris
University of Oxford
Nuffield Orthopaedic Center
Headington, Oxford OX3 7LD
England

I. EQUIPMENT

Biomechanical.

Walkway:	Total length 5.0 m		
	Run-in 2.0 m	Effective length 5.0 m	Run-out 2.0 m
	Force Plate	Accelerometer	
	Cine	Video	

Physiological.

nil

Physical Resources

1. Space

11.5m x 9.6m (can be enlarged to 15.5m x 9.6m). Exclusive use for experimental work.

2. Kinematics

(a) TV-computer (after Strathclyde). A special-purpose interface to link up to seven TV cameras to a PDP-11 computer. Resolution is 0.3% vertical and 0.1% horizontal for each camera. Selectable sample rates at 50 Hz and submultiples.

(b) 16mm cine cameras driven by synchronous motors at fifty frames per second. Manual reduction with resolution of approximately 0.2% horizontally and vertically. (System being phased out.)

(c) Accelerometer platforms allowing full kinematic analysis of pelvis or other spinal sites. Special-purpose transducers 5g full-scale, < 10μg noise and drift. Spatial system resolution not yet determined.

3. External Forces

Ground reaction: two Kistler force plates set into the floor, each measuring six force components. Also two parallel, vertical reaction walkways for consecutive paces, 3m long.

4. Recording

Racal 7-channel IRIG FM tape recorder.

Oxford cont.

5. Data Reduction

L-W analyzing projector
D-Mac Digitizer tablet (resolution 0.01 inch).

6. Analytical

PDP-11/34 with 32k memory
2 cartridge disc drives
16-channel, 10-bit analog-digital converter, 30k word/sec.
Graphics visual display
X-Y plotter
Direct memory access TV interface >50 word/sec. buffered onto disc memory.

II. PARAMETERS

Both limbs recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
  Spatial Relations: Joints and body segments
  Angular: Hip, knee, ankle, foot in sagittal and coronal planes
Forces: Ground Reaction: Vertical
  Joints: *In vitro*, hip and knee compression

Processing - Manual, Motion Analyzer, Computer

Sampling rates: 10m/s accelerometers
  50 and 20 fps cine
Time: Walkway: instant
  Accelerometer: 2 hours
  Cine: 7 days

III. PHILOSOPHY

Briefly the purposes are:

1. To investigate mechanical factors in locomotor disability, with a view to providing general guidance to orthopaedic treatments, rather than to assess individual patients. In particular, there is interest in the effect of different sequences of partial treatments for diseases with multiple foci in the lower limbs, best exemplified by rheumatoid arthritis. This work should lead to a structured description of a range of disease and treatment combinations, with their likely consequences.

2. To evaluate the mechanical effects of traditional and new orthoses. Again, the purpose is related to the orthosis/disease combination and not to the individual patient. It is recognized, however, that valid evaluations of orthoses will not be possible until the disability that they are used to treat is properly described.

The center has also considered the locomotor system as a physical experiment, and have concluded that:

1. The range of physical variables which can usefully be measured is quite limited. They are external forces (as applied to the ground), loads in structures worn or carried (as in an orthosis), external kinematic quantities, and electromyograms. The measurement systems were chosen to allow these variables to be measured in as generalized and flexible a way as is presently possible.

2. None of the above variables is suited to direct interpretation. For the analyses of locomotion being made, processing and careful representation are required. The use of a computer for this purpose is essential.

3. With the correct choice of measurement and analytical equipment, it is possible to set up a gait laboratory which will allow most locomotor analysis problems to be solved. The initial cost may be quite high, both in terms of equipment and preparation, but the benefits come in the relative ease with which experiments can be modified to suit the current problem.

IV. PROJECTS

1. Analysis of the effects of rheumatoid arthritis and osteoarthritis on the kinematics of the knee joint. This work has been completed for angular movements in the sagittal plane. It is being extended to consider frontal plane movements also. Detailed work is carried out by engineering research students. One has recently completed his studies and left, and another is recently started.

2. A study of knee joint instability caused by soft tissue injury in the knee. This project is just beginning and is to be carried out by an orthopaedic research student. An interesting feature is an attempt to improve the accuracy of kinematic measurements by radiographic studies of the relative movement between skin markers and the skeleton.

3. Movements of the pelvis will be measured by an accelerometric scheme which has been gradually developed here over the last seven years. The current project occupies one engineering research student who has been working for about one and one-half years developing new transducers and analytical software. The purpose of the project is to examine the role of spinal movements in compensating for joint dysfunction in the lower limbs.

4. A project which is an exception to the philosophy of using general-purpose measurements is the development of a foot-switch and timer system using Spherax (Pressex), as originally proposed by the Rancho Los Amigos Hospital, California. This instrument will be used for gait retraining. This work is done by a Research Assistant.

Proposed projects which have yet to begin are largely indicated in the paragraphs above on the philosophy of the center.

VI. OTHER GROUPS INVOLVED IN GAIT STUDIES

Professor G. Murdoch
Limb and Appliance Center
133 Queen Street
Broughty Ferry
Dundee, Scotland

Mr. Gunar Holmgren
Een-Holmgren Ortopad A.B.
Bergsbrunnagat 1,
Uppsala 75323
Sweden

Mr. G. Veres
National College of Prosthetics
Sophies Minde Orthopaedic Hospital
Trondheimsveien 132
Oslo 5
Norway

Dr. E.H. Furnee
Technische Hogeschool Delft
Laboratorium voor Technische Natuurkunde
Lorentzweg 1
Delft
Nederland

Professor U. Boenick
Technical University of Berlin
Berlin
Germany

Note: The author acknowledges Dr. J.P. Paul who brought these names to his attention. Regretfully, time did not permit the opportunity to gather information from them for this report.

AREA

NORTH AMERICAN - EASTERN

I. ATLANTA, GEORGIA

ADDRESS
Regional Rehabilitation Research
  and Training Center
Emory University School of Medicine
Atlanta, Georgia 30322

Director: Dr. J.V. Basmajian, M.D.

I. EQUIPMENT

Treadmill
14-channel recording system
Amplifiers and power supplies
16 mm Motion Analyzer
16 mm Camera
Split screen video systems
Foot switches
Goniometers
Balance platform
Indwelling or surface EMG electrodes
PDP 8/E Laboratory Computers

II. PARAMETERS

1. Both limbs singly or simultaneously. Stride length, cadence swing, stance and velocity.

2. Muscular tension, individual or muscle groups.

Analysis.

1. Computer analysis of 16 mm film or on-line analog to digital conversion of multi-channel EMG.

2. Computer analysis of balance in 3 components of force and location of point of force application.

Usage
  Gait training

Kinesiology Laboratory: Size 24' x 47'

II. BOSTON, MASSACHUSETTS

ADDRESS

Gait Analysis Laboratory
Children's Hospital Medical Center
300 Longwood Avenue
Boston, Massachusetts 02115

Director: Sheldon R. Simon, M.D.

Deputy: Joseph Mansour, Ph.D.

I. EQUIPMENT

PDP 11/34; PDP 11/10
RK05 Disks (2)
DEC Tape system
Teletype
LPS
Tektronix 4014 Graphic Display Terminal
4631 Hard Copy Unit

Data Acquisition.

Walkway - Total length = 14 meters.
Run-in - 3.3m Effective length 2.6m Run-out 8m
Width 8 m
Cine - Frontal, Sagittal Plane (2)
Accelerometers
Force Plate (2)
Acoustic Foot Strike Indicators

Physiological.

EMG urface & indwelling electrodes.

II. PARAMETERS

All limbs recorded singly or simultaneously
Kinematic: linear-stride length, cadence, swing stance, velocity, base of support
Spatial relation - body segments
(upper and lower extremities and trunk)
Angular displacements, velocities, and accelerations of all joints and limb segments

Forces: Angular moments: In three planes for hip, knee and ankle.
Ground reaction - vertical, fore-aft, medial-lateral, center of pressure, torque.
Joints - compression, tension, shear in hip, knee and ankle-exclusive of synergistic muscle action.
Bone - compression, tension shear-lower extremity

Boston cont.

Processing:

a) EMG - Force Plate data-directly computer stored in line via 16 channel 12 bits differential input Analog-to-Digital Converter ± 5 volt input range.
Sample Rate: 500 Hz/channel with simultaneous computer recording, 16 channels.
Experimental Error - Force Plate 3%
Data acquired, processed, presented - 2 minutes

b) Motion-Semi-automatic system with film coordinates recorded and transferred via Vanguard Motion Analyzer and digitization system with GRAF PEN under computer hardware and software control.
Experimental Error - 3% 3-D coordinate location
Data acquired, processed, presented (1 hour + 1 day for film developing)

Software Programs:

1. EMG - Force plate on line data acquisition with high degree of flexibility for various clinical demands.

2. Motor acquisition from film with flexibility for single to multiple limb segments for man or animal, recorded in the laboratory or in the field.

Data Storage and Processing and Display Dual:

1. Equipment - track, magnetic tape, Tektronix 4014 Graphic Display Terminal, 4631 Hard Copy Unit
   Software Program-Processing
   -motion-parallex correction and absolute 3-D coordinate determination with interpolation of obscured points.

2. Digital filtering and calculation of linear and angular displacement, velocity and acceleration of designated anatomical markers, segments or center of gravity.

3. Energy of body segments of lower limbs determined about all 3 axes.

4. Linear and angular momentum.

EMG force plate - Digital Filtering via fast fourier transformation
computer graphics - variety of curve plotting routines and stick diagrams.

III. PHILOSOPHY

The long term goal of the Gait Analysis Laboratory at Children's Hospital Medical Center is to incorporate knowledge of bioengineering and neurophysiological practices in the performance of clinical research on patients with various gait abnormalities. Objective, comprehensive information on the pathological gait patterns of handicapped individuals - with emphasis on childhood disabilities - for the evaluation and improvement of their ambulatory status, is planned.

Specifically, the laboratory's objectives are: (1) the testing of new scientific principles and technological advances in a clinical setting and assisting in their development for clinical utilization, (2) the development of diagnostic procedures (using biomechanical parameters) by which the identification of significant pathodynamic features of the gait patterns of handicapped children may be ascertained, (3) the evaluation and efficacy of various existing treatment programs such as physical therapy, surgery, orthoses and prosthetic apparel and the utilization of biofeedback devices, (4) the appropriateness of the timing and selection of the various treatment modalities, and (5) the evaluation of new treatment modalities developed to improve pathological gait patterns of the handicapped child.

IV. PROJECTS

Since its inception approximately two and one half years ago, the Gait Analysis Laboratory has been involved in developing new systems and improving existing systems to measure and process simultaneously all the major parameters of gait. This includes muscle group activity, motion of all limb segments and the external body force as manifested by the foot-floor reaction force. The system was designed to facilitate rapid and accurate acquisition of data with a minimum of effort. A data storage system was developed whose characteristics lend themselves toward a flexible modality of utilization of each of the three measured and stored parameters; independent modes of utilization or in combinations of data displayed in various modes. The latter is particularly valuable in establishing communication between the engineer scientist and the clinician.

In order to assess the clinical applicability and to anticipate possible difficulties in examining and evaluating the pathological gait patterns seen in handicapped individuals, two pilot clinical studies - the gait patterns of normal children between the ages of two and five and the specific pathological gait existing in children with cerebral palsy and genu recurvatum - were undertaken and completed. The former group of patients provided a baseline for assessing our techniques and the equipment when used on a subject group with highly variable gaits and limited attention spans. The second group provided an additional source for evaluating errors and problems in a group of patients having limited ambulation potential. The results of these studies in terms of both the development of the laboratory system and the clinical relevance of such a system assured us that the gait analysis system as currently being developed is a clinically feasible data acquisition and processing system and can readily and accurately handle almost any type of pathological gait problem needing investigation. Work to date has provided leads as to which biomechanical parameters presently measured might be clinically significant.

On the basis of the results of past year's work, studies proposed for the forthcoming year include: (1) An expansion of the population of patients with cerebral palsy having genu recurvatum to determine if preliminary results previously noted are confirmed. The application of recently developed software programs of engineering principles (i.e. limb segment energy changes) to the population group in order to determine their clinical significance. (2) The study of the dynamics of the body's center of mass in a group of patients with scoliosis to determine the dynamic function of conservative measures in the correction of this deformity. (3) A clinical study pre- and post-treatment of a group of cerebral palsy patients who have dynamic equinus to determine what the effect of specific abnormality and its treatment has upon the overall ability and quality of the gait pattern seen. (4) The further development and incorporation into the system of additional computer programs to derive and calculate gait parameters which can be derived from measured kinesiological data and foot-floor reaction forces. (5) The further development of the data acquisition and handling system to incorporate 16 additional channels of force-plate and EMG date. (6) The clinical field testing of new technological advances and devices as it is requested of us and the devices become available, specifically the testing of biofeedback devices of a limb load monitor.

III. CLEVELAND, OHIO

ADDRESS

Electronic Gait Laboratory
Case Western Reserve University
Veterans Administration Hospital
10701 East Boulevard
Cleveland, Ohio 44106

Director: Ernest B. Marsolais, M.D., Ph.D.

I. EQUIPMENT

Biomechanical.

Walkway: Total length 10.0 m
Run-in 3.0 m Effective length 4.0 m Run-out 3.0 m
Automated 3-D strobe Video (Sel-spot)

Physiological.

EMG surface and indwelling electrodes

II. PARAMETERS

Both limbs recorded simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: Hip, knee, ankle, foot in three planes
Forces: Angular Moments: Hip and knee only at present in three planes
Ground Reaction: Vertical, AP and ML shear, center of pressure
Joints: Hip and knee only - compression and tension
Bones: Compression, tension, shear, in pelvis, femur, tibia, and fibula
Muscular Tension: Individual muscles and major groups.

Physiological: EMG, nerve conduction

Processing

Sample rates: 1,400/min.
Experimental error: ± 15%
Time: up to 7 days

III. PHILOSOPHY

It is the philosophy of our group that locomotion studies must provide information to help in clinical care of the patient. In order to do this:

a) Laboratory must be reasonably accessible.
b) Procedure must be relatively rapid and reporting must be relatively rapid.
c) The material must be presented in a fashion that it can be easily understood and utilized by the clinician.

IV. PROJECTS

At present we are working on the following projects:

a) Development of a computerized clinical foot contact laboratory. This is in operation at the present time.
b) Development of computerized Selspot Laboratory. This laboratory will provide complete dynamic information including the kinetics and kinematics. It is hoped that this will be available for clinical use within six months. The laboratory will allow estimates of forces in the hip joint and knee joint, and eventually also the ankle.
c) Comparison of the Neural Muscular Assist with the Double Upright, AFO, the VAPC Clip, the Engen AFO, the FEPB and no brace at all in the treatment of the drop foot patient. This study will be completed in approximately another two months. This study evaluates use of an implanted electrical stimulation brace on a significant number of patients.
d) Feasibility study on use of electrical stimulation to augment hip control in the hemiplegic and hemiparetic. This is the first step in our effort to utilize electrical stimulation for synthetic gait in the paraplegic.
e) Evaluation of implanted instrumented total hip and total knees. These will telemeter loading information to the laboratory in conjunction with our routine gait analysis. It is hoped that these will provide essential design information.
f) Feasibility of use electrical stimulation in treatment of the cerebral palsy patient.

IV. GUELPH, CANADA

ADDRESS
Biomechanics Unit
Department of Human Kinetics
University of Guelph
Guelph, Ontario
CANADA

Director: Dr. J. Brooke
Prof. J. Charteris

I. PHILOSOPHY

The department has general interest in human biology, and human gait if of focal concern to it.

II. PROJECTS

Projects underway include the development and use of a technology to pursue kinematic (cyclographic) analyses of gait patterns. Our interests in this regard center on normative perspective; differences in pattern which may be attributable to ontogenetic features, sexual dimorphism etc. Presently we are conducting research into treadmill versus overground gait patterns at selected relative speeds, and are also investigating the process of habituation to treadmill walking.

We use a PDP Lab-8E minicomputer, interfaced with Tektronix CRT and a sonic digitizer (DEK). 16 mm film is made (processing delay 1-2 days) and projected from behind onto the digitizer plate. Requisite software has been developed in-hour for data-entry and processing according to the theory first enunciated by Grieve, and using a methodology not essentially dissimilar to that of Milner.

Additionally we have constructed a plexiglass walkway, after the model of Ducroquet, which permits multi-planar viewing/filming, and are in the process of developing footswitch technology for analysis of the temporal aspects of gait in projects such as listed above. An expert in this technology is joining our faculty imminently and will doubtless pursue this form of work.

V. HAMILTON, CANADA

ADDRESS
Locomotion Laboratory
Chedoke Rehabilitation Center
(Teaching Unit of McMaster University)
Hamilton, Ontario
CANADA

Director: Dr. Morris Milner, Ph.D.

Deputy: Dr. H. de Bruin

I. EQUIPMENT

Biomechanical.

Special self-aligning electrogoniometers for measurement of relative angular motions at hip, knee and ankle.

Heel and toe contact switches attachable to footwear.

Grass force transducers

Walkway: Total length 13 meters, run-in and run out ± 2 meters each.

Physiological.

EMG: Surface and indwelling electrodes, O_2 consumption.

Digitimer Equipment for electrostimulation:

4030 Timer Unit
2 x 2533 Isolators
1 x 3072 Stimulator Unit

Data Collection and Processing:

A stroboscopic flash photography system is available for collecting stick diagrams. These data can be fed to a CDC 6400 system by the use of a digitizer system. Appropriate programs for data management are available.

Selspot system for 3-D tracking has just recently been acquired. It is expected to implement this shortly.

Computer System:

On-line PDP 11/10 faculty incorporating 28k Core, RK11 Disk, Dec Tape system, Teletype with paper tape reader and punch, LPS system (8 A/D channels and 2 D/A), Tektronix 4006-1 Computer Display Terminal with 4631 Hard-Copy Unit.

Processing times: Virtually all on-line interactive processing.

Recorders:

1x Honeywell 1858 CRT Visicorder
Potential for 18-channels
Present capacity 8-channels

2 x Tektronix 7613 Storage Oscilloscopes

II. PARAMETERS

8 Analog channels and 2 Digital Channels simultaneously

Motions: Linear, stride length, cadence, swing, stance

Spatial Relations; body segments, angular variations in sagittal plane.

EMG - raw and average envelopes.

III. PHILOSOPHY

The Laboratory is concerned with locomotor function particularly as it relates to pathological conditions. It is considered essential to embody a team approach to studies of human locomotion in order to provide clinical relevance to research and developmental pursuits. The team is comprised of physiatrists, physiotherapists, bioengineers, electronic and mechanical technologists. Special attention is directed to the generation of "clinically digestible" displays of information utilizing appropriate computational facilities.

IV. PROJECTS

1. Follow-up of patients undergoing knee-joint replacements using angle-angle displays (Expected date of completion 1978)

2. Elucidation of key factors in hemiplegic gait. (Pending funding,date of completion 1979)

3. Multifactorial analysis of lower limb amputee gait using computer-generated displays. (Expected date of completion 1978)

4. Fundamental studies on functional electrostimulation of skeletal muscle to facilitate locomotion in cases of paralysis. (Continuing study)

5. The development of a charge-coupled device (CCD) sensor camera system for on-line tracking of body motions. (Expected date of completion - 1978)

VI. NEW YORK, NEW YORK

ADDRESS

Advanced Systems Laboratories Bioengineering Research Service Veterans Administration Prosthetics Center 252 Seventh Avenue New York, New York 10001	Director: Anthony Staros Asst. Director: Edward Peizer, Ph.D. Projects Manager: Carl Mason

I. EQUIPMENT

Biomechanical.

Treadmill: 1-6 mph

Walkway: Total length 15 1/4 m

Run-in 4.0 m	Effective length 7.3 m		Run-out 4.0 m
Force plate	Foot switch	Elgons	Accelerometer
Barograph			
Cine	Video	Static and gliding cyclograph	

Physiological.

Oxygen consumption	Dynamometer	EMG surface electrodes

II. PARAMETERS

Each limb singly
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: Sagittal and coronal planes only - all joints
Forces: Angular Moments: Sagittal and coronal only - all joints
Ground Reaction: Vertical, AP and ML shear, center of pressure
Joints: Compression, tension, and shear in all
Bone: Compression, tension, and shear in all
Muscular Tension: In individual and muscle groups

Physiological: EMG, energy cost

Processing - Manual

Time: 8 weeks

VII. PHILADELPHIA, PENNSYLVANIA

ADDRESS

Krusen Center for Research and Engineering
Temple University
Moss Rehabilitation Hospital
12th Street and Tabor Road
Philadelphia, Pennsylvania 19141

Director: Richard M. Herman, M.D.

Deputy: F. Ray Finley

I. EQUIPMENT

Biomechanical.

Walkway: Total length 13.0 m

Run-in 5.0 m	Effective length 2.0 m	Run-out 5.0 m
Force plate	Foot switch	Elgons
Force transducer		
Cine	Ultrasound	

Physiological.

EMG surface electrodes   Equilibrium

II. PARAMETERS

Recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
Spatial Relations: Joints
Angular: Hip, knee, ankle, sagittal plane, hip, subtalar, coronal
Forces: Angular Moments: Knee and ankle, three planes - stance only
Ground Reaction: Vertical, AP and ML shear, center of pressure

Physiological: EMG, nerve conduction

Processing: Manual, Computer

Sampling rate: up to 200/s
Experimental error: 10%
Time: 1/2 hour

III. PHILOSOPHY

Develop a facility and the expertise to conduct a balance of research, development, evaluation and clinical services directed toward increasing the independent mobility of the neuromusculoskeletally impaired.

a) Engineering: to develop tests and measures, design devices, and apply engineering principles in the rehabilitation process.

b) Clinical: to develop an integrated, multidisciplinary consulting group approach devoted to problems of the disabled, evaluate new devices and treatment techniques, and provide clinical training of health personnel in the utilization of advanced instrumentation and techniques.

Philadelphia cont.

c) Biological: to develop concepts of neural control of locomotion and to study role of eye-head-neck coordination in the control system.

IV. PROJECTS

a) Force Line Visualization. Employ a force plate, a cathode ray tube, an optical beam splitter, and necessary electronics to display the ground reaction force vector superimposed upon the image of the subject or patient. The purposes are to provide a teaching tool, an aid for the prosthetist/orthotist in making more precise and reliable judgements about proper alignment, and an aid for surgeons and physicians in assessing patients before and after surgery or other treatment.

b) Accelerometry: Ambulation Energy Meter. Employ triaxial accelerometer at lumbar area together with small stationary microprocessor and miniature tape printer to render an objective, permanent record of performance. Principle demonstrated in literature, but has not been previously reduced to practice. The output is a measure of energy expended against the external environment and is expected to discriminate among severity of disability and differentiate among treatments. Expected completion 1980.

c) Knee Mechanics and Orthotics. Assess various knee orthoses designed to enhance the medial-lateral alignment and/or stability. Expected completion 1979.

c) Therapeutic Applications of Phase-Dependent Reflex Reversals. Investigate the effect of somatosensory input on spinal cord integration during locomotion. Electrically stimulate superficial sensory nerves of cutaneous tissues to elicit or facilitate functional muscle synergies during walking in patients with central nervous system dysfunction. Results should further concepts of motor control and of rationale for future treatment.

e) Ultra-low Mass Prostheses. The advent of sheet polypropylene and vacuum-forming techniques makes it possible to provide lower-limb prostheses that weigh up to 60 percent less than conventional limbs (B/K: 24 oz. versus 64 oz.). The effect of light weight prostheses on locomotion performance will be evaluated. Expected completion 1978.

f) Clinical Classification and Functional Prediction. A Study of the Stroke Population: to clinically assess status in relation to general medical, demographic and function sets. Analyze gait performance to determine responsiveness to selected treatment. Search for predictors expressive of function on a basis closely identified with the nervous system. Expected completion 1978.

VIII. TORONTO, CANADA

ADDRESS
Amputee Research Center
Department of Orthopaedic Surgery
University of Toronto
West Park Hospital
Toronto, Ontario
CANADA

Directors: J.P. Kostuik, M.D., F.R.C.S.
G.R. Fernie, Ph.D., P. Eng.

I. EQUIPMENT

5 different gait deviations can be recorded using specially designed portable electronic instruments.

Displacement transducer system to measure postural sway.

Foot switch, counter and read-out devices to record the number of steps taken with a prosthesis over an extended period of time.

II. PARAMETERS

Postural sway: length of the locus in unit time, pattern of sway.

Gait deviations: control of the knee joint in A/K prostheses, limb load, forward trunk bending, lateral trunk bending, stride length.

Activity: daily count of the number of steps taken whilst in hospital, count over an extended period of time of up to 1 year.

Processing:

Present computer facilities are based on a Tektronix 4051 minicomputer, 32K core, 2 tape decks, hard copy unit, joy stick, graph plotter, multiplexer, digital volt meter and interface.

Data stored digitally. Presentation of data follows collection almost instantly.

IX. WATERLOO, CANADA

ADDRESS
Gait Laboratory
Department of Kinesiology
Waterloo University
Waterloo, Ontario
CANADA

Director: D.A. Winter, Ph.D., P.Eng.

Research Assistants: J. Cairns, B.Sc.
J. Pezzack, M.Sc.

I. ENGINEERING

Walkway: 32' x 4' x 1' high, with force plate in middle
Tracking cart with guide track at 12 ft. distance, TV and cine camera
6 channel biotelemetry system, with EMG, EKG, footswitches
Video tape recorder, 8 channel pen recorder, 10 channel storage scope,
8 channel instrumentation tape recorder
Master synchronization system for cine, telemetry and force plate

Conversion and Computing Facilities.

8 channel A/D to NOVA 1200 for EMG, force plate, etc.
Film coordinates converted via a NUMONICS film analyzer to NOVA 1200
All data transferred to IBM 370/158 or IBM 360/175

Software Programs - Saggital Plane only at present

Parallax correction and absolute coordinate determination
Digital filtering and calculation of linear and angular displacement, velocity and acceleration of any marker, segment or center of gravity
Energy of body segments, total body, energy changes during stride
Muscle moments, joint reaction forces
Linear or angular momentum, force impulse
Flow of mechanical power from muscles, across joints, etc.
Computer graphics - curve plotting, stick diagrams

III. PHILOSOPHY

Because our research is being conducted in a university environment in the Department of Kinesiology much of our directions are being influenced by interactions with our motor learning and exercise physiology groups. As such, gait is considered as one aspect of human movement on which we study normal and pathological movement. The major emphasis is therefore aimed at a better understanding of the mechanisms of normal and abnormal gait. We are not, at present, involved in routine clinical assessments; rather, our assessments of pathological gait are on a case study basis aimed at developing techniques and understanding mechanisms.

IV. PROJECTS

a) Mechanisms of Stability in Gait - cine, force plate and EMG. The interactive role of muscle activity at the hip, knee and ankle during weight acceptance is being investigated. Initial evidence is that a pre-programmed pattern results, and once this pattern has been validated the ariance of this pattern will be examined in pathological gait (total knee replacements, hemiplegia, cerebral palsy). M.Sc. project - expected completion of study on normal - June 1977.

Generation, Absorption and Flow of Mechanical Power in Normal Gait - cine and force plate. The mechanical power generated and absorbed (-ve work) by the muscles at the hip, knee and ankle are being analyzed in detail during stance and swing, along with the intersegment flow of power across joints. A complete accounting can be made of the power flows at both distal and proximal ends of each segment, and then compared with the rate of change of energy of each segment. The basic information derived from these analyses will give a better indication of the role of each muscle group and also show basic patterns that may give further insight into the neuromuscular integration. Similar patterns will be analyzed in pathological gait. M.Sc. project - expected completion - April 1977.

) Mechanical Energy of Walking as Cadence - cine only. A basic kinetic study is being done to test the hypothesis that we walk more efficiently at our natural cadence than at slower or faster speeds. The kinetic and potential energies of each segment are calculated, and the sum of all segment energies (total body energy) determined for each point in time. From this curve, the sum of the absolute energy changes is calculated over 1 stride to yield the mechanical energy requirements per unit distance walked. This will be compared for eight normal subjects at each of three walking speeds. Completion date - April 1977.

Case Studies of Cerebral Palsy Gait - cine and EMG. Assessments are being conducted on a population of cerebral palsy patients on a case study basis. Each case will be documented as to evident abnormalities in movement and EMG patterns. Pre- and post-surgery and therapy assessments will assist the surgeon and therapist in their planning and final assessment of their procedures.

X. WESTON, CANADA

ADDRESS
Amputee Research Center
Buttonwood Avenue
Box 4
Weston, Ontario
CANADA, M9N 3M6

Director: J.P. Kostuik, M.D.
G.R. Fernie, Ph.D.

The research at the center is largely concerned with the problems of the lower limb amputee. Concentration of effort is on the selection of the amputation site, problems of swelling and shrinkage in amputation stumps, problems of training elderly amputees to manage their prostheses safely.

The center had adopted the approach of fitting minature electronic sensors and counters to the patients to provide a record of the number of serious gait deviations made over a period of time.

AREA

NORTH AMERICAN - CENTRAL

I. IOWA CITY, IOWA

ADDRESS
Orthopaedic Biomechanics
Children's Hospital
University of Iowa
Iowa City, Iowa 52240

Director: Richard Brand - Orthopaedic Surgeon
Roy Crowninshield - Engineer

I. EQUIPMENT

Biomechanical.

Walkway:	Total length 10.0 m			
	Run-in 3.0 m	Effective length 4.0 m		Run-out 3.0 m
	Force plate	Foot switch	Elgons	Accelerometer
	Strobe	Cine		

Physiological.

Dynamometer EMG surface and indwelling electrodes

II. PARAMETERS

Both simultaneously or singly
Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: In all three planes - all joints
Forces: Angular Moments: All joints in three planes
Ground Reaction: Vertical, AP and ML shear, center of pressure
Muscular Tension: Major groups and individual muscles

Physiological: EMG, nerve conduction

Processing: Sampling rates: 1.0 ms up
Time: 11-21 days

III. PHILOSOPHY

The philosophy of this laboratory centers around mechanical analyses associated with gait. A newly developing laboratory (see below) is concerned with the development of evaluation and treatment techniques for musculoskeletal, neuromuscular, and cardiopulmonary physical disabilities.

Physical Therapy Laboratory
University of Iowa
Iowa City
Iowa 52242

II. IOWA CITY, IOWA

ADDRESS
Multifaceted Physical Therapy Laboratory
120 Westlawn
University of Iowa
Iowa City, Iowa 52242

Director: Gary L. Smidt, L.P.T., Ph.D.

I. EQUIPMENT

Energy expenditure equipment
Treadmill
Cybex and other muscle tension equipment
Bicycle ergometer
Instrumented walkway
Video tape equipment
Electromyography
Computer
Electrogoniometers
Recorders, oscilloscopes, etc.
Accelerometers
L.E.D.'S

II. PARAMETERS

44 temporal and distance factors
Energy expenditure
EKG
Pulse rate
E.M.G.
Kinematics

Processing: Manual
On-line in development

III. HOUSTON, TEXAS

ADDRESS

Biomechanics Laboratory
Texas Institute for Rehabilitation and Research
1333 Moursund Avenue
Houston, Texas 77025

Director: Lewis A. Leavitt, M.D.

Deputy: Efrain N. Zuniga, M.D.

I. EQUIPMENT

Biomechanical.

Walkway: Total length 10.4 m
Run-in 1.0 m
Effective length 8.4 m
Run-out 1.0 m
Foot switch
Elgons
Video

II. PARAMATERS

Both limbs simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity
Angular: Knee only in sagittal plane
Forces: Angular Moments: Knee only

Processing: Manual, Computer

Time: 1/2 hour

IV. ROCHESTER, MINNESOTA

ADDRESS

Mayo Orthopaedic Biomechanics Laboratory   Director: Edmund Y. Chao, Ph.D.
Medical Science Building
Mayo Clinic
Rochester, Minnesota 55901

I. EQUIPMENT

Biomechanical.

Walkway: Total length 12.0 m
Run-in   Effective length 10.0 m   Run-out
Force plate   Foot switch   Accelerometer
Cine

Physiological.

Dynamometer for knee joint

II. PARAMETERS

Recording singly or simultaneously
Motions: Linear: Stride length, cadence, swing and stance, velocity, width
Spatial Relations: Joints and body segments
Angular: Hip and knee in three planes - ankle and foot sagittal only
Forces: Angular Moments: Sagittal only - ankle and subtalar joints
Ground Reaction: Vertical, AP and ML shear, center of pressure, vertical torque between foot and floor
Joints: Compression, tension, shear in ankle only
Bones: Compression, tension, shear in tibia and fibula
Musculature: Tension in individual muscles

Processing:

Experimental Error: less than 10 percent
Time: 2 hours

V. SASKATOON, CANADA

ADDRESS
Human Locomotor System
Department of Anatomy
University of Saskatchewan
Saskatoon, Saskatchewan
CANADA

Director: Bruce R. Brandell, Ph.D.

Deputy Director: Keth Williams, Ph.D.

Technical Advisors: George Dyck, Bill Woodward and A.E. Krause

I. EQUIPMENT

Biomechanical.

Treadmill: 0 - 5.0 mph

Walkway: Indoor rectangular - total length: 25.0 m
Run-in 2 m. Effective length 7.0 m
Outdoor - 1/4 mile hard packed cinder track
Cine Camera: Bolex, Motordrive, 50 fps

Physiological.

EMG surface and indwelling electrodes
Analog tape recorder - 7 channel
Oscilloscopes and 35 mm linegraph cameras
Integrator and digital counter
Functional electrical stimulator
4 isolated channels
Controlled parameters: strength - current regulated
cycle frequency - free oscillating
foot switch phase lock loop
cycle phasing by decade switching start and finish of cycle to nearest 1/100 cycle.
Stimulus isolator: Facilitates recording evoked EMG and quantitative measurement of isolated EMG

II. PARAMETERS

Both simultaneously but usually right limb only
Motions: Linear: Stride length, cadence, swing, stance, velocity
Spatial Relations: Body segments
Angular: Sagittal place only - hip, knee, ankle, foot
Forces: Nil

Physiological: EMG
The effects FES on EMG and motion

Processing: Manual (Encoding and digitizing equipment being designed)

Error: 5%
Days: several

III. PHILOSOPHY

The general approach to the study of gait in this laboratory is the analysis and definition of motion and muscle coordination in the normal human walking gait under a variety of stress conditions of speed and tilt and the application of established normal standards to the assessment of pathological gaits and the evaluation of surgical and rehabilitative treatments. Recently these evaluative objectives realized by means of synchronized cinematography and electromyography have been supplemented by experimental manipulation of muscle tensions in normal and activation of paralyzed muscles in patient subjects by means of Functional Electrical Stimulation.

IV. PROJECTS

A. Functional Electrical Stimulation

1. Basic research. This research is using cine, EMG and FES to establish the detailed functional relationships of lower limb motions and muscle contractions during normal walking gait. At the moment we are concentrating on interplay between heads of the triceps sural (med. and lat. heads of gastrocnemius and soleus) and the quadriceps in producing the heel rise and push-off of stance phase. Subjects walk on a treadmill while the output of up to four isolated stimulus channels to surface electrodes is held in synchrony with the gait cadence by means of a foot switch activated by Phase Lock Loop System. Decade switches regulate the timing of each channel to the nearest 100th of a gait cycle. The EMG is recorded from indwelling wire electrodes, either on a seven channel analogue tape recorder or directly on 35 mm film from the face of a 502A dual beam oscilloscope, and is processed by a uniform blanking technique to remove the stimulus artifact. Simultaneously, subjects are photographed at 50 fps with a motor driven Bolex camera and a LED in the picture is activated by a foot switch which also triggers a spike on a separate channel of the EMG recording. Quantitative EMG data is, at present, electrically integrated and digitized manually but computerization is being developed. The motion data at present are measured and recorded manually from a Vanguard Motion Analyzer, and the data plotted as curves of position, velocity and acceleration by an IBM 370.

2. Application to patients. At present, a belt-worn portable stimulator with simple foot contact switching is being used to correct foot drop in hemiplegic patients. In addition, a "universal" control which uses foot contact with time delays, is being built so that our four-channel stimulator can be applied to patients for the simultaneous FES of four muscle groups. It is planned to use the "universal" unit for researching the requirements of individual patients, for each of whom compact portable dedicated units may then be built.

Saskatoon cont.

B. Pre- and Post-Operative Evaluation of Patients

In cooperation with individual surgeons in the Department of Orthopaedic Surgery, we are making pre- and post-operative cinematographic plots and analyses of lower limb motions in patients who undergo plastic or replacement surgery for the toes, knee or hip.

VI. WINNIPEG, CANADA

ADDRESS

Gait Analysis Laboratory
Shriners Hospital for Crippled Children
633 Wellington Crescent
Winnipeg, Manitoba
R3M 0A8, CANADA

Director: A. O. Quanbury

I. EQUIPMENT

Biomechanical.

Walkway: Total length 10.0 m
Run-in 2.5 m Effective length 5.0 m Run-out 2.5 m
Footswitch via telemetry
Cine frontal and sagittal planes
Video sagittal plane

Physiological.

EMG surface and indwelling electrodes via telemetry

II. PARAMETERS

Both limbs simultaneously, EMG and footswitches only

Motions: Linear: Stride length, cadence, swing and stance velocity
- Spatial Relations: Joints and body segments
- Angular: In sagittal plane only - all joints. Absolute angle in space of thigh, leg, and foot

Forces: Angular Moments: Hip, knee and ankle in sagittal plane
- Ground Reaction: Vertical and AP shear during single support
- Joints: Compression, tension, and shear in all
- Bones: Compression, tension shear in femur, tibia, and fibula
- Energy Power Flow: Instantaneous energies of limb segments, power flows across joints

Physiological: EMG

Processing
- Image Data: 60 TV fields/sec.
- Experimental Error: Coordinate Data $\approx$1.5 mm
- Time: EMG - 1.0 min.
  - Temporal - 1.0 min.
  - Kinematic - 3 days

III. PHILOSOPHY

Gait studies can provide important clinically useful information for the proper assessment of abnormal walking patterns. This gait laboratory has been set up to analyze walking patterns in children, both normal and abnormal, without causing undue encumberance to the patient. The current emphasis is on the study of abnormal walking patterns rather than fundamental studies on normal gait although normal gait is studied when necessary to establish basic patterns for reference. Factors such as short turn around time for data retrieval, minimum encumberance to the subject and reliability of equipment have a somewhat higher priority than obtaining a few less percent of error in measurements below a permissible maximum.

IV. PROJECTS

1. Cerebral Palsy Gait. General EMG and slow motion cine studies on fifty cerebral palsy patients with various walking problems in an attempt to define some of the specific problem areas to study more closely. Two specific projects that are ongoing are the study of hip muscles in relation of femoral intoeing in CP patients and a comparison of the passive measurement of the ranges of joint motion in a spastic child and those measured while the child is actually walking. The first of these studies should provide detailed knowledge that will be of value in recommending various surgical procedures and the second will indicate the applicability of passive joint motion measurements in determining dynamic joint contractures. Both these projects should be completed in 1977.

2. Prosthesis Evaluation. An ongoing research project to obtain a complete biomechanical analysis of lower limb prosthesis. Studies to date have included an evaluation of recent knee joint design and a study of the accommodation and learning effect of wearing a new prosthesis. Kinematic information is obtained with a video system, processed by computer and made available for subsequent analysis.

3. Congenital Dislocated Hip. A study of abductor muscles of hip and paraspinal muscles in patients with congenital dislocated hip before and after treatment. Project is ongoing as patients become available.

4. Muscular Dystrophy. A study of the effect of this disease on gait and on the development of scoliosis in non-ambulatory patients. An ongoing project as patients become available.

5. Normal Children. A study to obtain both kinematic and EMG information on normal children for baseline references. An initial study is nearly complete on the gait kinematics of 25 children and the results should be available in a few months. More children will be added in each age group in the future.

6. Scoliosis. An investigation of paraspinal muscle activity during walking and various bending and flexing exercises in an attempt to learn more about the possible causes of idiopathic scoliosis. A series of normal subjects have been studied and analyzed and a study of a series of scoliotic patients has begun. This study should be complete in 1977.

VII. WOOD (MILWAUKEE), WISCONSIN

ADDRESS

Kinesiology Research Laboratory
Veterans Administration Center
5000 West National Avenue
Wood, Wisconsin 53193

Director: M. Patricia Murray, Ph.D.

I. EQUIPMENT

Biomechanical.

Treadmill: 0 - 7.0 mph

Walkway: 16.7 m long x 1.89 m wide, foot contact indication, strobe light, still camera, movie camera, instrumentated canes and crutches

Cybex II: System equipped with angular velocity and position indicators and modified torque sensor

Force platforms

Elgon for knee

Physiological.

EMG surface and indwelling electrodes

Data Handling.

2 Grass Model 7 polygraphs: 20 channels combined
Honeywell Model 5600 FM analog tape recorder: 7 channels available
Computer Automation Alpha LSI-2/10 mini-computer: 32 k core memory, assembler, BASIC, 16 channel analog acquisition dual floppy disc, Model 33 teletype, 2 channels analog output
Analog X-Y plotter
Vanguard Motion Analyzer
Recordak film reader
Calculators
Time sharing with Xerox Sigma IX at Marquette University Computing Center

II. PARAMETERS

Motions: Linear: Stride length, cadence, swing and stance, velocity, gait width, successive step length, foot angles, vertical and forward trajectories of any anatomical point, lateral trajectories of head, thorax, pelvis, etc.

Spatial relations: Multiple joints and body segments

Angular: Hip in two planes; knee, ankle, foot - sagittal only

Wood (Milwaukee) cont.

Forces: Moments: Bending moments and torque applied to instrumentated cane

Ground Reaction: Vertical force and center of pressure, axial force on recording canes and crutches

Muscular Tension: Major groups and individual muscles

Physiological: EMG

Processing: Experimental error: 1-3%
Time: variable

III. PHILOSOPHY

We are seeking quantitative information which will contribute to a deeper understanding of normal and abnormal human locomotion. The ultimate objective and significance is to obtain information which will provide a basis for early recognition and more effective treatment of patients with a wide variety of neuro-musculo-skeletal disorders.

IV. PROJECTS

1. We are utilizing our standards of normal locomotion as a basis for comparison and characterization of gait disorders in patients with selected neuromusculoskeletal disabilities. We have developed a method to record the simultaneous displacement patterns of more than 20 anatomic points in two planes of space during locomotion and have used this method in seven studies to establish ranges of normal variability for the gaits of normal men and women in broad, yet specific, age and height groups, walking at free and fast speeds and with different types of foot gear. We have also developed force-recording canes and crutches which record the amount and nature of assistance the patients require during walking.

2. We are measuring and evaluating mechanisms which are operable in the causation of gait abnormalities. We have developed methods to obtain quantitative measurements of basic mechanisms and have begun to establish the reliability, reproducibility and ranges of normal variability for these mechanisms, which will serve as baselines for comparing the deficits in disabled patients. The mechanisms under study are: muscle weakness, muscle rigidity and spasticity, joint immobility, deficits in weight-supporting ability, postural unsteadiness and instability, and incoordination of muscular activity.

3. A multifaceted approach will be used to evaluate the effect of various therapeutic procedures on abnormal walking performance and on the deficits in mechanisms of motor performance which contribute to the gait abnormalities in patients with severe arthritis or with hemiparesis, spinal cord injury or Parkinson's disease. Therapeutic procedures may include major reconstructive orthopaedic surgery, drugs and surgical procedures directed at reducing spasticity, or use of assistive devices. The relative effectiveness of different treatment procedures directed toward improving functional performance of groups of patients with similar disabilities will be assessed.

AREA

NORTH AMERICAN - WESTERN

I. BERKELEY, CALIFORNIA

ADDRESS
Biomechanics Laboratory
University of California
5144 Etcheverry Hall
Berkeley, California 94720

Director: C. W. Radcliffe

Deputy: Larry W. Lamoreux, Ph.D.

I. EQUIPMENT

Biomechanical.

Treadmill: Speed range 50 - 350 cm/sec. Inclination -5° to $+15^{\circ}$.
Special string transducers for remote sensing of angular positions, and linear positions, velocities, and accelerations of body segments.
Special self-aligning goniometers for measurement of relative angular motions at hip, knee, or ankle in 1, 2, or 3 dimensions.
Small (5g) piezo-resistive accelerometers suitable for body mounting.
Foot switches: Heel contact switches outside shoes.
Heel and toe contact switches inside shoes or on bare feet.

Walkway: Total length = 9 m. Effective length between photo detectors = 4m.
Run-in and Run-out = 2.5 m. each. Conductive walking surface available.

Physiological.

EMG: surface and indwelling electrodes.
Heart rate from electrocardiogram.
Max Plank Respirometer with manual O_2 and CO_2 analyzers.

Data Collection and Data Processing.

7 Channel Analog Instrumentation Tape Recorder.
Computer, Data General Corporation "Nova" (2.6 μs cycle time).
Data Acquisition:
  16 channel, 12 bit, differential input Analog-to-Digital converter. ±10 volt input range.
  4 channel digital pulse input.
  48 channel static switch-closure input.
  Sample rate up to 1000/s; 200/s usually used.
Data storage: 7 track IBM compatible magnetic tape.
Data processing in NOVA or, via modem or hand carried mag tape, in campus computer (CDC 6400).
Data display:
  Tektronix 4013 graphic display terminal.
  Access to Gerber digital plotting machine.
Data processing time from 0 to 1 hour in NOVA; possibly longer in campus computer.

II. PARAMETERS

Up to 16 analog and 4 digital simultaneously

Events: experimental error <5%. Heel and Toe Contact. Times measurable to 1 millisecond.

Motions: experimental error <5%.

Treadmill:
- Absolute linear and angular positions of body segments (with string transducers) in 1, 2, or 3 dimensions.
- Relative angular positions at joints (with goniometers) in 1, 2, or 3 dimensions.
- Accelerations.

Walkway:
- Average velocity (Photo Detectors).
- Relative angular positions at joints (with goniometers and cable connection to computer).
- Accelerations (with accelerometers and cable connection to computer).

Forces: experimental error <10%.
Forces and moments in prosthetic limbs.

Physiological: experimental error <20%.
Electromyograms.
Electrocardiograms.
Oxygen consumption and CO_2 production.

III. PHILOSOPHY

The objective of the Locomotion Laboratory is to obtain experimental data on walking that provide meaningful measures of gait performance and lead to a better understanding of the mechanics of normal and pathological walking. Unanswered questions in the area of gait disability have been the primary motivation for development of the laboratory which focuses on the design of prosthetic and orthotic devices and related biomechanical studies of locomotion. Current limitations in the following three phases of locomotor rehabilitation emphasize the need for improvements in our understanding of the mechanics of human walking:

1. Diagnosis: Diagnosis of a locomotor disability requires identification of those specific abnormalities in walking patterns that characterize the disability.

2. Treatment: Establishment of a treatment program requires a recognition of the causes of the abnormal motions and an awareness of the requirements for maximal restoration of lost function.

3. Evaluation: Effective rehabilitation requires the ability to determine whether a prescribed treatment has benefited the patient.
   Not only are techniques for measurement needed, but knowledge is also required of the functional significance of each of the variables measured,

in order to achieve objective evaluation of the degree of disability or the effectiveness of treatment.
First and foremost, measurements must be reasonably repeatable in order to be useful at all. Laboratory measurements have shown that virtually all gait variables are influenced to some degree by walking speed. Consequently, repeatable measurements can only be obtained when speed is taken into account. Careful attention must be given to the attachment of measuring instruments to body segments.

IV. PROJECTS

The accomplishments of the laboratory include contributions to a more basic understanding of human gait, effects of gait parameters on metabolic and mechanical energy expenditure, studies of physiological and psychological problems resulting from amputation, kinematics of joint action in the normal lower extremity, interpretation of gait studies leading to design criteria for improved prosthetic components, development of modular prosthetic devices, and development of biomechanical fitting and alignment principles for all levels of lower-limb amputation.

The emphasis of the research program has changed often to reflect the current interest and abilities of the professional and technical staff as well as the needs of the Veterans Administration. During 1976 the principal research was in the areas of biomechanical studies of human locomotion and engineering design and development of devices to aid the orthopaedically disabled. A more modest effort is undertaken in research, directed toward understanding the problems associated with spinal supports.

During 1977 the major effort of the laboratory will be related to the following projects: (1) assistance to VAPC in the procurement and testing of 50 production models of the UCBL-Four Bar Polycentric Knee. (2) Development of a new Shank Axial-Rotation Unit to minimize problems of rotation instability. (3) Completion of development and documentation for the Six-Bar Knee-Disarticulation prosthesis with potential for pneumatic swing control (4) Completion of development of a new metal heel SACH foot. (5) Development of a new friction stabilized knee unit. (6) Extension of a gait dynamics project to include more subjects. (7) A collaborative effort with the University of Uppsala in the testing of clinical gait evaluation.

II. DOWNEY, CALIFORNIA

DDRESS

Pathokinesiology Service
Professional Staff Association
Rancho Los Amigos Hospital
12808 Erickson Avenue
Downey, California 90242

Director: Jacquelin Perry, M.D.

Deputy: Daniel J. Antonelli, Ph.D.

I. EQUIPMENT

Biomechanical.

Walkway: Total length 20 m
Run-in 3 m   Effective length 15 m   Run-out 6 m
Foot switch   Gait analyzer   Accelerometer
Strobe   Cline   Video
Electric goniometers

Physiological.

Oxygen consumption, dynamometer, EMG surface and indwelling electrodes

II. PARAMETERS

Recorded simultaneously
Motions: Linear: Stride length, cadence, swing, stance, velocity
Angular: Hip, Knee, ankle by electric goniometers
Physiological: EMG and energy cost

Processing: Sampling rate: 500-20,000/s
Experimental error: ± 2%
Time: 1 hour to 2 days

III. PHILOSOPHY

To contribute to improved patient care by establishing and applying quantitative techniques to more accurately define disabled performance. To determine therapeutic effectiveness of clinical measures designed to improve function and correct deformities.

IV. PROJECTS

1. Interpretation of Muscle force from Quantitated EMG.
A series of studies are underway to quantitate electromyography and to develop a mathematical model for muscle. When completed electrical output of a muscle will be able to be used to estimate muscular force output. This is estimated to be at least a five year project. Studies will be of eccentric, concentric, fixed and variable velocity contractions, damping, signal definition and mathematical model development.

Downey cont.

2. Definition of Lower Extremity Muscle Action in Stroke, Cerebral Palsy, Head Trauma, Spinal Cord Injury and Muscular Dystrophy.
On-going clinical analysis of muscle function via EMG is routinely done to aid the surgeon in his operative decisions. Studied are walking EMG's using indwelling wire electrodes.

3. Correlation of Physical Impairment with Stride Characteristics.
Pre-operative, followed by a series of post-operative studies are done on all total hip and total knee replacement arthroplasties. Gait parameters such as velocity and single limb support are collected. These parameters are compared with the Harris factors in order to find the relationship of the two testing methods.

4. Energy Cost Determination.
Oxygen consumption studies are currently being done to define the efficiency of ambulation for spinal injured paraplegics, diplegic cerebral palsied persons, bilateral BK amputees and patients with muscular dystrophy. In addition pre- and post-treatment O_2 studies are being done on rheumatoid arthritis patients undergoing endurance training and patients with cerebral palsy participating in Rolfing treatment. A modified Douglas Bag method of expired air collection is used as patients traverse a 60 meter outdoor track. Heart rate, respiratory rate, and foot contact are telemetered to recording equipment to eliminate the need for cables.

5. Evaluation of Assistive Devices.
The laboratory evaluates assistive devices to determine effectiveness in aiding the patient's gait. Currently, a study of the effectiveness of different AFO's to support the collapsing tibia (i.e. inadequate ankle plantar flexion force) is being done. Gait parameters, knee and ankle motion and forces on the braces are being studied. The effect of lightweight vs standard BK prostheses on gait efficiency is being studied by oxygen consumption and gait parameter analysis. In another study in patients with joint disease the support forces and gait patterns using various walking aids will determine the proportion of body weight being supported on the lower extremity vs that on the supporting device. Presently the assistive devices are being instrumented for force measurement.

6. Development of Single Concept Instrumentation.
Currently a gait analyzer has been developed which is small enough and inexpensive enough to be used outside of major gait laboratories. This device monitors velocity and single limb support times. Velocity is a measure of gait efficiency, while single limb support time indicates weight bearing tolerance. A significantly lower than normal single limb support time would be caused by limb pain or instability.

III. PALO ALTO, CALIFORNIA

ADDRESS

Department of Rehabilitation Engineering Children's Hospital Stanford University 520 Willow Road Palo Alto, California 94304	Director: E. E. Bleck, M.D. Deputy: Maurice A. LeBlanc, C.P.

I. EQUIPMENT

a) Biomechanical walkway: freewalking with telemetry in area of 20m x 15m, foot switches and light pattern equipment to trace the trajectory of light measuring, particularly vertical displacement, physiological EMG telemetry with surface and indwelling electrodes, straingages to record postural shift, Nova computer.

b) Oxygen consumption measuring system for children on trackway with EKG linked to Nova computer.

c) Fixed 35mm cameras, overhead and lateral projections for recording light patterns.

II. PARAMETERS

Recorded singly
Motions: Linear: Stride length, cadence, swing, stance
Spatial Relations: Body segments
Physiological: EMG and equilibrium

Processing: 7 gait cycles
Time: 3 days

III. PHILOSOPHY

The laboratory is called a "motion analysis laboratory" and is part of the Rehabilitation Engineering Center at the Children's Hospital at Stanford. The philosophy is to conduct research and development for measuring objectively components of human locomotion, with the eventual aim of making this a practical clinical tool. It is hoped, eventually, that the laboratory will be able to give a clinician a reduction of the analog data to digital form and then to graphic printout as an analysis of the gait within one hour. This digital and graphic recording would be comparable to an electrocardiogram or an electroencephalogram.

IV. PROJECTS

1. A study of the spinal cerebellar system through quantitative measurements of postural reactions and motor coordination in normal and scoliotic children. Through these studies, it may be shown that idiopathic scoliosis is a central nervous system disorder and if so, then appropriate treatment methods might be devised and objectively tested. The expected date of completion of this project is January 1978. Force-plate measurements of

posture are made and the subject's ability to compensate for the posture is measured. The system is linked to a computer for reduction of the analog data to digital form and to graphic printout. In parallel with this, electronic and electrical methods to measure vestibular function are being used.

2. An eight channel electromyographic telemetry system, developed by NASA, is being linked to a computer. Footswitches are used to record the stance and swing phases of gait and these will be linked by telemetry to the computer as well. Electromyograph and foot switch patterns will be used to study a variety of clinical problems.

3. It is planned to study the energy requirements of various handicapping conditions in children, as well as the effect of orthotics and mobility aids on the energy requirements. This will necessitate measurements of oxygen consumption, EKG, etc., all linked to the Nova computer system.

4. The group is in the process of designing a television tracking system to measure joint ranges of motion during gait and other activities, linking this with a computer program for immediate reduction of data obtained and graphic printout. The clinical implications of this are that such a system could be used as a valuable objective examination of gait abnormalities, comparable to the EKG in heart function and the EEG in cerebral function.

IV. SAN DIEGO, CALIFORNIA

ADDRESS

Gait Analysis Laboratory
Children's Health Center
8001 Frost Street
San Diego, California 92123

Director: David H. Sutherland, M.D.

Deputy: Savio Woo, Ph.D.
Lester Cooper

I. EQUIPMENT

Biomechanical.

Walkway: Total length 18 m
Run-in 4.5 m Effective length 3.6 m Run-out 9.9 m
Force plate
Cine

Physiological.

EMG surface and indwelling electrodes

II. PARAMETERS

Both limbs recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing, stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: In three planes - hip, knee, ankle, etc., but not toes

Forces: Angular Moments: All joints in three planes
Ground Reaction: Vertical, AP and ML shear, center of pressure
Joints: All - compression, tension and shear
Instant center measurement capability
Bones: None
Musculature: Tension - individual as well as group

Physiological: EMG

Processing: Manual, Motion Analyzer, Computer

Rates: 25-500 frames per second - photosonic cameras
10-5000 frames per second - Hycam camera
Force plate: 1000/s
Experimental error: 2%
Time: 2 days

III. PROJECTS

1. Gait Studies of Normal Children in Their Growing Years.
Objective: (a) To provide a reliable data base for comparison of children with gait problems to children with normal gait. The purpose for this comparison is to provide an objective base for the treatment of gait disorders in children. (b) To study a hypothesis that regular initial

San Diego cont.

heel strike in stance phase in a child denotes the development of an adult gait pattern in terms of angular rotations at the hip, knee, and ankle in the sagittal plane. When this stage in gait has been achieved, sagittal plane rotations can be compared with adult normal values. Free speed cadence, walking velocity and step length are related both to height and age and must, therefore, be compared with age related normals. Transverse rotations are closely related to walking velocity, but if normalization of velocity is achieved by free speed cadence, rotations in the child requiring the establishment of normals by age for a proper establishment of the normal pattern.

2. <u>Gait Analysis for the Muscular Dystrophy Clinic</u>.
   Objective: (a) To provide reliable and comprehensive gait measurements of selected children with chronic muscle disease problems. (b) To investigate the abnormalities of gait produced by progressive muscular diseases. (c) To improve brace design.

3. <u>Kinematic Assessment of Gait in Rheumatoid Arthritis as Modified by Implant Arthoplasty</u>.
   Objective: The specific purpose of this proposal is to evaluate the effect of joint deformities of the lower extremity in rheumatoid arthritis on the adjacent joints in the same patient.

4. <u>The Use of Gait Analysis to Achieve Precise Alignment of Lower Extremity Prostheses</u>.
   Objective: To provide a precise, definitive method of aligning a lower extremity prosthesis that would eliminate time-consuming trial and error methods currently in use. This method would hopefully allow prosthetic alignment to be done more efficiently and would eliminate the need for repeated adjustments of present devices based on subjective patient response and on the "educated guesses" of the prosthetist. Movement measurement determinations with graphic representation of angular rotation, velocity, step length, and a variety of other measurements, will be carried out as well as force plates determinations of the floor reaction for both right and left extremities. Simultaneous electromyograms will be obtained to supplement movement measurements and force plate data recordings. Particular use will be made of force vectors derived from the floor reaction values to quickly and accurately permit alignment of the lower extremity prosthesis on the stump in a relationship that will be dynamically correct for the unique musculoskeletal problems of the involved patient and will achieve minimal energy expenditure because of this alignment.

5. <u>Determination of the Effect of Plantar Flexors of the Angle Upon Walking in Normal Human Subjects</u>.
   Ongoing project.

V. SAN FRANCISCO, CALIFORNIA

ADDRESS
Shriners Hospital for Crippled Children
1701 - 19th Avenue
San Francisco, California 94122

Director: Roger A. Mann, M.D.

Deputy: John L. Hagy

I. EQUIPMENT

Biomechanical.

Walkway: Details not available
Force plate
Foot switch
Accelerometer
Cine
Video

Physiological.

Oxygen consumption. EMG surface and indwelling electrodes. The equipment available in the gait analysis laboratory consists of four cine-motion picture cameras capable of 500 frames per second; a force platform; accelerometers; and electromyographic equipment.

II. PARAMETERS

Recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing, stance, velocity, gait width
Spatial Relations: Joints and body segments
Angular: In three planes - all joints except subtalar and toes
Forces: Angular Moments: In three planes - hip, knee, and ankle
Ground Reaction: Vertical AP and ML shear, center of pressure and torque

Physiological: EMG, nerve conduction, and energy cost

The parameters that can be studied on each individual walk cycle are as follows:

a) Angular Data

The angular data taken from cine-cameras are:

Pelvic Tilt
Hip Flexion-Extension
Knee Flexion-Extension
Plantar Flexion-Dorsiflexion
Pelvic Obliquity
Pelvic Rotation
Femoral Rotation
Hip Rotation
Tibial Rotation
Knee Joint Rotation
Hip Ab-adduction
Foot Rotation

San Francisco, cont.

b) Force Data

The forces available are taken from the quartz-crystal force plate and include:

Vertical Force	Torque
Fore-Aft Shear	Center of Pressure
Medial-Lateral Shear	

Processing: Sampling rate: 500/s
Experimental error: ± 2%
Time: 1.5 hours - 1 day

The processing equipment available is an 18-bit Electronic Processors, Incorporated Model 118 Computer System. This system includes two Diablo Disk Drives for storage; Read-Write Cassette Tape Recorders; Line Printer; and a 12-bit Analog to Digital Converter and Analog Plotter.

III. PHILOSOPHY

Any research that is conducted has to apply clinically to the individual patient. Each patient run through the laboratory for analysis first has a physical examination. EMG, force-plate and angular data are then gathered. Recommendations for surgery or treatment follow from data reduction. Clinical research has a major priority.

IV. PROJECTS

Those nearing completion are entitled "The popliteus muscle and its function in normal walking", "The initiation of gait" and "The role of the posterior calf muscle in normal walking". New projects are: "A complete study on the effects of jogging on the body" and "A study of 35 scoliosis patients in relation to their abnormalities in normal walking".

VI. SEATTLE, WASHINGTON

ADDRESS

Orthopaedic Biomechanics Laboratory
Seattle VA Hospital
4435 Beacon Avenue, South
Seattle, Washington 98108

Directors: F.G. Lippert, III, M.D.
G.S. Kirkpatrick, Ph.D.

Deputy: G.A. Spolek, M.S.

I. EQUIPMENT

Biomechanical.

Walkway: Instrumentation can be used in any location and is not confined to a specific walkway
Force plate
Miniature force transducers incorporated into shoe sole and heel
Strobe Cine

Microcomputer in laboratory, use of minicomputer and large computer facilities available; 16-channels of magnetic tape and 8-channels of paper recording equipment available; equipment for accelerometer studies; x-ray microradiograph equipment in laboratory; bone torsion testing equipment in laboratory; tension/compression testing equipment available; machine shop and electronics laboratory for assembling research equipment. Prosthetic research facilities at Eklund Hall and Veterans Administration Hospital which include walkways and interface pressure monitoring devices. Forceplate, treadmill, cinematographic motion analysis system located in Department of Physical Education.

II. PARAMETERS

Limbs recorded singly
Motions: Linear: Stride, cadence, swing, stance and gait width
  Spatial Relations: Joints
  Angular: Sagittal and coronal planes only - all joints except hip
Forces: Angular Moments: In three planes - all joints except hip
  Ground Reaction: Vertical, AP and ML shear, center of pressure
  Joints: Compression, tension, and shear in hip, knee and ankle, exclusive of synergistic muscle action
  Bones: Compression, tension and shear - all bones

Processing: Manual, Computer

Data can be processed in analog state or digitally
Time from collection to presentation of data: 1 day

III. PHILOSOPHY

This group is devoted to basic research into loading environments of the joints of the lower extremities, and the derivation of exact three-dimensional motion patterns between the bones of the joints.

IV. PROJECTS

1. Development of a portable shoe-mounted force-measuring device which measures floor reaction forces and three angles. A portable micro-computer system processes data to yield three forces and the torque acting on the tibia will be used with a cinematographic motion analysis system based in the University of Washington, Department of Physical Education, to calculate forces acting on all joints during gait. The system is expected to be operational in summer 1977.

2. Patellar tracking through x-ray photogrammetry. This precisely measures the three-dimensional motion of the femur, tibia and patella as the knee is flexed from 0° to 90°. The system uses stereo x-ray heads and analytical photogrammetry (University of Washington, Department of Civil Engineering). This information is needed to be able to understand the load distribution through joints during gait. It is currently operational.

VII. SEATTLE, WASHINGTON

ADDRESS

Department of Rehabilitation Medicine Research
CC 814 University Hospital
University of Washington
Seattle, Washington 98185

Director: Justus F. Lehmann, M.D.

Deputy: C. Gerald Warren

I. EQUIPMENT

Biomechanical.

Treadmill: No details given

Walkway: Total length 10 m

Run-in 4.25 m	Effective length 1.5 m	Run-out 4.25 m
Force plate	Foot switch	Accelerometer
Strobe	Cine	Video

Physiological.

Oxygen consumption   Dynamometer   EMG surface and indwelling electrodes

II. PARAMETERS

Both limbs recorded singly or simultaneously
Motions: Linear: Stride length, cadence, swing, stance, velocity, gait width
  Spatial Relations: Joints and body segments
  Angular: In three planes - all joints except toes
Forces: Angular Moments: In three planes for hip, knee, and ankle
  Ground Reaction: Vertical, AP and ML shear, center of pressure
  Joints: Compression, tension, and shear in knee and ankle
  Bones: Compression, tension and shear in femur, tibia, and fibula

Physiological: EMG, nerve conduction, and energy cost

Processing: Computer

Sampling rates: 200 Hz max.
Experimental error: 2% max.

VIII. VANCOUVER, CANADA

ADDRESS
Division of Orthopaedics
Faculty of Medicine
University of British Columbia
Vancouver, British Columbia
CANADA

RESOURCE ONLY. Mr. J. Foort
No gait laboratory facilities per se.

I. PHILOSOPHY

The philosophy of this resource group is that studies of a scientific nature have two aims: (a) to increase knowledge; and (b) to help solve clinical problems. Of these, our primary aim is to obtain information about gait on particular persons, so that we can formulate better treatment or aids for rehabilitation. A specific solution may be applicable to a group of people with similar disabilities. Thus, the thrust of gait studies can be said to be clinical and to relate to disabled people with lower limb deficiencies (but eventually other joints such as arms and spine). Also, we would be quite prepared to take data of a specific type and to forward it to a "mother laboratory" for interpretation to the end that the patient would benefit either by being classified in a way that would help in the selection of a solution to his problem, or learn directly what his disabling factors were.

II. PROJECTS

A goniometric study of knee function bilaterally, on elderly arthritic patients with and without knee implants, is underway. Also, we are doing normals as a base group to educate therapists. Effects of cane use on knee function is being studied, (Which is the best hand to hold it in for a particular disability - dominant hand, etc.). The effects of shoe wedging are being studied. How do changes on the abnormal side effect the normal? (Evidence is that the normal side is sometimes more affected by changes done on the abnormal side than appear on the abnormal.) Because our efforts are clinical in nature, they are ongoing, and will shift according to the patients for which goniometric studies are most appropriate. This should lead us to studying cerebral palsy people, amputees, etc. For our studies, we now rely heavily on engineers, but increasingly will depend on therapists. Eventually we expect to pull out completely and leave use of the equipment and system to the therapists, providing only services that they might need and interpretations.

AN OVERVIEW OF THE CURRENT STATUS OF EXISTING GAIT LABORATORIES

Morris Milner, Ph.D. P.Eng.

INTRODUCTION:

In the time allocated I hope to provide an overview of existing gait laboratories and incorporate a general review of present projects, methodologies and purposes, while recognizing the chief interests and directions of existing gait laboratories. Of necessity, this will have to be a limited presentation. Limitations will be those of the information at my disposal and the interpretations I inject. At the outset, I wish to express my appreciation to the various groups and individuals to whom I appealed for information and for their readiness in forwarding material.

CONCERNS OF GAIT LABORATORIES

Different gait laboratories have differing specific goals and objectives, usually arising out of specific interests of individuals, their backgrounds, constraints imposed by, or stimuli derived from the milieus in which they function and the resources they can muster. In an attempt to integrate all of known gait laboratory endeavor, overall concerns might be delineated as follows:

1. The study of normal locomotor function in all its facets including neural aspects, muscular activities, joint and limb motions and concomitant forces acting within and upon the subject, energy consumption and distribution, and times of contact with the walkpath surface. Statistical data to delineate "normality" are required and these must take cognizance of numerous factors such as speed of walking, anthropometric data, age, and repeatability of gait. Proper understanding of normal locomotion provides an effective backdrop for dealing with pathological, diagnostic, therapeutic and training aspects pertinent to gait.

2. The study of pathological conditions with a view to gaining complete understanding of their mechanisms on the one hand, and, on the other, the generation of pertinent follow-up data to mark the progress of a patient or subject.

3. The design, development and evaluation of rehabilitative aids and techniques, prostheses and orthoses to facilitate locomotor function in cases of impairment due to pathological conditions or circumstances arising from accidents.

4. The provision of guidance in regard to patient management where surgical intervention is suggested, and follow-up to confirm the efficacy or otherwise of procedures undertaken.

Milner cont.

5. To develop or inspire the development of equipment and techniques to enable efficient and effective gathering of pertinent data, its processing and presentation in suitably digestible forms for the end user to take the most appropriate action.

SETTINGS

Gait laboratories are to be found in various settings. These include University departments such as Physical Education, Kinesiology, Biomechanics and Anatomy. Other settings are within hospitals or clinics where patient services, usually of a rehabilitative character, are rendered. In some instances laboratories have the fortunate advantage of being located in settings where service, education and research are of approximately equal concern. This has the obvious potential advantages of mutual, beneficial interactions between these various segments and the promotion of the effective facets of usage of gait laboratories.

MULTIDISCIPLINARY ATTACK

Because of the challenging complexity of locomotor function in both normal and pathological states, and the possible variety of approaches to dealing with problems and issues arising in regard to descriptions of conditions encountered, consequent treatment and its efficacy, many disciplines have been attracted to the field. The disciplines include medical specialists drawn from physical medicine and orthopaedics, engineers, bioengineers, kinesiologists, anatomists, physical therapists, physicists, computer engineers and scientists. Thus many locomotion laboratories are able to launch multidisciplinary attacks upon the problems they must deal with.

GENERAL

In general, gait laboratories require substantial space and necessitate the incorporation of costly, sophisticated equipment. The space requirement is to ensure an adequate walkpath, to enable several steps of a steady-state walk to be achieved. A walkpath several meters in length is required to provide for suitable lead-in and run-off lengths. Where movement information is required in several planar views including overhead, underfoot, front, back and sides, a substantial space volume is necessary. Some space can be saved by resorting to special arrangements incorporating mirrors or by the use of treadmills. The latter are generally not favored for clinical studies largely because of the management of the patient who has to adapt to an additional machine component. Provision must be made for the incorporation of data lines which may be connected to the subject for the collection of signals such as footswitch contacts, electromyographic and electrogoniometric data. (These data might be telemetered). Data can be recorded (film, videotape, fm tape recorder) or taken to a data reduction center or, as is generally preferred, immediately submitted for direct analysis by a computer system. Recognizing the vast amounts of data involved with each locomotion run, the need for computational systems is underscored. This need is further emphasized when it is appreciated that for clinical purposes, rapid data processing and display are of great value. Incorporating such systems adds to the space requirement allied with locomotion laboratories. Most modern laboratories embody computer systems. Trained staff, drawn from a variety of disciplines, are required in the various aspects of measurement and recording of gait characteristics, interpretation of data and the delineation of future areas of pursuit. Where routine clinical studies follow from fundamental studies, stringent constraints are implied in terms of the maintenance of regular, efficient service. It is probable that the most significant gait studies will emerge from laboratories closely involved with clinical problems.

METHODOLOGIES

Some methodologies have already been alluded to; major methodologies are as follows:

1. Footswitches. Fitting footwear with switches to respond to contact times of the extremities with the walking surface, enables temporal information relevant to cadence, stance and swing times to be acquired and recorded. Several footswitches distributed underfoot facilitate a rendering of the time-space sequences which occur during the stance phase. Asymmetries between body sides and sequences of stance activity reveal valuable basic gait information. Some groups have developed special techniques to enable spatial data to be acquired regarding stride lengths and foot placement characteristics. There does not appear to be a universally used system.

2. Electrogoniometry. A number of groups are utilizing electrogoniometers to measure joint angle variations under dynamic conditions. Useful design concepts have emerged to deal with problems of self-alignment. This is important since joints are not simple hinge joints and their centers of rotation vary dynamically. Fixation is usually a problem and set-up is often time-consuming. Data can be transferred to a recorder by an "umbilical cord" or telemetry.

3. Kinematic Data. Whilst electrogoniometry constitutes one form of kinematic data derivation, the more general concerns are with trajectories of selected anatomical members and the velocities and accelerations (linear and rotational) of these members. Methods of data capture range from simple stroboscopic flash photography (or light interrupted photography) through cine-photography, video data capture and special optoelectronic devices. There is enormous tedium in having to extract data from still or cine-film on a frame-by-frame basis and while there are devices available to facilitate this process by generating the converted data immediately into computer compatible formats, technology has been moving rapidly towards making available special optoelectronic devices. These enable the direct conversion of movements of illuminated markers into electrical signals which can be entered into a computer system, undergo relevant processing and then be displayed appropriately. Patterns of movement are of concern in describing various pathologies.

4. Kinetic Data. Here investigators are concerned with measurements of ground reaction forces, joint reaction forces, torques, energy imparted by muscles to limbs and the like. The most widely used device is the force-plate, which enables measurements of ground-force reactions and the locations of

instantaneous centers of pressure. Coupling these data with simultaneously acquired kinematic information leads, by applied mathematical methods, other force variables such as joint reaction forces can be determined. Energy components can also be calculated. Accelerometers attached to limbs enable components of acceleration to be derived. Signal processing can lead to velocity and spatial information.

5. Electromyographic Activity. The use of surface and indwelling fine-wire electrodes, appropriately coupled to recording equipment, enables phasic activities of muscle groups to be determined. Programmatic sequences of muscular activity can thus be elucidated.

6. Energy Consumption. By determining oxygen uptake during the course of locomotion activity it is possible to gain insights regarding overall body energy needs.

COSTS

Exclusive of staffing and building construction, a laboratory which is to have up-to-date resources for performing locomotion studies would require capital expenditures approximately as follows:

Computer System with display and hard copy capabilities	$45,000
Optoelectronic Body Tracking System	$15,000
Multichannel electromyographic equipment, amplifiers etc.	$15,000
Force-plate system	$15,000
Total	$90,000

REGISTER OF GAIT LABORATORIES

Table 1 is an updated version of data reflected in a Preliminary Register of Gait Laboratories developed in 1975 by the Committee on Prosthetics Research and Development of the National Academy of Sciences. (Further work on this particular project is anticipated under the auspices of the Rehabilitation Services Administration). Since the original material was drawn up, some laboratories have augmented their capabilities, new ones have been developed and others have redeployed their resources, but most are at least maintaining their momentum. It should be noted that the laboratories are grouped by geographical areas and are listed from North to South.

Appendix 1 updates the earlier Committee on Prosthetics Research and Development information.

CURRENT PURSUITS OF VARIOUS LABORATORIES

The philosophies of a number of gait laboratories are presented in Appendix 1, together with an indication, wherever possible, of current projects being pursued. The activities of most of the groups are well-published and a number of the laboratories produce annual reports describing their activities.

CONCLUSION

Gait laboratories encompass human resources from a diversity of disciplines, physical resources which for rapid, effective data acquisition require much of what modern technology has to offer, and they require substantial space.

[illegible] these are generally costly resources to establish and maintain, they hould be nurtured with care in order to facilitate the realization of their ull potential in the area of clinical service which, ideally, should be olidly underpinned by appropriate research endeavor and effectively promulgated r meaningful educational thrusts.

Milner cont.

TABLE I.

SOME GAIT LABORATORIES AND PRINCIPAL PARAMETERS AVAILABLE WITHIN THEM

PRINCIPAL PARAMETERS AVAILABLE

	LOCATION OF GAIT LABORATORIES	SIMULTANEOUS RECORDING		LINEAR AND TEMPORAL	LINEAR FORCES				JOINTS			PHYSIOLOGICAL DATA			UPPER-LIMB DATA
		YES	NO		GROUND REACTION	SKELETAL IN BONES	SKELETAL IN JOINTS	IN MUSCLES	SPATIAL RELATIONS	ANGULAR MOTION	ANGULAR MOMENTS	E.M.G.	NEURAL CONDITION	ENERGY COST	
N. AMERICA WEST	Los Angeles - Rancho Los Amigos H.	X		X	X	X	X		X	X	X	X	X	X	
	Palo Alto - Children's Hospital at Stanford		X	X					X			X		X	
	San Diego - Children's Health Cent.	X		X	X		X	X	X	X	X	X			
	San Francisco - Shriners Hospital for Crippled Children	X		X	X				X	X	X	X	X	X	X
	San Francisco - UC Berkeley	X		X					X	X	X	X		X	
	Seattle - VA Hospital		X	X					X	X	X				
	Seattle - University of Washington	X		X	X	X	X		X	X	X	X	X	X	
	*Vancouver - University of B.C.									X					
NORTH AMERICA CENTRAL	Iowa City - University of Iowa (i)	X		X	X			X	X	X	X	X	X		X
	- University of Iowa (ii)			X					X	X	X	X		X	
	Houston - Texas Institute for Rehabilitation and Research	X		X					X			X	X		
	Rochester - Mayo Clinic	X		X	X	X	X	X	X	X	X				
	Saskatoon - Univ. of Saskatchewan	X		X					X	X		X			
	Winnipeg - Shriners Hospitals for Crippled Children	X		X	X	X	X		X	X		X			
	Milwaukee - VA Center	X		X	X			X	X	X	X	X			
N. AMERICA EAST	Atlanta - Emory University	X		X	X			X	X	X		X	X		
	Cleveland - Case Western U. (VA)	X		X	X	X	X	X	X	X	X	X	X		
	Hamilton - Chedoke Rehab. Centre	X		X				X	X	X		X	X	X	
	New York - VA Prosthetics Center	X		X	X	X	X	X	X	X	X	X		X	
	Philadelphia - Moss Rehab. Hospital	X		X	X				X	X	X	X	X		
	Waterloo - Waterloo University	X		X	X	X	X		X	X	X	X		X	
UNITED KINGDOM	Birmingham - University of Birm.	X		X	X										
	Glasgow - University of Strathclyde	X		X	X	X	X	X	X	X	X	X			X
	London - BRADU Roehampton	X		X	X				X	X	X	X			X
	+London - Medical Research Council	X		X	X			X	X	X		X			
	Manchester - University of Man.	X			X		X	X	X	X	X				
	Oxford - University of Oxford	X		X	X				X						

* Resource Group

\+ Redeployment of resources for purposes other than gait studies

APPENDIX 1

SOME GAIT LABORATORIES IN THE U.S.A., CANADA AND THE U.K.:

Their Physical Resources and Capabilities

Data made available as of February 28, 1977

Listed alphabetically by location.

NOTE: This material is an augmentation of data drawn from a Preliminary Register of Gait Laboratories, produced by the Committee on Prosthetics Research and Development, National Research Council, National Academy of Sciences, drafted in 1975.

NIH
GAIT RESEARCH
WORKSHOP

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Public Health Service   National Institutes of Health

GAIT RESEARCH WORKSHOP

Children's Hospital Health Center

San Diego, California

March 9, 1977

Chairman: Dr. John V. Basmajian

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PURPOSE OF WORKSHOP

The aim of this Workshop was to examine the current status of gait-locomotion research in man and other vertebrates. NIH applications in this area are reviewed by the Applied Physiology and Orthopedics Study Section and members have viewed the continuing proliferation of Gait Laboratories with some concern. Are all these expensive installations really necessary? Are they being used primarily as pre- and post-surgery diagnostic tools? How much sound and necessary research is being performed in these installations? What research problems have been solved with this tool? What remains to be solved? The range of concerns of the Workshop, therefore, extended from the theoretical concepts underlying the recording and analysis of gait patterns, to the potential application of these techniques to basic and clinical research and to direct applications in the clinical setting. It was hoped that the interaction of the panelists would produce a clear picture of the directions that the field is taking and would help to establish priorities regarding present and future needs. In addition to the members of the Applied Physiology and Orthopedics Study Section (NIH), ten authorities currently working in locomotion research were invited to participate. Papers were presented by six of these invited participants and these form the basis of this Proceedings. Condensed discussion is included to illustrate the trends of the interaction and the conclusions that the Workshop participants reached.

AGENDA

MORNING PROGRAM

1.	Dr. David Chadwick	Welcome on behalf of Children's Hospital
2.	Dr. Morris Milner	An Overview of the Current Status of Existing Gait Laboratories
3.	Dr. Sheldon Simon	Techniques in Gait Research and Management of Data
4.	Dr. David H. Sutherland	The Value of Normative Data in Gait Analysis
5.	Discussion	

AFTERNOON PROGRAM

6.	Dr. Jacquelin Perry	Clinical Use of Gait Analysis
7.	Dr. M. Patricia Murray	Normative Data Collection in Adults and Evaluation of Hip & Knee Prosthetic Replacements
8.	Dr. Edmund Y.S. Chao	Justification of Goniometric Method as a Means to Evaluate Joint Replacement Patients.
9.	Discussion and Summary	

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A Subcommittee of the Applied Physiology and Orthopedics Study Section made arrangements to hold this Workshop at San Diego in early 1977 and Dr. Wayne Akeson, University of California, San Diego, invited participants and served as Local Chairman. His careful consideration of details culminated in a most productive meeting and an opportunity for specialists in the gait field to exchange pertinent information. The Medical Director of Children's Hospital, Dr. David Chandler, and Dr. David Sutherland deserve thanks for the excellent meeting facilities that they provided at Children's Hospital. Dr. John Basmajian skillfully chaired the Workshop, elicating discussion on all major issues about which the Study Section had expressed concern. The six speakers spent a great deal of time preparing their excellent papers and re-editing them later for publication. Their research results and opinions form the framework of the Workshop. In particular perhaps, Dr. Morris Milner should receive commendation for conducting a questionnaire survey, in advance of the Workshop, to obtain up-to-date data regarding existing gait laboratories in the United State and abroad. This information is included in his Proceedings paper. Ms. Patricia Digges, DRG, NIH, is to be commended for her careful typing of the Workshop Proceedings.

Copies of the Proceedings may be obtained by writing to: Office of Grants Inquiries, Division of Research Grants, National Institutes of Health, Bethesda, Maryland 20014. Please quote the publication number that appears on the back cover.

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