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6. AUTHOR(S)
Dr. Lisa Schutte
Michael Young

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Transom Technologies, Inc.
201 S. Main Street, Suite 300
Ann Arbor, MI 48104

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The purpose of the Phase I research was to investigate and prototype methods to simulate realistic human activities utilizing physics-based motions and limb trajectory control strategies. Under the Phase I work, researchers successfully simulated dynamic motion, impacts, and control schemes utilizing an advanced human model and 3D computer graphics program (Transom Jack). A comprehensive survey of potential control schemes was completed and documented, and the most promising control method was further developed.

Potential applications for this work include dynamic simulation of human movement and locomotion under varying timing and loading conditions. The combination of 3D graphics, a realistic human biomechanical model, physics-based motion, and dynamic control capabilities will allow assessment of energy expenditure, joint loading, and man-equipment interface issues.

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FIRM NAME: Transom Technologies, Inc.

MAIL ADDRESS: 201 South Main Street
Suite 1000

CITY: Ann Arbor **STATE:** MI **ZIP:** 48104

SUBMITTED TO:

U.S. Army Research Office
ATTN: AMXRO-ICA (Sylvia Hall)
4300 S. Miami Blvd.
P.O. Box 12211
Research Triangle Park, NC 27709

PROJECT MANAGER/PRINCIPAL INVESTIGATOR	**CORPORATE OFFICIAL (BUSINESS)**
NAME: Dr. Lisa M. Schutte	**NAME:** Michael J. Young
TITLE: Senior Scientist-Biomechanics	**TITLE:** VP, Product Management
TELEPHONE: 313-761-6001 x237	**TELEPHONE:** 313-761-6001 x224

SIGNATURE OF PRINCIPAL INVESTIGATOR — DATE 7/1/98

SIGNATURE OF BUSINESS OFFICIAL — DATE 7/1/98

Nothing in this report is classified or proprietary information/data

Background

This report summarizes the work done under Contract No. DAAG55-98-C-0012 Phase I SBIR. Our Phase I work has been focused on six explicit objectives:

1. Evaluate current techniques of dynamic simulation models of human motion/locomotion; propose and prototype implementation of a real-time physics-based motion system.
2. Develop physiological human performance models and derive assessments of segment/joint loading and energy expenditure driven by force/torque computations.
3. Explore methods of dynamic motion control for complex human motions; formulate, prototype, and test motion control techniques.
4. Collaborate with a motion analysis laboratory for data acquisition and motion/force validation.
5. Survey current research work in clothing and equipment modeling, evaluate methods, and compile/develop models or libraries.
6. Develop a suite of test problems (the "testbed") for systematic comparative application.

We commenced work 1-December-1997 and completed work May 31, 1998. Progress is due to significant contributions and ongoing time commitments from Dr. Lisa Schutte, Dr. Ulrich Raschke, Dr. Ovsei Volberg, Dr. Kurt Skifstad, and John Granieri, all full time Transom employees.

The following sections outline our progress on the objectives stated above.

Progress on Objectives

Objective I: Evaluation of Current Techniques of Dynamic Simulation Model of Locomotion

Implementing generalized, efficient physics-based motion simulation is absolutely necessary in enabling us to carry out the control system development and formulation of physiological assessments. We have made significant progress in defining and prototyping dynamics capabilities:

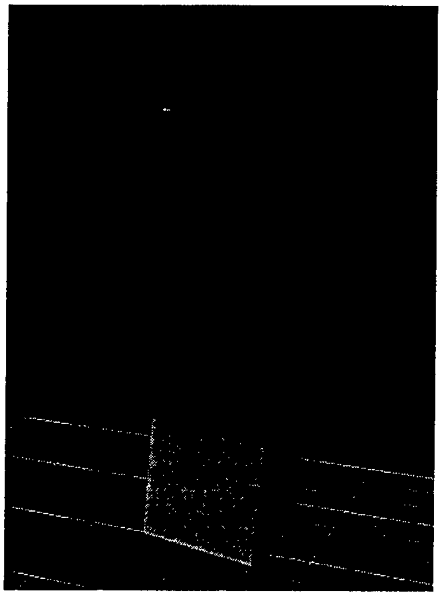
Completed a literature review on methods of dynamic simulation of mechanical systems.
Dr. Volberg completed a thorough review of methods of fast dynamic simulation of mechanical systems.

Identified key advantages of our dynamic simulation method and software architecture.
These are summarized below:

- Fast (order N algorithm) – Near interactive rates even with systems with many degrees of freedom
- Deals with stiff collisions/impacts
- Implementation potentially allows for part of a linkage to be controlled dynamically and motion for rest either specified kinematically or controlled through inverse kinematics. This approach allows the number of degrees of freedom that need to be controlled dynamically to be minimized and allows best simulation methodology (forward dynamics, inverse kinematics, forward kinematics) to be selectively applied.
- Potential for common constraint mechanism for dynamics and kinematics.
- Potential for seamless interface for dynamic and kinematic systems is possible so that the complexity of using dynamics simulations is minimized for users.

Implemented robust inverse dynamic capabilities for a generalized segmented model.
We have completed an initial implementation of the real time dynamics solver. The prototype solver works in our "Jack" 3D graphical software environment.

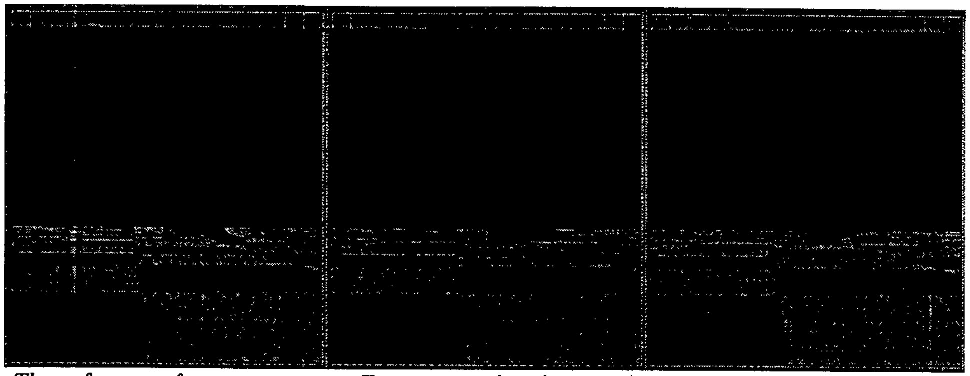
Prototyped real-time forward dynamics engine in custom software and validated initial results.
We have demonstrated near real time performance of dynamic simulation of a 50+ degree of freedom system with collisions using these prototypes. An example of the initial dynamic simulation model appears below:



Real time dynamics model

Implemented real time collision detection and response mechanism integrated with forward dynamics.
We have demonstrated collision detection for models which are convex polyhedra, utilizing the special characteristics of convex polytopes to very quickly determine contact status. It exploits temporal coherence, so that collision query times are extremely fast when the models are moved only a relatively small amount between simulation steps. (The implementation is based upon the "I-Collide" library from the University of North Carolina - Chapel Hill.[†]

Evaluated human model complexity required for accurate human simulation.
We have completed a 2-D assessment of foot modeling methods in order to evaluate whether a simplified two-segment jointed foot model with collision response can accurately simulate the foot-ground interaction. Simulation results appear realistic (see figure below) and suggest that a 2 segment model will be sufficient. The simulation conclusions will be verified with a 3-D model in Phase II work.



Three frames of an animation in Transom Jack software of the results of a 2-D simulation of ground contact with the 2 segment foot model.

[†] Reference: http://www.cs.unc.edu/~geom/I_COLLIDE.html

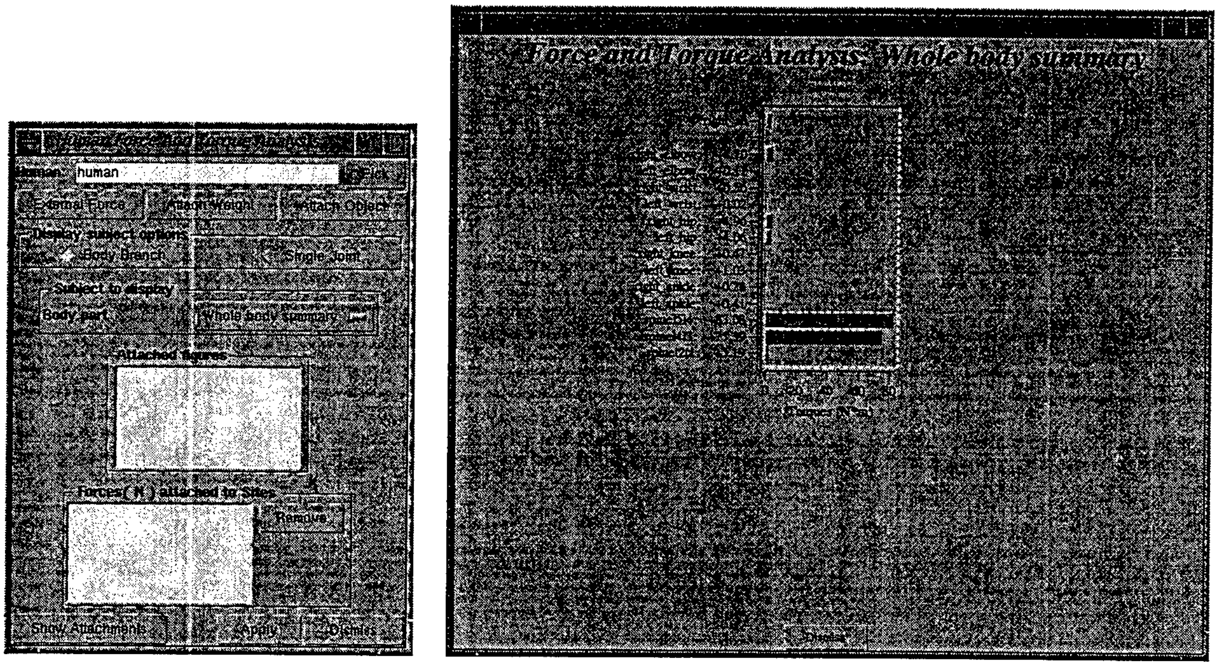
We completed an initial implementation of locomotion simulation capabilities in the software simulation environment. We currently have the ability to generate realistic locomotion along an arbitrarily specified path spline for arbitrarily scaled human models. This simulation capability includes a standard GUI for specifying walking path, options (arm swing, crouch, etc.), and replaying the walking simulation. The interim work plan includes additional capabilities such as pivoting to position and running.

Objective II: Phyiological Models Derived from Joint Torque Calculation

A complete set of physiological data (bone stress, energy models, fatigue models, and comfort models) is needed to accurately define dynamic models and assess performance. In addition, accurate reactions must be calculated in real-time to drive the assessment models. Thus far we have:

Verified segment dynamic and joint force/torque calculations analytically for simple test cases.
This was done by comparison to known solutions to a set of prescribed simulation problems. This provides the analysis capabilities to begin the implementation of physiological models based upon calculated joint torques.

Completed specification and prototype of graphical user interface for torque calculations.
This provides real-time access to joint torque values for physiological assessments. This capability will be implemented in core development software, providing real-time access to joint torque values for physiological assessments. A prototype interface and report screen appears below:

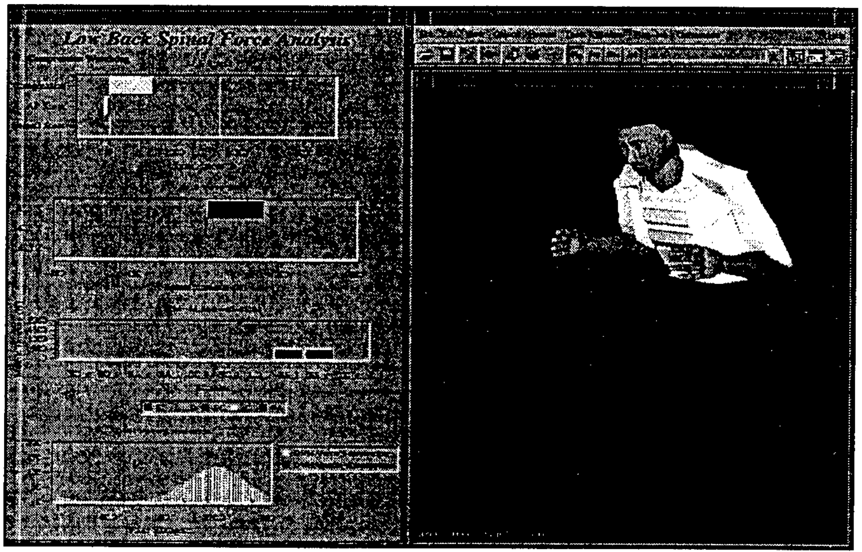


Prototype GUI for Dynamic Torque Calculations

This Human Force and Torque analysis was done for an attached 10kg load on the right arm in a slightly forward-leaning posture. The output summary shows the static torques for the major joints.

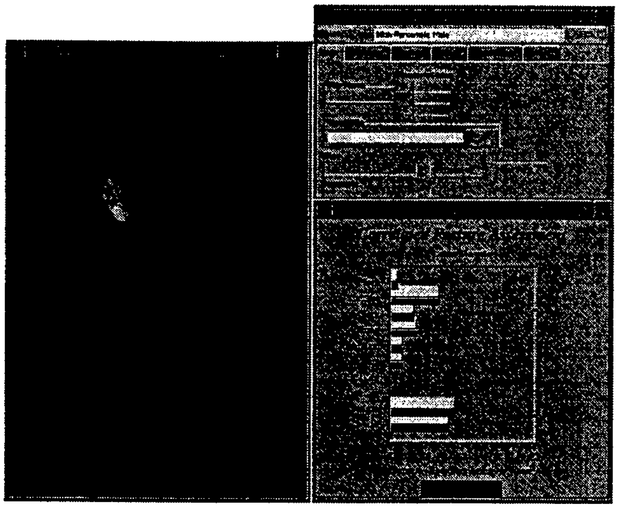
This interface has been implemented in the Jack software environment.

Developed detailed low-back biomechanical model to evaluate spine compressive and shear forces during any simulated task.
We have completed a literature review and initial research for published data on physiological characteristics This led to the completion of development and software implementation of a low-back model which uses the dynamic force and moment values calculated at the lower spine. The analysis is based on the Distributed Moment Histogram (DMH) method and estimates total physiological spinal compression and sheer forces during a motion. An example of the analysis interface appears in the figure below.



Interface to Low Back Spinal Force Analysis Module

Completed a literature review and implemented joint-angle based and multiple-joint (regression model) based comfort/fatigue assessment model.
We have completed a prototype physiological task analysis capability. This model provides a multi-joint correlated comfort and fatigue assessment based upon simulation task postures. The analysis is based upon published dissertation research conducted at Eichstatt University, Germany[‡]. The analysis provides a subjective measure of upper and lower body joint comfort, overall comfort, and fatigue. We have completed a prototype GUI for the analysis and demonstrated real-time assessment during task sequences for several operations.



Multi-Joint Fatigue and Comfort Assessment – Technician in Chemical Suit

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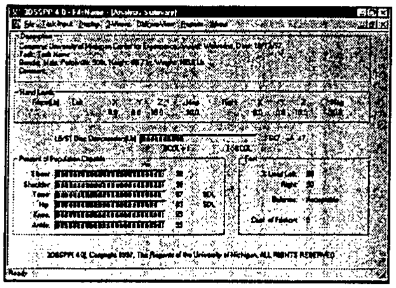
[‡] Renate Krist, *Modellierung des Sitzkomforts – Eine Experimentelle Studie*, Schuch-Verlag, 1993

Began implementation of a set of validated joint strength equations, providing normative strength assessment. We made significant progress on the implementation of a validated strength model in the simulation software. This model is based upon the static strength equations developed at the University of Michigan Center for Ergonomics†. This simulation capability will provide baseline strength prediction based upon subject postures for lifting and reaching tasks. An example analysis output screen from the 3D Static Strength Prediction Program is shown below.



Strength Assessment Analysis Output

We have begun integration of this capability in the simulation software, and will be able to generate population capability studies for tasks based upon this work.

Objective III: Explore Methods of Motion Control

This area was a primary focus of the Phase I research effort. The challenge is to define and implement an efficient control scheme for complex, physics-based human motion simulation within the context of a generalizable 3D simulation tool. We have done extensive work on this objective and have seen promising results:

Completed a thorough review of literature on human motion control techniques.
Results were summarized in paper presented at the *SAE Digital Humans Conference*. The paper, entitled "Control Strategies for Simulating Human Movement," was presented at the April 28-29 *Digital Humans* conference in Dayton, OH.

Defined detailed requirements for the dynamic controller and explored a number of different strategies.
We reviewed control techniques that might be used to control human motion. Techniques considered:

- Neural Net and Fuzzy Controllers - initial impression is that these are more appropriate for cases where characteristics of "plant" being controlled are not known. We don't have that problem...we know our model.
- Cartesian path controllers (Ulrich's potential fields idea - which in the robotic literature is referred to as a transpose Jacobian Cartesian control scheme) - these are simple to implement and seem to have a great deal of potential, especially for arm reaching tasks. With this type of controller it is possible to achieve more realistic arm motions than with inverse kinematics (gravity effects are accounted for). We implemented this type of controller on our arm model in Working Model and the results looked pretty realistic.
- Impedence Control - there is a fair amount of evidence that the human motor control system uses some form of impedence control (work of Neville Hogan at MIT is a good example). For gait where interaction with ground is important or interaction with other environmental objects, impedence control might be appropriate.
- Passive Walking Machines - several researchers have had a great deal of success in developing real and simulated walking machines that use no active control (Tad McGeer, Andy Ruina, Art Kuo for example). Principals used to get these passive devices to walk combined with small amounts of active control might be a useful approach.
- Model-based predictive controllers - we need to learn more about these. Their limitation may be that the motion trajectory needs to be specified first. The controller then tracks that trajectory.

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† Chaffin and Andersson, *Occupational Biomechanics* (2nd Edition), 1991

Implemented prototypes of most promising control techniques and completed preliminary testing in dynamically-controlled reaching and walking tasks.
Specifically, we simulated a very realistic 2D reach to a specified goal using a control technique known in the robotics field as the transpose Jacobian method [1]or more generally as virtual model control[2] For such controllers the controller is conceptualized as a set of virtual mechanical components (spings, dashpots, potential and dissipative fields, latches) that will cause the system to act in the desired manner and for which equivalent joint torques are calculated and applied. In our simulation the virtual component was a spring force applied at the hand, pulling the hand towards the goal location. The resulting motion appears very life-like. This technique is very intuitive and has previously been applied control complex and life-like bipedal walking machines[3] so we feel confident that the technique can be applied to produce realistic simulations of human motions.

Successfully simulated passive multiple step walking.
We demonstrated a reasonable dynamic walking sequence (8+ steps before instability due to cumulative error) with a planar 6 degree of system model of the lower extremities. This is a passive forward dynamic simulation (no applied control) similar to the kneed walking machine described by Tad McGeer[4] and previously simulated by Andy Ruina and his students [5]. These results demonstrate that very realistic simulations can be achieved with minimal amounts of active control.

Successfully simulated limited active dynamic control in walking.
The passive walking simulation was extended by the addition of applied torques/forces. This was a simplified addition to the dynamic model designed just to see if it was possible to positively influence the simulation under active control. This simulation will be the basic starting point for implementing more complex control strategies.

Defined characteristic control system requirements.
The results of the Phase I simulation efforts suggest to us that a reasonable strategy for controlling dynamic human motions can be based on the following principals:

- Use a goal directed strategy such as virtual model control where possible.
- Make sure that the motion is physiologically reasonable (i.e., modify controller as necessary to assure that the required joint torques are physiological)
- When empirical data is available for how humans perform the motion make use of that information to guide the choice of characteristics for the virtual components.
- When virtual components cannot adequately define the motion and when the physiological motor control strategy is unknown rely on natural passive dynamics.

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[1] Craig, J. J. "Introduction to Robotics: Mechanics and Control", Addison-Wesley, Reading, Massachusetts, p. 248 (1986)

[2] Pratt, J.,, Dilworth, P.,, Pratt, G., "Virtual Model Control of a Bipedal Walking Robot", In Proceedings of the 1997 International Conference on Robotics and Automation. (1997)

[3] Pratt, J., Pratt, G., "Intuitive Control of a Planar Bipedal Walking Robot", In Proceedings of the 1998 International Conference on Robotics and Automation. (1998)

[4] McGeer, T., "Passive Dynamics Walking", International Journal of Robotics Research, Vol. 9, p. 62-82, 1990.

[5] Coleman, M.J., Garcia, M., Ruina, A.L., Camp, J.S. "Stability and Chaos in Passive-Dynamic Locomotion", Proceedings of 1997 IUTAM Conference on new applications of Nonlinear Dynamics and Chaos in Mechanics (1997). and http://www.msc.cornell.edu/~garcia/pdw.html

Initial specification and development of dynamic control strategy.
During Phase I, our research focus has been narrowed down to succinct definitions of our proposed approach for applying dynamic motion control to human figures.

Phase I progress included the following accomplishments:

- Outlined plan for developing virtual force constraints as a tool for dynamic control of goal based motions.
- Developed strategy for using empirical data to guide the development of physiologically reasonable virtual force controllers.
- Identified a method for slaving low degree of freedom dynamic simulations to high degree of freedom kinematic simulations, providing the ability to drive a high-fidelity biomechanical assessment model from the lower DOF dynamic human model.

For background, these developments are outlined in the sections below.

Virtual Force Constraints

Our research indicates that the infrastructure needed to control goal based motions dynamically can be presented to the user in a way that is consistent with the *constraints* currently used in our simulation software environment for inverse kinematic control of human behavior and the motion of linkage chains. This kinematic constraint mechanism allows desired positions and orientations of some frames of the simulated figure (the end-effectors) to be specified relative to some goal entity (a point, a reference frame, a line, a plane) which can itself be manipulated. A common presentation of kinematic and dynamic constraints will enable users to specify dynamic controllers as simply as they specify kinematic constraints. The common presentation will also make it possible for the goal based animation system (which allows users to script sequences of motions of different objects) to be used to describe simulations controlled through both inverse kinematics and forward dynamics. The current objective is to allow users to mix both simulation engines even on the same figure so that the most appropriate engine can be used for each situation (i.e., control arm using forward dynamics and rest of body using inverse kinematics or study inverse dynamics of an attached load by imparting forward kinematic body motions).

The planned implementation will be the dynamic analog of the kinematic constraints realized as a virtual model controller. In robotics, the virtual model control technique uses virtual mechanical components, which interconnect the physical links of the robot, to generate generalized virtual forces. This approach creates a convenient notation to describe motion control tasks which are generally difficult to describe. Each virtual component requires the definition of an action frame and a reaction frame. Our variation of this scheme is that the second frame is not attached to the simulated system but associated with the *goal* of the desired motion.

Physiologically Reasonable Virtual Force Controllers

The virtual force controller can be implemented as a virtual attractive force between the limb end effector and goal site. This attractive force can be represented as a vector with magnitude and direction, which acts to pull the limb toward the final position during forward dynamics simulation. Depending on the configuration of the reach task, the number of body segments involved in the reach can vary and may be modeled as multiple segment chains constrained by joints whose states are not uniquely specified by the position of the end effector alone. The joints are, however, subject to physiological constraints in that they must remain connected and the torques cannot exceed the realistic strength limits available from the postural muscles. To satisfy these constraints and also create physiological motions, a method will be required through which the virtual force is mapped onto the joint torque space in such a way that the pattern of torques along the kinematic chain results in the desired motion. The mapping is indeterminate, however, as there are many more degrees of freedom than virtual force parameters and, thus, a pattern must be derived to collapse the joint degrees of freedom. We have experience in solving these types of problems in computationally efficient ways from our work on low back modeling, in which complex torso muscle recruitment patterns are derived from only three spinal moment constraints[†]. We will apply the same approach in the derivation of the joint torque state space from the virtual force.

[†] Raschke, U., Martin, B.J. and Chaffin, D.B. (1996 b) Distributed Moment Histogram: a neurophysiology based method of agonist and antagonist trunk muscle activity prediction J. Biomechanics, 29 (12) pp. 1587-1596.

The derivation of the mapping will involve four sub tasks.

a) Acquire empirical data of people reaching to a range of locations. Data will be collected of subjects with a range of anthropometries, strength, and task conditions performing natural motions. These empirical data will serve to animate the human figure through a range of reaching motions. As these figure animations are driven by data of subjects actually performing the task, the motions are by definition physiological. These data will be collected with our collaborative partners at the University of Michigan HumoSim Laboratory.

b) Estimate joint torques for physiological reaching motions. The animations of the empirical data created in sub-task (a) will be used to derive the biomechanical joint torques during typical reaching motions. The inverse dynamics capability developed under Phase I of this effort, and the biofidelic human figure model that includes an accurate representation of segment weight and inertia properties, will be used for these calculations.

c) Establish a mapping pattern of a virtual force to the joint torque state space for reaching tasks. The virtual force parameters will be mapped onto the joint torque states found in subtask (b) to mimic the torque pattern used by the central nervous system to execute typical reaching motions. Segment properties (anthropometry), posture, motion velocity, goal characteristics, empirical joint strength data and neurophysiological data will be explored as factors to establish the mapping pattern.

d) Validate the prediction of novel motions using the torque state mapping found in subtask (c). Novel motions will be simulated using the virtual force to joint torque state space mapping and compared against empirical data not previously used to derive the mapping pattern. This test will provide data on the physiological validity of the predictions.

Figure Slaving

We have determined the requirement to develop a family of low degree of freedom dynamical generators ("templates") for human reaching motions whose output can be mapped kinematically ("slaving") onto the high degree of freedom human figure in a visually convincing manner. The generators must be capable of achieving point goals (and, possibly, more complex goals such as limit cycles) while avoiding fixed or slowly moving obstacles. They must be "tunable" to mimic reference motions of interest to a user and supplied in the form of motion capture playback.

By "template" we mean a low degree of freedom mechanical system whose (relatively few) joints capture the salient "gross motion" features of a reaching maneuver. For example, the template for a human rising from a chair might be a three-degree of freedom linked segment model (ankle, knee, and hip) with tunable springs at each joint.

By "slave" we mean the kinematic map (and its associated "infinitesimal kinematics" - the velocity and force/torque relationships between joint space and work space that it induces) from the low degree of freedom template into the full human model. Concretely, each degree of freedom in the human model is specified as a function of the template degrees of freedom. Motions generated in the low degree of freedom template by the chosen Lagrangian system map through this slaving into motions of the human figure itself.

Objective IV: Collaborate with Motion Analysis Lab

During Phase I, we have explored possible collaborative relationships with three University of Michigan research groups:

Center for Ergonomics.
Collaboration with Dr. Don Chaffin, director of the Center, is likely to provide experimental data to use in the development of controllers. We are working to formalize participation in the Human Motion Simulation lab which is currently being formed at the University. The laboratory work will provide motion analysis data as well as regression models for task motion trajectories and timing. These data and models will be used to provide reference motions for the dynamic motion simulator. We plan to retain Dr. Chaffin on a consulting basis in Phase II.

Motion analysis laboratory.
Dr. Melissa Gross, director of the gait analysis laboratory, may collaborate to provide validation data acquisition via a Motion Analysis System. This system allows a human to be instrumented and tracked via video based techniques. We have developed the first implementation and demonstrated a motion data file translator for the optical motion measurement system. This will allow us to use laboratory motion capture data to drive animations of locomotion and to use these animations to compare with simulation results. We anticipate that we may need to fund limited work in a motion analysis laboratory during Phase II to provide validation data.

Advanced Technology Laboratory.
We have discussed control methodologies with Dr. Dan Koditschek, of the ATL, throughout Phase I. During Phase II, Dr. Koditschek's laboratory will make significant contributions to our implementation of control methods. We plan to formally fund work in the laboratory during Phase II.

Objective V: Evaluate Methods of Clothing and Equipment Modeling

We have begun to gather a database of military clothing and equipment, and have done initial assesment of the possible approach to this objective. During Phase I, we:

Concluded a licensing agreement to provide military clothing models.
The models, developed at Armstrong Labs at Wright Patterson Air Force Base, will provide a database of military clothing. The models were developed as part of the Air Force DEPTH program, a personnel maintenance task simulator (created as a superset of the Jack software system) developed at Wright-Patterson AFB in Dayton, OH under the direction of Mr. John Ianni. These models will provide accurate graphical representations of protective gear. We have converted and demonstrated models for *fatigues*, *arctic gear*, and *chemical gear* for use in our simulation environment. These models include realistic graphical representations of the clothing as well as modeling the motion and vision restrictions of the protective headgear and motion restriction of gloves and oversize footwear.

Planned the development of an equipment "interface definition" specification.
This will allow the user to specify the attachment of simulated equipment loads and model the dynamics of the interface.

Explored the licensing or transfer of other existing military clothing models.
We met with Mr. John Lockett of the U.S. Army Research Laboratory (HRED,AMSRL-HR-MB,Building 459, Aberdeen Proving Grounds, MD). Topics discussed included possible collaboration or transfer of his research work in clothing models and smoothly-deformable surface geometry. We may pursue this further during Phase II work.

Objective VI: Develop a Suite of Test Problems

During Phase I, we did initial work to define the test suite and compile testbed procedures for validation and comparative assessment of our prototype and development software work. This is valuable for testing and documentation (and, ultimately, commercialization) of our work. This work is dependent upon and will lag the prior stated objectives; however, we have made progress during Phase I in defining specific tasks to concentrate our simulation efforts. Specifically we have:

Categorized key motion types to be simulated and tested.
We divided these into four distinct areas:

- Motion of non-human objects that impact or interact with the human .
- Motion of humans interacting with objects in the environment– mainly involves arms and torso with the legs providing support and balance only. Likely to include both kinematic and dynamic simulation.
- Whole body maneuvers of humans where the objective is to move whole body and any applied loads. May involve both leg and arm motions and support may be provided by legs and/or arms.
- Locomotion. Mainly involves legs, typically cyclic motion. Objective is to get body from one place to another while employing a particular strategy (walk, run, etc.)

Identified and formulated simplified test models (shoulder/arm, pelvis/leg/foot, torso only) for various simulation goals.
During Phase I, we developed simple body dynamic models that include collisions with ground to try out control ideas. These were implemented in Working Model 2D. We have developed a simple foot-leg model, a torso, shoulder, arm model and a simple 2D biped model for the purposes of testing control techniques.

Conclusion

We have completed our Phase I work and have made significant progress in all stated objective areas. We have significantly surveyed, defined, and focused our research direction as a result of our Phase I work.

Based upon our work thus far, we are confident in the basic scientific, technical, and commercial merit of our proposal through our planned Phase II research and development.