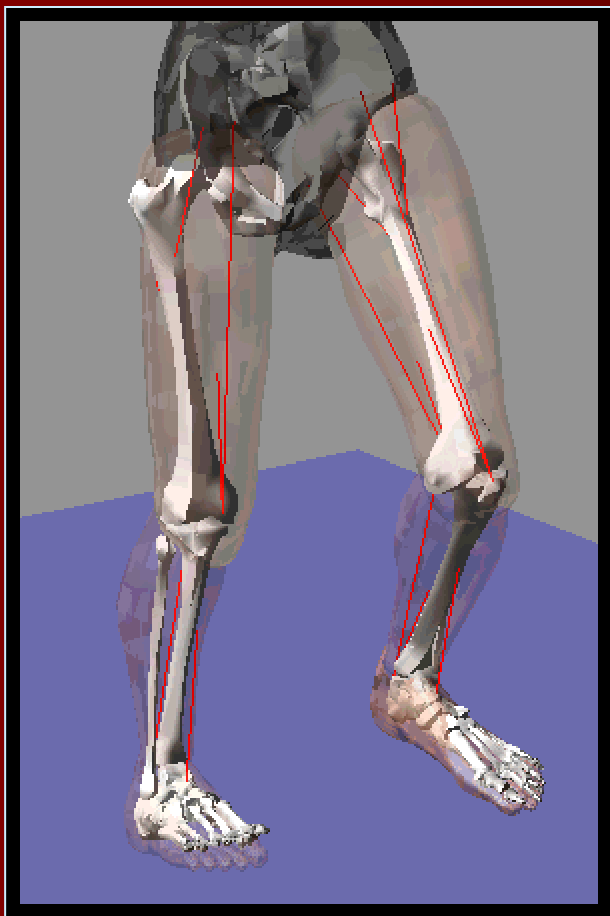
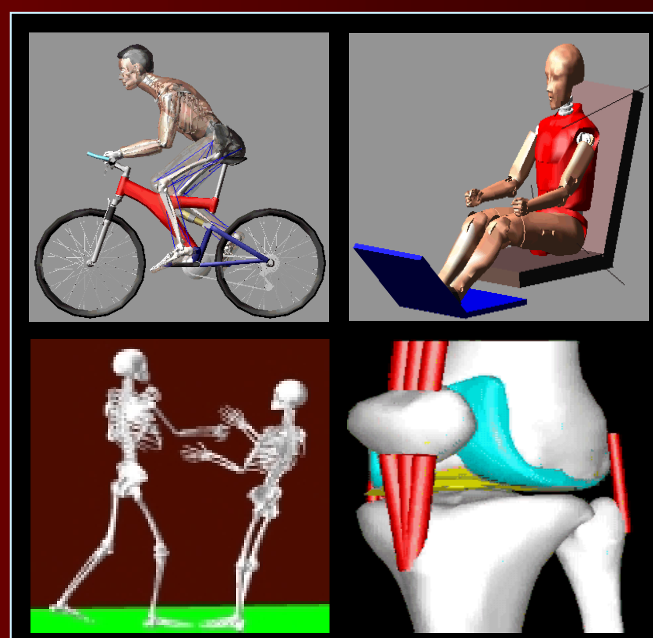


Virtual Biomechanics



The genesis of the *LifeMOD*® Biomechanics Modeler

Biomechanics Research Group Inc.®

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INTRODUCTION

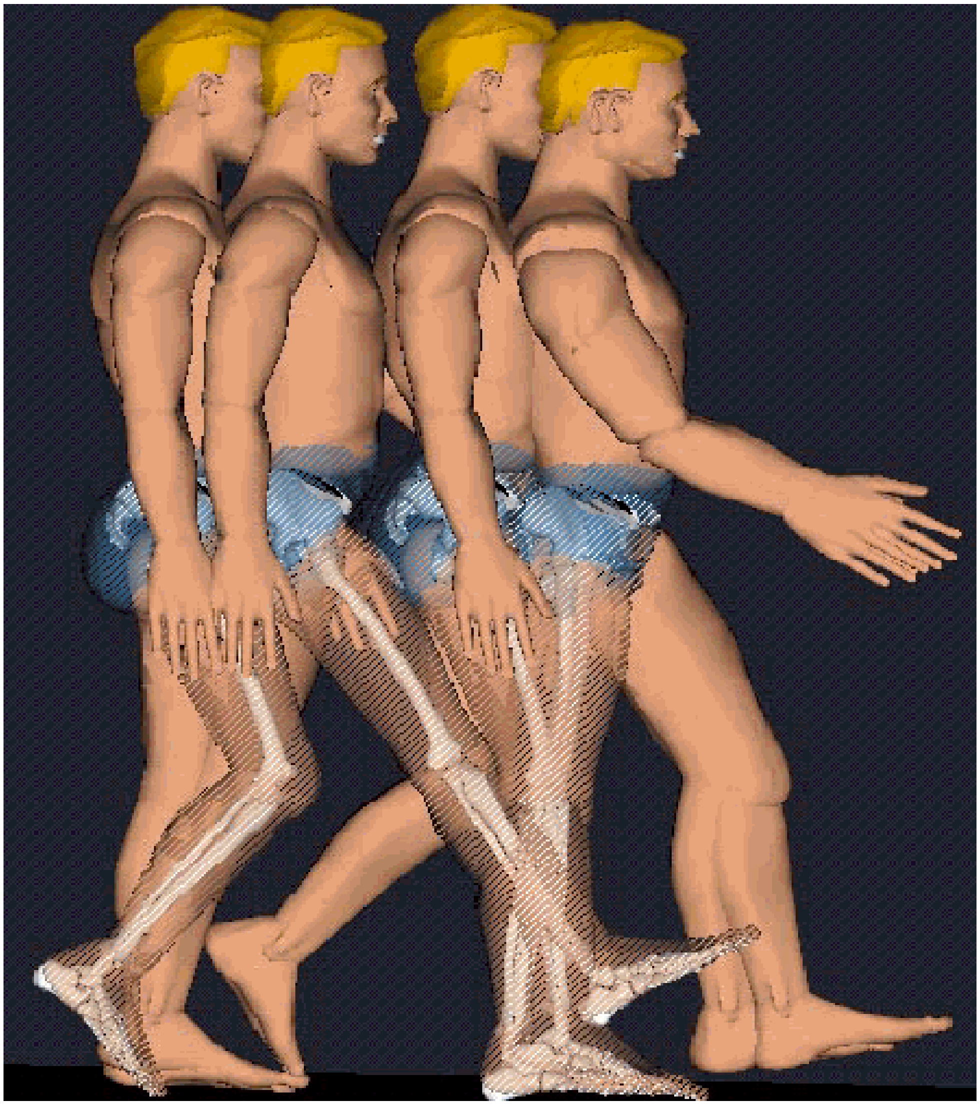
Virtual prototypes, in the form of mechanical simulation computer models, have been used by many researchers, clinical professionals and commercial companies, to study human movement and to develop products used by, on, for and in humans. The Biomechanics Research Group Inc., in collaboration with several major orthopedic companies, sports equipment manufacturers, clinical laboratories and research institutions, has developed computer tools based on the popular ADAMS (MSC.software inc.) software product. This collaboration has resulted in the powerful biomechanics simulation environment, the LifeMOD Biomechanics Modeler.

As *this report documents a sample of the wide variety of commercial projects which served to develop the technical foundation of LifeMOD. Developed this broad base of application, LifeMOD is capable of generating human models with a level of sophistication ranging from simple to very complex addressing a wide range of applications from sports performance to injury evaluation, from gait simulation to vehicle ride comfort.*

For more information about the use of the LifeMOD Biomechanics Modeler, please contact Shawn McGuan, Biomechanics Research Group Inc., 2730 Camino Capistrano, Suite 7, San Clemente, California, USA 92672 Phone: (949) 366-6829 . *E-mail: smcguan@lifemodeler.com*

For detailed information, technical papers and a FREE TRIAL of the LifeMOD Biomechanics Modeler please visit www.lifemodeler.com

HUMAN MOTION SIMULATION AIDS REHABILITATION RESEARCH



A neurophysiology research project at California Institute of Technology's Jet Propulsion Laboratory (JPL) in Pasadena, CA, in conjunction with the ***Biomechanics Research Group Inc.*** *uses mathematical models of the human body to study the way the brain transmits signals to lower limbs for walking, running, and other locomotion.*

"Investigations will aid in the develop-ment of ways to rehabilitate patients with lower-limb paralysis," explains Neural Repair Project Director Jim Weiss. "Findings also will be useful in under standing and preventing muscle and tissue deterioration in astronauts during prolonged weightlessness."

According to Weiss, the initial phase of the project will focus on rehabilitation of patients disabled by stroke, spinal cord injury, and other lower-limb paralysis.

Experiments demonstrated that the spinal cord has the unique ability, through repeated physical exercise,
to "learn", how to generate signals for controlling leg movement in the absence of neural stimulation from the brain. In one rehabilitation strategy, patients are suspended by a harness over a treadmill with their feet lightly touching the moving surface. Assisted by therapists, the patient's lower limbs repeatedly go through a stepping motion on the treadmill. Over time, patients require less assistance as they independently start to achieve a new gait.

In an effort to refine this approach, JPL is working on a body-suit-like mechanism to be worn by rehabilitation patients. Force transducer technology for the system is derived from work on robotic exoskeletons developed by JPL for space station use. The body suit will have force transducers coupled with electromechanical sensors and controllers capable of exerting force and measuring resistance simultaneously with six degrees of freedom. This enhanced capability will provide a consistent, higher quality approach for stroke and spinal cord-injured people re-learning the ability to walk. It will also provide more accurate data on the level of patient improvement as well as the amount of assistance required over time.

"Subsequent efforts will apply the same technology to a NASA program studying the reasons and possible preventive measures for astronaut muscle and tissue degeneration observed during prolonged weightlessness," explains Weiss. "A vital part of this work is analyzing the kinematics of human locomotion as well as the forces on lower-limb joints that is where the ***Biomechanics Research Group Inc.*** *comes in".*

In particular, the exoskeleton will be used to analyze astronaut exercise routines and can assist walking and exercising in zero-G, thus helping maintain normal motor *control, muscle mass, and bone calcium levels.*

Collaborative Efforts

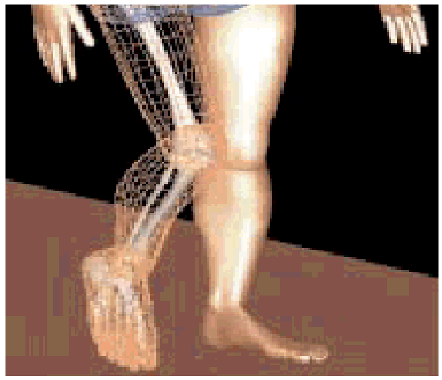
For this neurophysiology project, researchers from JPL, the UCLA Brain Research Institute, and the ***Biomechanics Research Group Inc****. are collaborating to develop the simulation needed to analyze and predict human motion.*

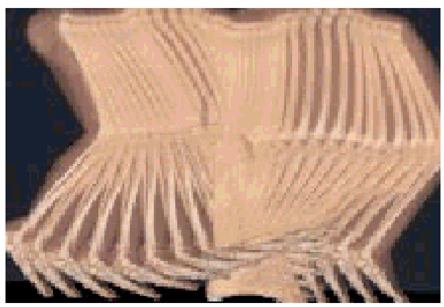
Data generated by the exoskeleton will be fed into a human model built using the popular ***LifeMOD™ Biomechanics Modeler.*** *The resulting system is expected to provide researchers with a tool to simulate walking, calculate force and rotation levels at joints, pinpoint which portions of the step cycle need augmentation, and devise ways of placing less stress on muscles and bones.*

Each leg of the full-body model is comprised of 26 bone segments representing the femur, tibia/fibula, and the many intricate bones in the foot. These bones are coupled with mechanical joints and bearing surface contact joints (knee and subtalar joint). Redundancy issues such as soft tissue spanning several joints (lateral ligament complex in the ankle) are included in the model. Methods for handling ill-conditioned properties such as agonistic/antagonistic muscle activity are also included.

The muscles in the model are activated through a neural network-based controller which sends activation patterns to the muscle actuators. The architecture is based on the central pattern generator (CPG) structure for the human nervous system. The control system is a multiple input, multiple output (MIMO) form and utilizes proprioceptive feedback of the states of the body segments (position, velocity, floor contact, etc.), to generate the muscle activation patterns.

These controlled human models will be built through a custom graphical user interface. The models will be "personal-ized" with features such as parametric hard tissue geometry and joint axis orientation, soft tissue geometry and configuration, and a controller which can be configured to the state of the patient.





The performance of the model and the controller will be tuned to match digitized kinematics, EMG, and ground reaction force history data for a series of patients. Compensation and adaptation of the controller will be evaluated and tuned to match specific test subject compensation. The robustness and accuracy of the controller compensation will be related to the number of test subjects and accuracy of the experimental data.

This advanced controlled locomotion model, once verified against a wide range of patients, will have great significance and utility for understanding locomotor strategies for spinal cord-injured patients. Musculoskeletal intervention (i.e., tissue shortening, relocation, etc.) and neural intervention (addition of a feedback pathway) may be explored on the model before they are attempted on the patient. This model will allow scientists to understand the many interrelations between the musculoskeletal and neural variables, thereby accelerating treatment innovation and effectiveness.

The controlled locomotion model will also provide utility for understanding locomotor compensation strategies in micro-gravity. Altering the gravity in the model involves the simple act of altering the gravity constant parameter (g). With the gravity environment changed, the model will adapt to maintain stable locomotion and establish comfortable ground reaction force dissipation potential throughout the joints of the human model. Using this model, we can then determine how the nervous system will adapt to this change, and can input specific locomotor strategies for micro-gravity to test for their effectiveness.

In addition to this practical utility, the model of the controlled human for locomotion will be combined (merged) with a mechanical simulation model of the robotic exoskeleton for a complete virtual prototype of the human-in-the-loop system. This virtual prototype will be developed in order to design the mechanics and controller of the exoskeleton. Using this virtual prototype method, the geometry, actuators, and controller function will be designed before hard prototypes are completed, thereby accelerating the design process. "These modeling efforts represent a significant step forward in lower extremity neuromuscular modeling," says Weiss. ***The Biomechanics Research Group Inc.*** *was selected as a partner because of their well-established knowledge of lower extremity simulation."*

OPTIMIZING ORTHOTIC DESIGNS THROUGH VIRTUAL GAIT SIMULATION

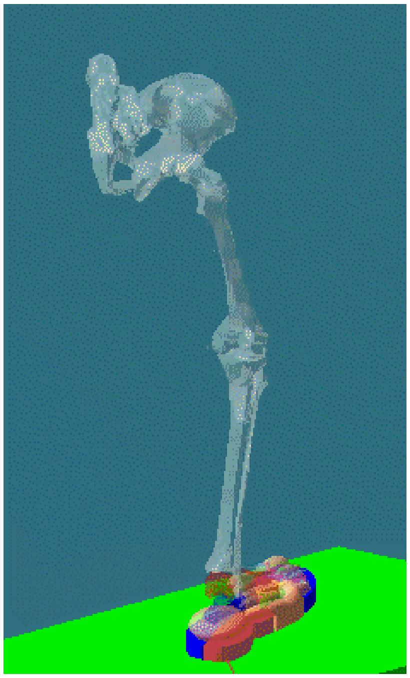
Therapists and technicians have raditionally corrected their patients' foot or ankle abnormalities by recommending an orthotic insert, which is worn for several weeks, then adjusted incrementally until the pain is eliminated or at least reduced to a tolerable level. However, it can take months before any results are observed. Moreover, the orthotic inserts sometimes merely displace stress to other bones and joints so that other problems surface years later. A patient with foot pain might be helped for a few years, for example, only to develop knee problems later. Ir

"There are just too many variables to consider," said Brent Konantz, president of Prothotics Corp. in Winnipeg, Manitoba. "A patient going to 20 different clinics will get 20 different orthotic devices to correct the same problem."

Konantz knows from personal experience. In 1983, a ruptured Achilles tendon ended his career as a sprinter for provincial and national running teams in Canada. In working with a team of health-care professionals during rehabilitation, Konantz was fascinated by the way they corrected pressure on lower-limb bones and joints through the use of orthotics, which change the angle the foot hits the ground during walking and running.

By raising or lowering the various areas of the feet, orthotic inserts ease the pain experienced by patients with sports injuries as well as foot and ankle anomalies related to arthritis, diabetes, and other debilitating diseases. Orthotics also help promote proper muscle function during rehabilitation for those with disabilities, such as cerebral palsy, stroke, and head injuries.

Konantz became so interested in orthotics that he trained as pedorthist - a professional who designs and manufactures corrective footwear prescribed by a physician. Konantz quickly saw limitations in the way in which inserts are sized and positioned. "I soon realized that orthotic design was more of a craft based on experience and on trial and error than a science," he said, "so I set out to find a way of

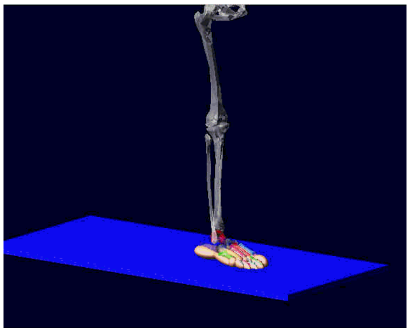


using computers to quantify and simulate a patient's movement."

*After founding Prothotics, Konantz selected biomechanics simulation software to put orthotic design on a more scientific basis. One firm he approached was **Biomechanics Research Group Inc.** Shawn McGuan, President and founder of (BRG), worked closely with Konantz to customize the **LifeMOD™ Biomechanics Modeler** for orthotic design applications.*

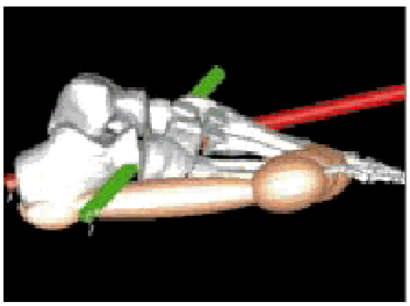
The resulting package simulates a patient's walking and running gait based on leg and ankle measurements. Based on these simulations, clinicians can immediately visualize the effects of various orthotic insert designs to find the best one for each patient without going through the time and expense of making and trying one after another until pain subsides.

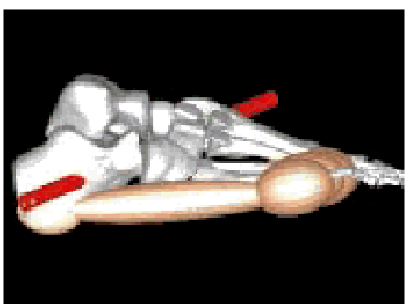
*"This approach has the potential to revolutionize the way we treat lower-limb pain, disability, and rehabilitation," Konantz said. "We've already used the software to help hundreds of patients, and have plans to expand operations to clinics in other cities. This is possible because of our ability to simulate biomechanical systems with **LifeMOD**, and the expertise and willingness of BRG's staff to customize their software for our application."*



McGuan worked with Konantz to develop an interface that enables an orthotic clinician with little or no computer training to enter patient data and interpret results easily. Specifications compiled by Konantz for the project included parameters defining the movement for "medical normal limb functions gathered from interviews with doctors and measurements of human anatomy. Also included are results of cooperative research with Nike and other footwear manufacturers.

The human locomotion model developed for Prothotics is based on the Shock dissipation lower extremity model McGuan developed for Nike, used in the development of stable sport shoes. The model produces a biomechanics "map" of how the lower extremity dissipates the ground reaction force. The map shows the effect of the ground reaction force at the foot and traces up through the ankle, knee, hip, and lower back. Research has shown that this dissipation profile should be smooth and continuous, since any sharp spikes could represent acute stress sites. Considering how many thousands of steps the average person takes per day, any abnormality in the shock dissipation capability of the lower extremity could translate to chronic pain and degenerative injuries.





The software system developed around this human locomotion model uses patient information gathered by the clinician as initial input. This input includes age, gender, weight, and measurements including the alignment of several effective articulation axes in the foot, as well as the range-of-motion about each axes. From these measurements, a "personalized" model is built.

On the basis of this information, the software simulates the gait of the patient and compares that replication with the normal gait as determined by the computer for a numerically average individual of similar age, weight, and proportions. The software iterates on the geometry under the foot necessary to normalize the ground reaction force dissipation signature in the patient's lower extremity. The resultant geometric contour represents the geometry of the proposed orthoses.

"Basically, the computer shows the clinician how the patient is walking, how he or she is supposed to be walking, and what can be done to get the walking equivalent to what is considered normal," Konantz said.

Output from the software includes animated graphic images showing the patient walking and running at various speeds, which can be slowed or magnified for closer study. The animation shows the full gait, from heel strike to toe-off, and can display limbs as realistic solid models or in skeletal form. The software also provides graphed data, such as stresses and velocities on certain bones, and forces and torque rotations on joints.

Output of data and images is provided for the patient's present condition plus the medical normal profile and the predicted gait if the suggested orthotic inserts are implemented. Of course, these suggested orthotics can be overridden or modified by the clinician, and the simulation can be rerun to see the effects of other inserts as determined by the clinician.

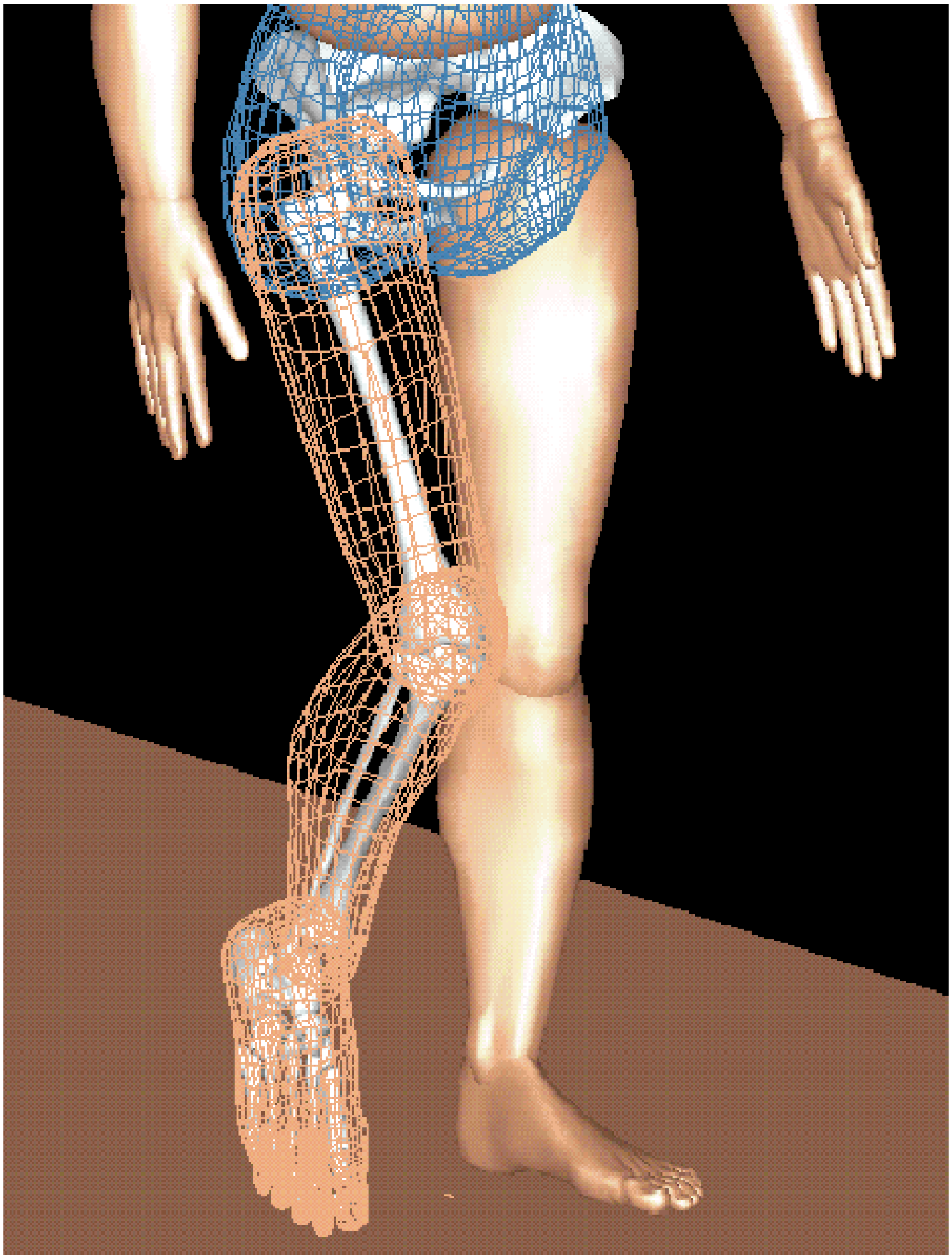
"You never want to make the system so fully automatic that you take flexibility away from the orthotic clinician," Konantz said. "The software is a tool, and if the clinician wants to try something different based on patient experience, we want to have the capability to support such individuality."

After the orthotic device is refined, the system produces instructions for making the appliance on a numerically controlled milling machine. The patient can then wear the orthotic, usually on the same day as the evaluation visit.

Prothotics' gait-simulation software is the first part of Konantz's 10-step, five-year plan to license turnkey orthotic systems around the world for use by clinics, health care facilities, professional sports teams, and rehabilitation centers. In Konantz's plan, manual measurements of limbs will be replaced by signals from a force plate on which the patient stands to obtain specific loads on critical pressure joints of the foot. Also, magnetic resonance imaging scans will be used to more accurately depict the structure of bone mass as well as ligaments, tendons, and muscle groupings.

This future software may also have the capability to "age" the gait simulation model to investigate probable long-term effects of the problem or dysfunction. Such a capability is particularly important in predicting and studying chronic, repetitive stress associated with osteoarthritis.

MODELING THE HUMAN LOWER EXTREMITY DURING A DROP LANDING



INTRODUCTION

A computer model of the human leg and foot was generated to explore the kinematic and kinetic properties of the human leg and foot during a drop landing.

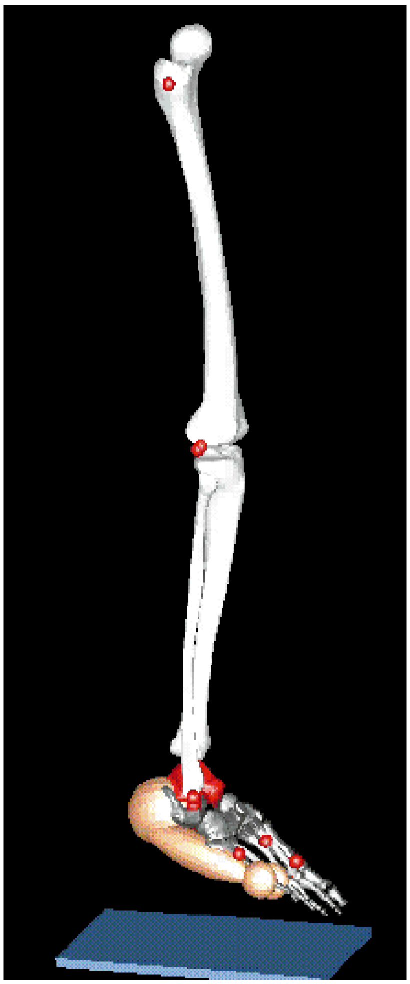
Experimental data from an actual drop landing was used to produce the model. A goal is to develop this modeling approach into a tool to investigate the effects of mechanical and geometric characteristics of sports shoes on acute injury, such as an inversion-related injury to the lateral ligament complex.

REVIEW AND THEORY

Rearfoot stability during running and general sports activities is related to foot anatomy and the kinematic changes that result from footwear, Nigg (1986). To study the effects of changes in footwear design variables, researchers have predominantly relied on laboratory analysis. Simple analytical models, Stacoff et al. (1988), Nigg (1986), Miller, et al. (1973), Jonsson (1987), have also been used. However, researchers continually stress the need to develop more detailed models to supplement and complement existing laboratory methods, Stacoff et al. (1988), Clark et al. (1984), Cavenaugh (1980), Cavenaugh (1990), Miller et al. (1973), Jonsson (1987).

As early as 1960, researchers have recognized that the human locomotor system can be characterized by a set of differential equations, Miller (1973). This characterization can be expanded to include a mechanical model of the shoe. Simple analytical models have been useful in obtaining relationships between rearfoot eversion and a changing moment arm due to varying midsole geometry and cushioning properties, Stacoff et al. (1988), Nigg (1986). Although a computer is used to find solutions to the set of differential equations characterizing the dynamics of these models, the set of equations themselves were usually derived and assembled by hand, limiting the detail and complexity of the mechanical system described.
With the evolution biomechanics simulations tools such as the ***LifeMOD™ Biomechanics Modeler****, it is now convenient to generate a system of non-*

linear (differential/algebraic) equations, representing a set of constrained six degree-of-freedom parts by working on a computer graphics analogy of the system. The system of equations is then assembled into matrix format and solved through time, Chase (1984). The simulation results are interpreted using computer animations and data graphs. This relatively new generation of software simulation tools removes the analyst from the complexity of the underlying mathematics, allowing the focus to shift to model behavior and function.



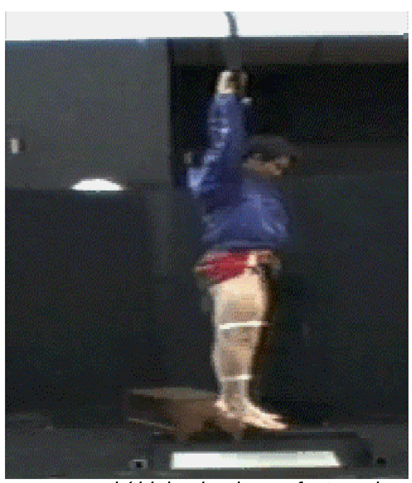
Due to this increased convenience, the analytical models generated using mechanical simulation tools will be of a higher order of sophistication and detail than those used in the past for sport shoe evaluation, and will include many more interacting kinematic variables.

For example, the model presented here couples pronation/supination with full inversion/abduction/dorsiflexion, not just calcaneal inversion, to study the effects of pronation/supination on tibial rotation. In addition, the shoe model, complete with flexure and cushioning properties, is capable of capturing the effects of a continuously varying moment arm during a jump landing. This cushioning surface can also be used to model the partial interaction between the shoe and obstacles, such as landing on another player's foot. Through discretization, the foot and shoe model will better adapt to the ground surface, with or without obstacles, to provide increased kinematic accuracy of the entire human locomotor system.

PROCEDURES

Data Collection

A barefoot male subject dropped onto a Kistler™ force plate by releasing his grip from a "hang-bar." The drop height (distance from subject's toe to ground) was 14 cm. A Watsmart™ optoelectronic 2-D motion analysis system was used to collect the drop landing kinematic data for two seconds at 200 Hz. A Watscope™ system was used simultaneously to collect force plate data at 600 Hz. Data collection was conducted on the subject's right lower extremity. Kinematic data were obtained using infrared markers at boney locations. A four-segment experimental model



was assumed (thigh, shank, rearfoot, and forefoot) for data collection. Three-dimensional joint motions for the hip, knee, ankle, and the ihpseudo-jointla between rearfoot and forefoot were calculated using data analysis software provide with the Watsmart system. Data was collected for both a flat landing and a landing on a 3 cm obstacle under the first metatarsal head.

Computer Model

*To simulate the lower extremity response to the drop landing, three types of **LifeMOD** lower extremity models were constructed: a coarse model, a detailed model, and a skin model. The coarse model was built with four parts to reflect the discretization employed during data collection. The degrees-of-freedom (DOFs) in this kinematic model was driven with the experimental data produced by the Watsmart system. A detailed model of the complete musculoskeletal lower extremity was developed using 26 parts and a lumping scheme in the foot similar to Scott (1993). Mechanical joints were used to connect all parts in the model except for the subtalar joint where a 3-D surface contact force was employed. A skin model was developed to provide a contact force between the musculoskeletal model and the environment (i.e., shoe, force plate, etc.).*

SIMULATIONS

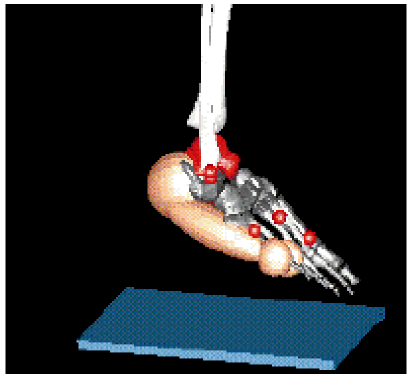
A model overlay technique was employed to drive the 26 parts of the detailed model with the four parts of the coarse model using the experimental displacement data. Spring-damper elements were used to anchor the coarse model to the detailed model at the diode locations used in the experiment. The spring and damping rates of the connection elements were normalized to the specific accuracy of the diode, to allow for the more accurate diode locations to provide the dominant motion contributions. Viscous dampers were applied to the rest of the model to prevent any motion in the free DOFs during free-

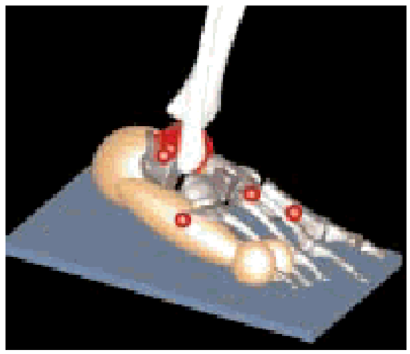
fall. The skin model was then overlaid on the detailed model to provide for foot-to-floor interaction. Dynamic simulations were performed with this overall arrangement to record the relative rotational and translational displacements at the joint connections.

The coarse model was then stripped from the detailed model. Muscle-ligament forces acting at the joints were described using a controller element positioned at each DOF with the error function being based on the difference between the recorded instantaneous displacement from the previous simulation and the current simulation displacement. This controller would produce the internal muscular-ligament reactions necessary to guide the motion at each DOF in order for the segments of the model to match the segment motions in the experiment. Simulations were then performed with this dynamic model. The gains of the controller elements were iteratively adjusted using an optimization technique to match model results to experimental results (segment motion and external reaction forces).

Model verification was performed by comparing the ground reaction forces for model and experiment and the CP travel history. With the external reactions of the model correlating with the experiment in conjunction with a correlation of segment motion, it is assumed that the internal reactions or muscle forces and ligament loadings of the model will also correlate to loads the experimental subject experienced.

Simulations using this method were performed for both flat landing and obstacle landing cases. With the model validated for both cases, the height of the obstacle was increased in the simulations to cause an ankle inversion in the model. Stresses on the spring elements representing the lateral ligament complex were monitored to gauge injury and rupture. With this acute injury-producing mechanism isolated, research is now focused on the development of a sports shoe model to overlay onto the detailed model to stabilize and reinforce the ankle.





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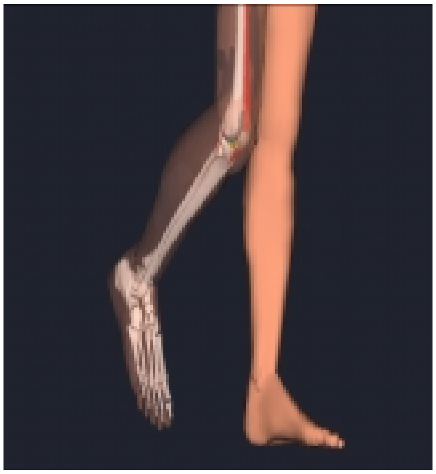
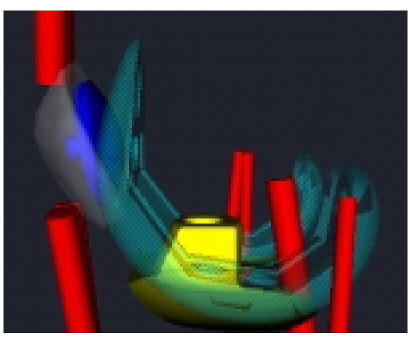
FORCE-BASED KNEE SIMULATION FOR THE DESIGN OF TOTAL KNEE REPLACEMENT PROSTHESES



The objective of this research was to develop a six degree-of-freedom articulating knee joint for a lower extremity with a Total Knee Replacement (TKR) prosthesis. This simulation capability will be used to define the articulating surface profiles of the TKR to suit a specific patient's gait pattern and physiology.



To accomplish this, the ***LifeMOD™ Biomechanics Modeler*** *software was customized to develop a parametric, 3-D, dynamic model of the total knee replacement (TKR) prostheses. A high-resolution skeletal model, developed from tomographic scan data, was assembled into a lower extremity model. Surfaces representing the TKR are imported and fixed to the femoral condyles and the tibia menisci plateau.*

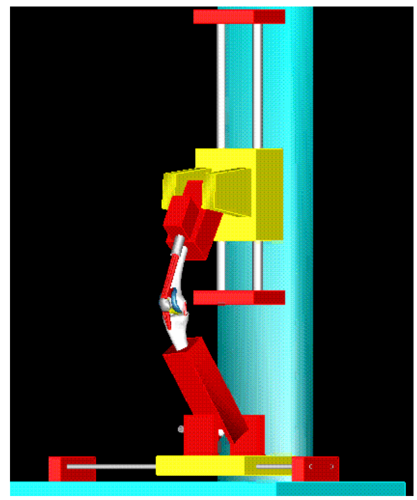
A surface contact algorithm was implemented to model the contact between the articulating surfaces of the femoral and tibial components of the TKR and the femoral component and the patella bone. This contact algorithm defines the surface surface contact of the condyles-menisci articulation as a force, thus permitting rolling and sliding as well as intermittent contact and surface depression (locally deformable). This approach allows the greatest versatility to model:

1. *stabilized prostheses,*
2. *condylar surface prostheses,*
3. *human specimens.*

The cruciate and collateral ligaments were positioned at insertion points and the elastic properties are described using non-linear stiffness properties. All soft tissues wrap appropriately around hard tissue obstructions to permit proper force direction. The patella, patellar tendon, and the quadriceps muscle are also modeled and included for joint actuation and stability.

This functionality has been developed into a product from the ***Biomechanics Research Group Inc.*** *called* ***LifeMOD/KNEE™***. *LifeMOD/KNEE represents the culmination of 10 years of research and collaboration with six orthopedic companies and three orthopedic research hospitals. Before any simulation results could be considered in the TKR design process, LifeMOD/KNEE was run through an extensive validation process, performed by merging the musculoskeletal model of the leg into a model of the Purdue Knee Simulator Machine (Oxford Rig). The actuator loads of the machine, including body vertical force, quadriceps and hamstring forces, and ground reaction forces, were imposed at the hip, across the joint, and at the ankle, respectively. The reactions of the knee joint, including six degree-of-freedom motion of the tibiofemoral and patello-femoral joints, contact forces, and contact areas and soft tissue loads were compared to those from the experiment. Through several test cycles, LifeMODKNEE has been calibrated to consistently match experimental data.*

With the results validated, TKR designers are using LifeMOD/KNEE to evaluate the in-vitro performance of a total knee design before any parts are created. This allows engineers to test many design characteristics in a consistent, reproducible environment.



Currently, with the focus of knee design teams on mobile bearing implants and high-conforming insert knees, LifeMOD/KNEE is becoming an even more integral parts of the design process. In this arrangement, the stabilizing forces in the knee are to some degree mitigated to the soft tissues. LifeMOD/KNEE provides a measure of the load transfer, allowing engineers to tune the kinematics of the design to minimize the stress on the soft tissues and the implant during normal daily activities.

In the applied research area, LifeMOD/KNEE is used to simulate patient-specific skeletal geometry from MRI scans to aid in selection of the optimal TKR and optimal placement before surgery.

INVESTIGATING AN INJURY-PRODUCING MOTORCYCLE CRASH

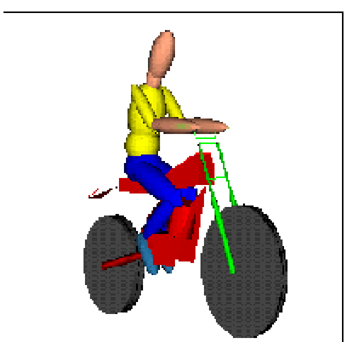
INTRODUCTION

A motorcycle rider must be constantly attentive to environmental disturbances - potholes, insects, wind, etc. These disturbances can cause crashes, and crashes usually result in injury.

*The **LifeMOD™ Biomechanics Modeler**, from the **Biomechanics Research Group Inc**. was used to explore the event of an injury-producing motorcycle crash, both from the standpoint of interpreting the rider's actions to avoid a road obstacle during a lane change maneuver at 30 mph, and the evaluation of the biodynamic response of the rider to the resulting crash conditions [1].*

MODEL DESCRIPTION

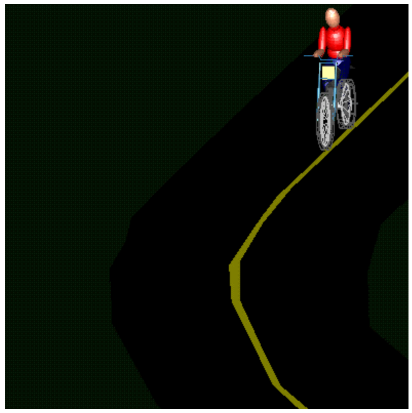
To analyze the actions of the rider for motorcycle stabilization, the rider-cycle system must be viewed as a mechanical system, with the motorcycle as the



controlled element, and the rider as the controlling element.

The controlled element, the cycle, consists of three parts: the two wheels, the steering assembly, and the body, connected with revolute joints. This results in a system with eight degrees-of-freedom, including the six components of vehicle gross motion and the rotational freedoms of the front wheel and the steering assembly.

The rear wheel is driven with a motion resulting in a vehicle speed of 30 mph. The inertia of the rotating masses of the wheels helps to dampen the roll mode of the cycle.



The controlling element, the rider model, is capable of affecting or controlling the motorcycle during the riding event (active mode), as well as responding biomechanically during the crash event (passive mode). The active and passive modes of rider model are switchable during the simulation, depending on the status of attachment between the rider and the cycle model. The rider is coupled to the cycle using break-away attachment (springs) forces.

*The rider model was created using the **LifeMOD Biomechanics Modeler**. This software tool produced the correct motion resistance relationships, or human joint strength, between the segments of the human model using the best source of human data available. This allows for accurate kinematic rebound of the surrogate during a crash (passive mode), as well as proper joint loadings for injury assessment. For the active mode, a dynamic compensator controller model [2] representing human control is introduced to couple the states of cycle roll angle to rider-initiated steer torque and cycle path deviation to rider lean angle. A first order filter is applied to the motorcycle roll angle to produce a time delay in rider response inherent in human neuro-muscular actuation.*

SIMULATIONS AND RESULTS

To create a baseline simulation, the lane change maneuver is performed for the steady state condition without a disturbance. In a second case, a disturbance is introduced by simulating the front tire going over a pothole at the apex of one of the turns in the maneuver. This represents a lateral disturbance to the rider-cycle model, and the control system must stabilize the roll motion to prevent it from capsizing.

To explore the possibilities of delayed response of the rider (e.g., possible rider intoxication) contributing to the cause of the accident, the neuro-muscular time lag in the control system is increased. For this case, the rider model is unable to stabilize the motorcycle and a crash occurs. The resulting impact loads, acceleration loads, and joint forces are compared against injury criteria for assessment.

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