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Report developed under SBIR contract. This Phase I SBIR demonstrated a novel technique for physics-based simulation of realistic human behavior. The technique combines a control system that uses life-like motion recorded from live humans with versatile and rigorous physics-based simulation. The project demonstrated use of the technique in the context of human running at different speeds, with varying backpack loads and over varying terrain.

The next step is to use these human simulations to create a "Digital Biomechanics Laboratory" (DBL.) DBL will be used for simulation based acquisition (SBA) and new product testing. DBL will allow experiments that are too expensive, difficult or dangerous to perform on live humans, and augment experiments on live humans by permitting a wider range of variations. The experiments will be used to evaluate new clothing, footwear, equipment, weapons, tactics, and movement strategies. Rapid product evaluation cycles using simulated humans in the DBL will shorten product development and acquisition cycles.

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HUMAN DYNAMICS MODELING:

THE DIGITAL BIOMECHANICS LAB

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SBIR PHASE I
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HUMAN DYNAMICS MODELING: THE DIGITAL BIOMECHANICS LAB

HUMAN DYNAMICS MODELING: THE DIGITAL BIOMECHANICS LAB

Abstract

This Phase I SBIR demonstrated a novel technique for physics-based simulation of realistic human behavior. The technique combines a control system that uses life-like motion recorded from live humans with versatile and rigorous physics-based simulation. The project demonstrated use of the technique in the context of human running at different speeds, with varying backpack loads and over varying terrain.

The next step is to use these human simulations to create a "Digital Biomechanics Laboratory" (DBL.) DBL will be used for simulation based acquisition (SBA) and new product testing. DBL will allow experiments that are too expensive, difficult or dangerous to perform on live humans, and augment experiments on live humans by permitting a wider range of variations. The experiments will be used to evaluate new clothing, footwear, equipment, weapons, tactics, and movement strategies. Rapid product evaluation cycles using simulated humans in the DBL will shorten product development and acquisition cycles.

A. Introduction

The Army studies human physiology and performance as a part of its mission to enhance the war-fighting capabilities of the soldier. Goals of these studies are to :

- optimize human performance through advanced equipment design and training
- minimize the risk of injury
- minimize the time and cost of developing and acquiring new equipment
- predict human performance in a wide range of scenarios

The work done under this SBIR Phase I grant tested the feasibility of implementing a Digtital Biomechanics Lab (DBL), a physics-based human simulation tool that can be used by the Army and others to achieve these goals.

In BDI's vision of the DBL, simulated humans will work to perform useful tasks under novel conditions. Equipment designers will use the DBL to evaluate the benefits and effects of clothing, footwear, chem / bio gear and other equipment. Rapid evaluation of products and military tactics will improve group performance and shorten the product development and acquisition cycle. Researchers will use the DBL to study the mechanics and principles of human performance and injury. The DBL will allow experiments that are too costly, difficult, or dangerous to perform with human subjects.

The Digital Biomechanics Lab will complement live subject experimentation, reducing its cost and effort, and expanding its utility and range. Currently, experiments that study human performance and new equipment involve live subjects. Experimental subjects perform predefined tasks while researchers gather data. For example, they collect oxygen consumption data to measure energy expenditure, kinematic data to measure body movement, and force plate data to estimate ground reaction forces. These experiments give designers feedback on the effectiveness of the equipment. Since it is impossible to test the many variations of each design, researchers also create models to predict human performance under new conditions by correlating experimental variables. They might show that backpack weight correlates to oxygen consumption and produce an empirical model predicting energy expenditure for new backpack designs. These kinds of live subject experiments and predictive modeling currently play an essential part of human performance study and they will continue to do so.

However, there are shortcomings to experiments with live humans. Live subject tests are complex, risky, and expensive. Live subject tests do not provide complete data from the subject's body. For example, using current methods, it is impossible to know the internal joint loads and stresses of the subject. Finally, some tests are impossible to perform on live subjects, such as tests that might lead to injury. The Digital Biomechanics Lab will provide simulation tools that complement live subject testing to overcome these deficiencies. The DBL would be useful to biomechanics researchers, equipment designers, and strategic analysts whose mission it is to optimize the performance and guard the safety of the troops.

B. Phase I Summary: Realistic Simulation Of Running

While the Digital Biomechanics Laboratory we envision does not yet exist, our Phase I results give us confidence that it is within reach. In Phase I we demonstrated a new kind of physics-based simulation of realistic human running. Using a novel control system design technique invented at BDI that combines the realism of motion capture data with task level robot control theory, we have created simulations of human running (Figure 1) with the following features:

- stable controlled running that uses physics-based calculations
- most lifelike simulated motion to date
- lifelike response to disturbances
- accommodation to variable backpack loads
- variable running speed
- accommodation to variations in terrain

Simulation experiments produced data including kinematic data, energy consumption, foot-ground reaction forces, and joint loads (Figure 2). We have included a video tape with this proposal that summarizes the results of this project.

Figure 1: In Phase I we produced physics-based simulations of running at various speeds with varying backpack loads.

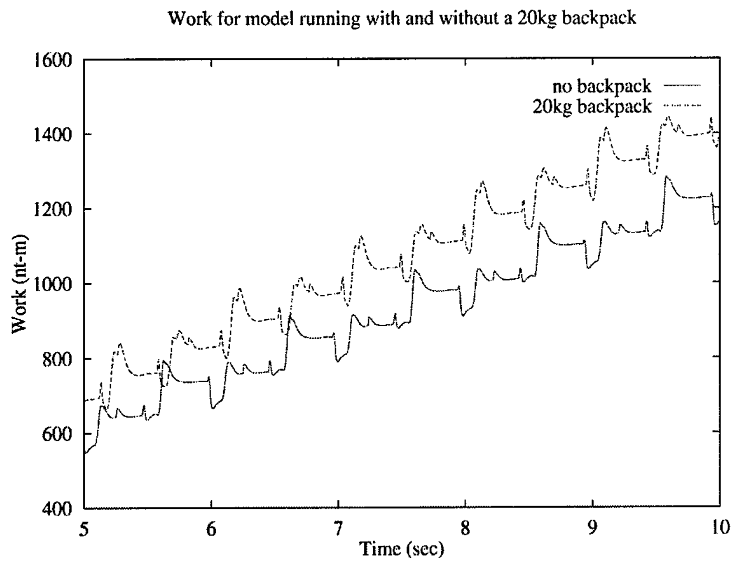

Figure 2: Data from a running experiment showing the accumulated mechanical work done by each of the characters shown in Figure 1. They are running at 3.9 m/s. The backpack weighs 20 kg. Each character uses the same control system with only minor changes in control system parameters to accommodate the extra load. The runner with the backpack is doing more work to run the same speed.

In Phase I we identified the key technical problem hindering the development of the Digital Biomechanics Lab to be the lack of **control systems** that can coordinate the joints of a dynamic human model to create life-like motion. The control system plays the part of motor cortex and cerebellum and spinal cord for the simulated human. It coordinates the activity of the muscles and joints of the human model (Figure 3). The control system design method we invented for this project combines recorded human motion and task-level control. The recorded data serves as nominal joint motion for the control system to emulate. By itself this control approach could not produce dynamically stable human motion. However, by adjusting the nominal motion with a task level controller that monitors the overall goals such as dynamic balance and running speed we are able to produce dynamically stable, controlled running.

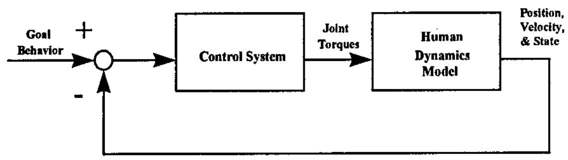

Figure 3: A block diagram showing the role of the control system in a physics-based human simulation. The human model is represented by a set of non-linear equations of motion which describe how the body moves when external forces or joint torques are applied to it. The control system monitors progress towards the goal and computes joint torques to accomplish the task.

C. The Ideal Human Simulation System

The ideal human simulation system will be capable of producing life-like, controlled human behavior. It will include physics-based simulation for its flexibility in changing parameters and it's ability to produce realistic data. It should provide for 3D visualization and analysis of the physical data, and ideally, it should run at interactive rates on commonly available computers. After discussing each of these features we describe the current state-of-the-art in simulation technology with regard to this ideal.

C.1 Realistic, Controlled Human Activity

The need for accurate simulations of human activity is the central issue addressed in this proposal. To test the design and effect of equipment on human performance, we must simulate working activity like running, walking, crawling, standing, climbing, etc. We want to use simulation to answer questions such as, "Is the equipment too heavy?" or "Can the load be better distributed?" "Does the equipment impede normal motions?" These questions must be analyzed in the context of useful human tasks. Furthermore, we want to be able to direct experimental subjects to perform these tasks using high-level commands such as, "Stand up, run to the wall, then crouch behind it" without the need to program each detail.

C.2 Experimental Capacity

The DBL must allow the simulated human to perform tasks under a range of conditions and they must provide data for analysis. The user will vary equipment, body type of the subject, environment, and task strategies. The user will choose variables to measure such as, speed, joint loads, ground forces, equipment-body interface forces, energy consumption, and heat dissipation. The data must be accurate and physically realistic. The experimental design must be flexible.

C.3 3D Visualization

In addition to collecting and plotting data, the DBL will have facilities for viewing the behavior in 3D and in real time. There is no substitute for watching the simulated human perform the experiment. Observers can immediately see problems that can take hours to assess through examination of numbers or plots of data. The engineer should be able to observe the experiment from any vantage point. Simultaneously viewing the subject and visual representations of physical data such as forces or energy can also help the user formulate cause and effect relationships.

C.4 Interactive Performance

Ideally one could run and observe experiments in real time to make the experimental cycle short and increase a simulation's utility. For most experiments, it is not possible to run in real time on lower end computers, but very possible on higher end computers. Short of this ideal, the ability to run simulations at interactive rates is necessary to make simulated experiments useful.

D. Background: The State-of-the-Art in Human Simulation

In this section we review the state-of-the-art in human simulation. Current simulation systems vary broadly in the techniques they use to model human motion. None currently provide the functionality needed in the Digital Biomechanics Laboratory. Figure 4 is a simple representation of the breadth of simulation techniques currently in use. At one extreme are techniques that use either hand crafted or recorded data for animation purposes. These produce nice looking behavior but are not versatile and do not provide biomechanics data. At the other extreme are algorithmic approaches that compute simulated data from constitutive equations.

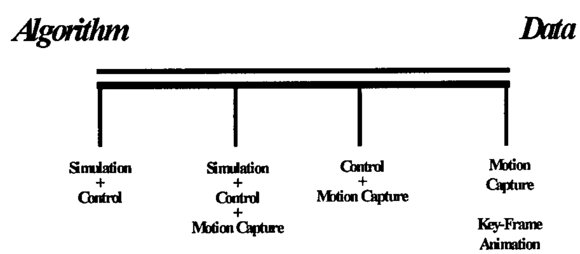

Figure 4: Range of simulation strategies. At one extreme are animation techniques. At the other extreme is physics-based simulation and control. *DI-Guy* combines recorded data with control to enable interactive performance. The DBL will combine recorded motion with physics-based simulation and control to provide realistic, life-like behavior.

Table 1 summarizes existing classes of human simulation and the proposed Digital Biomechanics Lab with respect to the features of an ideal human simulation system outlined in the previous section. There is currently no human simulation system that incorporates all the most important features. The DBL will address this need. Next we describe each of the classes of simulation which represent the state-of-the-art.

Table 1: Relative Advantages of Three Different Types of Simulation Systems

Features	Physics-Based	Inverse Dynamics	Inverse Kinematics	Recorded Motion	DBL
Realistic, Controlled Human Activity		X		X	X
Experimental Capacity	X	Data but no flexibility	Limited data		X
Visualization	X	X	X	X	X
Real-Time Performance			Limited	X	

D.1 Recorded Data Animation

This is the realm of traditional key frame animation and newer motion capture techniques in which sensors record the motion of an actor during a performance. These systems are capable of realistic, life-like motion because the data is either hand crafted or recorded from human actors. Real-time display is possible because the motion and thus the images can be pre-computed. However, there is typically no associated physical data that could be used for analysis and the motions can not be changed for experimentation. This technique may employ an inverse kinematics solution to solve for joint angles from the sensor data.

Figure 5: Toy Story used data oriented animation techniques.

D.2 DI-Guy™

DI-Guy ™ is a COTS visual simulation product available from Boston Dynamics, Inc. (Koechling 98). It is used to create real-time displays of animated soldiers that respond to high level commands. These characters use motion recorded from live soldiers, motion blending techniques, and high-level control systems. The motion is realistic because it derives from recorded data. The characters respond to user commands such as run, walk, crawl, shoot, die. DI-Guy does not use physics-based simulation so it can not provide the kind of data necessary for the Digital Biomechanics Laboratory. The proposed DBL builds upon what we have learned from DI-Guy, but goes way beyond DI-Guy.

Figure 6: DI-Guy uses motion capture and control systems.

D.3 Inverse Kinematic Simulation

Another common technique for simulating human behavior relies on inverse kinematics (IK). JACK is an example of such a system (Badler89). This is a computational technique that uses information regarding the link-joint structure of the model. Inverse kinematics refers to the calculation of a set of joint angles that place the hand or foot in a desired position. The IK algorithms are flexible enough to provide limited experimental capacity and some may run in real-time. IK algorithms are important in many motion capture systems for converting recorded data into data required to animate an articulated model. Advanced IK techniques may consider joint limits, approximate static joint torques or forces required to support a load, but they do not generally consider inertial or dynamic loads. Unless they use recorded data as input, the movement resulting from IK systems is generally not life-like, and the lack of a deep model of behavior and the underlying dynamics of the human body and its control greatly limits it's utility.

Figure 7: JACK uses inverse kinematics techniques.

D.4 Inverse Dynamics Simulation

Inverse dynamics is a simulation technique that produces detailed force and acceleration data. Recorded human motion data is combined with an inertial model of the human to compute the forces that would allow the model to replicate the recorded motion. A common application of this technique is to solve for joint load data from recordings of body motion and force plate data. This approach lacks versatility because the solution is a slave to the pre-recorded data. Any change that may result in new joint position data, for example running down a step instead of running on level ground, requires new input data. In other words, the simulation can not inherently change its motion to accommodate new experimental conditions.

D.5 Physics Based Simulation

Physics-based human simulation employs a mathematical formulation of the physical laws which govern the movement of the human body. Newton's laws are applied to the mass, inertia, and link-joint structure of the human body. Forces and torques applied to bodies produce accelerations which are integrated over time to yield velocity and position. Forces and torques arise from gravity, contact with other moving bodies or the ground, and the activation of muscles which apply forces across joints. Physics-based simulation provides the most information and is the most flexible of the simulation systems mentioned here. However, it is computationally expensive and difficult to make produce realistic task level behavior.

There are several important applications of physics-based human simulation that do not need to demonstrate task level behavior. Simulations of passive falling, colliding, or accelerating humans may not require task level behavior because the primary effects being studied are those due to inertial or gravitational forces. Rocket sled tests, car crashes, and unconscious falling are common applications. Currently available software such as Adams Android™ provide this functionality (Figure 8). However, if task level behavior is required, a control system must be included to coordinate the activation of the muscles and joints to produce the behavior.

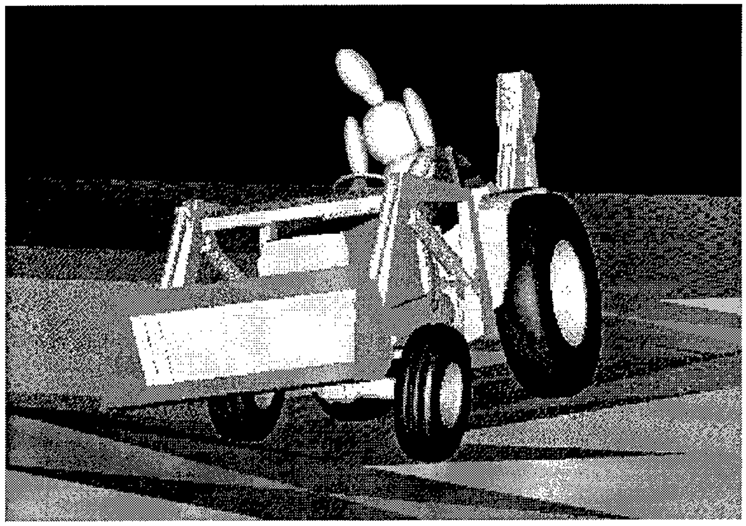

Figure 8: Adams Android is well suited to modeling passive falling, colliding, or accelerating motions. It can not f produce life-like controlled behavior like running and walking.

There are few examples of physics-based simulations that produce life-like behavior. Hodgins (Hodgins98, Hodgins96, Hodgins95), a former member of our research team from MIT, has simulated 3D running, bicycling, and simple gymnastic and diving maneuvers. Playter has simulated planar running and gymnastic maneuvers (Playter96, Playter94). These examples employed task-level control principles to maintain dynamic stability. Most of these examples, while an improvement over previous work, still produced motion that was easily recognized as simulated. Furthermore, these simulations used specially tuned and painstakingly programmed control systems that reproduced a limited range of behavior. What is still needed is the creation of a simple technique for producing the control systems that will enable a broader range of life-like human behavior. The DBL includes the control design technique demonstrated in our Phase I project to solve this problem.

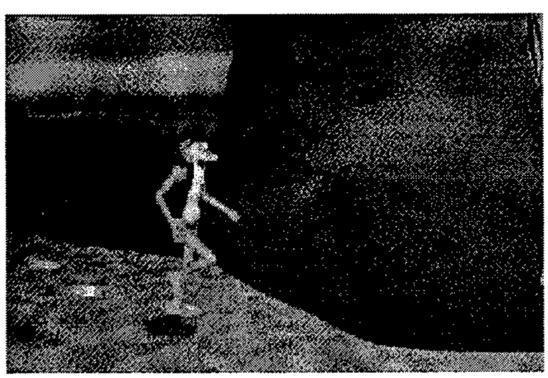

Figure 9: Hodgins techniques for animating character motion uses physics-based simulation and task-level control.

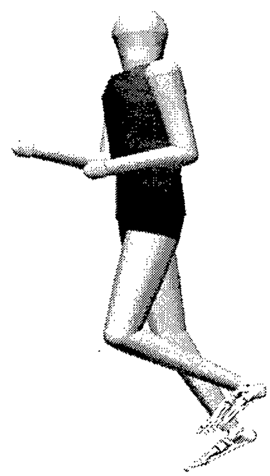

Figure 10: BDI's physics-based simulation of a runner with complex foot model used task-level control to produce dynamically stable running.

The Digital Biomechanics Lab will combine the best of the previously described simulation systems. In the DBL ,inverse kinematics are used to transfer motion capture data into joint angle data that can then be used as input to the control system. This combination provides the realistic motion of recorded motion with the flexibility of physics-based simulation and control. Our approach also has similarities to inverse dynamics. In a sense, we are using a servomechanism and the desired trajectory from motion capture data to solve the inverse dynamics problem. The servomechanism computes joint torques to nearly replicate the motion capture data as is the case for the inverse dynamics solution. The difference is that the servomechanism solution can be easily combined with a task level controller to modify the behavior or accommodate disturbances.

E. Results of Phase I Project: Physically Realistic Simulation Using a Novel Control Design Technique

The goal of Phase I was to demonstrate the feasibility of building the Digital Biomechanics Laboratory. This goal involved demonstrating a control design method that would enable physics-based simulation of a range of realistic, controlled, task-level behavior. By combining recorded human motion and task level control principles into a control system, we have demonstrated simulated planar running that sets a new standard in terms of the realism of the overall motion. Besides enabling the most realistic physics-based simulated motion to date, this technique is extensible to variations in motion and experimental conditions as needed in the Digital Biomechanics Laboratory. The key is to use recorded human motion inside the control system as the starting point for the design of task level controllers.

E.1 Simulation Results

We built a dynamic simulation of a planar human model that has thirteen degrees-of-freedom. The inertial properties of the model were derived using the approach of Yeadon (Yeadon84).We applied Yeadon's approach using anthropometric measurements taken from a retired Army Ranger from whom we recorded motion data. The simulation software for the human was created automatically from a high level description of the model. It included optimized equations of motion, numerical integrator, a graphical user interface for interactively running simulations, and 3D visualization software. Using the control design techniques we described above we created simulations of the model for the following cases:

- running at a range of speeds (2.5-3.9 m/s), Figure 11
- running with a variety of backpacks (5,10,20 kg), Figure 12
- running over a step down (10 cm), Figures 13, 14

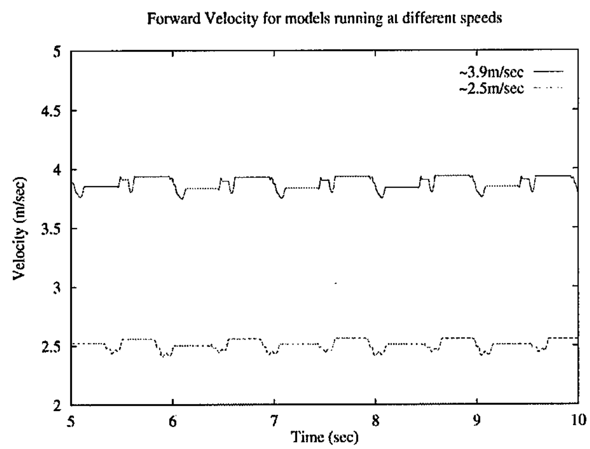

Figure 11: Simulated data showing running speed for two different simulated experiments.

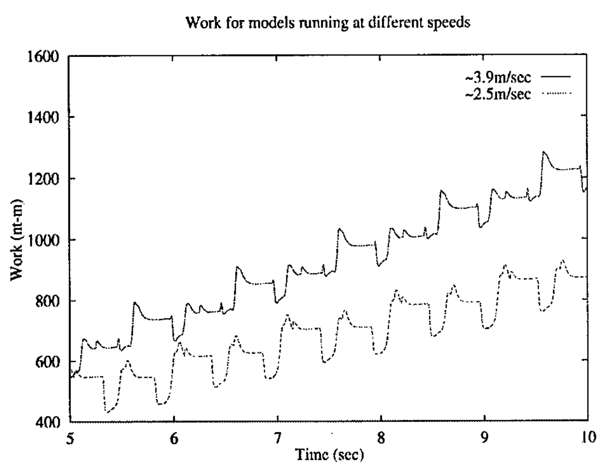

Figure 12: Simulated data showing accumulated mechanical work for two models running at 2.5 and 3.9 m/s.

The controllers for each of these cases were nearly identical. They differed by the values of task-level control parameters or by the recorded data used as the nominal goal trajectories for the servomechanisms. The controllers produced dynamically stable running. No special accommodations were made to enable the running over the step down.

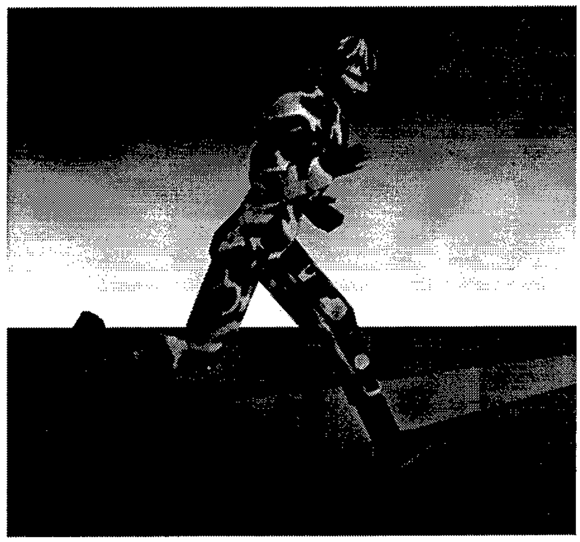

Figure 13: Screen image from a simulated run down a 50 cm step. The runner eventually fell down after several additional steps although a runner for a 10 cm step remained stable. The control system allowed the runner to accommodate the step without additional programming effort.

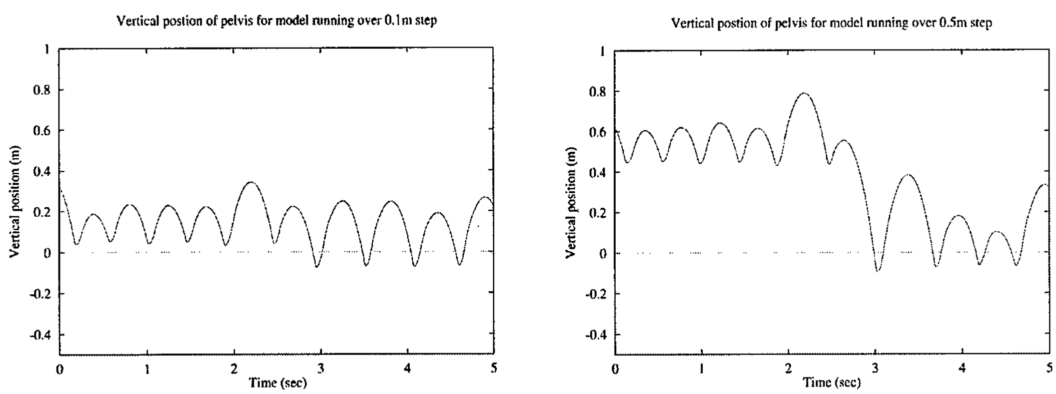

Figure 14: Simulation data showing height of the pelvis while running over of two different sized steps down (10 cm and 50 cm).

The simulation system includes a 3D visualization program for viewing the simulated characters as they run (Figure 13.) Another important element of this simulation system is a data analysis program that allows users to examine time history or phase plots of the simulated experiments (Figure 15).

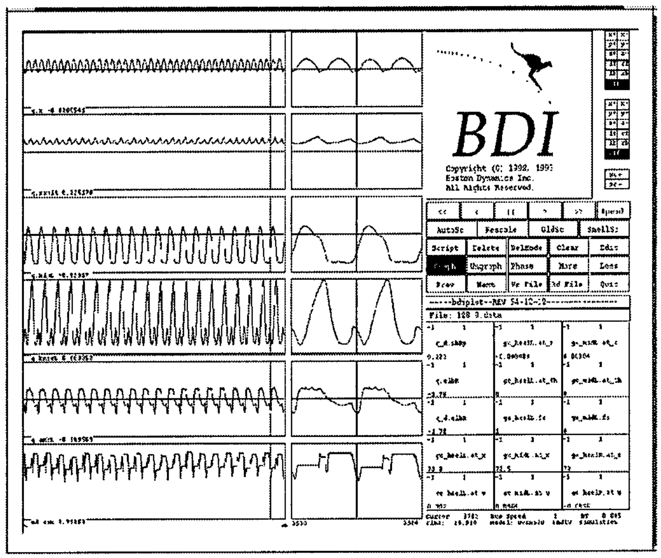

Figure 15. BDIPlot is a data analysis program that allows users to examine time history or phase plots of the experimental data.

E.2 Simplifying Control System Design Using Recorded Motion

Control system design involves finding ways to manipulate the powered degrees of freedom (joints) of a system to accomplish a specified task. A simple task such as moving a limb from one point to another can be accomplished with many different trajectories. The complexity of the solution will depend upon the number of degrees of freedom in the limb. An effective control design strategy must choose among the many possible solutions.

One approach that engineers have used to find a unique solution to complex control problems is to use optimization criteria like minimizing time, torque, energy, or average errors. While some approaches such as minimum jerk optimization (minimizing the derivative of acceleration) or impedance control (Hogan87, Hogan80) produce solutions that resemble human movement, they are difficult to apply to complex movements like running.

Another approach to control system design for complex systems is to use a simplifying principle that eliminates the excessive number of possible solutions. One such simplifying principle that we have used is to make a simulated human run like a simpler mechanism that we already know how to control. In previous work we adapted control algorithms for a bipod robot to the control of human running. In this approach the extra degrees of freedom of the human model are constrained to follow the simpler mechanism of the robot. The problem with this approach is that you end up with a simulated human that runs like a hopping robot! We need yet another way of simplifying the control problem that is more indigenous to human movement.

Our approach is to use standard patterns of human movement as a simplifying principle for control system design.

E.3 Recorded Joint Data as Input to Joint Servomechanisms

We use recorded human motion as a template for the goal motions of a human simulation. We solve for joint angle data from recorded human motion and use this data as the goal for a set of joint servomechanisms of the human model. These servomechanisms can then approximately replay limb motions recorded from human actors. However, this simple servomechanism controller does not by itself produce dynamically stable, task- level behavior. Even if the limbs of the physics-based simulation reproduce the recorded limb movement patterns exactly, it is unlikely that the simulated movement will follow the recorded movement for long. Slight errors in timing, initial conditions, or coordination of the overall body movement force the simulated motion to diverge from the recorded motion and lose stability. Furthermore, this simple controller provides no mechanism to accommodate changes in the desired task or environment. Never-the-less, for a nominal set of conditions, this controller will, however briefly, approximate the desired behavior. As such, this simple playback controller provides an excellent starting point for task level control system design.

E.4 Augmenting Recorded Data Playback with Task Level Control

The servomechanism replay of recorded data has no ability to accommodate errors or adjust to external variations in dynamic simulations. The task level controller adds this capability. The task level controller can modify the nominal desired trajectories being delivered to the servomechanisms to accomplish dynamic stability. The task level controller makes adjustments to the joint trajectories to accommodate changes in running speed, body attitude, and vertical motion of the center of gravity.

The task level controller is derived from our own work on building controllers for dynamically stable running robots (Raibert90) For example, the task of controlling a family of hopping machines could be decomposed into three parts. One part sustains the machine's bouncing motion, the second part regulates the angle of the body, and the third part stabilizes the forward running speed. We found that these same principles when combined with the goal trajectories and servomechanism control could produce realistic, dynamically stable running.

Ultimately, the successful development of these techniques could lead to a human simulation system that allows us to physically simulate, study, and experiment with any class of movements that we could record. Low level controllers will use recorded motion to approximately control the system. By using recorded motion as goal behavior of the dynamic simulation we force the simulation to be 'close' to the desired behavior. The closeness of the nominal simulated behavior will enable a relatively simple task level controller to monitor and adjust the action to maintain stability and progress towards the goal. The control system derived from this technique will not exactly reproduce the recorded motion. The motion and activity will have been modified to accommodate the physical model, the environment, and the task. However, the organic quality of the simulation will be evident. It will be life-like and it will have detailed physical data amenable to analysis.

F. Conclusion

In Phase I, we demonstrated the effectiveness of a new control system technique that combines the realism of motion capture data with task level robot control theory. Using this technique, we created stable, controlled simulations of human running that exhibited lifelike simulated motion. The simulations were robust in that they were able to respond in a realistic manner to variations in terrain, accommodate different backpack loads, and run at several speeds. The simulation experiments ran faster than real-time and produced kinematic data including energy consumption, ground reaction forces and joint loads.

The control system technique that we have developed can be applied to other motions. Perhaps some day allowing us to simulate any activity for which one can obtain motion capture data. Our results indicate the feasibility of implementing a Digital Biomechanics Lab where experiments can be performed with the physics-based human simulations to test performance with various equipment and various scenarios.

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