ACHIEVING COMMERCIAL SUCCESS WITH BIOMECHANICS SIMULATION

Shawn P. McGuan
Mechanical Dynamics Inc., Ann Arbor, MI, U.S.A.

This paper surveys the usage of human simulation by the commercial industry. The intention is to provide students with an awareness of potential job opportunities and the appropriate skill set the various sectors of the commercial industry would find attractive. A wide spectrum of biomechanics market segments are identified and a commercial application for each one is described. The commercial industry segments addressed include sports performance/equipment, orthopedics, clinical applications, injury evaluation and task simulation.

KEY WORDS: biomechanics, simulation, modeling, and education

INTRODUCTION: For the past 13 years, I have been the director of a Biomechanics Research Group, providing software and services to a wide variety of commercial clients. As such we have been involved in using human simulation to develop leading edge solutions for a vast spectrum on applications in the areas of sports (optimizing performance and equipment), orthopedics (joint and tissue mechanics), clinical (locomotion and rehabilitation), injury evaluation (injury mechanism simulation) and task simulation (virtual factory). From this involvement we have identified a favorable skill set, which each industry segment would find quite attractive. This paper introduces several representative cases from each area, discusses the problem to be solved, the approach, and identifies the required skills for this particular application. References are provided at the end of the paper which provide detailed descriptions of each commercial example.

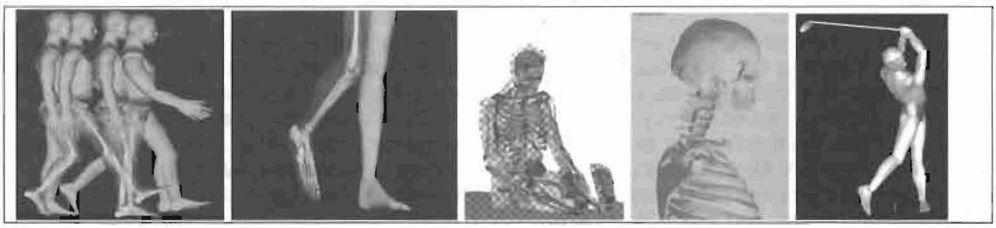

Figure 1. Human perceived as a mechanical system

VIRTUAL HUMAN: In engineering design, virtual prototyping or mechanical simulation has been recognized by the commercial sector as a method to slash years of labor and millions of dollars from the design process. And since they can be created fairly quickly, viewed from any angle, and changed with a few keystrokes, virtual prototypes can lead to better products by making it easy for engineers to explore many design possibilities. Such is the case with humans, where virtual prototypes, in the form of mechanical simulation computer models have been used by many researchers, clinical professionals, commercial companies, coaches and athletic trainers to study human movement and to develop products used by a human, on a human, for a human, and in a human (Figure 1). In the development of computer models to emulate human motion and activities, the human is viewed as a mechanical system the same way a car or satellite is viewed as a mechanical system. The human body, as a mechanical system, consists of parts, joints, forces and a control system reflecting limbs, joints, muscles and the neuromuscular system. The body moves and interacts with its environment by virtue of the neuromuscular system, creating loads on bones, joints and muscles (see ref [1]). In what would appear to be widely disparate industries such as orthopedics, sports equipment, safety systems, etc., the modeling approach and requisite skill set is surprisingly similar. Largely, the difference lies in how they apply the model and what type of data they extract from it. For example, the sports equipment industry is interested in a coupling of the human model with a computer model of the particular piece of sports equipment to determine the optimal set of equipment variables to optimize the performance of the man-machine system. The sports performance industry is interested in optimizing body mechanics for a particular outcome. The rehabilitation sector is interested in testing intervention strategies on a model before they are introduced to the patient. The orthopedic industry is interested in evaluating the performance of a total joint replacement system in a musculoskeletal human model before any physical prototypes are built. All these applications require generally the same type of model and skills to develop it.

MODELING APPROACH: The basic approach the seasoned investigator uses in almost every modeling case involves answering the following questions:
Problem: What specific problem am I trying to solve? What "question" am I asking? What is my plan of attack?
Model: How do I create a reasonable computer model of this phenomenon? What detail do I need to include without being overly complicated?
Boundary Conditions: Where is my model? What does it interact with? What is the state of the model at the beginning of the simulations?
Accuracy: Is my model accurate? How do I verify the performance of the model? Will the "answer" be correct?
Simulation: How many simulation trials do I need to perform to provide me with my "answer"?
Results: How do I interpret the simulation results and arrive at this "answer"?
What problem am I trying to solve? This step involves developing the overall approach and investigation strategy. What type of model do I need? What type of simulations must be performed? All these questions must be asked to determine the overall plan, strategy and selection of software tools and laboratory experiments. This step also provides cost estimates and manpower requirements for the particular project. This is the "proposal" stage.
How do I create a reasonable computer model of this phenomenon? Once the investigation strategy is determined, the next step is to create a computer model of the phenomenon. The central paradigm in the development of computer models for biological simulation concerns *condensing the biological entity and environment into a mechanical analogy.* This mechanical analogy is then embodied in the equations of motion. This step relies heavily on the experience from the investigator to create the model appropriate for the task. Obviously, the human body is an extremely complicated system and it would appear to be overly trivial to condense it into mechanical elements. The human body is not a robot. However, it may be considered a robot for the level of detail and the type of investigation we are interested in. The model represents a fine balance between fidelity and efficacy. It must not be overly complicated so as to have prohibitively long run times with more opportunities for inaccuracies and error, and not too simple so as to not produce the correct or accurate response. The specialist proceeds using a method called lumping, whereby various model detail is grouped into a single set. For example, if a model of the foot were required for a locomotion model, it might be appropriate to consider the bones of the midfoot and forefoot as single rigid segments connected via a hinge joint with an effective torque function instead of muscle force groups spanning the joint.
What are my boundary conditions? The next step is to consider the *model space*, or how does the model fit in the environment and interact with the various components. Is there a floor? Are there objects the model may interact with? Are there other human models to interact with? What speed is it performing these tasks at? What is the model state? In accordance with the investigative strategy defined in the first step, there may be a range of answers to the questions above. Also in many cases, a range of boundary condition values are defined to determine the robustness and hence the applicability of the model.
Is my model accurate? Before the actual simulation trials are to be run, the model must be *validated* against available experimental results, closed form analytical solutions, published results, etc. This step also requires a savvy investigator. It is this step where shortcut can completely invalidate the entire project. Interpreting/validating model response is a very tricky process. Model response is usually classified as sets of output parameters that are compared to experimental output parameters. Responses such as model segmental motions (kinematics), ground reaction force, muscle tension (kinetics), etc. may all be considered in the validation process. If experimental data is impossible to achieve for the targeted output parameter, other model parameters must be examined. For example, if the desired response

in a golfer simulation were the joint torque histories for the swing, a reasonable validation approach would be to compare the individual segment motion trajectories of the model with segment motion histories of a human subject via digitized video. The assumption would be that if the segment mass properties were accurate, and the segment motion trajectories are similar to experiment, the internal joint reactions should be reasonable. Model validation must also include examining the response trends, or how the model responds to minor changes or perturbations in input variables. This parameter sensitivity analysis is used to determine model robustness and ultimately determine the range of applicability of the model. Also, sometimes the model is evaluated in a piecemeal fashion, by validating subsystems against experiment, to imply the integrity of the complete system.

How many simulation trials do I need to perform? With a measure of confidence in the model gained through the validation process, the *simulation sweep* is then performed. Due to the highly non-linear nature of human models, the validation process does not end in the preceding step. The results from the simulation trials should be periodically validated, and so as to make sure the simulations do not dwell too far outside the validation space. There are always a number of simulation trials to be performed. Even if the investigator is interested in one specific case with one specific set of input variables, simulations should be run with small deviations (perturbations) from the nominal set to determine parameter sensitivities. Sometimes various strategies are used to determine the sensitivities of the parameters such as design-of-experiments techniques. There usually is never a single "answer" as a result of the simulation process, but a range of values to indicate the response of the model. Parameter variation studies may be performed using an intelligent approach such as design-of-experiments (DOE), which selects a new set of parameters based on trends from the results history, or a random approach using Monte Carlo methods.

How do I interpret the simulation results? After the simulation trials are performed (and there can be many), *data must be analyzed.* This process also involves much investigator intuition; rarely the results of the simulation boil down to a single "answer". In many cases the results are viewed as a response surface or a database of responses with spreadsheet access. The latter represents the "product" of the simulation effort, and is extremely valuable to product designers such as designers of golf clubs, occupant restraint and safety systems, entertainment ride safety, total knee joint replacement, etc., who are interested in an optimal set of parameters for a product.

NECESSARY SKILL SET: Human simulation can be approached from three levels: fundamental, modular and specific. The fundamental approach relies on using mechanical dynamics theory, robotics methods and programming skills to generate the necessary physics equations to be embodied in computer programs. The modular approach requires the investigator to utilize a commercially available physics-based mechanical simulation software packages to assemble the components of the biological system. These packages then generate and solve the equations of motion through time to produce the results. The specific approach, involves a commercially available software package containing scalable predefined human model, which the investigator can customize and individualize to suit the task at hand. Usually these packages are specific to a particular type of industry such as injury analysis, sports performance, or gait modeling. The last approach can be the most powerful, removing the investigator from many of the mundane tasks such as deriving equations of motion. This allows the investigator to concentrate on more complicated phenomena such as complex control systems, flexible bones, soft tissue wrapping, etc.

Utilities included in some specific programs such as airbag models, muscle models, bearing surface contact models, balance control algorithms, etc. can take years to develop, but can be included in the model quite easily. By the time the model is completed, say a musculoskeletal human model swinging a flexible golf club, the model represents hundreds of man-years of development, with a level of sophistication and fidelity impossible to achieve using the two former approaches. The keen specialist must be very careful with this tremendous power; extreme diligence must be practiced to recognize the limitations and applicability of these subsystems.

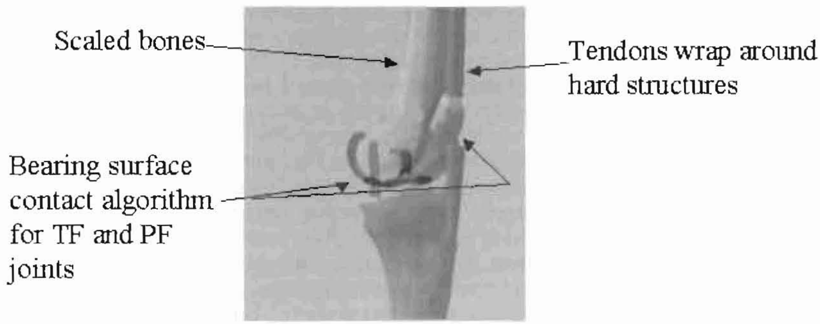

Figure 2. Combination of three approaches used on one model

The most seasoned specialists use a combination of all three approaches. The specific software package is used to build the general model and to include as many components as possible. The modular approach is then used to piece together mechanical elements to create a subsystem of the model. And finally, the specialist may develop a set of equations representing a phenomena not covered in either of the software packages, such as a set of differential equations representing a new muscle model, or joint bearing surface contact algorithm. An example of this approach is displayed in Figure 2. The force-based knee model consists of bone geometry and mass properties which were scaled from a human modeling package, the modular approach was used to develop the mechanical elements representing the quadriceps tendon wrapping around the distal head of the femur, and the fundamental approach was used to develop a bearing surface contact algorithm representing the interaction of the patello-femoral and the tibio-femoral joints. The basic requisite skills necessary to be an effective human modeler are a thorough understanding of dynamics, robotics, controls, structural mechanics, mathematics, physiology, biology, motion capture, data analysis and computer programming. This broad spectrum of skills is required for any combination of approaches used for human modeling in any commercial market segment. The depth of mastery for each discipline would vary depending on which modeling approach the investigator would specialize in. For example, the fundamental human modeling approach necessitates the thorough understanding of dynamics, robotics, and computer programming. Given the commonality of the modeling paradigm across the spectrum of the commercial industry, a specialist educated in the above areas and familiar with the available software tools would have the widest range of choices in job opportunities. (For a sample curriculum introducing these methods with the appropriate software see ref [2])

SPORTS EQUIPMENT/PERFORMANCE COMMERCIAL SAMPLE: This particular company is interested in introducing a new high-end basketball shoe into the marketplace (See refs [3], [4], [5] for detailed model descriptions). *Problem: How to develop a basketball shoe, which optimizes jump-landing shock attenuation, yet stabilizes the ankle?* A model of the lower extremity would be built coupled to a parameterized model of the midsole, to determine the optimal cushioning map to produce a high performance shoe for a wide variety of body types and playing styles.

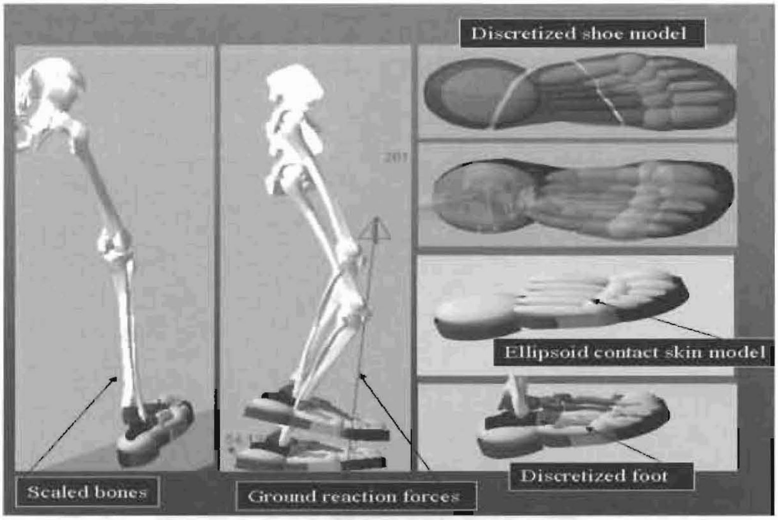

Figure 3. Foot model for sports shoe design

Model: The discretization of the model is depicted in Figure 3. The model consisted of the effective body mass, the thigh, shank, talus, calcaneaus, midfoot segment, 5 metatarsals and the toes. The parts are connected together using the proper constraints and orientation consistent with values reported in the literature. The muscle forces acting on the model were derived using inverse-dynamics approach based digitized motion data (see ref. [1] for technique) The fat-pad contact forces at the calcaneaus, metatarsals, and phalanxes (toes) were derived using an ellipsoid to plate contact algorithm. The foot model was augmented with a network of non-linear stiffness/damping compression elements to represent the midsole. These elements were placed on the plantar surface of the foot at locations consistent with the geometry of the outsole of the particular shoe. The non-linear force generated by these elements was based on laboratory force-deflection data (static test), and force-deflection rate data (dynamic test) for each zone. The elements produced both normal (compression) forces and transverse (friction) forces. *Boundary conditions:* The ground was defined to be a set of spring elements representing various basketball playing surfaces, the jump height, landing vector, and midsoles stiffness zone properties were set up as the controlled parameters in a simulation sweep. *Accuracy:* The model was validated against motion capture data and force plate measurement data for a set of test subjects, at various jump heights for various midsole stiffnesses. The midsole compliance algorithm was tested independently of the model setting up a virtual test similar to the mechanical impact tester in the laboratory. *Simulation:* A design-of-experiments algorithm was employed to create a large range of simulations through parameter variations. At times some test cases would not solve to completion. These were analyzed to understand the failure mode to determine if more specific validation were needed. *Results*: The results from the model were organized in a relational database and presented to the customer. The customer was able to se these results to determine the optimized stiffness/damping properties of different regions of the midsole for various human body types for the deployment of a new high-performance basketball shoe.

ORTHOPEDICS INDUSTRY COMMERCIAL SAMPLE: This particular company is interested in developing a new total knee replacement (see refs [5], [7], [8], and [9] for complete model development descriptions). Evaluation of joint replacement components before any clinical use is important in assuring device safety and efficacy. *Problem: How to develop a knee joint replacement, which replaces the stabilization lost with missing soft tissue, yet provides full range of motion?* A model of the lower extremity coupled to a virtual model of the cadaver knee test machine will be created to test various types of new total knee replacement concepts.

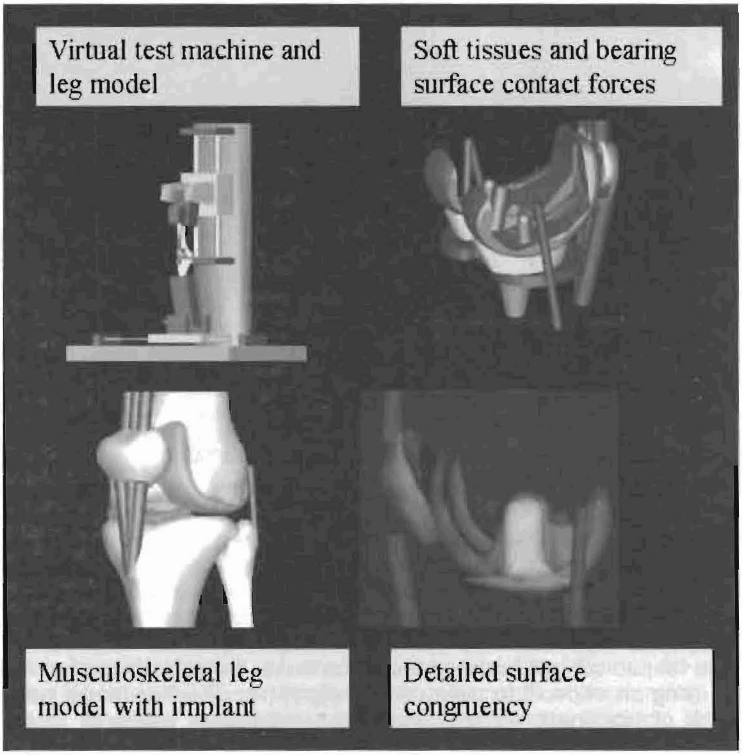

Figure 4. Virtual test machine and leg model for evaluation of total knee joint replacement

Model: A six-degree-of-freedom bearing surface contact algorithm was incorporated into a model of the lower extremity to model tibio-femoral and patello-femoral articulations. The surface contact force calculates the forces of penetration and traction and is based on the mechanical properties of the interaction, including the stiffness, damping, and static and dynamic friction values. Combined with the model of the lower extremity, was a model of the experimental electro-hydraulic knee simulator. Basic geometry and mass properties of the experimental knee simulator and TKR were imported into the model. Cruciate and collateral ligaments were positioned at average insertion points. All the soft tissues wrap appropriately around hard obstructions to permit proper force direction. The 4-axis knee simulator uses actuators to impart a vertical load at the "hip", and tibial torque and varus-valgus forces at the "ankle". A quadricep force balances the vertical load through the patellar tendon. *Boundary Conditions:* Input load and motion profiles, which would be induced on the lower extremity via the virtual test machine, were developed from simultaneous 3D motion and force plate data to represent gait and stair ascent/decent activities. *Accuracy:* First, the bearing surface contact algorithm was isolated from the model and validated against the results from a mechanical apparatus. Second, the virtual machine was given the same input parameters as the electro-hydraulic machine, and the output parameters (knee kinematics) were compared for several cadaver specimens. *Simulation:* With the performance of the virtual simulator within an acceptable margin of error to the physical simulator, many new TKR design variations were tested in the virtual knee simulator. These include both global and local geometric changes to explore the stabilization and range-of-motion qualities. *Results:* For this process, new TKR designs existing as CAD models were tested individually and compared against performance characteristics of other designs. The virtual simulator allowed the customer to test a much wider variety of designs, before any physical prototypes were created. This capability greatly accelerated the innovation necessary to create a high performance and competitive knee joint replacement.

CLINICAL APPLICATION INDUSTRY COMMERCIAL SAMPLE: This particular institution is interested in predicting the best various mechanical and sensory rehabilitation strategies for spinal injured patients. (See refs [10], [11], [12], [13] and [14] for model descriptions) *Problem: How to examine the effects of sensory stimulation and/or tissue intervention as a possible rehabilitation protocol?* A controlled musculoskeletal model of locomotion will be created to test mechanical intervention (tissue shortening) and sensory intervention (stimulation) on the walking pattern.

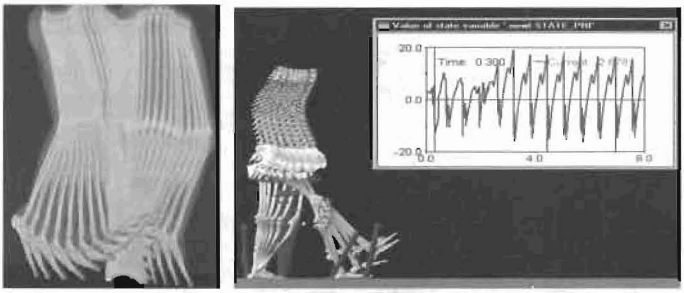

Figure 5. Musculoskeletal model with neuro-oscillator controlled gait

Model: A controlled musculoskeletal model of locomotion was created. Generally, the musculoskeletal model consisted of: a) eight segments including a pelvis, 2 thighs, 2 shanks, 2 feet and a lumped upper body segment; b) seven joints, two each at the hips, knees and ankles, and one at the trunk; and c) flexor and extensor "muscles" that generate active torques around the joints in proportion to the output of the neural system. Muscle forces were modeled as net torques about each joint. The model also included frictional torques at each joint and torques exerted by passive joint structures at the knees that limited the range of motion. This mechanical model was considered the "plant" in the control scheme. The inputs to the plant included the muscle activations, the outputs from the plant included proprioceptive feedback such as segment inertial angles, foot/floor contact indicators, etc. The control system consisted of seven pairs of neuro-oscillators. *Boundary Conditions:* The foot/floor contact was handled using an ellipsoid-plate contact algorithm, which would create normal and frictional forces at the ellipsoids placed at the contact points of both feet. The inclination of the ground was changed to test how the model responded to walking uphill and downhill. Also, a random perturbation force, acting at the upper body segment was introduced to determine the robustness of model recovery. *Accuracy:* For this investigation, the model was constructed not for a specific test subject but was based on a model put forth in the literature. The only validation of this version of the model was to test the see if the performance characteristics were within acceptable parameters to the published results. *Simulation:* Once the model was deemed similar to the published model various conditions of the model were altered to simulation various intervention strategies. To simulate proprioceptive stimulation, amplifiers were placed on the feedback signals and the model walking performance was measured. To simulate soft tissue alteration, delays were introduced in the torque signals at specific joints. *Results:* The model was used as a test bed for general intervention strategies. As such, no specific simulation results were called for. Using the model, the investigators gained a level of understanding of the effects of various mechanical and sensory alterations had to the walking signal pattern.

INJURY EVALUATION COMMERCIAL SAMPLE: The simulation was performed for a legal case of an injury that resulted from a motorcycle hitting a pothole in the road during a lane change maneuver. (See ref [15] for complete model description) *Problem:* Two aspects of a motorcycle injury crash were studied. 1) *What were the rider's actions which led to unsafe handling of the motorcycle*? 2) *What were the injury-producing mechanisms present during* *the crash*? To provide additional evidence for this case, a rider/motorcycle was created complete with a motorcycle control algorithm. The delays of the feedback signals in the controller were altered to simulate the delayed response of a person under the influence of alcohol, to see if the system was stable after the perturbation (pothole). When the model crashed, the injury pattern was estimated based on the impact forces to the individual segments and the joint torques.

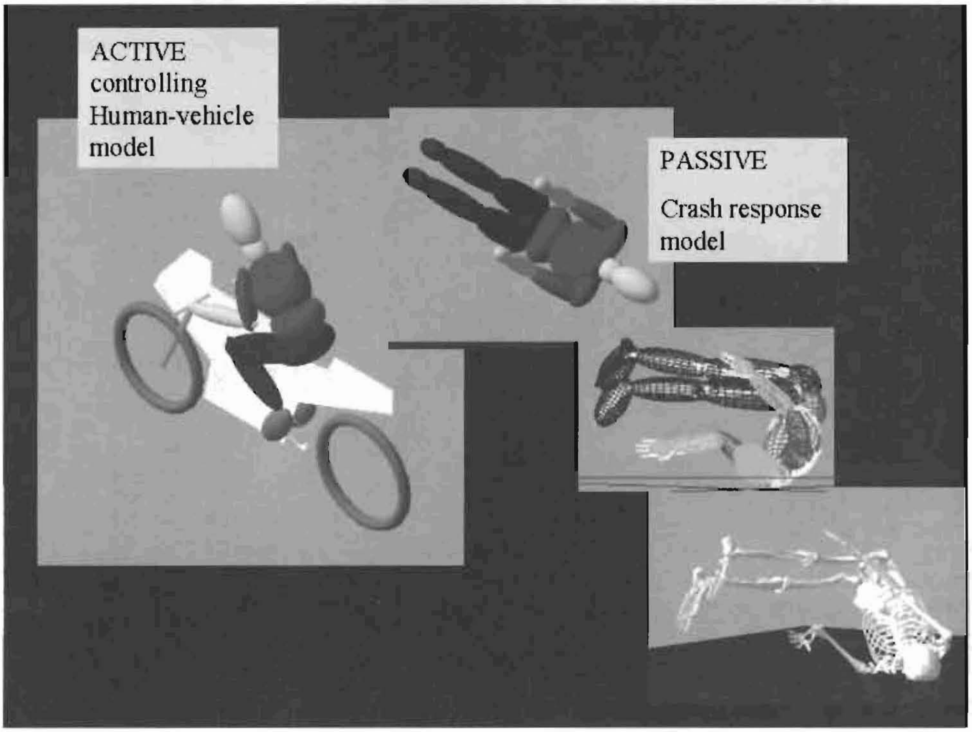

Figure 6. Active/passive human model of a motorcycle crash

Model: The approach was to build a 15 segment human model coupled to a model of the motorcycle using "breakaway" forces at the hands, feet and pelvis. The human joint forces consisted of both an active and passive mode. In the active mode the joint forces were governed by a feedback control system which senses motorcycle roll, yaw and path deviation and actuates the human rider model to adjust the steer torque input to stabilize the vehicle, and to adjust its lean angle to maintain the proper heading. The model would switch to the passive mode when it sensed the human rider model was decoupled from the motorcycle (i.e., crash). The joint torques present in the passive mode were based on stiffness, damping, friction and joint limit data measured for he Hybrid III crash dummy. This passive representation would allow the model to produce the appropriate kinematic rebound during the ballistic impact. *Boundary Conditions:* A tire force algorithm was used to model the six components of the tire-road contact at the contact patch. The pothole was introduced by supplying a impulse force based on the vehicle speed. The control system was set up to maintain a heading during a lane-change maneuver at a range of speeds. *Accuracy:* Due to a lack of laboratory data for this type of maneuver, the system was verified in a piecemeal form. The passive strength model was evaluated in the human model by comparing the response of the model for a series of crash pulses to data from the actual dummy. The rider control system (active mode) was derived from literature, and the response of the model was compared against the results from these studies. The tire force subroutines were validated against actual tire mechanical tests. *Simulation:* Simulations were first performed for the lane change maneuver for the unperturbed case to test for system stability. The perturbation was then introduced at the apex of the turn for the case of a normal neuro-actuation time delay on the path sensing function of the controller, and one with a time delay which represented an impaired person. *Results:* The system remained stable for the first case, however, capsized for the second case. During the capsizing, the human model switched to the passive torque model and rebounded off the ground. Segment impact forces, and joint torques were measured and compared against injury norms to assess a range of possible injury scenarios.

TASK SIMULATION COMMERCIAL SAMPLE: This simulation was performed for a client concerned about the recoil force of an automatic weapon on the shot accuracy. *Problem: At what point does the recoil force cause unacceptable shot error for the soldier?* A feedback controlled human model was created to continually aim the weapon at a target. Recoil forces for the weapon were introduced at the interfaces between the weapon and the soldier. Shot accuracy would be estimated based on shot "drift".

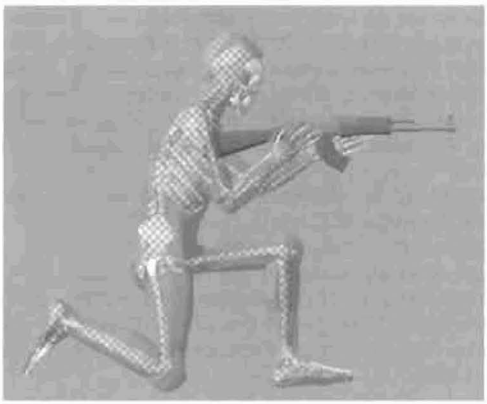

Figure 7. Human model firing a weapon

Model: A basic 19-segment human model was scaled to the proportions of a specific soldier. A simple model of the weapon was attached to the human model using bushing elements based on an estimation of grip strength. The 18 joints in the model were specified as active or passive. All joints from the waist on down were designated as passive and involved with the stabilization of the model and not specifically involved in the aiming of the weapon. The active joints, or the joints involved with the aiming of the weapon were controlled with a closed-loop aiming controller. The controller would alter the instantaneous spring "free length" of each spring-based torque joint based on the results of the previous shot. *Boundary Conditions:* The model was attached to ground using bushing elements at the feet and the right knee. A recoil force history was imposed on the weapon using the magnitude and frequency recorded from the test weapon. *Accuracy:* Shot accuracy was assessed by examining the location of a ray, cast from the barrel of the weapon, on the target at the time of firing. The offset from the target would be considered the error in the targeting control system for the next shot. Accuracy of the model was assessed, by comparing the motion of the body segments of the model, to the video taped motion of the soldier firing the test weapon. Controller gains were tuned to produce an acceptable motion match. *Simulation:* Once the model was tuned and verified, simulations were performed with variations to the recoil force magnitudes and frequency. *Results:* The model was used to produce recommendations to recoil force magnitudes and shot frequency which would produce the most accurate hit rate. In addition, the recoil loads on the soldier were examined by assessing the reactions of the weapon load to the joint and segments of the model.

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