

# Human Modeling – From Bubblemen to Skeletons

**Shawn P. McGuan**  
Mechanical Dynamics Inc.

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## ABSTRACT

This paper introduces a novel human modeling system utilizing the ADAMS (Mechanical Dynamics Inc.) multi-body simulation program. The FIGURE Human Modeling system is a plug-in to ADAMS, which provides users with the capability to generate human models of various levels of detail and fidelity, permitting simulations ranging from passive response (crash, falls, etc.) to active participation (sports performance, task simulation).

One of the major innovations of FIGURE is how human motion is simulated using a concept of "motion agents". Motion agents are parts, which are positioned on the body segments at the location of the motion target marker from the motion capture system. The motion agent is attached to the body part with a 6 degree-of-freedom spring so as to be a "motion influencer" rather than a "motion governor". Data from the motion capture system drives the agents thereby driving the human model. Since the human model is physics-based, the model will not violate joint restrictions, environment contacts, etc. From this simulation, resulting muscle elongation histories are then captured. A second simulation is performed using these muscle elongation histories via proportional derivative (PD) controllers to drive the human model using a direct dynamics approach.

The paper introduces the modeling paradigm of FIGURE and provides an example of direct dynamics simulation based on data from a newly introduced motion capture device.

## INTRODUCTION

Currently, software tools, which address the computer simulation of the human being, target specific application areas. In considering the variety of human simulation programs available today, the application target areas can be divided into the areas of crash simulation (vehicular occupant injury), slips/falls (environmental

injury), orthopedics (joint and tissue mechanics), gait simulation (rehabilitation), task simulation (virtual factory) and sports performance simulation.

The approach of targeting a specific application area has resulted in specialized software solutions with a high degree of biofidelity for the appropriate task.

However, this specialized solution approach represents significant challenges in the academic and industrial sectors. Most challenges relate to the complications of selecting the appropriate tool for the specific task as well as the burden on students/professionals in becoming proficient with the tool(s).

Perhaps an alternative solution in the university sector would be to have available a generalized program which would address a broad application space. This approach would provide students with exposure to the various application areas of biomechanics requiring the student to master one software tool instead of numerous specialized tools.

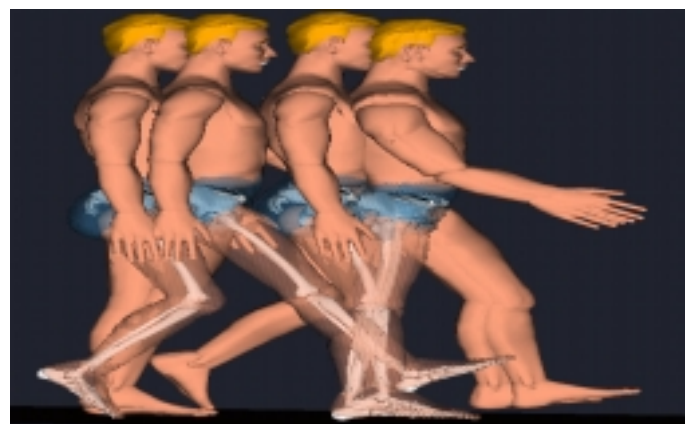


Figure 1: Human Simulation using FIGURE

This was the intention of the FIGURE Human Modeler (see fig. 1). This software tool was developed via consortium of over 30 leading sports equipment manufacturers, orthopedics companies, vehicle

manufacturers, universities, research institutions and government agencies. In order to address the challenges from a community with a wide range of needs, FIGURE evolved into a broad-based application in the biomechanics arena.

The intent of the product offering was to provide a single tool to easily create human models with a level of sophistication ranging from simple to very complex. In order to address the needs of each member of the consortium, the human models would be appropriate for a wide range of applications from sports performance to injury evaluation, from gait simulation to vehicle ride comfort.

## HUMAN MODELING PARADIGM

The basic model building paradigm in FIGURE is to start with a base human model representation and refined it to the appropriate fidelity depending on the application.



Figure 2: Base human model discretization.

Figure 2 depicts the base level human/biological models built in FIGURE. The base models are the 15 segment 16 joint type (head, neck upper torso, middle torso, lower torso, upper and lower arms, upper and lower legs, feet).



Figure 3: Highly detailed foot models

Included in FIGURE are the model files for all the bones in the human skeleton. The bones are scalable based on several anthropometric databases. The 15-segment body representation involves a grouping of these bones. The grouping may be broken up into individual bones or

individual segments for more detailed modeling of various body parts. For example in gait simulation, it may be appropriate to model as individual parts, the talus, calcaneus, metatarsals and the mid-bones in the foot as separate segments in order to maintain balance, while maintaining the relative coarse discretization in the rest of the body (See fig. 3).

In addition to full body simulation, partial body simulation may also be performed. Figure 4 displays examples of body segments with improved levels of biofidelity for specific types of analysis. A leg model is used to understand the shock absorption mechanism of the plantar surface of the foot. This specific model includes many joints throughout the foot and contact ellipsoids at the metatarsal heads, hallux and the calcaneus. The leg model was used to develop an understanding of the inversion sprain mechanism during an acute ankle injury. The wrist model is used to provide insight to the dynamics of the carpal bones during flexion.

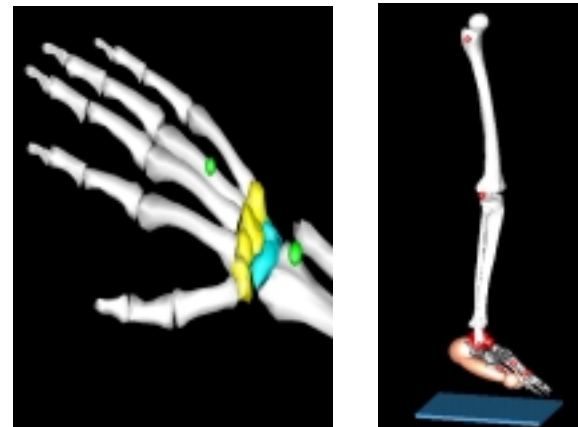


Figure 4: Partial body models used to simulate various events.

Using this method of segment refinement even non-human biological entities or robots may be constructed (see fig. 5).

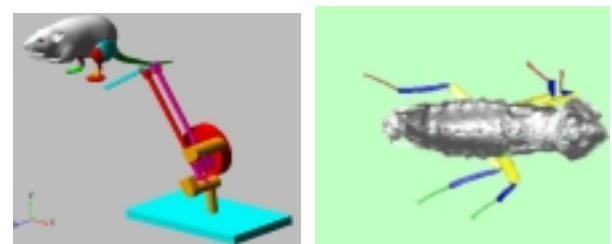


Figure 5: Non-human entities may also be built with FIGURE.

The joints in the base human model are tri-axis hinge joints created at anatomical locations. As with the segment discretization, the joint may be refined from its original basic representation. The joint tri-axis hinge arrangement may be replaced with a force set or other constraint arrangements. For example in figure 6, the knee joint is modeled as a force-based joint consisting of the tibio-femoral contact forces and the patello-femoral

contact forces, all stabilized with ligaments and actuated with muscles.

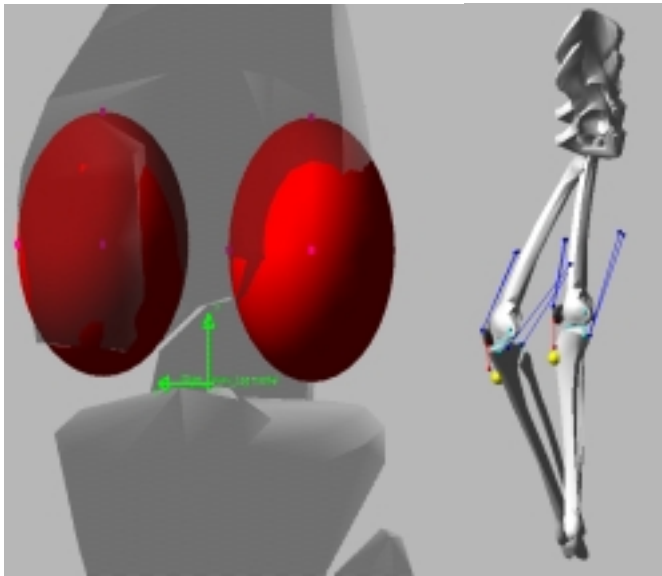


Figure 6: Force-based knee joint.

Another example of force-based joints is the modeling of prosthetic joint for the hip and the knee (see fig. 7). Here the base kinematic joints are forgone for a detailed force representation. For the evaluation of the dynamic performance of a total knee replacement system, a contact force joint is used to describe the articulation between the congruent surfaces of the femoral condyler component and the tibial insert of a total joint replacement prosthesis. Major ligament and muscle forces are included in the model, as well as the underlying bones. For the hip joint in figure 7, basic stabilizing musculature is included with the skeletal representation for a stability analysis of a new hip replacement system.

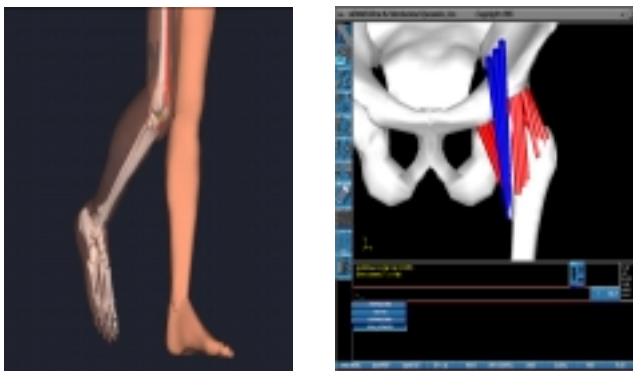


Figure 7: Force-based joints are introduced into the model for evaluation of joint replacement prosthetics.

Forces acting across the joints may be of the passive or active type. Passive simulation involves the human body's response to the physics of the environment. The applications in this area include crash, falls, impact, etc. The human models created for these events have the segment mass properties and dimensions, joint stiffness,

damping friction and limits consistent with the Hybrid III crash dummy used by many automotive companies to evaluate safety potential of automotive equipment. Data received from these simulations include segment contact force, displacement, velocity and acceleration, joint force and torques, and may be compared against injury norms for evaluation of the potential harm of a physical event (see fig. 8).

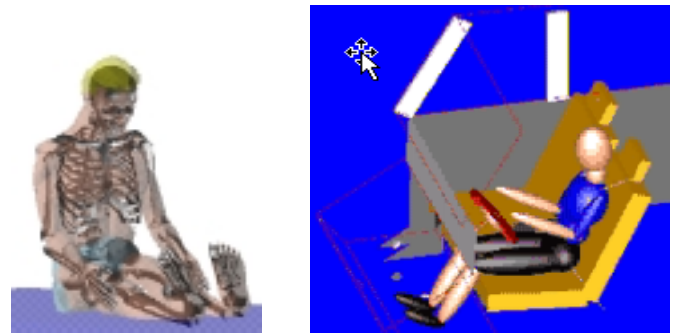


Figure 8: Passive simulation models.

Active simulation involves the human body becoming an active participant in the physics of the environment (see fig. 9). The environment may include vehicles, surfaces, sports equipment, etc.

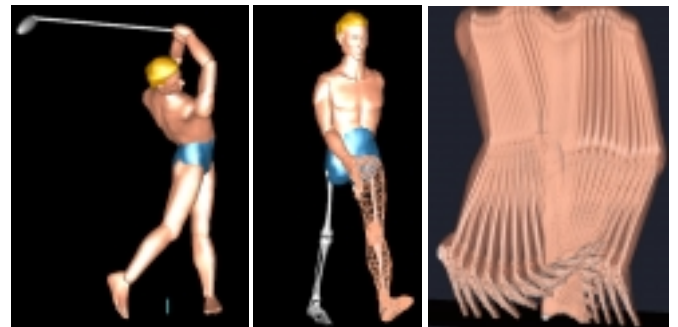


Figure 9: Active simulation models.

There are a number of options to drive the motion of the human to simulate these events. The human model may be activated by imposing torques at the joints or by imposing muscle forces. It may be thrown to the ground or knocked around in an automobile.

For an active simulation, a forward dynamics approach may be used. Here, the user describes the angulation history of the particular degree-of-freedom and generates a torque using the automatically generated proportional-derivative (PD) controller. This angulation history may be imported from a data table or generated using an inverse-dynamics approach. If muscle forces are used, muscle elongation histories or activations may be used to drive the model using elongation histories generated from an inverse-dynamics simulation (see fig. 10).

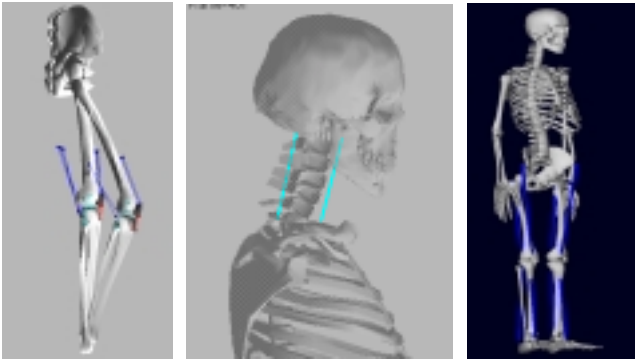


Figure 10: Force-based joints with ligaments, tendons and muscle groups.

In FIGURE, marker trajectory data may be imported from a data source such as a motion capture system. Data splines are automatically created. The user then places "motion agents" at the locations in the model, which correspond to the marker locations on the subject. A simulation is performed where the motion agents are moved based on the motion capture data, moving the body segment with it. During the simulation the angulations at all degrees-of-freedom in the joints are recorded as well as the muscle elongation histories. It is this recorded angulation history or muscle elongation history, that may be used for a subsequent forward dynamics simulation where the model is driven exclusively with torques produced by the PD controllers or forces from the muscles.

Figure 11 represents another approach for a specific application. Here point-to-point muscle forces were added to the skeletal model. Their activation is controlled by signals from a central pattern generator (CPG) type control system. In this example, Matlab is used to solve the equations of the CPG controller, while FIGURE is used to solve the dynamical equations. The gait simulation is performed using a co-simulation process where data is piped between Matlab and FIGURE.

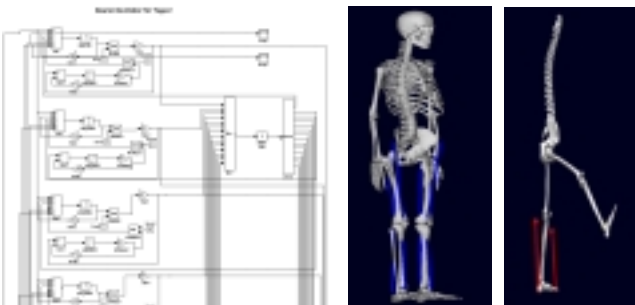


Figure 11: co-simulation, using MATLAB generate neural activation signals to muscles in human model.

Human models may be placed into dynamic models of mechanical systems. Figure 12 shows the usage of a body segment built using FIGURE installed in a model of a knee-testing machine, for the comparison of model data to cadaver experiments.

The ADAMS model of the machine simulates the behavior of the machine and is combined with the leg model for true virtual prototyping. By simulating both the tester (machine) and the sample (knee joint) model correlation and validation with experiment is greatly simplified.

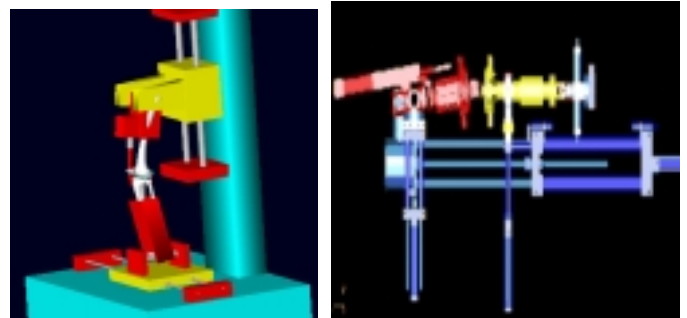


Figure 12: Simulation of knee testing machines with knee models.

After completing the simulation, the model may be interrogated for results. Results that can be extracted from the simulation include all kinematic and kinetic information such as joint forces, tissue loadings, body segment displacement, velocity and acceleration. For example, figure 13 displays the disk compression history of the cervical vertebrae during neck motion in gait simulation. This measure is displayed during the animation of the model.

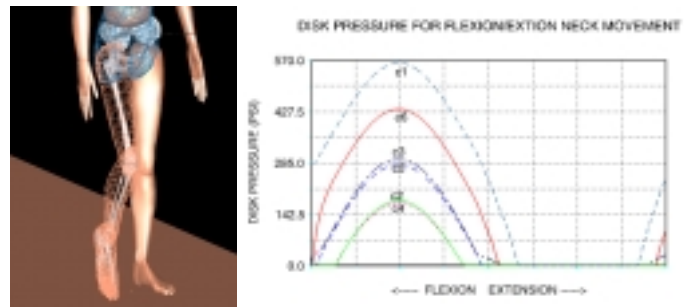


Figure 13: Animation and data measure used to display model information.

Another example of animation and data measure is displayed in figure 14 where the ground reaction force vectors as well as the hip angle during gait are displayed.

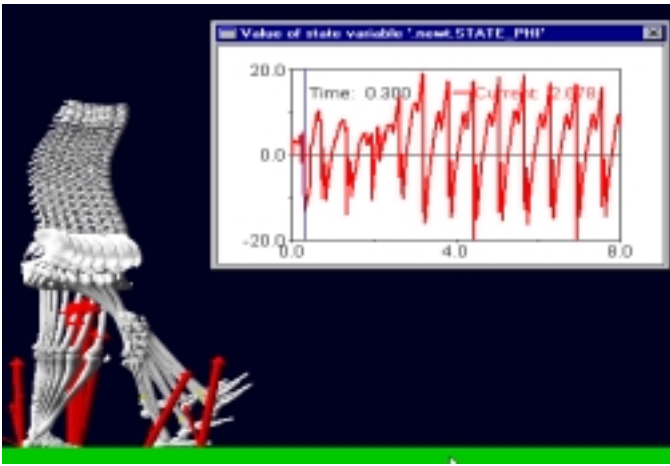


Figure 14: Animation and data measure from gait simulation.

## SIMULATION EXAMPLE

**INTRODUCTION** - The purpose of this section is to introduce a new body motion data acquisition technology and incorporate the function with a sophisticated computer model of the human neck built using the FIGURE Human Modeler. The ultrasonic device captures the changing of the length of the skin between sets of sensors during movement. By strategically placing the sensors on the human body, the skin motion can be equated to body segment motion through a calibration procedure or by applying the data to actuators in a computer model of the human neck. The computer model of the neck can provide insights into the biomechanical behavior of the cervical spinal column by producing data on disk pressure during certain activities.

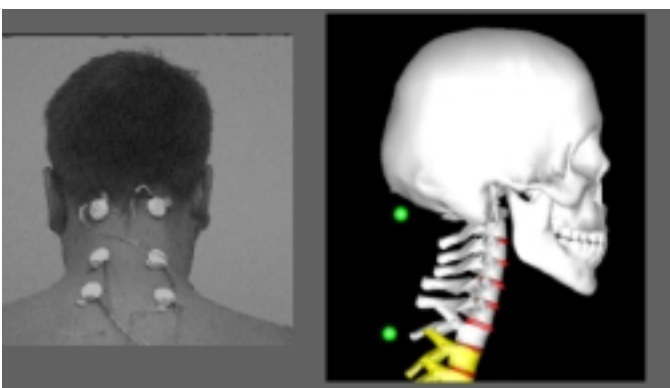


Figure 15. The sensor setup and the equivalent computer model with actuators.

**METHODS** - The data collection device (Orthoson), which is portable and attached to the subjects waist, assesses body movements with an ultrasonic measurement method. For this purpose, four small ultrasonic sensors are applied to skin points with a distance changing during body movements. The

changes in distance are measured with an accuracy of 0.3 millimeter. Both ultrasonic sensors are attached to the skin with stick rings. The ultrasound is coupled on the body under a flat angle to the skin surface.

Detection of body movements/positions is performed using an ultrasonic distance-measuring device with sensors, which are applied to the skin. The device operates using pairs of ultrasonic sensors. One sensor is the transmitter and on sensor is the receiver. Each pair records the skin dilation between the two and can calibrate it to a distance measurement. These distance measurements, when placed strategically on the body can be used to capture and record body segment motion (i.e., joint rotation).

Figure 15 displays the arrangement of the sensors on the back of the neck. The first pair are located at the base of the neck with the nearest vertebrae being the atlas, the second pair is located at the location of the C3 and the third pair is located at the C7 vertebrae. Data for the flexion/extension neck motion is recorded at 10 hz. for a motion duration of 6 seconds.

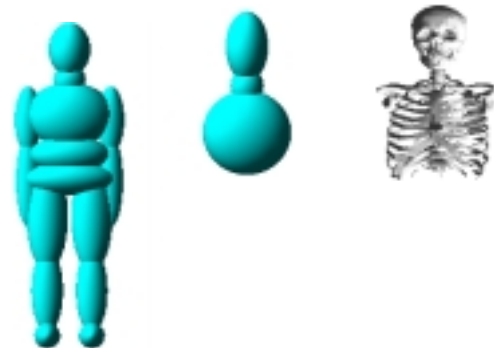


Figure 16: Refining neck model from base representation.

Figure 16 displays the model of the cervical spine and head. The base model is created for the human subject based on the height and weight. The base model is refined to represent the cervical spine with 9 parts (C1-7) the skull, and the upper torso. The parts are modeled as rigid bodies and coupled together with hinge joints since the motion is strictly in the sagittal plane for this flexion/extension example.

To determine mass properties for the model basic body-slice density (Baughman '83) is used for the head and the neck mass and inertial properties is distributed about 7 equally dimensioned cylinders representing slices of the neck (see fig. 17). For this present study, the ligament forces are represented as spring/damper elements to deny bone impingement. Rotational spring/damper elements are used at the hinge joints to represent the composite stiffness of the stabilizing musculature in the neck. Data for these forces were derived from (Kelps '88). Contact forces at the anterior side of the vertebrae provide the compliance properties of the disks using force/deflection data from (Matyjewski '95).

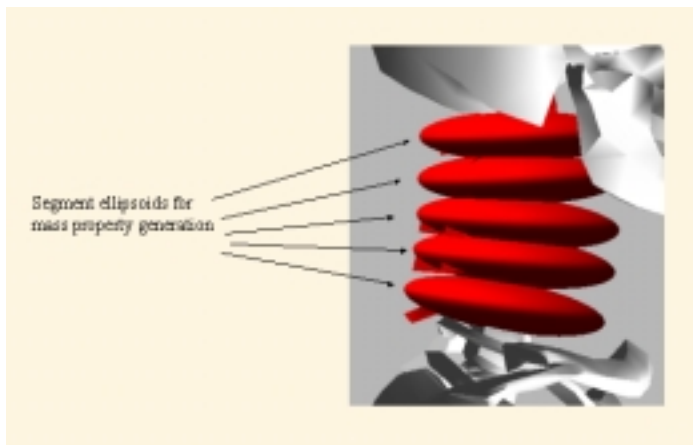


Figure 17: Approximating the mass-properties of each vertebrae.

To drive the dynamic model using data from the ultrasonic device, motion agents are added to the model. A motion agent consists of two parts: one which moves via the motion reported from the ultrasonic sensors, and one which is connected to the local bone. The two parts themselves are connected together by a 6 DOF spring. This arrangement allows for error between data collection and the model by constraining the motion produced by the data to the physics of the model.

A simulation is then performed to capture the muscle elongation history of the flexion/extension muscle groups. After this simulation is performed, the motion agents are stripped from the model and PD controllers are automatically installed to create the muscle forces. The PD controller provides muscle tension force based on tracking the elongation history from the previous simulation (see fig. 18).

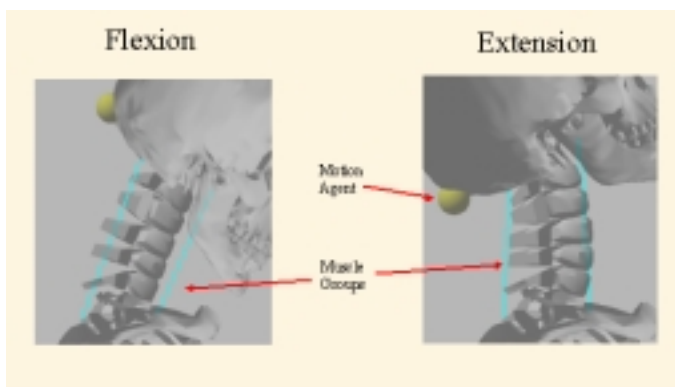


Figure 18: Approximating the mass-properties of each vertebrae.

Data retrieved from the simulation includes cervical joint kinematics, contact forces and disk pressures for the flexion/extension motion of the neck.

RESULTS - The intention of this study was to create computer model of the head and spine, which closely

parallels the human experiment using the Orthoson device. This arrangement produces the internal forces of the neck based on skin deformation of the test subject. The disk contact force profiles produced by the simulation are show in figure 19.

This data was in agreement with the general profiles reported in (Begeman '73). Some over-prediction occurs in the model with the usage of basic hinge joints representing the intra-vertebrae constraint. In reality, the intra-vertebrae joint is a six degree-of-freedom joint permitting 3 axis of translation and rotation. The model presented here will overly compress the disk by forming a lever arm between the vertebrae and sandwiched disk.

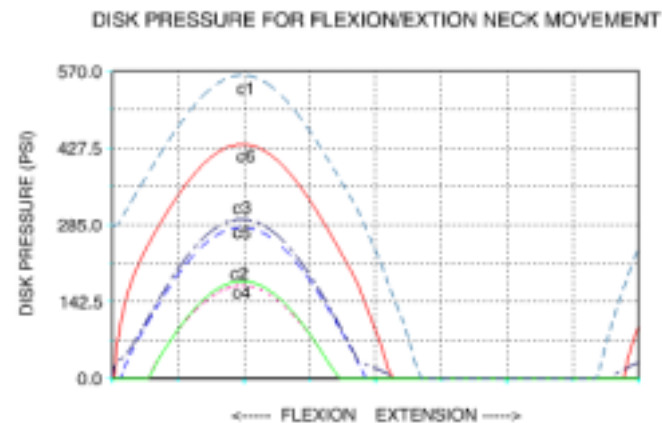


Figure 19. The Disk Contact Pressures for Flexion/Extension Movement.

Figure 20 provides data on the neck muscle forces necessary to produce the recorded motion and the vertebrae rotational motion.

The model in its present form is useful to predict disk compression trends for flexion-extension, internal-external rotation and side flexure of the neck. Various marker configurations of the Orthoson device have been explored to drive the model to produce these motions. Future plans call for reducing the assumptions in the model including: 1. Replacing the hinge joints with 6 degree-of-freedom contact joints, 2. Disk forces capable of transmitting axial, shear and rotational forces. 3. Spring damper elements representing major stabilizers in the neck.

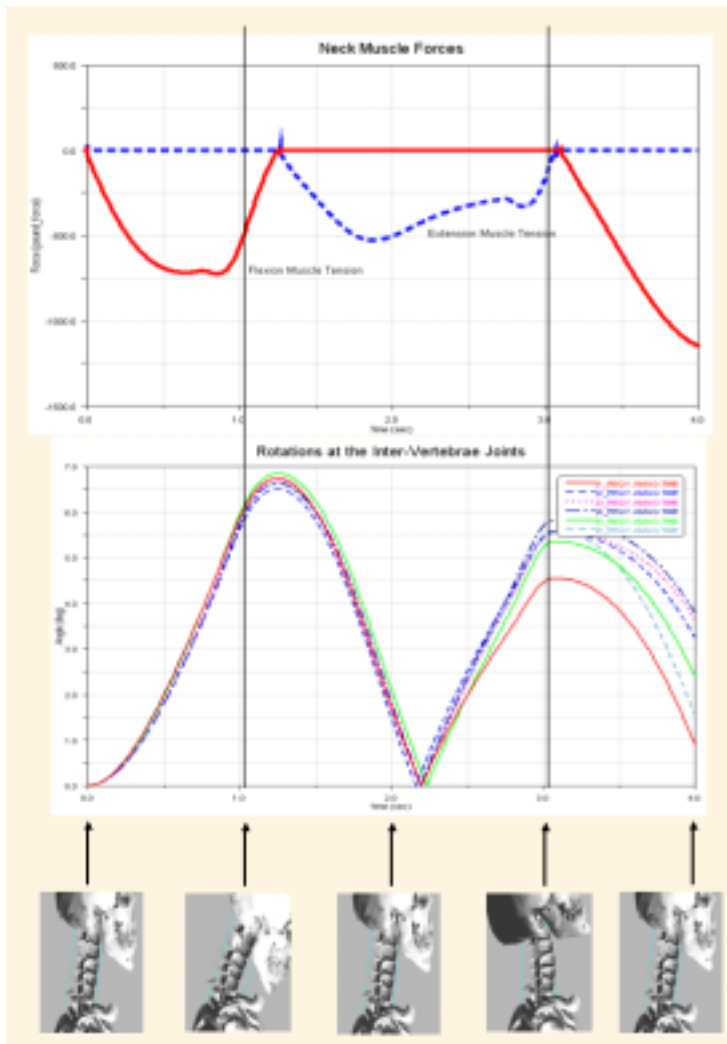


Figure 20. Neck muscle forces and vertebrae joint rotations data.

## CONCLUSION

This study was intended to provide the reader with an exposure to the modeling paradigm of the FIGURE Human Modeler by developing a methodology to generate the internal reactions of the neck based on skin deformation data from the newly introduced Orthoson device. The near-term practical utility of this work is to predict range-of-motion in daily workspace environment or to study the effects of cervical joint fixation. This methodology can also be extended for cadaver tests to study automobile impact injuries to the spine, such as whiplash.

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## CONTACT

Shawn McGuan is a Biomechanics Technical Specialist at Mechanical Dynamics Inc. He has advanced degrees in mechanical engineering and mathematics and has over 20 years experience in the field of mechanical simulation in terms of large-scale software development and consulting. He is the principal author of several major commercial engineering simulation programs with a combined usage of over 30,000 engineers and scientists world-wide. He has pioneered the usage of mechanical simulation tools in orthopedics, sports and clinical biomechanics as well as admissible evidence in the courtroom for human injury evaluation, where he has served as an expert witness. [smcguan@adams.com](mailto:smcguan@adams.com)  
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