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AN EXPERT SYSTEM FOR DIAGNOSING GAIT FOR CEREBRAL PALSY PATIENTS

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Preface

This report is an updated version of my thesis, which was submitted to the Department of Electrical Engineering and Computer Science at MIT on May 16, [illegible] for the degree of Master of Science. Since the thesis was written the therapy module of the program has been implemented. This report discusses the actual implementation. Thus sections 5.2.3 and 6.1.5 have been changed. In additon the system has been tested on a set of cases. The results are discussed in chapter 7.

Acknowledgements

No thesis is completed without the help and encouragement of all the people around you. I would like to thank my thesis supervisor, Peter Szolovits, for all his help during my research for this thesis. I am especially thankful for all those pep talks when everything seemed to be moving in the wrong direction. I would also like to thank all the present and past members of the Clinical Decision Making Group for giving me such a wonderful environment to work in. I appreciate all the help the workers, physical therapists and doctors at The Gait Analysis Laboratory provided in my quest to understand gait analysis. Jim Dzierzanowski was very helpful in getting me started and in setting up the GENIE system on the computer at the Gait Analysis Lab. A special thank you goes to Dr. Sheldon Simon of The Gait Analysis Lab. Our numerous meetings which often continued late into the night provided me with the necessary understanding of gait and gait analysis in order for this research to succeed. Everyone would be better off if we could all have Dr. Simon's enthusiasm, dedication and understanding. I would also like to thank Rosemary Hegg for editing the final version of this report. With the realization that life is not all work, I must thank Dennis Fogg who on numerous occasions forced me to take some time off from working to go out and enjoy what Boston has to offer.

This report describes research performed at the Laboratory for Computer Science of the Massachusetts Institute of Technology and at the Gait Analysis Laboratory at Children's Hospital in Boston. Support for this research has been provided in part by the National Institute for Handicap Research of the Department of Education under contract G008300074 and also in part by the National Institutes of Health Grant No. R24 RR01320 from the Division of Research Resources. A special word of thanks is also due to Professor Randy Davis for the use of the computer facilities supported by a grant from Digital Equipment Corporation.

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by

David Edward Hirsch

Submitted to the
Department of Electrical Engineering and Computer Science
on May 16, 1986 in partial fulfillment of the requirements
for the Degree of Master of Science

Abstract

Many first generation expert systems in medicine assumed that a single fault was the cause of the patient's problems. However, this is not always so and in the domain of gait analysis this is usually ***not*** the case. This work looks at an expert system for performing gait analysis on cerebral palsy patients. The system is able to handle cases where there are many interacting faults causing the patient's gait deviations. A qualitative-torque model of gait is used as a framework for analyzing the patient's disorders. This model allows the effects of individual faults to be examined and also explicitly captures the interaction between various faults. The incorporation of this model into an expert system leads to a more complete and robust expert system for gait analysis than any existing previously.

The qualitative-torque model of gait models gait by using torque equations represented as incremental qualitative (IQ) algebra equations. Because everything is not known about the torques, the system has to make assumptions to arrive at some values. These assumptions are kept consistent by using an assumption-based truth maintenance system. The only part of the model specific to cerebral palsy is the set of heuristics used to score competing assumptions. Thus, the gait model developed for this system could easily be adapted for use in an expert system diagnosing gait disorders of any given etiology.

Thesis Supervisor: Dr. Peter Szolovits
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Computer Science

1. Introduction

The field of Artificial Intelligence (AI) has grown over the past decade from relative obscurity to prominence in the world of business. Although this growth in attention has been accompanied by the creation of new ideas and techniques, the art[1] of building AI programs is still a difficult task. There are two paths which lead to advances in this field. One path is that of the continuing invention of new techniques which can solve previously unsolvable problems. The other is the application of existing techniques which help the researchers better understand and further refine these techniques. The work presented in this thesis follows the second path.

This thesis examines the design and implementation of a knowledge based system, Dr. Gait, which interprets measurements of a cerebral palsy patient's gait pattern. The program, Dr. Gait, is given joint motion data, EMG data, force plate data and physical exam data which it interprets to find the underlying deviations in the patient's gait pattern, their causes and possible therapies.

First, a prototype system, Dr. Gait-1, was built. This system tries to emulate the reasoning of the expert physicians. It takes a very simple approach to gait analysis and was built in order to better understand what a gait analysis program has to do. The prototype uses empirical associations represented as production rules as well as domain specific knowledge stored in frames to arrive at its conclusions.

Based on what was learned from the prototype system, a final system, Dr. Gait-2, was built. This system is based on causal reasoning. The causal knowledge is stored in incremental qualitative algebra (IQ) equations. The values constrained by the IQ equations are kept consistent by means of an assumption based truth-maintenance system. In addition, Dr. Gait-2 uses frames, rule bases and discrimination trees to store other domain knowledge.

We will see that the naive approach taken by the prototype system, Dr. Gait-1, has several

[1] The field is still to young to be accurately called a science.

problems. The system does not give enough attention to the muscles, which have an important effect on a person's gait. It has only limited abstraction abilities and in addition, it makes many implicit assumptions which may lead it to incorrect conclusions in abnormal cases. The final system, Dr. Gait-2, corrects many of these problems by having a qualitative model of gait. The model gives the system a framework in which to organize the problems and a means to study the interactions between problems. The result is a system which can successfully handle more cases, can be expanded to handle other disorders, and can express its conclusions in terms of the mechanisms of gait.

1.1 History

1.1.1 Artificial Intelligence in Medicine

It has long been recognized that computers could be put to beneficial use in the medical field. However, computers were used initially only for administrative tasks such as scheduling hospital admissions, controlling medical laboratories and maintaining patient records. As Schwartz noted in 1970,

> The computer thus remains (in the light of conventional projections) as an adjunct to the present [health care] system, serving a palliative function, but not really solving the major problems of that system.[2]

The use of the computer only as an administrative tool did not address the more important issues of the shortage and uneven geographical distribution of physicians and the difficulty they encountered in retaining and fully utilizing the rapidly expanding medical knowledge. However, Gorry envisioned another role for the computer in the medical domain:

> One intriguing possibility is to use the computer as an "intelligent" or "deductive" instrument - a consultant that is built into the very structure of the health care system ...[3].

In the early 1970's several medical computing groups began searching for potential solutions to the problems described. The emerging field of Artificial Intelligence seemed to be a good place

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[2] Schwartz, W.B. "Medicine and the Computer: The Promise and Problems of Change," *New England Journal of Medicine* 283:1257-1264,1970.

[3] Gorry, G. Anthony, "Computer-Assisted Decision Making", Readings in Medical Artificial Intelligence, Clancey and Shortliffe, eds., Addison-Wesley, Reading, MA, 1984.

to start doing this. This led to the development of the "first generation" Artificial Intelligence in Medicine (AIM) systems. The foundation for the AIM field was laid by such programs as the Present Illness Program (PIP) [Pauker 76] which determines the present illness of a patient, CASNET [Weiss 78] which evaluates and prescribes treatment for glaucoma patients, MYCIN [Shortliffe 76] which recommends treatment for patients with infectious blood diseases and Internist [Miller 82] which recommends treatment for patients with problems in internal medicine. These programs not only demonstrated that creating such expert systems was feasible but also led to some early insights into knowledge representations (e.g. PIP - disease prototype frames, MYCIN - production rules, CASNET - causal networks) and reasoning strategies (e.g. INTERNIST - partitioning heuristic, MYCIN - goal driven recursive control).

Even though these systems were impressive programs demonstrating the benefits of using AI techniques in the field of medicine, their use revealed many more problems still needing to be addressed relating to such matters as dealing with multiple disorders, representing deeper causal knowledge, the better representation of anatomical and physiological medical knowledge, and achieving more explicit control. Certain second generation AIM programs such as ABEL (dealing with multiple disorders and deeper causal knowledge) [Patil 81] and NEOMYCIN (dealing with more explicit control knowledge) [Clancey 81] have begun to examine these issues.

1.1.2 Examples of Past Medical Data Interpretation Programs

Most AIM programs perform diagnosis and make therapy recommendations for their particular area of expertise. Based on different reasoning strategies these programs ask for various kinds of information (e.g. Is symptom X present?, What was the result of test Y?, Has the patient been exposed to A?...). The questions asked and the order in which they appear depend on the particular case that the program is examining. The program then uses this information to discover the underlying disorder and recommend treatment. However, a few AIM programs have had a slightly different orientation (although they can still be viewed in the above framework). These programs performed more of a data interpretation task; they had to interpret a *fixed* set of data representing such things as standard test results, routine patient history information or information from a monitoring device. This subclass of programs includes PUFF [Aikens 83] and VM [Fagan 80].

1.1.2.1 PUFF

In the late 1970's, Janice Aikens of Stanford University collaborated with doctors from the Pacific Medical Center (PMC) in San Francisco to develop an expert system, PUFF [Aikens 83], to interpret pulmonary function test results. Using the EMYCIN [vanMelle 80] environment, which is based upon MYCIN [Shortliffe 76], they constructed a system with production rules. The program is given lab results that can measure the volume of the lungs, the ability of the patient to move air into and out of his lungs and the ability of the lungs to get oxygen into the blood and carbon dioxide out. With each of these measurements PUFF calculates a percentage of the predicted value. Then an interpretation of the data and a final diagnosis are provided.

There are several things to note about PUFF. First, the domain of pulmonary function interpretation is reasonably complex but not overly so since it does not require temporal reasoning or complex interactions. Second, PUFF is one of the very few expert systems to be used in a clinical setting on a regular basis.

1.1.2.2 VM

Larry Fagan, in a collaborative research effort between Stanford University and the Pacific Medical Center in San Francisco, developed an expert system called VM [Fagan 80]. The VM program interprets data from the intensive care unit in order to aid in the management of postoperative patients on mechanical ventilators. Like PUFF, VM's design was heavily influenced by the MYCIN architecture. However, the domain requires descriptions of events that *change over time*. VM is able to do temporal reasoning by providing a mechanism for accessing and evaluating data in each new time frame. Each parameter's value has a time interval associated with it to indicate when this value is pertinent. VM also has a symbolic model to represent the ongoing processes and transitions that a patient experiences from intensive care unit admission to the end of the critical monitoring phase. The stage the patient is in determines acceptable ranges for the parameters and expectations for future values.

The Dr. Gait program is also a data interpretation program like PUFF and VM. The program does not hold an interactive dialog with the physician but instead receives a *fixed* set of data and patient history (e.g. past surgeries, treatments, initial diagnoses, etc.) which it then must interpret, in the same way as PUFF, in order to determine the underlying causes of the deviations noted in the data. This program, like VM, has to deal with data that is interrelated temporally. Unlike PUFF and VM, it has to consider multiple problems and their interactions.

1.1.3 Examples of Past Gait Analysis Programs

Most of the research done on the analysis of gait is either statistical in nature [Wong 83] or concentrates on the functionality of a particular joint or muscle group [Simon 78]. There has not been a good attempt to formalize a method of gait analysis. Most of the computer systems have tried to model gait using mathematical means [Winarski 74]; these models help one understand gait better but do not help analyze the data. However, there have been two attempts to write gait analysis programs using artificial intelligence techniques. Below, we will first look at a system developed at Stanford University in the mid-1970's and then at another system developed at Vanderbilt University in the early-1980's.

1.1.3.1 Stanford's Gait Diagnosis Program

In the mid-1970's several researchers at Stanford University developed an expert system to help diagnose gait disorders [Tracy 79]. The program gathers information about the patient's gait deviations from the user. Once the program decides which known deviations stored in its data base match the described situation, it tries to determine possible muscle weaknesses and tightnesses. This diagnosis is done in one of three ways. Mode one, infer, attempts to diagnose the muscle conditions without asking for any further information from the user. In mode two, diagnose, proceeding anatomically from the trunk down to the ankle, the program considers the condition of each muscle, and the user may enter new information as necessary. Finally, mode three, menu diagnose, allows the user to specify which muscles should be examined and in which order. Again the user can enter new information to the system as needed.

The system is composed of a knowledge base of 345 MYCIN-like production rules. There are three types of rules: description of deviations, muscle weakness/tightness and negative. Description of deviation rules define technical descriptive terms by associating them with a set of positional and dynamic descriptors. Muscle weakness/tightness rules relate deviations with muscle weaknesses and tightnesses. Negative rules are used as heuristic rules of thumb to help guide the program in its reasoning. These negative rules inform the program that certain conditions are mutually exclusive or that some deviations are necessary for a particular muscle weakness or tightness.

The program uses these rules in a MYCIN-like fashion of backward chaining. Even though the rules and control mechanism are MYCIN-like, the MYCIN formulation was not perfectly suited for the gait analysis domain. There are a few problems with using MYCIN that had to be corrected.

MYCIN had no provisions for time sequencing of symptoms which is needed to deal with the different phases of gait. Second, in the MYCIN framework it is difficult to direct the program to diagnose a deviation in an organized manner, such as an anatomical or a sequential manner. Unfortunately the researchers didn't elaborate on how these deficiencies were corrected. Later we will see how Dr. Gait dealt with these difficulties.

The gait analysis program at Stanford was a good first attempt at developing an expert system for gait analysis. It not only showed that such a system was feasible, but also elucidated issues (e.g. time and more organized control) important to a successful gait analysis program. However, there are still several things that need improvement. For example, instead of identifying disorders from the gait data, the program analyzes disorders fed in by the user. Also, although there are other possible causes such as joint contractures and muscle spasticities, the program only considers muscle tightnesses and weaknesses. In addition, it does not relate these problems back to the original deviations nor does it recommend therapies to alleviate the deviations.

1.1.3.2 GAITSPERT

In the early 1980's at Vanderbilt University, Jim Dzierzanowski and other biomedical engineers built an expert system called GAITSPERT [Dzierzanowski 84]. GAITSPERT is an attempt to link signal acquisition and analysis techniques to artificial intelligence systems. GAITSPERT reports deviations from normal gait patterns, traces temporal trends in individual patients, examines synergy patterns,[4] and produces therapy recommendations and prognostics. GAITSPERT was built using the GENIE[5] [Sandell 84] knowledge engineering tool which combines frames and rule bases. It has several large frames to store static knowledge and eleven rule bases which are used to verify and identify synergies, to check for the patient's ability to perform therapies, and to recommend therapies.

GAITSPERT first asks the user questions to identify high level synergies. Then by asking the appropriate questions it tries to better classify the problem into lower level synergies. This reasoning process works well enough but is confusing to the physical therapists using the system who are accustomed to the opposite mode of reasoning. They start with the low level manifestations in a patient and build up to higher level synergies. It is thus apparent that there is a need for an interactive system to reason in a similar manner to the user so that the user has a clearer understanding of what the system is doing.

After identifying the lower level synergies the program uses the therapy rule bases to recommend therapies. In recommending therapies the program takes into account the patient's ability to perform the desired therapy. GAITSPERT also mentions any side effects that the therapies might have.

Some of the problems that the Stanford people encountered with the MYCIN-like system also had to be dealt with by the people at Vanderbilt. GAITSPERT deals with time by using generic rules which can be applied to a certain class of gait phases. Agendas, semi-procedural steps that

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[4]A synergy is high level concept which groups together and explains a set of lower level observations.

[5]Dr. Gait also used this system so it will be explained in more detail later.

tell the program what to do next, are used to control the program. They give GAITSPERT more explicit organization of control over the system.

Thus, by looking at Stanford's gait analysis program and Vanderbilt's GAITSPERT, we see that the domain of gait analysis is amenable to solutions through expert system technology. However there is still much that needs to be done to make a more robust useful system. The Dr. Gait program is an additional step in this direction.

The Dr. Gait program is a step forward for several reasons. First, it deals with gait disorders of a different etiology, CP-neurological, whereas Stanford's program dealt with orthopedic and GAITSPERT with stroke related disorders. Thus it not only adds more breadth to the attempt to build expert systems for gait analysis, but also concerns itself with more complex problems. Second, Dr. Gait-2 explicitly deals with multiple problems which interact and third, gathers most of its information directly from the data gathered by the gait monitoring system. Thus, it has more complete data about a patient's gait.

We will see that the Dr. Gait program has to tackle many of the same problems as did Stanford's Gait Analysis program and GAITSPERT. Dr. Gait deals with time much like GAITSPERT by using generic rules that can apply only to a certain class of phases of the gait cycle. It also attaches time tags to values of parameters which change over the gait cycle. The issue of more precise control is resolved by using a top-level procedure to control the processing rather than the general backward chaining scheme of MYCIN.

1.2 Approach Taken in Designing Dr. Gait

The goal of this research is the development of an expert system which, when given the same data as the doctors at the Gait Analysis Lab at Children's Hospital, will produce an analysis comparable to that of the physical therapists and doctors. Thus, what data the program should receive is fixed by the practice of those physicians. We want to address the questions of how this data can be best represented for the expert system and how to analyze this data.

We desire the expert system to analyze gait in the same spirit that the human experts. Why? Because in this way one can both gather knowledge and explain the program's behavior. Dr. Gait-1 only has empirical associations which draw conclusions directly from observable features. However, the doctors have a deeper knowledge of gait than this. They understand the mechanisms of gait. For example, they understand that a spastic hamstring will contribute to increased knee flexion. We want the system to have the same understanding. This implies a need for a deeper model of the gait process. Such a model is incorporated in Dr. Gait-2. Past models of gait have been quantitative in nature. While a quantitative model could perform the necessary modeling, it is not the ideal solution. A proper qualitative model has advantages over a quantitative model for several reasons. (1) Numerical simulation provides a large amount of information but is limited in its capacity to explain. Furthermore, the doctors reason with the data qualitatively. Instead of saying that the spasticity of the hamstring causes the hamstring torque to increase by 13 Newton meters, which in turn causes the knee flexion to increase to 40 degrees, a doctor would say that increased hamstring spasticity is causing the increased knee flexion. (2) Qualitative reasoning may be useful for constraining the number of equations which need to be solved. (3) A qualitative model will be faster than a quantitative model. (4) A qualitative model lacks quantization but it has the necessary information to predict significant characteristics. (5) A qualitative model explains its results in a more efficient manner since the unnecessary details are already abstracted away [Rajagopalan 84]. Taking these reasons into account, we decided that a qualitative model was a better fit for our domain. In short, the doctors reason qualitatively so we want the system to do the same.

1.3 A Roadmap through the Thesis

The rest of the thesis examines the task of gait analysis and the methods used in the Dr. Gait program. First, we will look at the domain of human gait and gait analysis to gain a better understanding of what gait is, the scientific terms used to describe gait, and how gait analysis is carried out. The next chapter explains where a gait analysis program fits into the gait analysis process. The inputs and outputs of the program will also be specified. Next we will look at the prototype system and an example which illustrates the shortcomings of the naive approach. By examining these shortcomings we will discover some characteristics that a good gait analysis program should have. We will then examine the final system, Dr. Gait-2, which incorporates these necessary characteristics. In looking at Dr. Gait-2 we will see that its qualitative model solves most of the deficiencies of the earlier system. Finally, we will conclude with what has been accomplished and suggestions for future research.

2. A Primer on Human Gait and Gait Analysis

In this chapter we will first examine human gait. In so doing, we will be able to distinguish and better understand the important characteristics of a person's walking motion. Interested readers might want to look at Inman's book [Inman 81] for a more in depth discussion of human walking. After examining gait we will then go over some of the details of gait analysis. We will discover how the different forms of data are gathered and how they are then presented to the attending physician. All this will give the reader sufficient background to understand the matters with which the program, Dr. Gait., is concerned.

2.1 Human Gait

Everyone faces the problem of how to get from one place to another. Furthermore, each of us would like to do this with minimum effort, adequate stability and acceptable appearance. Each person's unique solution to this problem represents his gait (walking) pattern. Remarkably enough, most of us learn to walk with reasonable facility and surprising efficiency.

2.1.1 Gait Cycle

Usually, when talking of gait, one thinks of a cyclic movement of body parts which is repeated over and over again, step after step. A basic assumption is that this cyclic pattern is the same from cycle to cycle. While this is not always true, it is a good approximation. Thus, most analyses and descriptions of gait deal with what happens over one gait cycle.

A *gait cycle* consists of the time between two consecutive heel strikes of the same foot.[6] The distance between these heel strikes constitutes the person's stride length. The gait cycle can also be divided into phases which are determined by significant events. We will use the following significant events to determine our phases:

1. *Right Heel Strike* (RHS) - When the heel of the right foot first touches the ground.

[6] In this thesis we will always consider a gait cycle as going from ***right*** heel strike to ***right*** heel strike.

2. *Left Toe Off* (LTO) - When the toes on the left foot have their last contact with the ground.

3. *Left Heel Strike* (LHS) - When the heel of the left foot first touches the ground.

4. *Right Toe Off* (RTO) - When the toes on the right foot have their last contact with the ground.

Using these significant events to divide the gait cycle we get the following phases:[7]

1. ***Weight Acceptance*** (WA) From RHS to LTO, 0 to 16% of gait cycle. During this phase the body weight is being transferred from the left leg to the right leg. Since the body is being supported by both legs during this phase it is also called double limb support.

2. ***Single Limb Stance*** (SLS) From LTO to LHS, 16-50% of gait cycle. During this phase the body is only being supported by the right leg. As the body raises itself up and over the right leg, the left leg is being swung forward.

3. ***Weight Release*** (WR) From LHS to RTO, 50-66% of the gait cycle. During this phase the body weight is being transferred back to the left leg. Again this phase is also called double limb support since the body is being supported by both legs.

4. ***Swing*** (swing) From RTO-RHS, 66-100% of the gait cycle. During this phase the right leg is free to swing forward. While the right leg is swinging forward the body is being supported by the left leg.

Figure 2-1 shows these different phases of the gait cycle.

2.1.2 Components of Gait

Now that we have definitions for a gait cycle and its different phases we have some idea of how to break up a person's walking motion in order to examine it. However, we must still ask what factors determine the form of a person's gait. A person's gait pattern is the result of several torques acting upon the body. There are internal torques which are produced by the muscles pulling on the limb segments. Then there are external torques caused by gravity acting upon the body mass, momentum and counteraction of the floor's reaction force. The result of all these torques is the particular motions of the different joints.

Even though trunk movement and arm swing play an important role in walking, we can

[7] These phases are from the point of view of the *right* leg.

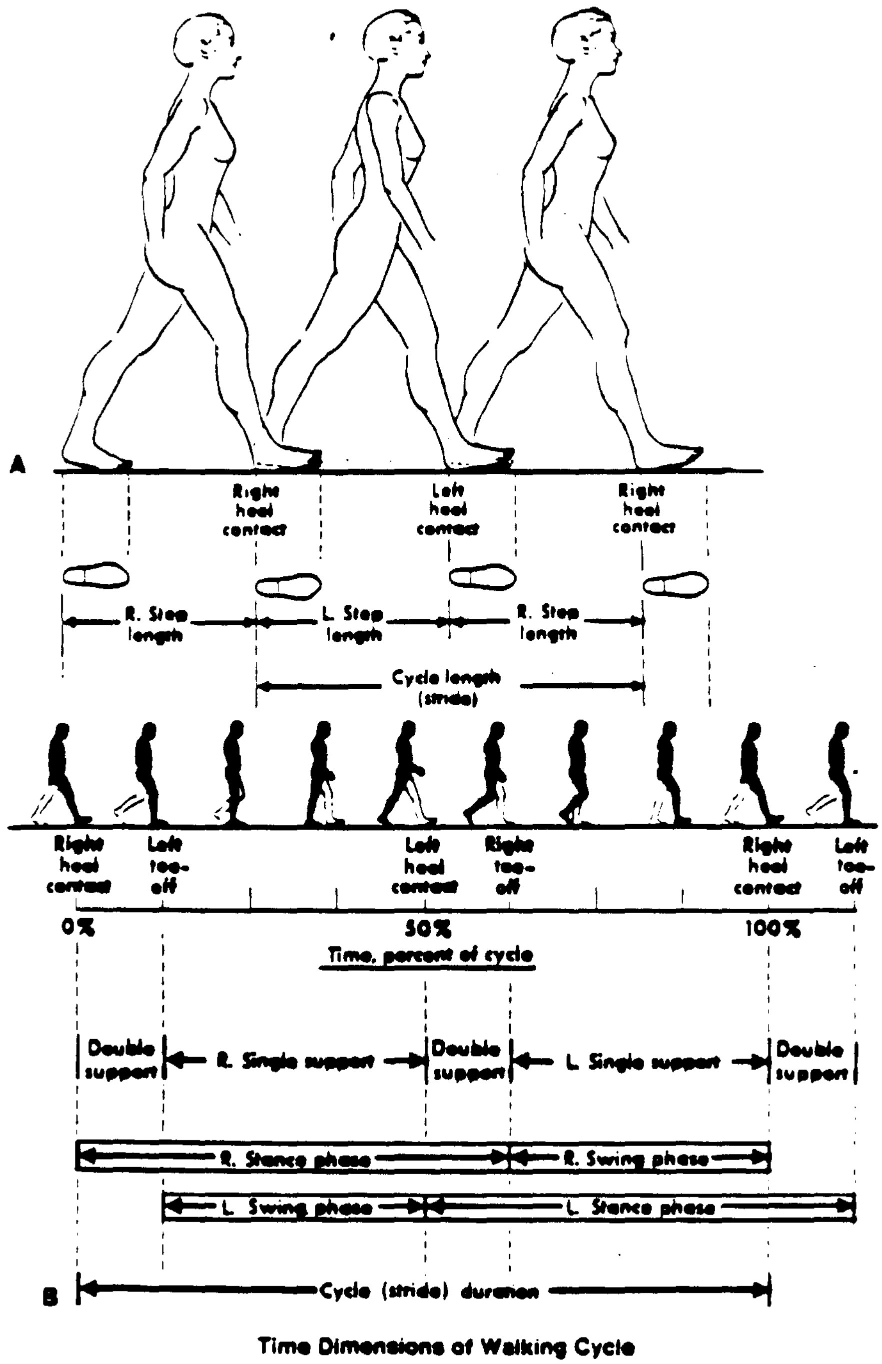


Figure 2-1: Gait Cycle
(Reprinted from page 26 of [Inman 81] with permission of the publisher)

understand much about human gait by looking only at the lower extremities. Thus, to examine gait, we look at the joints and muscles in the legs. The three joints of concern in each leg are the hip, knee and ankle. The three dimensional motion of each of these joints can be broken into projections onto three orthogonal planes. These three planes are named coronal, transverse and sagittal. See figure 2-2 for an illustration of these planes. The motions of the joints in these planes have names such as flexion, extension, adduction, internal rotation, etc. See figure 2-3 for illustrations which define each of the motion terms.

The muscles with which will be concerned all act upon the legs. We will take the simplistic view that when a muscle is on, it shortens and thus pulls on the joint in the corresponding direction (or else is opposing a torque in the opposite direction). When a muscle is off, it is at rest. Thus, an inactive muscle does not pull on the joint or resist pulls that oppose it. Appendix A gives a list of all the muscles we are concerned with and what actions they each perform.

2.1.3 Gait Disorders

A gait disorder is any abnormality in a person's gait pattern. An abnormality could be the improper positioning of a limb or improper activity of a muscle. These abnormalities hinder a person's gait and thus make it more difficult for him to walk.

A gait disorder can either be temporary or chronic. A temporary gait disorder usually results from an accident or an acute illness. These disorders are usually alleviated through the passage of time as the body heals itself. Sometimes physical therapy is needed to help in rehabilitation. Chronic gait disorders usually occur because of a chronic condition such as cerebral palsy, or arthritis, or a stroke. Chronic gait disorders are usually more serious and are more difficult to treat.

There are three types of gait disorders: muscular problems such as muscle weakness or tightness, joint problems such as tight or inflamed joint capsules, and neurological problems (which are the most difficult). A patient with a neurological disorder is not able to activate his muscles or therefore control movements of his limbs. This leads to poor gait which is difficult to

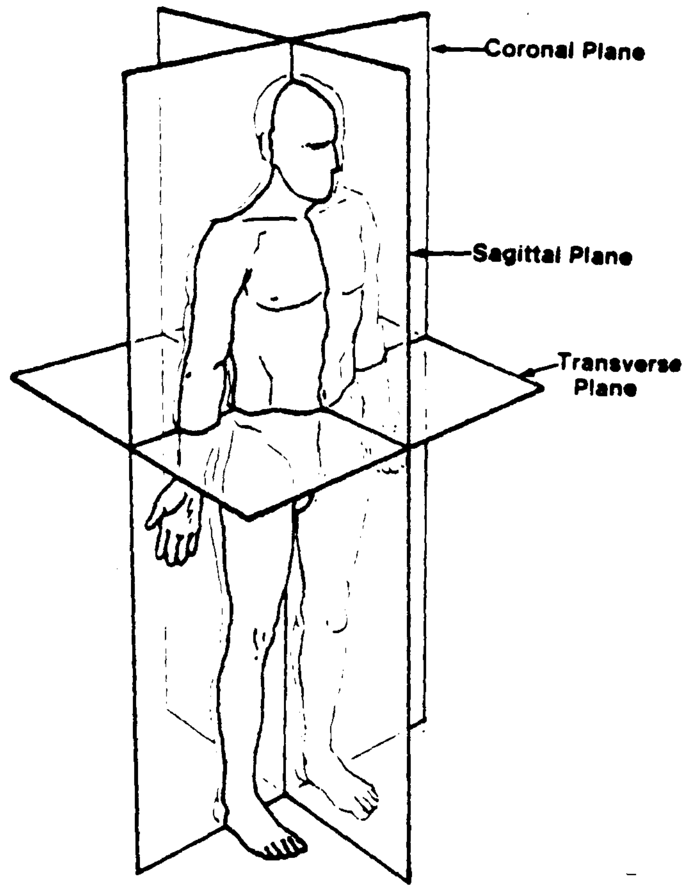


Figure 2-2: Three Orthogonal Planes for Gait Motion
(Reprinted from page 34 of [Inman 81] with permission of the publisher)

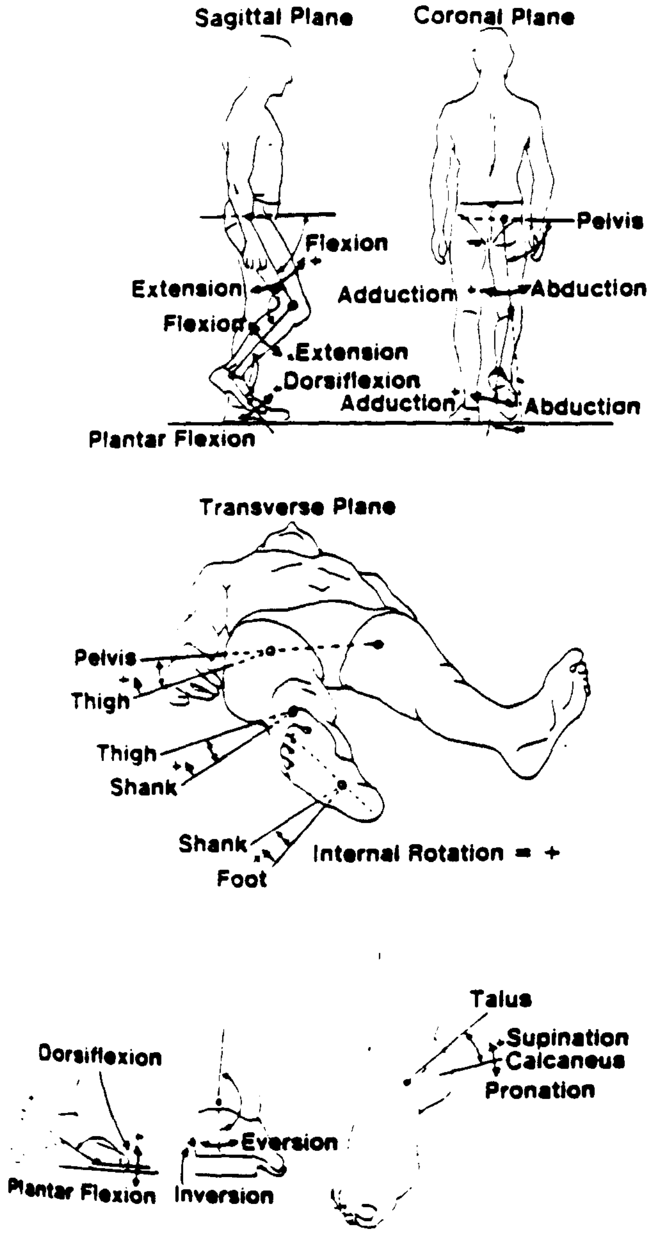


Figure 2-3: Motions of Gait
(Reprinted from page 35 of [Inman 81] with permission of the publisher)

treat beacause it cannot be treated directly. One must treat the manifestations of the control disorder instead of treating the control problem itself.

2.1.4 Treatments of Gait Disorders

Physical therapy, bracing and surgery are the three ways to treat gait disorders. It is used for minor problems. Physical therapy could include stretching to loosen up tight muscles or exercises to strengthen weak muscles. For more severe problems there is a choice between bracing and surgery. Bracing is used either to restrict the range of motion of a joint or else to keep the joint in a fixed position. For example, if the patient has a dropped foot in the swing phase, an ankle brace could be used to keep the ankle in the neutral position (90 degrees) and thus prevent the dropped foot in swing.

The most severe treatment is surgery. The types of surgery available are numerous. Most of them involve changing the muscles. There is muscle lengthening used to offset the affect of overactive muscles, muscle shortening used to counteract weak muscles, and muscle transfer used to change how the muscle effects the joint.

2.2 Gait Analysis

2.2.1 History

For many years there has been a need to help people with gait disorders and thus a need for gait analysis in order to know how to better correct their disorders. However, until recently the analysis of gait was done mainly by casual observation. The doctor would watch the patient walk by several times and then make an educated guess as to how to correct any observed problems. This led to problems, in that doctors were unable to make accurate and complete diagnoses of the gait disorders. Furthermore, doctors could not be sure if the treatments they prescribed would improve the patient's gait. Many times a treatment would help one deviation, which the doctor had observed, but in doing so would aggravate another problem that the doctor had missed. The outcome of all of this was that some patient's were no better off than before, even after six or seven surgeries.

2.2.2 Current Gait Analysis Techniques

Over the last several years half of the problem has been solved. Now there are monitoring systems which can gather data about a patient's gait. For example at the Gait Analysis Laboratory at Children's Hospital in Boston,

> ...a patient's gait pattern is monitored with the simultaneous measurements obtained of the motions of all four limb segments and trunk with three 16mm high speed cameras, the motor activity of the major muscle groups in the lower extremities with EMG electrodes and foot floor reaction forces generated by means of a force plate.[8]

All this data is sent to a computer where it is stored so that it can later be processed to yield useful information about a patient's gait.

By placing special anatomical markers at key points on the body, these points can then be traced on the film. After the film is digitized, frame by frame, various calculations can be made regarding a patient's gait. Such parameters as limb segment positions, shown as stick figures, and joint angles for each joint in each of the three planes, shown as flexion/extension graphs, are calculated. See figures 2-4 and 2-5 for examples of stick figures and flexion/extension graphs. In addition, from the film various parameters such as velocity, stride length, step width and the time spent in each phase can be calculated.

The electromyogram (EMG) electrodes gather a record of the muscle motor activity. After performing much complex filtering of this data to eradicate the noise, a graph of the motor activity for each monitored muscle is obtained. See figure 2-6 for an example of EMG data.

The force plates provide data on the foot-floor reaction forces, whose magnitude and direction as a function of time can be calculated. The calculated forces are shown as vectors superimposed on the stick figures. See figure 2-4.

Currently the attending physician looks over all these graphs and parameters, in addition to taking into account the patient's past medical history to document the patient's gait deviations, determine the cause of the deviations and recommend treatment. Doctors now have more

[8] From a Gait Analysis Report, The Gait Analysis Lab, Children's Hospital, Boston, MA

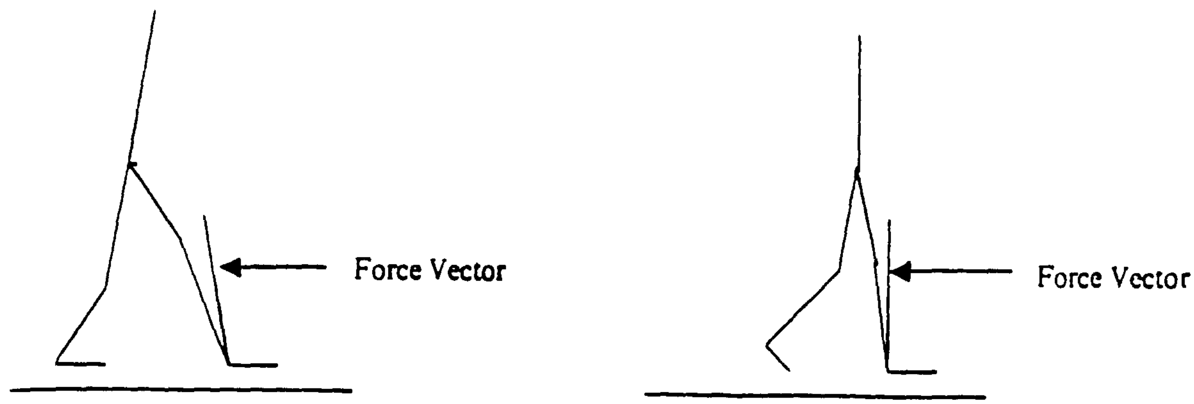


Figure 2-4: Stick Figures and Force Vectors

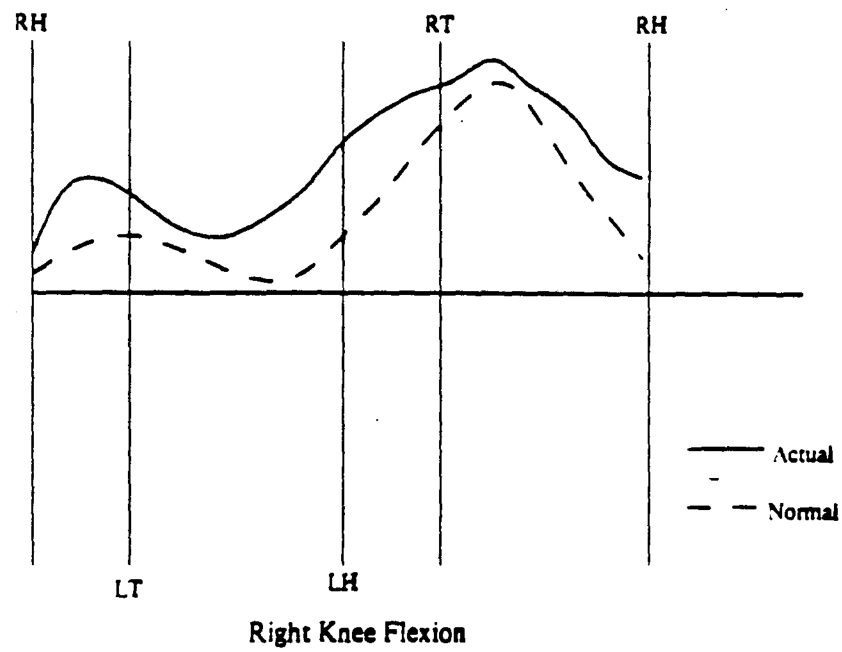


Figure 2-5: Flexion/Extension Graph

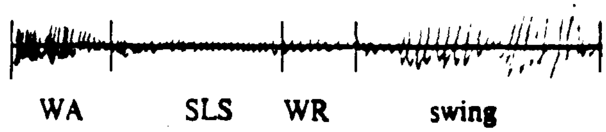


Figure 2-6: EMG Data

complete data to use in their decisions than in the past when only subjective observations were available. However, they are faced with the task of sifting through a large amount of interrelated data in order to diagnose and treat patients. This implies that if a computer system could be written to screen this data and start fitting the pieces together, it would make life much easier for the attending doctor. Dr. Gait is such a program.

3. Dr. Gait's Task

This chapter explains the specifications of the Dr. Gait system. First, we will see where Dr. Gait fits into the gait analysis process. This will give us a good idea of what Dr. Gait has to do. Next we will look at the data given to Dr. Gait. We will then explain the three tasks that Dr. Gait must accomplish. Finally, the goal we are trying to achieve by building this system will be stated and criteria listed to use in checking to see if the final system reaches the desired goal.

3.1 How the Dr. Gait System Will be Used

To understand how and when Dr. Gait will be used we need to look at the steps currently taken in a gait analysis of a patient. Current analysis takes the following steps:

1. *Data is gathered* using a gait recording system and is stored in the computer.

2. The film of a patient walking is *digitized* frame by frame to give the computer more information about the patient's gait.

3. All the data in the computer is *processed* by various programs to produce the graphs and figures discussed in section 2.2.2.

4. The graphs and figures are *examined and analyzed* by the doctors and physical therapists who then write up a gait analysis report.

The most difficult part of this process is the last step where the doctors and therapists have to look at vast amounts of data and then draw some conclusions. The intention is to add an additional step between steps three and four in which the data is also passed to the Dr. Gait program. The Dr. Gait program would produce a preliminary gait analysis report. The doctors and therapists in step four would then not only have the graphs and figures but also a preliminary report to work with. This should make it much easier to produce the final gait report.

One thing that is important to note is that there should be no need for the doctors to interact with Dr. Gait. Dr. Gait gathers its data directly from the computer. This eliminates the need for complex human interfaces and worries about the speed of operation. The goal is to have the program run automatically when each gait study is processed without any need for human interaction, but this has not been fully achieved. Currently, although much of the data is gathered directly from the computer, some of the data still must be input by the user. The input specifications in the next section tell which data currently comes from the computer and which from the user. After more patient data is put on line it should be possible to write additional interfaces to gather the rest of the data directly.

Taking all of this into account the new way to perform a gait analysis is:

1. Data is gathered using a gait recording system and is stored in the computer.

2. The film of a patient walking is digitized frame by frame to give the computer more information about the patient's gait.

3. All the data in the computer is processed by various programs to produce the graphs and figures discussed in section 2.2.2.

4. *The data in the computer in addition to the data produced by step three are fed into Dr. Gait. Dr. Gait analyzes all of this data and then produces a preliminary report.*

5. The *preliminary report along with the graphs and figures* are examined and analyzed by the doctors and physical therapists who then write up a *final analysis report.*

3.2 Inputs

The inputs to Dr. Gait consist of various kinds of measurements. Most of this data is an encoding of the data presented in section 2.2.2. This input data includes:

1. ***Motion Data*** - The motion data presented in the flexion/extension graphs for the different joints is scaled by degree of deviation from normal. The scale ranges from markedly decreased (-5) to markedly increased (+5). See table 3-1 and figure 3-1 for the scaling definitions and an example. Thus, the absolute joint position is *not* used by the program, only its *deviation* from normal is used.

   Our representation of the motion data scales a continuous quantity to a set of discrete qualitative values immediately. Others argue that the data should be left in its continuous form and only transformed to discrete values when needed. They claim that information is lost in this transformation. This is indeed the case. There is the problem that several different joint motions can be transformed to the same set of discrete qualitative values. Currently, if any of this lost information is later needed, the user is asked for this information. In the future if routines could be written to determine these additional characteristics directly from the data there would be no reason to ask the user for the information. The scaled qualitative information is used to help identify motion problems and to check the value of torques in the causality module. For both of these tasks the qualitative information is well suited. The causality module is using qualitative reasoning so that the qualitative values for the motions fit in perfectly. Furthermore, the experts naturally classify the motion data as some discrete descriptive value and then use this in their reasoning. If this value does not capture some information they later need they will refer back to the graph. Thus, the way we treat the motion data is the same as the expert appears to use it.

2. ***Interpretation of Motion Data*** - Also from the flexion/extension graphs other information is gathered. This information is currently gathered by asking the user to answer questions about the graphs. For example, "Is the hip's rate of increase of flexion in the beginning of swing increased, normal or decreased?" or "Is there a flattening of knee flexion in single limb stance?" Each question is only asked if it is relevant to the program's current investigation. It is hoped that in the future much of this information could be calculated directly from the motion data in the computer.

3. ***EMG Data*** - The EMG signal from each muscle is used to determine if the given muscle was off or on in a particular phase. See figure 3-2 for an example. Presumably more sophisticated interpretations could be made, but, first of all, more research into EMG interpretations is needed.

4. ***Information About the Patient's Medical History*** - The user is asked about particular past surgeries and use of walking-assistive devices. This includes such inquiries as, "Has there been previous use of a below the knee orthosis?" or "Has there been a previous hamstring lengthening?". Again a particular question is asked only if it is relevant to the current case. As more and more patient data gets stored in an online data base, it should be possible to get answers to there questions directly from the data base instead of asking the user.

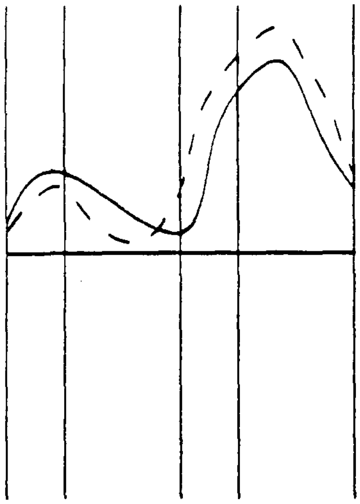
3.3 Output

A gait analysis report has the following sections: an introductory section discussing the patient's medical history and reasons for referral to the gait lab, another documenting a patient's motion and muscle activity deviations, a further one discussing the possible explanations for the patient's gait problems, and then possibly a final section recommending therapies to help alleviate the noted problems. Because we want the program to be a first step in producing such a report, the program should output similar information. Thus, the program needs to accomplish three tasks:

1. ***Identify*** all the deviations present and their consequences (e.g. decreased hip flexion is present in swing and this causes scraping of the toe).

2. For each identified deviation determine its ***cause*** (e.g. the increased knee flexion in single limb stance is caused by excessive hamstring activity).

3. ***Recommend treatments*** which will help alleviate the identified deviations (e.g. suggest hamstring lengthening to reduce excessive knee flexion).

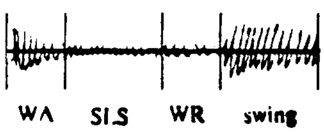


Right Knee Flexion

Phase	*Motion*
WA	mildly increased
first half SLS	increased
second half SLS	mildly increased
WR	decreased
first half swing	decreased
second half swing	mildly decreased

Scaled Motion Data

Figure 3-1: Motion Data Transformation



Right Anterior Tibialis
EMG Signal

Phase	*EMG*
WA	on
first half SLS	off
second half SLS	off
WR	off
first half swing	on
second half swing	on

EMG Data

Figure 3-2: EMG Data Transformation

Motion Description	*Scaled Magnitude*	*Measured Joint*
severely increased	+5	>25 degrees increased from normal
markedly increased	+4	20-25 degrees increased from normal
very increased	+3	15-20 degrees increased from normal
increased	+2	10-15 degrees increased from normal
mildly increased	+1	1-10 degrees increased from normal
WNL	0	normal - no deviation
mildly decreased	-1	1-10 degrees decreased from normal
decreased	-2	10-15 degrees decreased from normal
very decreased	-3	15-20 degrees decreased from normal
markedly decreased	-4	20-25 degrees decreased from normal
severely decreased	-5	>25 degrees decreased from normal

Table 3-1: Scale for Motion Data

3.4 Goals and Success Criteria

Our goal is to have Dr. Gait perform its three tasks successfully. This means that Dr. Gait has to identify the motion deviations, determine their causes and recommend treatments. The gold standard that we will be using is the set of results obtained from the expert. Thus, we need to see if Dr. Gait identifies the same gait deviations, discovers the same underlying causes and recommends the same treatments as does the expert on the same cases.

3.5 Summary

Dr. Gait's task is to produce a preliminary gait analysis report which the doctors can use in writing up a final report. To produce this report, Dr. Gait must identify the deviations, determine their causes and recommend therapies. Dr. Gait is given motion data represented as scaled deviations from normal, EMG data represented as on/off values and various other data obtained by asking the user specific questions. Thus, all we need now explain is how Dr. Gait takes this data and accomplishes its three tasks. In Chapter 4 we will see a naive approach taken by the prototype system, Dr. Gait-1. Later, in chapter 5, we will see a more sophisticated approach taken by Dr. Gait-2.

4. Dr. Gait-1

This chapter examines the design and implementation of the prototype system, Dr. Gait-1. A brief overview of the structure of the program is presented, after which there will be an explanation of Dr. Gait-1's analysis process. An example will be presented to illustrate the operation of the program and also to indicate some of the weaknesses of the naive approach. Finally, corrections to these problems are discussed.

The prototype system was built to mimic the expert's reasoning as closely as possible, in part to identify his knowledge. This led to a system based on empirical associations, with no deep understanding of how gait works but only associations between patterns of symptoms and causes.

A CP patient usually has multiple deviations with different causes. Thus, the single fault assumptions that many expert systems make is not valid for this domain. The prototype system deals with these multiple deviations and causes by finding patterns of symptoms which represent a set of deviations and then attributing some causes to this pattern of symptoms. Therefore, each deviation and cause is not dealt with in isolation. The resulting system is then limited in the cases it can handle. Only patterns of symptoms that are encoded into the system are found. If the patient's symptoms do not quite match these patterns, nothing is concluded.

4.1 Dr. Gait-1's Structure

The Dr. Gait-1 system is made up of five parts: some top level code which controls the system, the GENIE inference engine which is used to operate on frames and rule bases, a patient frame which stores the current information about the patient, a medical knowledge base which captures the essential medical knowledge necessary to perform gait analysis and several rule bases which perform the analysis. The system organization is shown in figure 4-1.

Below the important parts of the Dr. Gait-1 System are discussed:

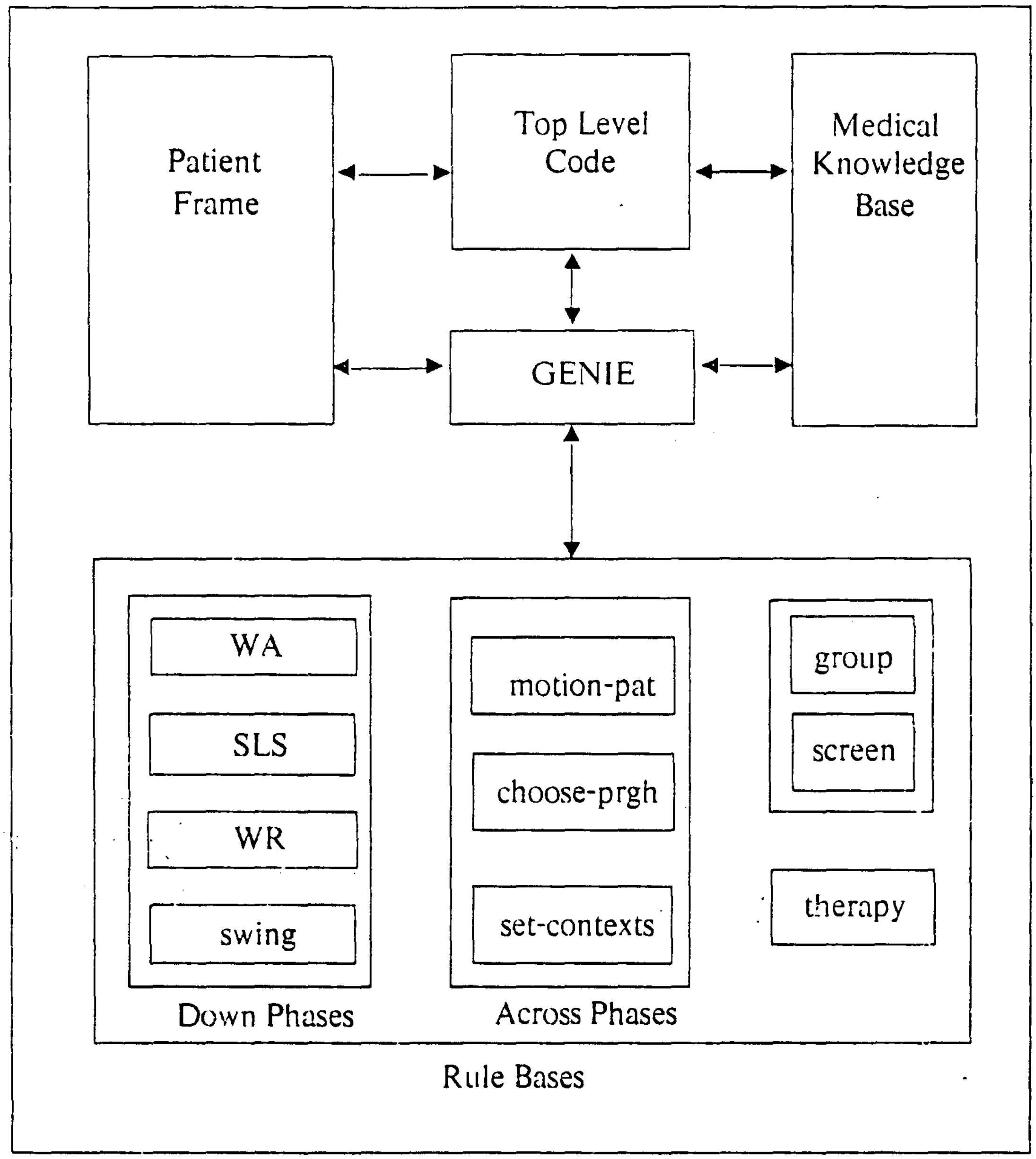


Figure 4-1: Dr. Gait-1's Organization

4.1.1 GENIE

GENIE [Sandell 84] is a general purpose knowledge engineering tool, developed at Vanderbilt University, for creating expert systems based both on rule bases and frames. Systems built with GENIE can use frames throughout the system as a uniform data structure in which to store static knowledge. Production rules can be partitioned into several rule bases which can then be applied individually. Context-dependent variables[9] can be included in the rule clauses, thus allowing rules with general knowledge to be applied to specific situations. GENIE uses the MYCIN [Shortliffe 76] scheme of certainty factors to deal with uncertainty. The rule interpreter of GENIE allows rules to be applied using backward chaining, forward chaining or data-directed rule application. We have modified the system so that whenever a rule causes a value to be placed in a frame slot, a record of dependency information is stored with it. Efficient control of the expert system can be obtained by combining the different rule-base application strategies to fit the problem domain. The GENIE system also includes facilities for explaining its reasonings through the display of rules, rule application order and frame contents.

Dr. Gait-1 uses the GENIE system to run rule bases and to access and create frames. GENIE provides a convenient tool to help build many of the components of Dr. Gait-1.

4.1.2 Medical Knowledge Base

The medical knowledge base captures the essential anatomical and physiological knowledge necessary so that the accompanying expert system, in this case Dr. Gait-1, can perform gait analysis. The knowledge base is built up of objects (usually nodes in a hierarchy), each of which is represented as a frame. The objects in the data base are divided into three classes: motion, time-measure and anatomical-entity classes.

---

[9] We modified the system so that specially designated global variables could be used in rule clauses.

4.1.2.1 Motion Class Object

The motion class objects give the system information about the different types of motion that are used in describing the motion of a joint. These motions include abduction, adduction, flexion, extension, internal rotation, external rotation, dorsiflexion and plantarflexion. Each motion tells which plane the motion occurs in, whether the motion is defined as the positive or negative direction and the name of its opposing motion. Figure 4-2 gives an example of a motion object.

```
dorsiflexion
    is-a
        motion
    in-plane
        sagittal
    direction
        -
    opposing-motion
        plantarflexion
```

Figure 4-2: Example of Motion Class Object

4.1.2.2 Time-Measure Class Object

There are two different entities in this class, *event objects* and *phase objects*. *Event objects* represent the significant events defined in section 2.1. These events serve as landmarks in the gait cycle and are ordered so that the system will know which event proceeds or follows another one. They include information on which phases or subphases they initiate and which ones they terminate. Figure 4-4 shows a typical event object.

Phase objects define names for the intervals between event objects in the gait cycle. These are exactly the phases defined in section 2.2. Furthermore, these phase objects are hierarchically organized so that some phases also have subphases. Figure 4-3 shows the time hierarchy. The phase objects keep track of the events that initiate and terminate them. Thus, the phases can be ordered using the knowledge of the ordering of the significant events. A phase object is shown in figure 4-5.

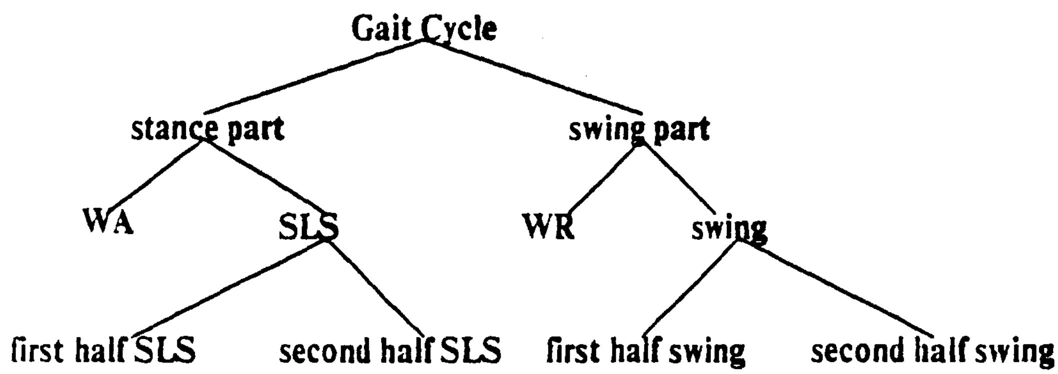


Figure 4-3: Time Hierarchy

```
ipsilateral foot strike
    is-a
       event
    initiates
        gait-cycle
        WA
    ends
        gait-cycle
        swing
        second-half-swing
```

Figure 4-4: Example of Event Object

```
SLS
    is-a
        stance-part
    subphases-of
        first-half-SLS
        second-half-SLS
    from
        opposite toe off
    to
        opposite heel strike
    motion-rule-base
         SLS-rb
```

Figure 4-5: Example of Phase Object

4.1.2.3 Anatomical-Entity Class Objects

There are three types of anatomical-entity class objects: *body segment objects, joint objects and muscle objects*. *Body-segment objects* define connectivity information about the various segments of the body which include the thigh, shank, foot and HAT (head, arms and trunk). Figure 4-6 shows a typical body segment object.

Joint objects store pertinent information about each of the joints in the leg. We can learn about the possible motions for each joint, which muscles act upon the joint in question, which joints are above or below, and which body segments are directly above or below. An example is in figure 4-7.

Muscle objects have information about a muscle's physiology which acquaints us with which joints the muscle acts upon and how the muscle affects each such joint when it is active. In addition, each muscle object has information about when the muscle is normally on. See figure 4-8 for an example.

```
thigh
    is-a
        body-segment
    proximal-joint
        hip
    distal-joint
        knee
```

Figure 4-6: Example of Body Segment Class Object

4.1.3 Patient Frame

This part of the system acts like the blackboard in the HEARSAY [Lesser 77] system to record information about the current patient and any results obtained or intermediate conclusions reached by any part of the system. The various rule bases can pass information to each other via the patient frame.

```
knee
    is-a
        joint
    motions
        flexion
        extension
    muscles
        quadricep
        hamstring
        gastroc/soleus
    proximal-body-segment
         thigh
    distal-body-segment
         shank
    joints above
        hip
    joints below
        ankle
```

Figure 4-7: Example of Joint Class Object

```
knee-flexor
    is-a
        muscle
    acts-on
        knee
            causing
                flexion
    stronger-than
        knee-extensor
    instances-of
        hamstring
        gastroc/soleus
```

Figure 4-8: An Example of a Muscle Class Object

4.1.4 Rule Bases

One advantage of the GENIE system over a system like MYCIN [Shortliffe 76] is that one can build an expert system with several rule bases and thus partition the rules into smaller sets. Dr. Gait-1 has nine rule bases which perform various functions. These rule bases are:

1. ***Group*** - This rule base uses backward chaining to classify the patient into one of three velocity groups (high velocity group, middle velocity group or low velocity group). This is a very small rule base. Rules are of the form:

```
group-rule2
  ifall
    (patient velocity) > 0
    (patient velocity) <= 35
  then
    conclude: (patient group)
       with value: low-velocity
```

2. ***WA, WR, SLS, Swing*** - Each of these rule bases is applied to a particular phase and tries to classify the motion at each joint as either a *primary cause*, a *compensation* for other deviations, a demonstration of *lack of compensation* for the deviations, a *passive problem* or a *passive compensation*. This classification is carried out by pattern matching combinations of observed motions with those in the predicates in rules. The rules in each of these rule bases is searched by backward chaining through the rules. A typical rule looks like this:

```
WR-rule7
 ifall
  (patient psm hip (context current-phase) motion-data)
     at-least mildly-increased
  not
    (patient psm ankle (context current-phase) motion-data)
       at-most mildly-decreased
  not
    (patient psm knee (context current-phase) motion-data)
       at-most mildly-decreased
 then
   conclude: (patient hip (context current-phase) Dx)
      with value: primary-cause
```

The (context current-phase)'s in the rule clauses allow the current value of the named frame slot, in this case current-phase, to be spliced into the name of the path to the parameter. This allows one to write a rule base, say for SLS, that can apply to both the first-half of SLS and the second-half of SLS subphases. To apply it to one or the other one need only set the frame slot appropriately. The above rule states that if the hip shows increased flexion, while the knee does not show decreased flexion and the ankle does not show decreased plantarflexion, then the hip's motion is diagnosed to be a primary cause.

3. ***Motion Pattern*** - This rule base tries to match the patterns of motions across the phases for a particular joint. These patterns were arrived at by having the expert examine many past case studies and abstracting the most common patterns. Currently, there are about ten patterns for each joint. To match the patterns the rule base uses backward chaining.

4. ***Choose Paragraphs*** - Using the motion patterns determined by the motion pattern rule base along with other information about the patient's gait, this rule base uses forward chaining to identify global problems that are affecting the patient's gait. In effect, what this rule base does is select applicable paragraphs which describe particular deviations. These paragraphs are selected by matching predetermined situations to the one at hand. Once again we are using superficial knowledge to arrive at conclusions. This moderately sized rule base has forty rules.

5. ***Set Contexts*** - The paragraphs selected by the choose paragraphs rule base are more like templates than full paragraphs. This rule base is used to fill in the blanks in the chosen paragraph templates. By doing so one specializes the selected paragraph to fit the case at hand. Since there are over one hundred slot, each of which can be filled in in several ways, this leads to a large rule base of over one hundred and fifty rules. The rule base is forward chained. GENIE's simple forward-chaining mechanism causes every rule to be tried once. This means that the rule base is very slow and inefficient. Furthermore, the slots can only be filled in in a few predetermined ways. This sometimes leads to cases where a paragraph gets chosen but not all the slots can be filled in with the appropriate information.

6. ***Therapy*** - The therapy rule base is much like the choose paragraphs rule base. Using information about matched motion patterns, chosen paragraphs emg data and motion data, this rule base selects paragraphs describing therapy recommendations. It also uses the empirical pattern matching approach. This rule base is only partially complete. Most of its information deals only with the ankle. Thus, there are very few therapy recommendations for problems at the hip or knee. Even those rules for the ankle do not work in many situations. The main problem with this rule base is that there are no intermediate concepts to guide the search. It tries to match the situation *exactly* to the conclusions it knows how to reach.

4.2 Dr. Gait-1's Analysis Process

The top level control gathers some background information about the user and then proceeds to run the rule bases in the order presented above. Thus the process has the following eight steps:

1. Gather initial patient information.

2. Apply the group rule base to classify the patient into a velocity grouping. This grouping gives one a good idea of the overall ability of the patient.

3. Apply the WA, SLS, WR and Swing rule bases to classify the motion of each of the three joints in each phase as a primary cause, compensation, etc.

4. Apply the motion pattern rule base to see if any common motion patterns are present across the phases for any of the joints.

5. Apply the choose paragraphs rule base to find local and global problems that are demonstrated by the patient.

6. Apply the set contexts rule base to fill in the slots in the paragraph templates just selected.

7. Apply the therapy rule base to find possible therapies to help the patient.

8. Write out all conclusions.

4.3 Example

Below we will present Dr. Gait-1 analyzing a patient.[10] This example will demonstrate the reasoning process of Dr. Gait-1. It will also illustrate some of the problems with the Dr. Gait-1 system. These problems will be indicated and ultimately some suggestions for alleviating these problems will be discussed.

4.3.1 The Case

Dr. Gait-1 is going to analyze John Patient's gait. John Patient is a CP patient who has difficulty walking. His velocity is only 55% of normal but his coordination is fairly good. His problem is that he has several weak muscles. It should be noted that muscles that are usually weak are not the causes of CP patients' problems. This case causes problems for Dr. Gait-1. Later we will see that Dr. Gait-2 has no problems with this case.

The motion data given to the program is shown in table 4-1.

	Hip	Knee	Ankle
WA	decreased	increased	WNL[11]
first-half SLS	WNL	decreased	decreased
second-half SLS	WNL	decreased	decreased
WR	WNL	WNL	mildly decreased
first-half swing	WNL	WNL	WNL
second-half swing	increased	increased	WNL

Table 4-1: Motion Data for John Patient

4.3.2 The Analysis

Step 1: Dr. Gait-1 gathers information on the session number, patient name, etc. It also gathers the patient motion data shown in table 4-1 and velocity data.

Step 2: Backward chaining through the group rule base to classify the patient. The patient can be placed in one of three groups: low-velocity if velocity <= 35% of normal, middle-velocity if 35% < velocity <= 65% or high-velocity if velocity > 65%.

Determining which group the patient falls into.

[10] The program's output will be in normal type and comments will be in *italics*.

[11] WNL = within normal limits i.e. motion is within normal range

It was determined that the patient was in group: middle-velocity.

Step 3: Apply the rule bases to the phases and classify the motions as either primary-cause, compensation, lack-of-compensation, etc. The system needs to look at each joint in each phase. For each joint and phase, it examines the joint's motion relative to the other joints during the same phase and then classifies the joint's motion.

The system now begins to scan each joint in each phase. We will look at some of them in detail and then summarize the classifications reached by the system.

...

It is now trying to classify the increased knee flexion in WA.
Running the WA rule base.
In order to DX the knee.

The system begins to backward chain through the WA-rb. It finds that WA-rule-12 fires successfully concluding that the increased knee flexion is a primary-cause. Rule WA-rule-12 is:

```
WA-rule-12
 ifall
  (patient psm knee (current context-phase) motion-data)
    at-least mildly-increased
  (or (patient psm ankle (context current-phase) motion-data)
        same-as WNL
      (patient psm ankle (context current-phase) motion-data)
        at-least increased)
 then
  Conclude: (patient psm knee (context current-phase) dx)
    with value: primary-cause
```

This rule says that if the knee shows increased flexion and the ankle shows normal or increased plantarflexion then the knee flexion should be classified as a primary-cause

I am concluding for (patient psm knee WA Dx) that it should be (primary-cause). This was done by rule WA-rb-rule12

...

The system now tries to classify the knee in the first-half of SLS.
Running the first-half-SLS rule base.
In order to DX the knee.

How would you characterize the quadricep's activity during first-half-SLS?[unknown]

1) on
2) off
3) unknown

```
Please enter choice(s):
    # 2
```

However, we see below that it cannot classify the deviation. There is no rule which handles the case where the knee has decreased flexion while the quadricep is off. Since the hip positioning is normal, the only way to account for the lack of flexion in the knee is to then assume that the gastroc/soleus is producing less of a flexion torque than normal. However, this is not what one would first guess as the cause of the knee's motion deviation.

Dr. Gait-1 asks the user for the answer since no rules were successful.

```
What is the Dx of the specified joint 's motion ?

patient
   psm
      knee
         first-half-SLS
            Dx

Please enter value:
     >> indeterminant

...
```

The same situation is evident at the knee for the second-half of SLS. Thus, once again the user must supply the information.

```
Running the second-half-SLS rule base.
In order to DX the knee.

...

What is the Dx of the specified joint 's motion ?

patient
   psm
      knee
         second-half-SLS
            Dx

Please enter value:
     >> indeterminant

...
```

Similarly, we could go through the other fifteen combinations of joints and phases to arrive at their diagnoses. Table 4-2 shows the result of all these rule-bases.

	Hip	*Knee*	*Ankle*
WA	primary cause	primary cause	normal
first-half SLS	normal	indeterminant	primary cause
second-half SLS	normal	indeterminant	primary cause
WR	lack of compensation	lack of compensation	primary cause
first-half swing	normal	normal	normal
second-half swing	primary cause	primary cause	normal

Table 4-2: Diagnoses for Joint Motions of John Patient

Step 4: Now the system needs to look across the phases to find global problems. The first step in looking across the phases is to find any common motion patterns for each of the joints. A motion pattern is a pattern of motion deviations of a joint across all the different phases. Table 4-3 shows the different motion patterns for the hip.

	WA	*1st-half SLS*	*2nd-half SLS*	*WR*	*1st-half Swing*	*2nd-half Swing*
pattern 1	N[12]	N	N	N	I	N
pattern 2	I	N	N	N	I	I
pattern 3	I	N	N	D	D	N
pattern 4	D	N	N	D	D	D
pattern 5	I	I	I	I	I	I
pattern 6	N	N	I	I	I	N
pattern 7	I	N	N	N	N	I

Table 4-3: Hip Motion Common Patterns

To try to find motion patterns Dr. Gait-1 does backward chaining through the motion-pattern-rb rule base. The rules are of the form:

```
motion-pattern-rb-rule11
  if-all
     (patient psm knee WA motion-data) at-least mildly increased
     (patient psm knee first-half-SLS motion-data) same-as WNL
     (patient psm knee second-half-SLS motion-data) same-as WNL
     (patient psm knee first-half-swing motion-data) same-as WNL
     (patient psm knee second-half-swing motion-data)
         at-least mildly increased
   then
     conclude: (patient psm knee motion-pattern)
       with value: pattern-1
```

Thus, to try each rule, the program must try to satisfy all the clauses in the if part of the rule. The problem with this approach is that a value of a parameter might have to be repeatedly found and checked. For example, the parameter (patient psm knee WA knee motion-data) had to be found and compared seven times in determining the knee motion pattern. This is obviously very inefficient. A better approach than using rules

[12] In the table, N = normal, I = increased, D = decreased.

would have been to use a discrimination tree. At the time that Dr. Gait-1 was built there was no facility to allow the making of discrimination trees so the technique adopted was chaining through rules in a rule base.

Backward chaining through the motion-pattern-rb three times, once for each joint, Dr. Gait-1 finds that the knee has knee pattern-3 and the ankle has ankle pattern-10. The hip motion did not match any pattern.

```
Finished analyzing down the phase - Now analyze across the phases.

I am concluding for (patient psm knee motion-pattern) that it
should be (pattern-3).
This was done by rule motion-pattern-rb-rule13.


I am concluding for (patient psm ankle motion-pattern) that it
should be (pattern-10).
This was done by rule motion-pattern-rb-rule23
```

Step 5: The next step in the analysis is to select paragraph templates which describe the problems of the patient's gait. This is done by having a rule base, choose-paragraphs-rb, which has forty rules. Each rule that succeeds in firing selects one or more paragraph templates. If a rule is being tried which requires more information than is known to make a decision, then the user is asked for further information. This rule base is forward chained and the names of all the paragraph templates chosen are stored in the patient frame. In the case at hand, one paragraph template that is chosen is called abnormal-dorsiflexion. The rule which selects this template is shown in figure 4-9. The template itself is shown in figure 4-10.

```
choose-paragraphs-rb-rule22
  ifany
     (patient psm ankle motion-pattern) eq pattern-6
     (patient psm ankle first-half-SLS motion-data)
       at-most mildly decreased
     (patient psm ankle second-half-SLS motion-data)
       at-most mildly decreased
  then
    conclude: (patient psm ankle paragraphs)
       with value: abnormal-dorsiflexion
```

Figure 4-9: Rule which Selects Abnormal-Dorsiflexion Paragraph Template

```
Abnormal dorsiflexion during ------ single limb stance is noted.
Gastroc/soleus activity ------  ------ is unable to counteract
body weight ankle dorsiflexion torque ------ ------.
```

Figure 4-10: Abnormal-Dorsiflexion Paragraph Template

As the choose-paragraphs-rb rule base proceeds it asks the user for some more information and selects several more paragraph templates in addition to the abnormal-dorsiflexion paragraph template.

```
How would you characterize the hamstring's activity
during SLS?[unknown]

     1)  on
     2)  off
     3)  unknown

  Please enter choice(s):
     # 2


I am concluding for (patient psm knee paragraphs) that it should
be (thrust). This was done by rule choose-paragraphs-rb-rule13

...

I am concluding for (patient psm hip paragraphs) that it should
be (hip-increase-swing2).
This was done by rule choose-paragraphs-rb-rule34.
```

Step 6: Now for all the paragraph templates the system has to fill in the blanks. Because each blank has a name, rules can refer to the different blanks. The rule base, set-contexts-rb, is the rule base which tries to fill in all the blanks of the chosen templates correctly. The rule which attempts to fill in the first slot of the abnormal-dorsiflexion is shown in figure 4-11. This rule states that if the paragraph template abnormal-dorsiflexion has been selected and the ankle shows decreased plantarflexion in the first-half of SLS but not in the second-half, then place the phrase "the first half of" in the slot named when-abnormal. This is the first empty slot in the template. For the patient John, this is not the case so the slot remains empty. For John it turns out that all the slots are left empty. This leads to the paragraph shown in figure 4-12.

Step 7: Finding therapies is the only analysis left to be done. To find possible therapies the system forward chains through the therapy rule base. This rule base is very similar to the choose-paragraphs-rb except that the paragraphs chosen by the therapy rule base are full paragraphs as opposed to being just paragraph templates. This rule base is only partially complete and thus does not always find appropriate therapies. The successful rule for this case is shown below.

```
set-contexts-rb-rule64
  ifall
     (contains (fget '(patient psm ankle paragraphs))
               'abnormal-dorsiflexion)
     (patient psm ankle first-half-SLS motion-data)
       at-most mildly decreased
     not
       (patient psm ankle second-half-SLS motion-data)
         at-most mildly decreased
  then
     (fput '(contexts when-abnormal) '(the first half of))
```

Figure 4-11: A Rule which Fills in a Slot

```
Abnormal dorsiflexion during single limb stance is noted.
Gastroc/soleus activity is unable to counteract body weight
ankle dorsiflexion torque.
```

Figure 4-12: The Filled in Paragraph Template

```
therapy-rb-rule15
  ifall
    (patient psm knee motion-pattern) eq pattern-3
    or
     (g= '(patient psm knee) 2 '(WA second-half-swing))
     (g= '(patient psm knee) 3 '(WA second-half-swing))
  then
   conclude: (patient psm knee therapy)
     with value: hamstring-lengthening
   conclude: (patient psm knee therapy)
     with value: ham-length-background
   conclude: (patient psm knee therapy)
     with value: adverse-effects
```

This rule states that if the knee has motion pattern number three and the severity of the increased knee flexion in the phases WA and second half of swing is grade 2 or grade 3 (i.e. 10-20 degrees above normal), then hamstring lengthening should be recommended to help the knee's motion deviation. If Dr. Gait-1's diagnosis, that increased hamstring activity was the the cause of the increased knee flexion, had been correct then this treatment would be the right recommendation. However, the hamstrings are not the cause of the knee's motion deviation. Thus, Dr. Gait-1's recommended therapy is incorrect.

Step 8: All that remains to be done is to write out the results.

Gait Analysis Report

Name: john patient DOB: 11/11/79
GS#: 4 DX: cp
Date: 3/27/86
MR#: ??????????? MD: simon

		WA		first-half-SLS		second-half-SLS	
	joint	motion	dx	motion	dx	motion	dx
1	hip	dec	primary	WNL	normal	WNL	normal
2	knee	inc	primary	dec	indeterm	dec	indeterm
3	ankle	WNL	normal	dec	primary	dec	primary

		WR		first-half-swing		second-half-swing	
	joint	motion	dx	motion	dx	motion	dx
1	hip	WNL	lack-cmp	WNL	normal	inc	primary
2	knee	WNL	lack-cmp	WNL	normal	inc	primary
3	ankle	mld-dec	primary	WNL	normal	WNL	normal

The conclusions are:

**********>hip<**********
A normal pattern and magnitude of hip flexion into extension is that present hip flexion is increased in the second half of swing resulting from the continuation of the momentum imported to the thigh in WR and early swing.

**********>knee<**********
The increased knee flexion noted in late swing and weight acceptance is related to increased activity of the hamstring during its normal timing.

Rather, motion to hyperextension in SLS is seen.

**********>ankle<**********
Abnormal dorsiflexion during single limb stance is noted. Gastroc/soleus activity is unable to counteract body weight ankle dorsiflexion torque.

Therapy Recommendations:

**********>hip<**********

No therapy recommendations for the hip.

**********>knee<**********

The recommended therapies are hamstring-lengthening.

The increase knee flexion noted above suggests the possibility that surgically lengthening the hamstrings may be a reasonable treatment. Experience to date suggests that lengthening the hamstrings has a minimal effect on increasing the limited stride length and velocity and reducing the subject's dependency on assistive devices. But an average twenty degree reduction in knee flexion will allow more knee extension at the end of swing and weight acceptance will allow the subject to have a more erect posture during stance.

While this treatment merits thought, if performed some significant adverse effects could arise if the abnormalities noted at the other joints are not corrected first or simultaneously.

**********>ankle<**********

No therapy recommendations for the ankle.

4.3.3 Problems with Step 5: Incorrect Paragraphs

Most of Dr. Gait-1's conclusions in this case are correct. However, the explanation for the increased knee flexion in late swing and WA is incorrect. The program attributes the increased flexion to an increased torque of overactive hamstrings, but the hamstrings are really weak and thus much more likely to produce a decreased torque on the knee. This problem is similar to the previously mentioned problem of weak muscles. Dr. Gait-1 never considers the possibility that muscles are weak and thus is limited in the range of cases it can handle. A further problem is that the paragraph has the assumption of "increased activity of the hamstring" fixed into the paragraph template. Dr. Gait-1 makes the most likely explanation the only possible explanation without checking to make sure the data actually supports its conclusion (i.e. It should have checked to see that the hamstring is weak and thus it is unlikely to be the cause of the increased flexion.)

The other problems are omissions of explanations. There is no mention of the decreased hip flexion in WA or the mildly decreased ankle plantarflexion in WR. The situations did not match any triggering conditions of the rules in the choose-paragraphs rule base and thus were not identified. In defense of Dr. Gait-1, the unidentified problems were either mild in nature or else occurred in less important phases of the gait cycle.

4.4 Conclusions About Dr. Gait-1

Before drawing conclusions about Dr. Gait-1, we must remember that the goal in building this system was to learn more about the knowledge needed to perform gait analysis. Furthermore, we tried to make the system as simple as possible and also make it mimic the expert's reasoning as closely as possible.

Dr. Gait-1 was informally tested on twenty cases. A case was tested by comparing Dr. Gait-1's performance on the three tasks of gait analysis[13] to the expert's performance on the same tasks. On the twelve simple cases Dr. Gait-1's performance was comparable to the expert's. It identified about 80% of the major deviations and gave the correct explanation of their causes. In over half of the cases Dr. Gait-1 failed to recommend therapy when the expert did because its therapy rule base is still incomplete.

As we just saw with our example, Dr. Gait-1 runs into difficulties when dealing with unusual cases. There are several reasons for this. First, Dr. Gait-1 uses empirical pattern matching to classify motion deviations, to discover problems and their causes and to find treatments. Only patient's whose symptoms match exactly the situations described by the rules can have their gait adequately analyzed by the program. One could constantly add new rules to cover each new specific situation encountered but this is not an attractive solution as the rule base would grow quite large. Furthermore, the possible explanation offered by such rules is poor. Take, for example, our patient John. If we ask the system why increased hamstring activity is the cause of the increased knee flexion, the best it can do is to show us choose-paragraphs-rule11 which concluded the corresponding paragraph. This rule states that if the knee shows motion pattern 1, 2, 3, 4 or 5 then choose the paragraph about increased knee flexion. Stating that the hamstring is the cause of the increased knee flexion because the knee showed some motion pattern is not a convincing explanation.

---

[13]The three tasks are: (1) identify motion deviations, (2) find the causes of the deviations and, (3) recommend treatment.

A second problem is that some of the explanations of the causes of problems are "hard-wired in". As we saw with the knee flexion in WA and the second half of swing, hamstring overactivity is the explanation always given whether or not there is any knowledge about the hamstring to support or discredit this claim. Again we have the problem that if we enumerate all possible combinations of potential causes and place each in a separate rule we will get a huge rule base.

Thus, the naive approach, which merely uses empirical matching without any deeper causal knowledge, leaves us with a system that has less than ideal characteristics. Either the system is reasonably efficient with a fair number of "holes of knowledge" or else the system is more complete but is large and very inefficient. We have this dilemma not because empirical rules are a poor way to implement our expert system, but because the empirical rules are too specific and disjoint. There are two significant characteristics of Dr. Gait-1's rule bases. First, very few of the rules utilize the conclusions of other rules. The conclusions made by the rules that classify the motion deviations are used by only a handful of the 250 rules in the rest of the system. The physical therapists found these classifications useful but the program does not use these conclusions to its advantage. Similarly, treatment rules do not use many of the conclusions reached before. They simply match the observed phenomena to treatments. By running the therapy rule base one could get most of the treatments that would have been recommended if the whole system had been run. One reason for this is that choosing paragraph templates is not sufficient as the system only gets a list of applicable paragraphs. The discovered problems and causes mentioned in these chosen paragraphs are never explicitly recorded in the patient frame.

Most rules go directly from a set of observations to a definite final conclusion. Hence, the system has very few intermediate concepts. For example, when Dr. Gait examined the knee, it went from observing a particular motion pattern to concluding that the knee flexion was caused by the hamstring. The lack of intermediate concepts is the main reason why the rules are disjoint. There is no means for rules to communicate without a language of intermediate concepts to form and pass from one rule to another.

Related to the lack of intermediate concepts is the lack of abstraction. Each rule refers to a particular situation . There is no capturing of ideas which are common to many situations. Thus, each situation needs its own rule and paragraph. However, in looking at the paragraph templates one sees that many are performing an analogous analysis but in a different situation. For example, there might be a paragraph analyzing the knee in SLS and another analyzing the hip in swing, but the only real difference is changing the name of the joint, phase and corresponding muscle names.

Taking all of this into account, we find that we need a system which explicitly records the problems, their causes, any assumptions made and any treatments recommended. Furthermore, we need some underlying abstraction or model which can deal with many of the situations. This model will help us keep track of problem interactions and formulate explanations step by step instead of by one big leap as before. The key to doing all of this is to use more knowledge about gait, which is that the joints' motions are caused by the combination of several torques. Thus finding a way to model and deal with the torques gives us a new basis for building an improved system. Dr. Gait-2, which will be presented in the next chapter, is able to do this.

5. Structure of Dr. Gait-2

5.1 Motivation

In the previous chapter we discovered several problems with the prototype system Dr. Gait-1. The rules are too numerous and disjoint because of a lack of intermediate concepts. The causes of deviations are "hard wired in" causing the most likely explanation to become the only possible explanation. Identified problems and their causes are not explicitly recorded but only implicitly recorded through the selection of paragraphs. To try to solve all of these deficiencies we need the system to understand the mechanisms of gait. Thinking back to our discussion of gait in chapter 2, the reader might recall that the observed motions of the joints are caused by the combination of various *torques* placed on each joint. If we could build a system that had knowledge of the different torques at a joint caused by muscular forces, body weight and momentum, and how the different torques combine and interact, this would give us a new language to use in describing and decomposing the observed problems. We could use the torques to model human gait, thus giving us deeper causal knowledge of gait. Most of the knowledge about torques would be general enough that the same set of ideas would apply to any motion deviation at any joint. Furthermore, if we limit the assumptions that the system makes in forming and combining the torques or if we at least make the assumptions explicit, the system should be able to handle any reasonable cause of a problem and not just the "hard wired in" causes which are in Dr. Gait-1. Finally, the language of torques gives us a description for intermediate concepts for the different rules to share and also for sharing between problems. Thus, we will see that giving Dr. Gait-2 knowledge about torques eliminates many of the problems of Dr. Gait-1 and results in a better, more robust system.

The Dr. Gait-2 system is not altogether an new system but rather a vastly reorganized Dr. Gait-1 that takes advantage of new knowledge about torques. Dr. Gait-2 is used in the same way as Dr. Gait-1 in the gait analysis process as was described in chapter 3. Dr. Gait-2 will produce a preliminary gait report to assist the doctors and physical therapists in preparing a final gait report. The inputs to the system are very similar although slightly more muscle data is gathered than before. However, Dr. Gait-2 gathers *all* of its information before it begins its analysis. Thus, there is no need for user interaction while the analysis is taking place. Not only does Dr. Gait-2 find out if a given muscle was on or off in a particular phase but it also asks for the relative strengths of the emg signal in each phase, whether or not the muscle shows continuous activity and whether or not the muscle is known to be weak. The output of the program accomplishes the same three tasks of identifying the present deviations, determining their causes and recommending treatments.

5.2 Dr. Gait-2's Structure

The structure of the Dr. Gait-2 system is composed of six parts: top level code which controls the system, the GENIE [Sandell 84] inference engine which is used to interact with the frames and rule bases, a patient frame which stores the current information about the patient, a medical knowledge base which captures the essential medical knowledge, and a set of modules which processes the data and performs the necessary analysis. The set of modules includes a preprocessor, problem identifier, problem enhancer, causality, and therapy module. Figure 5-1 shows the system organization.

5.2.1 GENIE

This was discussed previously in section 4.1.1.

5.2.2 Medical Knowledge Base

This was discussed in section 4.1.2. The knowledge base remains almost unchanged except for the correction of previous errors. Dr. Gait-2 uses more of the information in the knowledge base than does Dr. Gait-1.

5.2.3 Patient Frame

The patient frame acts as the central storehouse for information, just as it did in Dr. Gait-1. The frame has been slightly restructured to allow for both sides of the body and data for all three motion planes to be in the frame at the same time. Now there are separate sections for hypotheses about the causes of problems and data that are unchanging. Dependency information is recorded in the frame with the data. The dependency information is either a record of the rule that

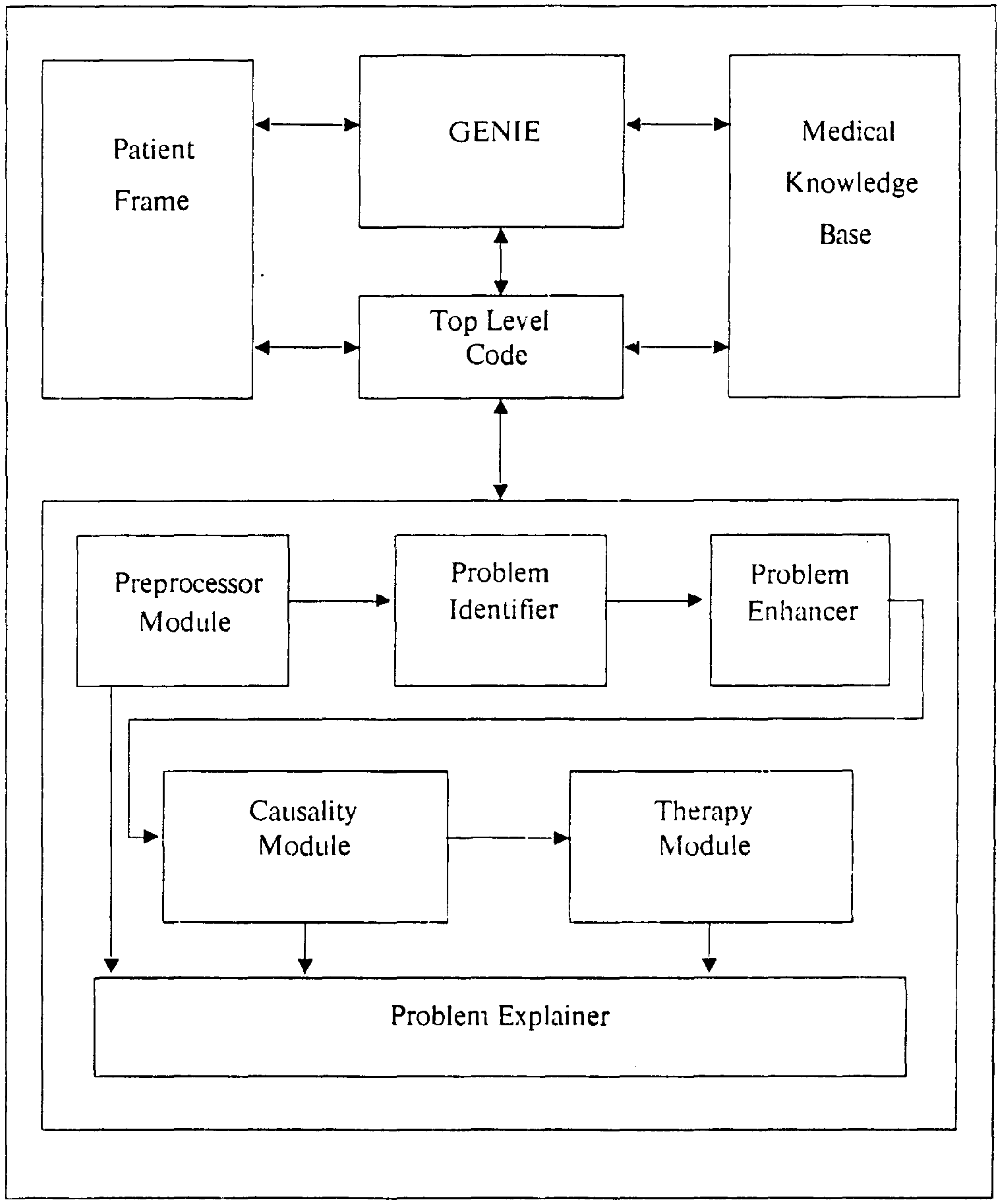


Figure 5-1: Dr. Gait-2 Organization

concluded the corresponding assertion or else a set of assumptions that support the assertion. The assumption system will be explained later in this chapter.

5.2.4 Preprocessor Module

The preprocessor's function is to set up the system so that it can begin its tasks of identifying, understanding and treating problems. The preprocessor consists of several parts. There is a program that takes the motion data stored in the data base[14] and converts it into scaled motion deviations. This transformation was shown in figure 3-1. There is also code which gathers the muscle and patient background data from the data base and the user. This module also invokes the same group rule base that classifies the patient into one of three velocity groups. Thus, after this module is run, the system has gathered all the necessary data and knows what joints in which phases of the gait cycle it should instruct the rest of the system to analyze.

5.2.5 Problem Identifier Module

By examining the gathered data, this module attempts to find the problems present in each patient. Each frame or class of problems has a knowledge frame associated with it. From these problem frames, we can obtain information on how to identify and set up a particular program, find both causes and explanation of it, as well as identify other necessary data. The reader should notice that the approach for dealing with problems has moved from a rule based approach of MYCIN [Shortliffe 76] to a more frame like approach of the Present Illness Program(PIP) [Pauker 76].

Currently there are three classes of problems: *limited range of motion class*, which deals with problems associated with very restricted ranges of motion throughout the gait cycle by any of the joints; *contracture class*, which deals with motion problems caused by tight muscles or tight joint capsules; and *motion deviation class*, which deals with any noticed motion deviation. These three classes have been sufficient to capture all of the problems encountered so far.

To identify a problem, Dr. Gait-2 looks in the problem-identify slot of the procedure's

---

[14] This is in the form of absolute joint angles for each 2% of the gait cycle.

corresponding frame. This slot either holds a procedure to run (usually for a whole class of problems) or a set of conditions necessary for the problem to exist. If the module determines that the problem is present, then the its set up procedure is called and it is added to the list in the patient frame.

5.2.6 Problem Enhancer Module

Once a problem has been identified, the system might want to take other actions. Such actions could include identifying other problems, refining the identity of a problem or anything else which adds to the understanding of the problem. Currently, none of the problems take advantage of this feature.

5.2.7 Causality Module

This module is the heart of the system; it does most of the analysis and takes advantage of Dr. Gait's knowledge of torques. To go back to an idea that was stated earlier, the motion at a joint is the result of the combination of torques acting upon this joint. Looking at the knee, for example, we can say that its motion is determined by all of the torques acting upon the knee. These torques are the hamstring-torque, the quadricep-torque, the gastroc/soleus-torque, the bodyweight-torque and the momentum-torque. If the knee's position is abnormal, then at least one of these torques must also be abnormal. Determining which torques are abnormal helps us to better understand the cause of the knee's motion deviation. If the knee shows increased flexion and we discover that the hamstring-torque is increased, we then know that the hamstring is contributing to the knee's problem.

We could say that the knee's torque must satisfy the equation:

knee-torque = hamstring-torque + quadricep-torque + gastroc/soleus-torque + bodyweight-torque + momentum-torque

However, knowing that the knee-torque is abnormal means that we now have to look at five torques at once to assign the blame. In most problems involving search and combination it helps to organize the entities. To organize our torques we need two concepts. First, we will say that a torque is a *flexion torque* if it normally causes flexion or analogously an *extension torque* if it normally causes extension. Hence, for the knee, the quadricep-torque is an extension torque and the hamstring-torque and the gastroc/soleus-torque are flexion torques. The classification for the momentum-torque and the bodyweight-torque depends on which phase we are considering. Second, we will say that torque is *internal* if it is produced locally or *external* otherwise. Thus, all muscle torques are internal while the bodyweight and the momentum torques are external. Using these two concepts we can classify our torques and then organize them in a tree.[15] See figure 5-2.

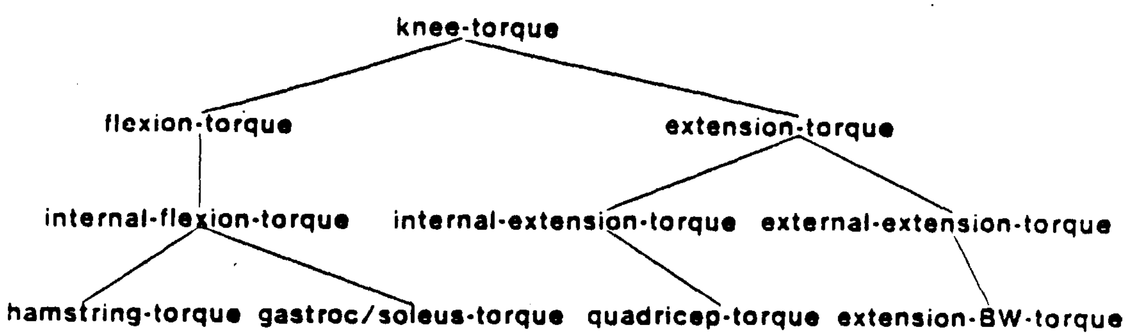


Figure 5-2: Tree of Torques for Knee in SLS

Using the tree as our guide we can get a set of torque equations for a joint by saying that a node equals the sum of its children. For the knee is SLS we get the equations:

[15] In Dr. Gait-2 the bodyweight-torque includes the effect of the body-weight and also momentum. Thus there is no momentum-torque.

```
knee-torque                  = flexion-torque -
                               extension-torque
flexion-torque               = internal-flexion-torque
extension-torque             = internal-extension-torque +
                               external-extension-torque
internal-flexion-torque      = hamstring-torque +
                               gastroc/soleus-torque
internal-extension-torque = quadricep-torque
external-extension-torque = extension-BW-torque[16]
```

Now that we have these equations, how do we use them? We describe all our motion data as scaled deviations from normal. In a sense, we just say whether the joint's position is increased, decreased or normal. If we use the same descriptions for the torques then a torque will have a value of *increased*, *decreased* or *normal*. The next question is how to use these values in an equation. Fortunately others have used similar equations. They are called incremental qualitative (IQ) equations [de Kleer 79]. The rules for IQ equations are shown in figure 5-3.

Looking at figure 5-3, we see that in all but two cases we can get an answer for C. In the two unknown cases we need more information about A and B to find C. An alternative is that we can obtain a value for C if we make assumptions about A and B. We introduce the relations *<diff*, *>diff* and *=diff*. The statement *A <diff B* says that "A has a smaller deviation from normal then B". Thus, if A is increased, B is decreased and A <diff B, then we can conclude that C is decreased. Using these new relations we get a modified IQ algebra whose rules are shown in figure 5-3.

Since we do not have a measurement of the various torques, we do not know for certain the relationships between the torques. However, we can make assumptions about what the relationships might be. We can then obtain a value for C depending on which assumptions seem more appropriate. The strategy that will be used is to assume anything which is physically reasonable and then at the end, to use heuristic knowledge about the particular disease the patient has, to choose the best set of hypotheses. Thus, by making assumptions and using domain specific knowledge we can obtain a value for all torques.

[16]This is a bodyweight torque which is causing extension.

A	B	C
↑	↑	↑
↑	N	↑
↑	↓	?
N	↑	↑
N	N	N
N	↓	↓
↓	↑	?
↓	N	↓
↓	↓	↓

IQ ALGEBRA

A	B	C
↑	↑	↑
↑	N	↑
↑	↓	set-1
N	↑	↑
N	N	N
N	↓	↓
↓	↑	set-2
↓	N	↓
↓	↓	↓

set-1 = { ↑, if A >diff B
N, if A =diff B
↓, if A <diff B }

set-2 = { ↑, if A <diff B
N, if A =diff B
↓, if A >diff B }

Modified IQ Albegra

Figure 5-3: IQ Algebra

As we have just seen, to deal with the torque equations, we need to make assumptions. If the system is making assumptions ine in different places, we need to make sure that they are consistent. We do not want the system at some point to assume the quadriceps are overactive in WA and then later to assume that they they are underactive. To keep the assumptions organized, a support system was built up on de Kleer's idea of an assumption-based truth maintenance system [de Kleer 84]. This system allows one to keep a set of alternative computations on hand and compare them. The values maintained by the system are made up of triples of an assertion, a supporting assumption set and some justifications.[17] Alternative sets of computations are chosen by picking the current "in set" of assumptions. Any value whose assumption set is a subset of this "in set" is part of the chosen computation. Notice that changing the "in set" of assumptions does not result in any new computation; only a different set of already determined values is selected.

If the causality module has to make any assumptions in determining the value of a torque, the set of assumptions will be recorded with the torque's value and also the assumption set will be entered into the assumption maintenance system. These assumptions will be passed along when the torque's value is used in the torque equations.

Given all of these equations, how does the causality module operate? It first uses rule bases and discrimination trees to assign values to the lowest level torques (muscle torques and bodyweight-torque). It then uses the torque equations to propagate values up to the joint's torque. However, we know the value the joint torque must have because we know the joint's motion. By imposing the constraint that the joint's torque must match this known value, the system will remove any values that are inconsistent.

At this point the system might be left with a value for the joint's torque that has several assumption sets, each of which represents a different possible explanation for the causes of the joint's abnormal torque. In this case, the assumption sets are scored using heuristic knowledge

[17] My implementation does not include justifications. The consequences of this decision are discussed in chapter 8.

about the patient's disease. The scoring is done by using heuristic "rules of thumb" that score each assumption on the basis of how likely it is to occur. Each possible assumption is, therefore, statically associated with a numeric estimate of its likelihood in the given population of CP patients. For example, for CP patients it is unlikely that a muscle is weak and thus all assumptions about muscles being weak will receive a high score. The higher the score of an assumption the less likely the assumption is true. On the other hand, it is very likely that a muscle is overactive and thus all assumptions mentioning overactive muscles will receive a low score. The score for an assumption set is the sum of the scores of its assumptions. The lower the assumption set scores the more likely that the assumption set is the correct explanation. The top scoring set is selected to be the best possible explanation of the torque's value and is called the problem's current environment.

5.2.8 Therapy Module

The therapy module prescribes the therapies that will help improve the patient's gait. There are three classes of possible treatments: surgery, bracing and physical therapy. Surgerical procedures include lengthening, shortening or transferring of muscles. Bracing therapy tries to keep a problem joint in a good neutral position and might use a rigid ankle brace, a flexible ankle brace or a knee brace. Physical therapy includes treatments like strengthening exercises or stretching and is a good treatment for minor problems.

Dr. Gait-2 selects therapies by considering each problem separately while at the same time examining the effect of each considered therapy on all of the patient's other problems. This prevents the program from recommending a treatment which might help one problem but aggravate others. In addition, if the program is considering two helpful therapies for a problem it can select the therapy which is the most useful overall.

The first step in the therapy process is to rank all of the patient's problems by taking into account the severity of the problem, the joint at which the problem occurs and the phase in which the problem occurs. The highest ranked problems (ones in most need of being treated) are considered before the lowest ranked.

The ranked problems are put through a two pass analysis. The first pass analyzes the problems and determines all possible surgical, brace and physical therapies. Each treatment is classified as "ok", "not desired", or "ruled out". In addition, each type of treatment is classified as "ok", "not desired" or "ruled out" depending on the classification of its treatments. For example, if a flexible ankle brace is classified as "not desired" but a rigid ankle brace is classified as "ruled out," the brace therapy would be classified as "not desired" since there is at least one possible brace treatment (even though it is not desired). Finally, Dr. Gait-2 gives each of the three therapy types a score. Each type of therapy has four scores - one each for the ankle, knee and hip plus a global score which is the sum of these three other scores.

The second pass actually chooses the treatments. For each joint a type of therapy is selected (which is called the preferred mode) based on the highest score. Then for each problem the selection process begins. Dr. Gait-2 first tries to find all of the "ok" therapy types. If the preferred mode is among them then it is chosen. Otherwise the least severe mode[18] is chosen. If there are no ok therapy types then the same process occurs with the not desired therapy types. All of the best treatments from the chosen therapy type become candidates for final selection. The program uses rules that take into account the therapies' global effects and the chosen therapy strategy to choose among the candidates. The selected therapies are then entered into the patient frame.

After the second pass a list of therapies has been entered into the patient frame. These therapies are what Dr. Gait-2 will recommend as treatments for the patient's problems. In this way all of the problems will be treated and the effects of a treatment for one problem will have been examined on the other problems as well.

---

[18] surgery $>_{severe}$ bracing $>_{severe}$ physical therapy

5.3 Dr. Gait-2's Operation

The operation of Dr. Gait-2 consists of the following six steps:

1. Use the preprocessor module to gather all the patient data.

2. Use the problem identifier module to find all the problems that the patient has.

3. Use the problem enhancer module to gather any additional data and also to check if the problem should be considered for examination and treatment.

4. Use the causality module to find the cause of motion-class problems. For contracture class and limited range of motion class problems the explanations are known just by the problem's existence; therefore these problems do not go through the causality module.

5. Use the therapy module to determine possible therapies to help the patient.

6. Use the problem explainer to write out all the results to the user.

5.4 Summary

We have now seen the organization of Dr. Gait-2. The key ideas embodied in this system are to explicitly record the problems that are identified by a given set of criteria and to explicitly record problem causes which are found by using a general model of gait which is based on qualitative torque equations. In the next chapter we will see Dr. Gait-2 working on some examples. These examples should illustrate the power of the methods used in Dr. Gait-2 and further clarify its operation.

6. Dr. Gait-2: Examples

In this chapter we will look at Dr. Gait-2 working on two examples. The first example illustrates the reasoning process and mechanisms used by Dr. Gait-2. The second example is the same one we saw in chapter 4. We will see that even though Dr. Gait-1 had a lot of trouble with this case, Dr. Gait-2 has no problems at all.

6.1 Example 1

For our first example, we have a patient, Jane Patient, who is able to walk at reasonable speed (60% of normal) with fairly good coordination. Table 6-1 shows the scaled motion data for Jane. Now we will follow Dr. Gait-2 through its analysis of Jane's gait. We will use the six steps of Dr. Gait-2's operation as our guide.

	Hip	Knee	Ankle
WA	increased	increased	increased
first-half SLS	WNL	WNL	increased
second-half SLS	WNL	WNL	increased
WR	WNL	WNL	increased
first-half swing	WNL	WNL	increased
second-half swing	increased	increased	increased

Table 6-1: Motion Data for Example 1

6.1.1 Step 1: Gather all the Patient Data

Dr. Gait-2 needs to gather the patient data, as did Dr. Gait-1. It asks the user for the patient name and background information and then gathers most of the motion data and emg data from the information in the computer. The motion data is represented as scaled deviations and the emg is converted to on and off values. In addition the program asks the user if he knows anything about the muscle's strength. All this data is placed in the patient frame before Dr. Gait-2 starts the analysis.

6.1.2 Step 2: Identify the Problems

Dr. Gait-2 looks at the triggering conditions in the problem frames to identify the patient's gait problems. It then prints out the name of each problem it tries to identify and whether or not it succeeds in doing so. We see that Dr. Gait-2 identifies right-ankle-LROM which stands for "limited range of motion of the right ankle." The triggering condition for this problem is:

```
(patient data right ankle sagittal range-of-motion) >= 15
(patient data right ankle saggital range-of-motion) < 20
(direction? (patient data right ankle sagittal WA motion-data)
            'plantarflexion)
(direction? (patient data right ankle sagittal first-half-SLS
             motion-data)
            'plantarflexion)
(direction? (patient data right ankle sagittal second-half-SLS
             motion-data)
            'plantarflexion)
(direction? (patient data right ankle sagittal WR motion-data)
            'plantarflexion)
(direction? (patient data right ankle sagittal first-half-swing
             motion-data)
            'plantarflexion)
(direction? (patient data right ankle sagittal second-half-swing
             motion-data)
            'plantarflexion)
(patient data right gastroc/soleus activity-type) eq continuous
(patient data right anterior-tibialis activity-type)
    eq continuous
(patient conclusion group) neq low-velocity
```

The program will conclude that there is limited range of motion of the ankle if (1) the range of motion is between 15 and 20 degrees, (2) the deviations in motion are all in the direction of plantarflexion, (3) the gastroc/soleus and anterior tibialis show continuous activity, and (4) the patient is not classified in the low velocity group. This is all true for Jane Patient; consequently, the program concludes that she has limited range of motion of her right ankle.

Any motion deviation from normal is found by the identify motion class problem's procedure and it is entered into the system. Contracture class problems are identified in the same way that the limited range of motion class problems are identified. It turns out that Jane does have a right ankle contracture. Taking this all into account, Dr. Gait-2 identifies the following problems in Jane's gait:

```
Finished finding the problems.
They are
    right-ankle-LROM
    right-ankle-contracture
    right-hip-sagittal-WA-flexion[19]
    right-hip-sagittal-first-half-swing-flexion
    right-hip-sagittal-second-half-swing-flexion
    right-knee-sagittal-WA-flexion
    right-knee-sagittal-second-half-swing-flexion
    right-ankle-sagittal-WA-plantarflexion
    right-ankle-sagittal-first-half-SLS-plantarflexion
    right-ankle-sagittal-second-half-SLS-plantarflexion
    right-ankle-sagittal-WR-plantarflexion
    right-ankle-sagittal-first-half-swing-plantarflexion
    right-ankle-sagittal-second-half-swing-plantarflexion.
```

6.1.3 Step 3: Enhance the Problems

All that is done here is to see if the problem should be considered in more detail. In Jane's case all the problems are deemed worthy of further consideration.

6.1.4 Step 4: Find Problem Causes

The limited range of motion problem and the contracture problem of the ankle do not go through the causality module since their causes are known just by knowing that they exist. Furthermore, the information stored with the contracture problem causes the ankle's deviations in both halves of SLS to be reclassified as static problems. This means that the cause of the increased plantarflexion in these phases is the joint contracture and not the dynamic muscle activity. Thus, any problem that is classified as static will not be put through the causality module. The remaining motion problems must be processed by the causality module. We will go through the problem right-knee-sagittal-second-half-swing in detail. The relevant muscle data for the knee is shown in table 6-2.

Muscle	Usual Activity	Actual Activity	Strength
gastroc/soleus	off	on	unknown
hamstring	on	on	unknown
quadricep	off	off	not weak

Table 6-2: Example 1: Knee Muscle Data

[19]This problem name identifies increased right hip flexion in WA.

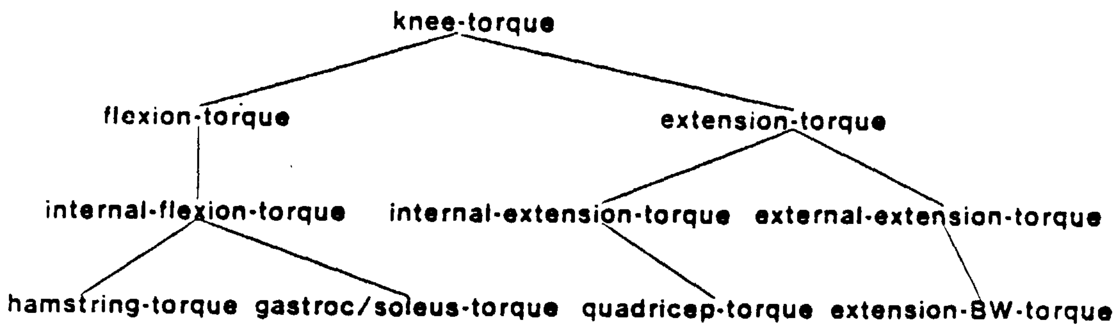


Figure 6-1: Torque Tree for Knee in Second-half-swing

The torque tree in figure 6-1 is instantiated. This gives us the following torque equations:

```
level1: knee-torque             = flexion-torque -
                                  extension-torque
level2: flexion-torque          = internal-flexion-torque +
                                  external-flexion-torque
        extension-torque        = internal-extension-torque +
                                  external-extension-torque
level3: internal-flexion-torque = hamstring-torque +
                                  gastroc/soleus-torque
        internal-extension-torque = quadricep-torque
        external-extension-torque = extension-BW-torque
level4: hamstring-torque   <---- from discrimination nets
        gastroc/soleus-torque <---- from discrimination nets
        quadricep-torque      <---- from discrimination nets
        extension-BW-torque   <---- from body weight rules
```

The system starts with the equations at level 4 and works its way up the tree to level 1.

```
Using the discrimination nets and body weight rule base Dr. Gait-2
gets the following value for the level 4 torques:
hamstring-torque = <increased, {hamstring not weak}>,[20]
```

[20]The torque values are of the form <V, {A1,A2,A3...}> where V is the assertion of the torque's value and the Ai's are the assumptions in the assumption set.

```
                    <decreased, {hamstring weak}>

gastroc/soleus-torque = <increased, {}>

quadricep-torque  = <increased, {}>

extension-BW-torque = <decreased, {}>
```

Using the modified IQ algebra and the torque equations we move up to level 3 and get:

```
internal-flexion-torque
         = <increased, {hamstring not weak}>,
           <increased, {gastroc/soleus-torque >diff
                        hamstring-torque, hamstring weak}>,
           <normal, {gastroc/soleus-torque =diff
                     hamstring-torque, hamstring weak}>,
           <decreased, {gastroc/soleus-torque <diff
                        hamstring-torque, hamstring weak}>

internal-extension-torque = <normal, {}>

external-extension-torque = <decreased, {}>
```

Again using the torque equations we move up to level 2, where we get the following values:

```
flexion-torque = <increased, {hamstring not weak}>,
                 <increased, {gastroc/soleus-torque >diff
                              hamstring-torque, hamstring weak}>,
                 <normal, {gastroc/soleus-torque =diff
                           hamstring-torque, hamstring weak}>,
                 <decreased, {gastroc/soleus-torque <diff
                              hamstring-torque, hamstring weak}>

extension-torque = <decreased, {}>
```

We use the torque equations a final time to get values for the knee-torque:

```
knee-torque
     = <increased, {gastroc/soleus-torque =diff hamstring-torque,
                    hamstring weak}>,
       <increased, {hamstring not weak}>
       <increased, {gastroc/soleus-torque >diff hamstring-torque,
                    hamstring-weak}>,
       <increased, {flexion-torque <diff extension-torque,
                    gastroc/soleus-torque <diff hamstring-torque,
                    hamstring weak}>,
       <normal,    {flexion-torque =diff extension-torque,
                    gastroc/soleus-torque <diff hamstring-torque,
                    hamstring weak}>,
       <decreased, {flexion-torque >diff extension-torque,
```

```
gastroc/soleus-torque <diff hamstring-torque,
hamstring weak}>
```

Imposing the known constraint that the knee-torque is increased causes the system to remove inconsistent values. Thus the remaining values for the knee torque[21] are:

```
knee-torque
     = <increased, {hamstring not weak}>
       <increased, {gastroc/soleus-torque =diff
                    hamstring-torque, hamstring weak}>,
       <increased, {gastroc/soleus-torque >diff hamstring-torque,
                    hamstring weak}>,
       <increased, {flexion-torque <diff extension-torque,
                    gastroc/soleus-torque <diff hamstring-torque,
                    hamstring weak}>
```

This leaves us with four possible explanations for the increased knee flexion in the second half of swing. The four corresponding assumption sets are sent to a scoring routine which uses heuristic knowledge about Jane's disease (CP in her case) to determine which assumptions are more likely and thus score each assumption and assumption set. The top scoring assumption set is "{hamstring not weak}"; it is chosen as the best possible explanation.

All of the other problems are fed to the causality module in a similar manner and an similar analysis is done.

6.1.5 Step 5: Find Therapy

This section illustrates how the therapy module processes this case. First the problems are ranked according to the phase in which they occur, the joint where they occur, and the severity of the problem. This gives the following ranking of the problems:

```
right-ankle-sagittal-first-half-swing-plantarflexion
right-hip-sagittal-second-half-swing-flexion
right-knee-sagittal-second-half-swing-flexion
right-ankle-sagittal-second-half-swing-plantarflexion.
right-ankle-sagittal-WA-plantarflexion
right-knee-sagittal-WA-flexion
right-hip-sagittal-WA-flexion
right-ankle-sagittal-WR-plantarflexion.
right-ankle-LROM
```

[21] Any inconsistent values for the lower torques are also removed.

```
right-ankle-contracture
```

The first pass of the therapy analysis must find the possible therapies and classify them for each of the problems. The program first examines the problem right-ankle-sagittal-first-half-swing-plantarflexion. In doing so it finds that possible bracings are rigid ankle brace and a flexible ankle brace. Each of these bracing therapies check against the appropriate rules to see how they should be classified. Both of these therapies are classified as ok. The possible therapies and their classifications for this problem are shown below. Similarly, possible therapies and classifications are obtained for the other problems.

```
Possible physical therapies: ankle-physical-therapy (ok)
Possible bracings: ankle-rigid-brace (ok)
                   ankle-flexible-brace (ok)
Possible surgeries: gastroc/soleus-lengthening (ok)
                    peroneal-lengthening (ok)
                    peroneal-split-transfer (ok)
                    peroneal-complete-transfer (ok)
```

Each therapy type for each joint receives a score that is determined by the classification of the therapy types for each joint. If a therapy type is "ruled out" or "not desired" then the score is decreased but if a therapy type is "ok" then the score is increased. Each therapy type has four scores. One score for each joint and a global score which is the total of these other three scores.

In the second pass of the analysis the system must pick the desired therapy for each problem. The first step is to pick the preferred therapy type for each joint. The preferred therapy is the therapy type with the highest score for the joint. The global scores are used to break any ties. If there is still a tie after examining the global scores then the least severe therapy is chosen. For the ankle the program chooses surgery, for the knee or the hip physical therapy. Now it needs to select the actual therapies. Looking at the problem right-ankle-sagittal-first-half-swing-plantarflexion it now needs to pick from among the four surgeries that were listed above. It looks at how each of the four surgeries effects the patient's other problems. The gastroc/soleus lengthening is found to be the most helpful and thus it is selected. The system then realizes that this treatment will help all of the ankle and knee problems. Thus, the only problem left to treat is the increased hip flexion in weight acceptance and the second half of swing. Since physical therapy is the desired therapy type for hip problems, the program selects hip physical therapy to help improve the hip's increased flexion.

In summary, the system selects gastroc/soleus lengthening to improve the ankle plantarflexion which occurs through out the gait cycle and the knee flexion which occurs during WA and the second half of swing. The system also recommends physical therapy to help improve the increased hip flexion which occurs during WA and the second half of swing.

6.1.6 Step 6: Write out the Conclusions

```
Problem name: right-ankle-LROM
Problem summary:
  The right ankle shows moderate limited range of motion.
  This appears to be due to co-contracture of
   gastroc/soleus anterior-tibialis which is modified by body-weight.


Problem name: right-ankle-sagittal-first-half-SLS-plantarflexion
Problem summary:
  The right ankle has increased plantarflexion during first-half-SLS.

The primary cause of this problem is:

  Problem name: right-ankle-contracture
  Problem summary:
    The right ankle has a joint contracture which is the cause
    of the noticed deviation.


Problem name: right-ankle-sagittal-second-half-SLS-plantarflexion
Problem summary:
  The right ankle has increased plantarflexion during second-half-SLS.

The primary cause of this problem is:

  Problem name: right-ankle-contracture
  Problem summary:
    The right ankle has a joint contracture which is the cause
    of the noticed deviation.


Problem name: right-ankle-sagittal-second-half-swing-plantarflexion
Problem summary:
  The right ankle has increased plantarflexion during
  second-half-swing.
```

Assuming the following:
1) (patient hypotheses right ankle sagittal second-half-swing dorsiflexion-torque)
has a smaller deviation from normal than
(patient hypotheses right ankle sagittal second-half-swing plantarflexion-torque).

The PRIMARY CAUSE(s) of this problem is(are):

increased gastroc/soleus-torque. which is due to abnormal-firing of a functionally-spastic gastroc/soleus.
increased peroneal-torque. which is due to abnormal-firing of a functionally-spastic peroneal.

The COMPENSATION(s) for this problem is(are):

increased anterior-tibialis-torque. which is due to normal-firing of a non-functionally-spastic anterior-tibialis.

Problem name: right-ankle-sagittal-first-half-swing-plantarflexion
Problem summary:
The right ankle has increased plantarflexion during first-half-swing.
Assuming the following:
1) (patient hypotheses right ankle sagittal first-half-swing dorsiflexion-torque)
has a smaller deviation from normal than
(patient hypotheses right ankle sagittal first-half-swing plantarflexion-torque).

The PRIMARY CAUSE(s) of this problem is(are):

increased gastroc/soleus-torque. which is due to abnormal-firing of a functionally-spastic gastroc/soleus.
increased peroneal-torque. which is due to abnormal-firing of a functionally-spastic peroneal.

The COMPENSATION(s) for this problem is(are):

increased anterior-tibialis-torque. which is due to normal-firing of a non-functionally-spastic anterior-tibialis.

Problem name: right-ankle-sagittal-WR-plantarflexion
Problem summary:
The right ankle has increased plantarflexion during WR.
Assuming the following:
1) (patient hypotheses right ankle sagittal WR dorsiflexion-torque)
has a smaller deviation from normal than
(patient hypotheses right ankle sagittal WR plantarflexion-torque).

The PRIMARY CAUSE(s) of this problem is(are):

increased gastroc/soleus-torque. which is due to abnormal-firing
of a functionally-spastic gastroc/soleus.
increased peroneal-torque. which is due to abnormal-firing
of a functionally-spastic peroneal.

The COMPENSATION(s) for this problem is(are):

increased dorsiflexion-BW-torque.
increased anterior-tibialis-torque. which is due to abnormal-firing
of a non-functionally-spastic anterior-tibialis.

Problem name: right-ankle-sagittal-WA-plantarflexion
Problem summary:
  The right ankle has increased plantarflexion during WA.
Assuming the following:
1) (patient hypotheses right ankle sagittal WA dorsiflexion-torque)
      has a smaller deviation from normal than
   (patient hypotheses right ankle sagittal WA plantarflexion-torque).

The PRIMARY CAUSE(s) of this problem is(are):

increased gastroc/soleus-torque. which is due to abnormal-firing
of a functionally-spastic gastroc/soleus.
increased peroneal-torque. which is due to abnormal-firing
of a functionally-spastic peroneal.

The COMPENSATION(s) for this problem is(are):

increased dorsiflexion-BW-torque.
increased anterior-tibialis-torque. which is due to normal-firing
of a non-functionally-spastic anterior-tibialis.

Problem name: right-knee-sagittal-second-half-swing-flexion
Problem summary:
  The right knee has increased flexion during second-half-swing.
Assuming the following:
1) (patient data right hamstring muscle-strength) equals notweak.

The PRIMARY CAUSE(s) of this problem is(are):

increased hamstring-torque. which is due to normal-firing
of a functionally-spastic hamstring.
increased gastroc/soleus-torque. which is due to abnormal-firing
of a functionally-spastic gastroc/soleus.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased extension-BW-torque.

Problem name: right-knee-sagittal-WA-flexion

Problem summary:
  The right knee has increased flexion during WA.
Assuming the following:
1) (patient hypotheses right knee sagittal WA extension-torque)
      has a smaller deviation from normal than
   (patient hypotheses right knee sagittal WA flexion-torque).

2) (patient data right hamstring muscle-strength) equals notweak.

The PRIMARY CAUSE(s) of this problem is(are):

increased hamstring-torque. which is due to normal-firing
of a functionally-spastic hamstring.
increased gastroc/soleus-torque. which is due to abnormal-firing
of a functionally-spastic gastroc/soleus.

The COMPENSATION(s) for this problem is(are):

increased quadricep-torque. which is due to normal-firing
of a non-functionally-spastic quadricep.

Problem name: right-hip-sagittal-second-half-swing-flexion
Problem summary:
  The right hip has increased flexion during second-half-swing.
Assuming the following:
1) (patient hypotheses right hip sagittal second-half-swing
    extension-torque)
     has a smaller deviation from normal than
   (patient hypotheses right hip sagittal second-half-swing
    flexion-torque).

2) (patient data right hamstring muscle-strength) equals notweak.

The PRIMARY CAUSE(s) of this problem is(are):

increased iliopsoas-torque. which is due to abnormal-firing
of a functionally-spastic iliopsoas.

The COMPENSATION(s) for this problem is(are):

increased hamstring-torque. which is due to normal-firing
of a non-functionally-spastic hamstring.

Problem name: right-hip-sagittal-WA-flexion
Problem summary:
  The right hip has increased flexion during WA.
Assuming the following:
1) (patient hypotheses right hip sagittal WA extension-torque)
      has a smaller deviation from normal than
   (patient hypotheses right hip sagittal WA flexion-torque).

```
2) (patient data right gluteus-maximus muscle-strength)
   equals notweak.

3) (patient data right hamstring muscle-strength) equals notweak.

The PRIMARY CAUSE(s) of this problem is(are):

increased flexion-BW-torque.
increased quadricep-torque. which is due to normal-firing
of a functionally-spastic quadricep.

The COMPENSATION(s) for this problem is(are):

increased gluteus-maximus-torque. which is due to normal-firing
of a non-functionally-spastic gluteus-maximus.
increased hamstring-torque. which is due to normal-firing
of a non-functionally-spastic hamstring.
```

6.2 Example 2

Our second example deals with John Patient. His case is more difficult than Jane's because his major problems are related to muscle weakness, which is unusual for a CP patient. Instead of looking at all of the steps of the analysis in detail, we will examine the parts of the analysis that highlight how Dr. Gait-2 deals with the problems that Dr. Gait-1 could not handle properly.

6.2.1 Finding the Correct Causes for the Knee Problems

Dr. Gait-1 had a lot of trouble in dealing with John's knee. It could not classify the knee's decreased flexion in SLS and it concluded incorrectly that overactive hamstrings were the cause of the increased knee flexion in WA and the second-half of swing. The program also incorrectly suggested hamstring lengthening to help fix the increased knee flexion. We saw that these problems occurred because Dr. Gait-1 did not confirm its implicit conclusions with the muscle data, and its "hard wired" causes made the most likely cause the only possible cause.

Dr. Gait-2 does not suffer from these deficiencies. It uses the muscle data and through the torque equations makes sure it is consistent with the motion data. In this example, if we had stated that the quadricep was definitely not weak, then the program would have found that the data was inconsistent for the knee in SLS. However, we make no such restriction here and we will thus see that a weak quadricep is the cause of the knee's problems in SLS.

As Dr. Gait-2 starts going through the problems to find their causes, it begins with the decreased hip flexion in WA. Several reasonable explanations for the hip's deviation are found. It scores all of them, and we discover that assuming the quadricep is *not weak* yields the most likely explanation. This explanation says that a spastic gluteus maximus is the primary cause of the problem with compensation from a weak hamstring and a decreased flexion body weight torque.

This works well until the increased knee flexion in WA is examined. Then we see the following:

. . .

The system discovers that assuming the quadricep is not weak does not allow for the increased knee flexion in WA.

```
removing the assumption set
  ((eq (patient data right quadricep muscle-strength) notweak))
```

. . .

We see that the system wants to assume that the quadricep is weak. However, this contradicts the assumption that the quadriceps are not weak which was made in examining the hip in WA. Thus, some adjustments need to be made.

```
Cannot add desired environment to right-knee-sagittal-WA-flexion.

The environment is
((>diff (patient hypotheses right knee sagittal WA extension-torque)
        (patient hypotheses right knee sagittal WA flexion-torque))
 (eq (patient data right quadricep muscle-strength) weak))
Will try to make appropriate adjustments.

Looking at other problems to see if can change their
environments to maintain consistency.

I added the environment
((>diff (patient hypotheses right knee sagittal WA extension-torque)
        (patient hypotheses right knee sagittal WA flexion-torque))
 (eq (patient data right quadricep muscle-strength) weak))
to right-knee-sagittal-WA-flexion

I added the environment
((>diff (patient hypotheses right gluteus-maximus WA
         gluteus-maximus-torque)
```

```
        (patient hypotheses right hamstring WA hamstring-torque))
 (eq (patient data right quadricep muscle-strength) weak))
to right-hip-sagittal-WA-extension
```

We see that the chosen environment for the hip in WA problem has been changed to maintain consistency. Thus, the hip in WA also is assuming that the quadricep is weak.

Dr. Gait-2 has no problem with the knee in the first-half and second-half of SLS.

```
I am concluding for
  (patient hypotheses right knee sagittal first-half-SLS
   extension-BW-torque value)
that it should be (decreased). This was done by rule
body-weight-rb-rule11.
I found the bodyweight to be abnormal

(patient hypotheses right knee sagittal first-half-SLS
 extension-ext-torque)
 has the value(s)
 (decreased).

(patient hypotheses right knee sagittal first-half-SLS
 extension-int-torque)
 has the value(s)
 (wnl).

(patient hypotheses right knee sagittal first-half-SLS
 extension-torque)
 has the value(s)
 (decreased).

(patient hypotheses right knee sagittal first-half-SLS
 flexion-ext-torque)
 has the value(s)
 (zero-torque).

(patient hypotheses right knee sagittal first-half-SLS
 flexion-int-torque)
 has the value(s)
 (increased decreased).

(patient hypotheses right knee sagittal first-half-SLS flexion-torque)
 has the value(s)
 (decreased increased).

(patient hypotheses right knee sagittal first-half-SLS knee-torque)
 has the value(s)
 (decreased wnl increased).
```

It now removes the assumptions that lead to improper values for the knee torque.

. . .

Similarly it continues finding the causes of the remaining problems.

The system now writes out its conclusions.

```
Problem name: right-ankle-sagittal-WR-dorsiflexion
Problem summary:
  The right ankle has increased dorsiflexion during WR.
```

This problem was not examined in detail because it is only a mild deviation

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This problem was not examined in detail.


Problem name: right-ankle-sagittal-second-half-SLS-dorsiflexion
Problem summary:
  The right ankle has increased dorsiflexion during second-half-SLS.
Assuming the following:
1) (patient hypotheses right gastroc/soleus second-half-SLS
    gastroc/soleus-torque)
       has a greater deviation from normal than
   (patient hypotheses right peroneal second-half-SLS
    peroneal-torque).

2) (patient data right gastroc/soleus muscle-strength) equals weak.

The PRIMARY CAUSE(s) of this problem is(are):

increased dorsiflexion-BW-torque.
increased anterior-tibialis-torque. which is due to abnormal-firing
of a functionally-spastic anterior-tibialis.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased gastroc/soleus-torque. which is due to normal-firing
of a non-functionally-spastic gastroc/soleus.

The COMPENSATION(s) for this problem is(are):

increased peroneal-torque. which is due to normal-firing
of a non-functionally-spastic peroneal.


Problem name: right-ankle-sagittal-first-half-SLS-dorsiflexion
Problem summary:
  The right ankle has increased dorsiflexion during first-half-SLS.
Assuming the following:
1) (patient hypotheses right gastroc/soleus first-half-SLS
    gastroc/soleus-torque)
       has a greater deviation from normal than
   (patient hypotheses right peroneal first-half-SLS
    peroneal-torque).
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2) (patient data right gastroc/soleus muscle-strength) equals weak.

The PRIMARY CAUSE(s) of this problem is(are):

increased dorsiflexion-BW-torque.
increased anterior-tibialis-torque. which is due to abnormal-firing of a functionally-spastic anterior-tibialis.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased gastroc/soleus-torque. which is due to normal-firing of a non-functionally-spastic gastroc/soleus.

The COMPENSATION(s) for this problem is(are):

increased peroneal-torque. which is due to normal-firing of a non-functionally-spastic peroneal.

Problem name: right-knee-sagittal-second-half-swing-flexion
Problem summary:
The right knee has increased flexion during second-half-swing.
Assuming the following:
1) (patient hypotheses right knee sagittal second-half-swing extension-ext-torque)
has a greater deviation from normal than
(patient hypotheses right knee sagittal second-half-swing extension-int-torque).

2) (patient hypotheses right knee sagittal second-half-swing extension-torque)
has a greater deviation from normal than
(patient hypotheses right knee sagittal second-half-swing flexion-torque).

The AUXILIARY CAUSE(s) of this problem is(are):

decreased extension-BW-torque.

The COMPENSATION(s) for this problem is(are):

decreased hamstring-torque. which is due to normal-firing of a weak hamstring.
increased quadricep-torque. which is due to abnormal-firing of a non-functionally-spastic quadricep.

Problem name: right-knee-sagittal-second-half-SLS-extension
Problem summary:
The right knee has increased extension during second-half-SLS.
Assuming the following:

1) (patient hypotheses right knee sagittal second-half-SLS extension-torque)
has a smaller deviation from normal than
(patient hypotheses right knee sagittal second-half-SLS flexion-torque).

2) (patient data right gastroc/soleus muscle-strength) equals weak.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased gastroc/soleus-torque. which is due to normal-firing of a non-functionally-spastic gastroc/soleus.

The COMPENSATION(s) for this problem is(are):

decreased extension-BW-torque.

Problem name: right-knee-sagittal-first-half-SLS-extension
Problem summary:
The right knee has increased extension during first-half-SLS.
Assuming the following:
1) (patient hypotheses right knee sagittal first-half-SLS extension-torque)
has a smaller deviation from normal than
(patient hypotheses right knee sagittal first-half-SLS flexion-torque).

2) (patient data right gastroc/soleus muscle-strength) equals weak.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased gastroc/soleus-torque. which is due to normal-firing of a non-functionally-spastic gastroc/soleus.

The COMPENSATION(s) for this problem is(are):

decreased extension-BW-torque.

Problem name: right-knee-sagittal-WA-flexion
Problem summary:
The right knee has increased flexion during WA.
Assuming the following:
1) (patient hypotheses right knee sagittal WA extension-torque)
has a greater deviation from normal than
(patient hypotheses right knee sagittal WA flexion-torque).

2) (patient data right quadricep muscle-strength) equals weak.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased quadricep-torque. which is due to normal-firing
of a non-functionally-spastic quadricep.

The COMPENSATION(s) for this problem is(are):

decreased flexion-BW-torque.
decreased hamstring-torque. which is due to normal-firing
of a weak hamstring.

Problem name: right-hip-sagittal-second-half-swing-flexion
Problem summary:
  The right hip has increased flexion during second-half-swing.

The PRIMARY CAUSE(s) of this problem is(are):

increased quadricep-torque. which is due to abnormal-firing
of a functionally-spastic quadricep.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased hamstring-torque. which is due to normal-firing
of a weak hamstring.

Problem name: right-hip-sagittal-WA-extension
Problem summary:
  The right hip has increased extension during WA.
Assuming the following:
1) (patient hypotheses right gluteus-maximus WA
    gluteus-maximus-torque)
        has a greater deviation from normal than
   (patient hypotheses right hamstring WA hamstring-torque).

2) (patient data right quadricep muscle-strength) equals weak.

The PRIMARY CAUSE(s) of this problem is(are):

increased gluteus-maximus-torque. which is due to normal-firing
of a functionally-spastic gluteus-maximus.

The AUXILIARY CAUSE(s) of this problem is(are):

decreased quadricep-torque. which is due to normal-firing
of a non-functionally-spastic quadricep.

The COMPENSATION(s) for this problem is(are):

decreased hamstring-torque. which is due to normal-firing
of a weak hamstring.

Now the system writes out the therapies.

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The therapies for this patient are:
anterior-tibialis-complete-transfer
knee-physical-therapy
hip-physical-therapy
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6.3 Conclusions

We have just seen that Dr. Gait-2 was able to handle the case of John Patient without any trouble, whereas Dr. Gait-1 had a lot of difficulty with this case. Two key ideas in Dr. Gait-2 led to this success. First, the idea of making everything explicit including the assumptions, and second, the idea of having a model of gait to provide a framework for the analysis.

We saw in the second example that making the assumptions explicit pays off. When Dr. Gait-2 examined the increased hip flexion in WA, it chose the leading assumption set which included the assumption that the quadricep was not weak. Later when it examined the increased knee flexion in WA, it discovered that it *must* assume that the quadricep was weak in order to arrive at any explanation. By having the explicit assumptions recorded, Dr. Gait-2 was able to go back and select an alternative explanation for the increased hip flexion in WA, which now included the assumption that the quadricep was weak. Thus, having explicit assumptions allows Dr. Gait-2 to make sure that any assumptions made are consistent throughout the analysis. Furthermore, stating these assumptions to the user allows the user to know exactly what assumptions the system made.

We also saw in the two examples how Dr. Gait-2 was able to use its qualitative torque model of gait as a framework to examine the causes of each problem. The interacting problems could be examined individually because their interactions were taken into account by the model. The bodyweight-torque and the torques of the two-joint muscles[22] capture any interaction between problems. By being able to examine problems individually, Dr. Gait-2 has to know only about the different types of individual problems that can occur. On the other hand, Dr. Gait-1 had to be

[22] These are the muscles which act on two joints. For example, the hamstrings which act on the hip and knee and the quadricep which also acts on the hip and knee.

knowledgeable about the effects of different combinations of problems and could deal only with the combinations that were previously thought of. All of this allows Dr. Gait-2 to handle more cases than Dr. Gait-1.

7. Performance of Dr. Gait-2

7.1 Testing Process

To test the performance of Dr. Gait-2, the domain expert selected a set of cases which would cover a wide range of the types of patients the program might be expected to deal with. The expert selected 22 cases. We then entered the data for these 22 cases into the computer and made Dr. Gait-2 analyze each of them. To analyze the results we decided to compare Dr. Gait-2's output to the gait lab's written reports. When the reports were incomplete[23] we asked the expert to determine if the conclusions reached by the program were reasonable or not.

Dr. Gait-2 has three tasks to accomplish - identify problems, determine their causes and recommend treatments. We decided to look first at how well Dr. Gait-2 performed on each of these three tasks and then draw our final conclusions about the performance of the program. The only problems, causes and treatments examined were those dealing with the events in the sagittal plane since this is the only plane that Dr. Gait-2 currently deals with.

7.2 Testing Results

7.2.1 Identification of Problems

In reviewing the 22 written reports we found a total of 170 problems. Of these problems, Dr. Gait-2 identified 151, which is almost 89% of the problems. Most of the problems that Dr. Gait-2 omitted were limited range of motion problems. It appears that the triggering conditions for this class of problems is too restrictive. Such problems as plantarflexion thrusts and attempts at dorsiflexion were also omitted. The system would need to gather additional data and have problem frames with triggering conditions to be able to identify these omitted problems.

Dr. Gait-2 also identified 46 problems which the reports did not mention. Some of these additional problems were minor. The others were probably not mentioned because they were either not found or were perceived to be insignificant.

[23] Not all problems had causes listed with them. Some reports did not list any therapies.

It appears that Dr. Gait-2 is very successful at identifying problems. With some refinements to the knowledge base it is possible that its performance on this task could be made even better.

7.2.2 Finding Causes of Problems

Dr. Gait-2 is also adept at identifying the causes of the problems. For the 196 problems it identified it only found incorrect causes nine times. Thus, Dr. Gait-2 found the correct causes 96% of the time. Six of the nine mistakes took place because the system thought the quadricep has more power to flex the hip than it actually does. The system knows how muscles act on a joint but not to what degree they can move the joint. Two of the nine mistakes occurred when it failed to recognize body weight as the cause of the problem and when there was excessive knee flexion at the knee in WA. This suggests that there is a missing rule in the body weight rule base. The only remaining problem that was misdiagnosed is the attributing of too much flexing power to the gastroc/soleus at the knee during swing. We thus see that the system does very well at determining the causes of the identified problems. Most of its mistakes occur because it doesn't know to what degree particular muscles can influence the various joints.

7.2.3 Therapy Selection

After analyzing the 22 cases, Dr. Gait-2 recommended the correct therapy ten times, partially correct therapy ten times, and incorrect therapy once.[24]

There are two situations in which Dr. Gait-2 has problems in prescribing therapies. In six of the cases it suggests gastroc/soleus-lengthening when it is inappropriate. The problem is that the program doesn't check for the effect of a therapy on *normal* motions. In all of these cases the patient had normal ankle motion in single limb stance and thus lengthening the gastroc/soleus will hurt the patient's gait severely. The surgery would prevent the patient from keeping his ankle from flexing during stance.

The other problems concern bracing. If the patient has a joint contracture which is severe enough to prevent him from moving his joint into a neutral position then he cannot wear a brace.

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[24] An astute reader might notice that this only covers 21 cases. One case was not considered because it had faulty data.

This situation occurred a few times. To alleviate the problem of the system incorrectly recommending bracing in this case, the system could ask an additional question to assess the severity of any observed joint contracture and eliminate bracing when it is inappropriate.

Thus, Dr. Gait-2 did reasonably well in prescibing therapies but we noted two deficiencies that hinder its performance: not considering the effect of contractures on braces, and not considering the effect of therapies on normal motions. These two deficiencies would have to be corrected in order for Dr. Gait-2's performance to be improved.

7.3 Conclusions About Performance

Overall the system performs well at all three of its tasks. Most of its problems seem to be due to lack of knowledge. One problem is the the lack of understanding of the relative influences of different causes on a problem. The system might find that the cause of the knee flexion is due to the gastroc/soleus, hamstring and body weight but it does not realize that the hamstring and body weight are the major culprits. The other problem is not checking the effect of a considered therapy on normal motions. One could change the therapy module so it not only checks the effect of a therapy on all of the problems but also on the normal motions as well It is hard to say how difficult it would be to do this.

8. Conclusion

8.1 Summary

Dr. Gait-2 is an expert system that analyzes human gait. Using a torque model of gait, it is able to capture enough principles of gait to do causal reasoning. This torque model leads to a system which is more robust than previous gait analysis systems. We saw that it can deal with cases that the prototype system, Dr. Gait-1, cannot. Furthermore, its model of gait is not disease specific. Thus, the gait model developed can be used in systems which diagnose gait disorders of a different etiology.

The first AIM systems made the assumption that there was only a single cause of the patient's problems. Later systems, such as ABEL, tried to relax this constraint and allow for multiple causes of the patient's problems. We have seen that in doing gait analysis for cerebral palsy patients, there are almost always multiple causes. We saw that Dr. Gait-2 is able to deal with these multiple problems by using a model of gait. The qualitative torque model of gait gives Dr. Gait-2 a framework to keep track of the interactions of the various problems. The body weight torques and the torques of the two joint muscles provides the mechanism for capturing the interactions. By keeping the interactions and assumptions explicit the system is able to arrive at possible causes for each motion deviation. By then using disease specific knowledge the system can choose the most probable cause from among the possible ones.

8.2 Future Directions

Dr. Gait-2 is not the final solution for a gait analysis program. There are still several limitations that need to be overcome and future directions that merit further exploration.

Dr. Gait-2's treatment of time is very elementary. The gait cycle is divided up into a fixed number of phases and each phase is treated as a single point in time. Dr. Gait-2's only knowledge about these phases is that one phase precedes another. Thus, the system merely looks at the gait data at six instances. This leads to conclusions that describe only what is happening in each phase. The system's limited notion of time makes it hard for it to produce a more global summary. A possible solution to this is to allow the significant phases to be determined dynamically as opposed to statically as it is currently implemented. The system could determine which events in the patient's gait cycle are significant and then make a phase out of each time period between significant events. Furthermore, the time tag for a conclusion should be allowed to grow if possible. For example, if the system determines that hamstring lengthening should be recommended for the knee in WA the first and second half of SLS, then the system should say that hamstring lengthening is recommended for the knee to correct the deviations in stance.

The qualitative torque model of gait needs to be improved. The model's knowledge of how torques are produced by the muscles should be enhanced. Currently, it only takes the emg signal and the muscle strength into account. However, the torque of the muscle is also affected by the position of the muscle relative to the joint. This positioning changes as the joints change their relative positions. The system also could use knowledge of the relative strengths of competing muscles at a joint. It would be helpful to know that the gastroc/soleus contributes about 85% of the plantarflexion torque while the peroneals only contribute about 15% of the plantarflexion torque. Thus, if the ankle shows increased plantarflexion and both the gastroc/soleus and the peroneals are spastic, then it should know that it would not be very beneficial to correct the peroneal and not the gastroc/soleus.

The model cannot handle all situations. In Dr. Gait-2, if the system determines that there is a joint contracture, then it reclassifies the appropriate motion deviations as static and they do not go through the causality module. A better solution would be to encompass the contracture in the model of gait. The contracture would have to be some special torque that turned on only when the joint angle was below a certain value and when on could not be overcome by any opposing torque. Currently, the gait model also cannot deal with patients who are using assistive devices such as a walker or crutches. One answer to this would be to change the body weight rule base so that it would take assistive devices into account when figuring out the body weight torque.

Gait analysis is a difficult skill to learn. It is possible that this gait analysis system could be modified for use in teaching. Such a modification would require extensive work on the system. The need for a good user interface would then be essential. The system would also need to formulate strategies on how to teach gait analysis. The system would have to have a model of the student to know better how to tailor the teaching to the particular student. The control of the modeling of gait also might have to be changed. In Dr. Gait-2 the torques are arranged in a tree. The torques get values by first filling in the values for the leaves and then percolating the values up to the root. One could imagine that if a student were using the system he might try to hypothesize about a value for a particular torque and then see its effect. This means that the system should allow any torque value to be set or retracted at any time. To do this the assumption based truth maintenance system would have to include justifications for each assertion, as was originally intended by de Kleer. Including justifications and modifying some of the access routines to the values maintained by the assumption-based TMS should allow for the appropriate characteristics.

8.3 Final Remarks

The work presented in this thesis took the existing AI techniques of knowledge based systems, modeling systems with qualitative equations and assumption-based truth maintenance systems, and applied them to the domain of gait analysis. The resulting system is a contribution to the field of gait analysis because it uses a qualitative model of gait which makes it more powerful than the previous gait analysis programs. The resulting system is also a contribution to the field of Artificial Intelligence in Medicine because it demonstrates that a qualitative model that uses assumptions to account for incomplete data is a feasible way to perform data analysis in the medical domain.

I.

Table I-1: Muscle Data for Dr. Gait

Muscle Name	When Usually On	Muscle Action
adductor	WA, WR	adducts thigh
anterior tibialis	WA, swing	Dorsiflexes and inverts foot
gastroc/soleus	SLS	Plantarflexes ankle, flexes knee
gluteus maximus	WA	extends and abducts thigh
gluteus medius	WA, SLS	abducts thigh
hamstring	WA, second-half swing	extends hip, flexes knee
iliopsoas	WR, first-half swing	flexes hip
peroneals	SLS	plantarflexes ankle
posterior tibialis	SLS	plantarflexes ankle
quadriceps	WA	extends knee and flexes hip

References

[Aikens 83] Aikens, J., Kunz, J., Shortliffe, E. and Fallat, R.
PUFF: An Expert System for Interpretation of Pulmonary Function Data.
Computers in Biomedical Research 16:199-208, 1983.

[Clancey 81] Clancey, M. and Letsinger,R.
NEOMYCIN: Reconfigurating a Rule-Based System for Application to Teaching.
In *Proceedings of the Seventh International Conference on Artificial Intelligence*, pages 829-836. Joint Conference on Artificial Intelligence, 1981.
In volume 2.

[de Kleer 79] de Kleer, Johan.
The Origin and Resolution of Ambiguities in Causal Arguments.
In *Proceedings of the Sixth International Conference on Artificial Intelligence*, pages 197-203. Joint Conference on Artificial Intelligence, 1979.

[de Kleer 84] de Kleer, Johan.
Choices without Backtracking.
In *Proeedings of the National Conference on Artificial Intelligence*, pages 79-85. 1984.

[Dzierzanowski 84] Dzierzanowski, J.
Artificial Intelligence Methods in Human Locomotor Electromyography.
PhD thesis, Vanderbilt University, 1984.

[Fagan 80] Fagan, L.
VM: Representing time-dependent relations in a medical setting.
PhD thesis, Stanford University, 1980.

[Inman 81] Inman, V., Ralston, H., Todd, F.
Human Walking.
Williams and Wilkins, Baltimore, MD, 1981.

[Lesser 77] Lesser, V. and Erman, L.
A Retrospective View of the Hearsay-II Architecture.
In *Proceedings of the Fifth International Conference on Artificial Intelligence*, pages 790-800. Joint Conference on Artificial Intelligence, 1977.
In volume 2.

[Miller 82] Miller, R., Pople, H. and Myers, J.
Internist-1, An Experimental Computer-Based Diagnostic Consultant for General Internal Medicine.
New England Journal of Medicine 307(8):468-476, August, 1982.

[Patil 81] Patil, R.S.
Causal Representation of Patient Illness for Electrolyte and Acid-Base Diagnosis.
PhD thesis, Massachusetts Institute of Technology, October, 1981.

[Pauker 76] Pauker, S. G., Gorry, A., Kassier, J. and Schwartz, W.
Towards the Simulation of Clinical Cognition: Taking the Present Illness by Computer.
American Journal of Medicine 60:981-996, 1976.

[Rajagopalan 84] Rajagopalan, Raman.
Qualitative Modeling in the Turbojet Engine Domain.
In *Proeedings of the National Conference on Artificial Intelligence*, pages 283-287. 1984.

[Sandell 84] Sandell, H.
GENIE User's Guide and Reference Manual.
Technical Report 84-003, Electrical and Biomedical Engineering Vanderbilt University, July, 1984.

[Shortliffe 76] Shortliffe, E.
Computer-Based Medical Decision Making: MYCIN.
American Elsevier, New York, 1976.

[Simon 78] Simon, S., Mann, R., Hagy, J., Larsen, L.
Role of the Posterir Calf Muscles in Normal Gait.
The Journal of Bone and Joint Surgery 60-A(4):465-472, June, 1978.

[Tracy 79] Tracy, K., Montague, E., Gabriel, R., Kent, B.
Computer-Assisted Diagnosis of Orthopedic Gait Disorders.
Physical Therapy 59(3):268-277, March, 1979.

[vanMelle 80] van Melle, W.
A domain-independent system that aids in contructing knowledg-based consultation programs.
PhD thesis, Stanford University, 1980.

[Weiss 78] Weiss, S., Kulikowski, C., Amarel, S. and Safer,A.
A Model-Based Method for Computer-Aided Medical Decision Making.
Artificial Intelligence 11:145-172, 1978.

[Winarski 74] Winarski, D.
A Computer Simulation of the Human Gait Cycle for Medical Applications.
Technical Report 12, University of Michigan Medical School Department of Physical Medicine and Rehabiliataion, 1974.

[Wong 83] Wong, M., Simon, S., Olshen, R.
Statistical Analysis of Gait Patterns of Persons with Cerebral Palsy.
Statistics in Medicine 2:345-354, 1983.