Editor: Michael J. Potel
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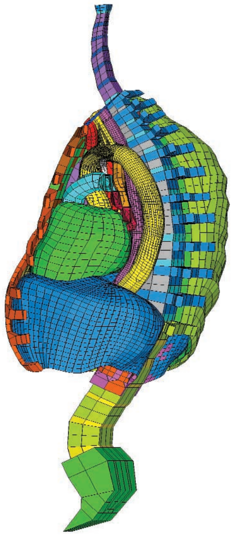
Biomechanics and the Cyberhuman

Stephen Figgins

The first modern-day studies of the human body's mechanics—biomechanics—were done at Wayne State University (WSU) in Detroit, Michigan, in 1939. By the late thirties cars were becoming common and so were accidents. To know how to make cars safer, engineers needed to know what the human body could take. At that time, engineers had detailed information about the mechanics of building materials like steel, wood, concrete, and glass but not the human body.

Researchers dropped steel balls on the heads of cadavers to determine the amount of force necessary to crack the human skull. The methods were crude, but the resulting data were extremely useful and long lasting. In 1972, this data formed the basis for the Head Injury Criteria adopted by the newly formed National Highway Traffic Safety Administration. Although new information is replacing the HIC, it's still this kind of biomechanical information that engineers use to determine the safety of car designs. More recently, researchers used information on the mechanical properties of the human body to validate finite-element models of the human body. These cyberhumans can give us more information than crash-test dummies about car design safety.



1 Wayne State University's highly detailed thoracic module has been the basis of study for many other models, including those by ESI and Toyota.

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WSU human models

Continuing the quest at WSU to understand biomechanics, King H. Yang directs the development of computer models of the human body. His hope is that computer models will potentially give us safer cars than we can design with actual crash-test dummies. "If you design a car based on [a] dummy response," Yang noted, "you're going to design a car that is good for dummies, but not necessarily good for humans. We have data to suggest crash dummies are helping the industry to design safer cars, but they are not human-like."

The first finite-element models of occupants in computer-modeled cars were of crash-test dummies themselves. (For more information on finite-element models, see the "Finite Elements" sidebar.) Dummies contain fewer parts and the mechanical properties of rubber and steel were well known and easier to study. It wasn't until 1990 that WSU, under the direction of Yang, began working on a human-based model.

"I wanted to design human body models to integrate them into the vehicle design process," Yang explained. At the time, no computer could run a simulation on a detailed model because there were too many elements. Yang attempted to create a human model with a simplified geometry, an abstract version of the body. The human body, however, was so complicated he could never get the simplification right. "I wasted about three years," said Yang. In 1994, he began again from scratch, creating a detailed model.

Although he couldn't run a whole body model, he could run part of a model. So he began with a human chest model (see Figure 1). While his original focus was on models for car crash simulations, Yang described his new focus as the mechanics of injury. He wanted to know how parts of the human body get injured in high-speed impact environments: "I think if I could understand the injury mechanism, it would be much easier to design protection devices to protect the human body during crashes." While not so good for putting models in production, the incredible detail of the WSU models are good for injury analysis. WSU's brain model alone consists of more than 300,000 elements. A head injury simulation on WSU's supercomputer would take about 24 hours to complete. That's not suitable for doing thousands of simulations per car platform.

"For Hollywood-type animation, you just need sur-

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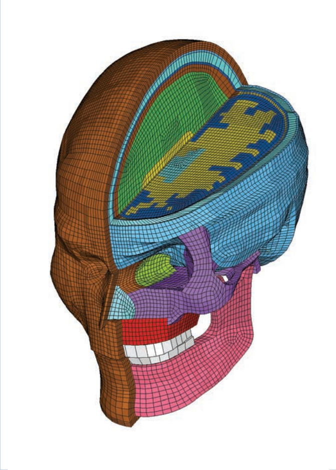
Finite Elements

Richard Courant pioneered finite-element analysis (FEA) in 1943, using it to obtain approximate solutions to vibration systems. Those early calculations were simple and done by hand. It wasn't until the 1970s that supercomputers made FEA a powerful tool for engineers. Computer models of automobiles preceded human body models. Compared to the human body, cars are simple. Their material properties are much better known. Crashing actual cars takes a long time to set up, is expensive, and is a one-shot experiment. In the 1980s, the automotive industry began doing preliminary testing on supercomputers. Being able to verify how a design would perform before actually building a car was an obvious advantage. The models, like the cars themselves, were constructed from parts that were assigned certain mechanical properties. Designers used computers to calculate the forces that can affect those elements over time, deforming them or breaking them.

Finite-element analysis involves defining each model with an unstructured mesh of nodes. The nodes serve as points to define elements. The elements fill the space of the object to be modeled. Two to eight nodes define the corners or end points of the three most common elements: bar or beam, thin-shelled, and solid. Bar or beam elements are two-node elements. They often represent connections between two nodes, like that formed by a ligament tendon or muscle. Thin-shelled elements are three- or four-point elements that create triangles or quadrilaterals. Four, six, or eight points define solid elements as pyramids or eight- or six-sided bricks.

Engineers sometimes refer to thin-shelled elements as 2D elements and solid elements as 3D elements, although they're both used to represent 3D objects. Thin-shelled elements are like planks, mostly 2D. While defined by only three or four points, they're assigned thickness. Because nodes are defined by their location and deformation as well as their rotation, they can also bend. The rotation of the nodes defining the element can bend it much like an artist might define curves in a drawing program. Solid elements require more memory and are harder to manipulate than their thin-shelled counterparts. Because they're 3D, however, solid elements can deform in ways thin-shelled elements can't. A thin-shelled element may bend, but it always has the same thickness at each nodal point.



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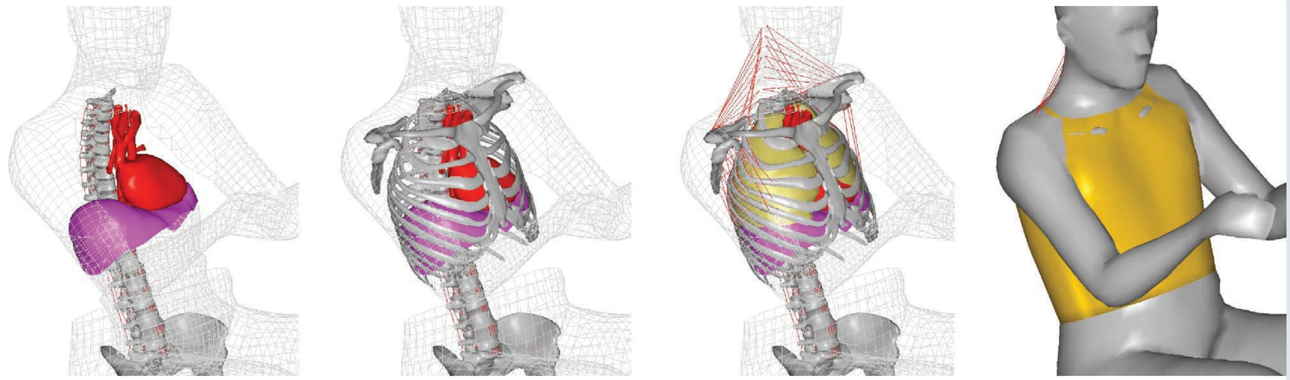
A **The bone of the human skull has three main layers—thin inner and outer layers and a thicker inside layer—and each layer has its own material properties. The Wayne State University head model uses thin-shelled elements to create the outer layers of the skull, and solid elements for the middle layer.**

Thin-shelled elements are typically used to represent thin-walled structures, like an eggshell or a gas tank. In modeling a human head, you might use thin-shelled elements to model the outside layers of bones or parts of a simple skull. For example, you would model the soft tissue of the brain with solid elements. A more detailed skull might also contain a mixture of elements, as the skull has three layers, and the properties of the middle layer are different than the other two. Human models are generally a mixture of element types (see Figure A).

As a whole, the models can be rigid or deformable. A rigid model would be a good choice as a first approximation. A crash simulation with a rigid model will run much faster than a simulation with a deformable model. Often simulations will use both. In a chest study you could take a rigid body model and plug in a deformable thorax module. You get some basic information about the rest of the body and all the detail you want on the chest (see Figure B).



Courtesy of ESI Software/IPS Int'l.

B **The H-Thorax plug-in module for ESI's H-Model provides deformable and damageable bone modeling. The thoracic organs and great vessels with internal air and blood modeling are suitable for a study of the chest region.**

faces," explained Yang. "For our model, we need everything in between, so we know the interaction. For example, driving into a crash accident, the steering wheel interacts with the rib cage, the rib cage interacts with the liver, and the liver interacts with your abdominal aorta. Will the pressure then rupture your abdominal aorta?" That adds up to a lot of elements. In addition to the nodes needed to do the geometry of each of these elements, each element has mechanical properties according to the tissues it represents. The properties, generally expressed as numbers, define each element's behavior.

A few of the properties important to human modeling are the elastic modulus, Poisson's ratio, and viscoelastic properties. The elastic modulus property is the amount of force required to stretch an element. Poisson's ratio defines how much an element expands or contracts when you apply pressure to it. For example, if you were to squeeze an eraser head, the sides of the head will expand. Poisson's ratio expresses how much it will expand. Water plays a large role in the human body and many elements have both elastic and fluid (viscoelastic) properties simultaneously. In addition to the many properties of each element, the model's nodes themselves have properties defining the load the structure is under and which nodes define boundary conditions when interacting with other models.

With so many factors, models comprised of a million elements could take days to run on today's fastest computers. Yang's group has now developed a human computer model from head to toe suitable for injury investigation, although it may be four or five years before computers will be fast enough to do a sophisticated whole-body simulation using them all.

ESI models

Eberhard Haug is "the senior pusher for all biomechanical activities at ESI." Haug explained that "an immediate sequel to crashing virtual cars was to put virtual occupant surrogates (articulated rigid and deformable models of dummies) into them and to simulate the preventive action of passive safety devices such as seat belts, air bags, knee bolsters, paddings, and so on. This is, after all, the real goal of crashworthiness design, not pretty pictures of a crashed car as such."

His pushing at ESI has contributed to the development of three families of human models—Robby, H-Model, and Humos. Robby, the first model, was designed as rigid models with articulated joints. ESI calls these Human Articulated Rigid Body (HARB) models. "We equipped [it] in a modular fashion with deformable FE parts (head, chest), which we licensed from WSU," Haug explained.

ESI further developed and tested these models, adding other modules to Robby. The H-Model eventually replaced Robby. "[A]bout five years ago, we started collaborating with our academic consultant Professor Hyung-Yun Choi of Hong-Ik University at Seoul, our Korean subsidiary, and a Korean company (IPS Intl.) to develop the emerging H-Model family from scratch, building on the so far achieved knowledge," Haug noted. Like Robby, the H-model is built around a rigid frame and has a deformable module that can be added to that frame. The Robby and H-Model differ not so much in overall design but in specifics and intended use. Designed later than Robby, the H-Model organs and structure have greater biofidelity. ESI conducts tests to refine the H-Model, regularly maintaining and updating the model to reflect new information. Robby is more often used by students and as a testing ground for new ideas.

Finally, there's the Human Model for Safety, or Humos project. This is a joint effort between several European universities, software developers, and auto manufacturers to create a unified model that's based on a database of information everyone developing human models could use.

The Humos model is mostly complete, but Haug points out that "there are no unified human models these days. There are anthropometric databases and software that give you body segment lengths and weights as a function of gender, age, and so on, but for biomechanical models we need much more detailed generic geometries of humans, as well as mass and inertia properties, [and] material properties."

Detailed generic geometries

Everyone's body is different, but most current generic models represent the average guy—the so-called 50th percentile male. Because people come in many shapes and sizes, there isn't really sufficient data today to create a truly generic model of the 50th percentile male, let alone the 5th percentile female, the 95th percentile male, the three-year-old child, and so on. Modelers must generate them, or declare whatever they get from a study as generic.

The data we do have for modeling is primarily collected from cadavers. This isn't the most accurate information source. Because people rarely die young, the data mostly reflect older people. The first Humos project's male model is an old man with roughly the dimensions and weight of a 50th percentile male, one with a bit of a potbelly. The second Humos project aims to create a more generic 50th percentile male and to prepare 5th percentile female and 95th percentile male models.

"In biomechanics, the most difficult thing turns out to get data, in particular for children," Haug explained. "While adults can dedicate their body to science, two-year-olds cannot, and neither can their parents for them. The scientific community tries to replace the need for child cadaver tests with indirect, noninvasive and nondestructive methods, such as bone density scans or comparison of young and old animal test responses." These offer some insights, but not the level of detail we can obtain from a cadaver.

There's a pressing need for more data to build better models. "Basically, the computer models have more or less used up all the available data that can be used for model validation," Yang explained. "Now we have to generate more data for validation." Haug would eventually like to see a database of human geometries, mesh rules, conventions for scaling, morphing and aging modes, biomaterial information, whole-body tests, and validation procedures.

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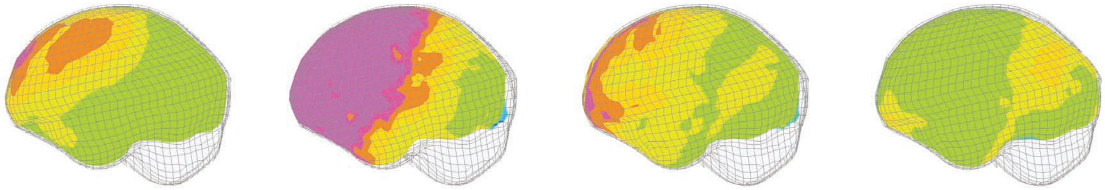
2 X-ray images taken of a cadaver in a rear-end impact simulation at Henry Ford Hospital. The black dots represent 2-mm diameter lead markers, one placed in the front and back of each cervical spine. The detailed information gathered will be used to validate the behavior of human models.



Courtesy of ESI Software/IPS Int'l.

3 A brain surface pressure wave shown in the ESI H-Model. While what happens inside the brain during such a wave isn't fully understood, we can plot the pressure wave itself. The colors indicate the pressure on the brain at 2, 4, 6, and 8 ms after a frontal pendulum impact.

Validation of human models

"We use a lot of old data for model validation," Yang noted. "The problem with old data is that the past experiments have been rather crude." In the past, scientists might have attached an accelerometer on the head and thoraxic vertebra to study whiplash injury. Data from accelerometers attached to the bones and different parts of the body provided a global validation of body movement. Using this data, however, a model can only be validated in the head and the first thoraxic vertebra. That isn't detailed enough to fully understand neck injury.

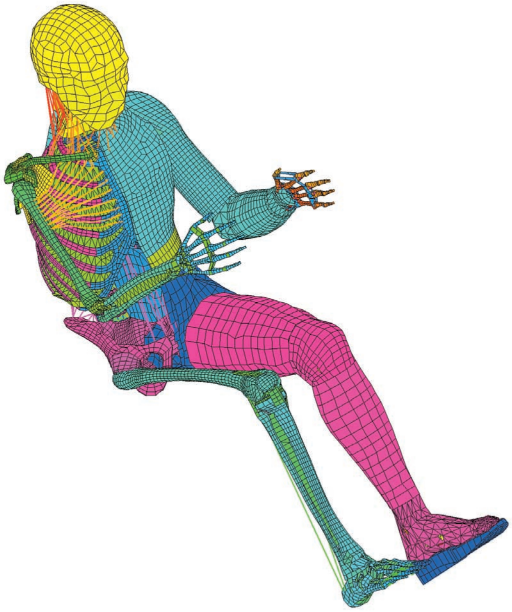
Yang's most recent experiments provide more details on the behavior of the skeleton in a high-speed impact. Yang uses a high-speed 3D x-ray system at the Henry Ford Hospital, about 1.5 miles from WSU. "We put x-ray markers into cadaver bodies," Yang described, "then, using a portable mini-sled, we push the body into a crash scenario." The high-speed x-ray provides Yang precise information on how each bone in the neck moves during a whiplash injury (see Figure 2).

The markers and high-speed x-ray let Yang see the bony segments' individual movements. Pressurizing the lungs with one atmosphere's pressure and pressurizing the blood vessels with fluid, the cadaver's response comes close to human behavior. What's missing is muscle. In certain conditions, muscles aren't very important. For example, when hit by surprise from behind you wouldn't tense up your muscles. But what if you see it coming? This kind of skeletal validation has another shortcoming. It doesn't give details about the inside of the body. We don't have much data on the mechanical properties of organs. The National Library of Medicine's Visible Human Project helps determine basic shapes and placements of organs, but not the material properties of those organs. Without that information, you can't fully validate your model.

There are also limits to what engineers can model and validate. While scientists can readily deduce negative pressure in countercoup areas (where the shock reflects on the side opposite to the impacted side as a tension wave), the indirectness of the mechanical output presents a problem (see Figure 3). The liquids inside the tiny vessels of the brain may briefly vaporize and damage the neurons. Parts of the brain matter may undergo larger stretches, further damaging neurons. When stretched, the brain matter is still there, but its connections won't work anymore. A hematoma inside the skull may compress the brain, cutting the neurons off from their normal blood supply, leading to irreversible damage. "The brain is a tofu-like composite material with the set of small and tiny blood vessels acting as reinforcing fibers," Haug explained. "As long as we cannot model this detailed structure, we have the correlation problem."

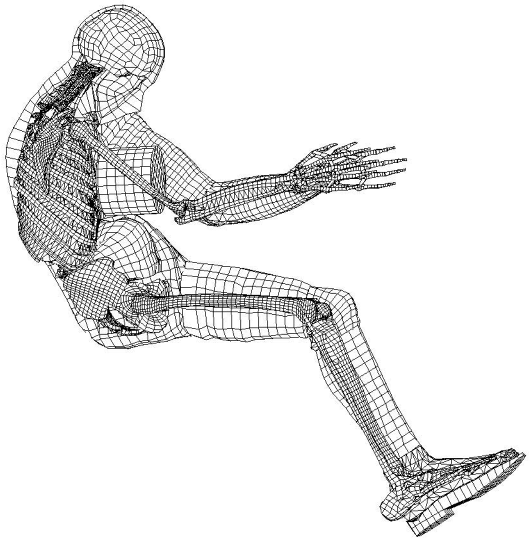
For structural engineers, working with the skeleton is much clearer. The skeleton is a structure made to carry and move about the body. Bones are similar to concrete, a well-known material for engineers. Joints are held together by ligaments, which can be seen as rubber-like tapes. That's within the reach of structural mechanics. Muscles can contract, which normal structural materials don't do. But there are models of active muscle contraction (and fatigue) that help engineers consider the action of "bracing" in an accident—that is, when your neck muscles stiffen up when you see the rear impact accident coming in the rear-view mirror.

For higher velocity frontal impacts you can't sustain the g-forces by any bracing action. In a lower velocity rear impact, however, whether you brace or not may modify the resulting type and severity of injury, sometimes for the worse. Bracing isn't always beneficial.



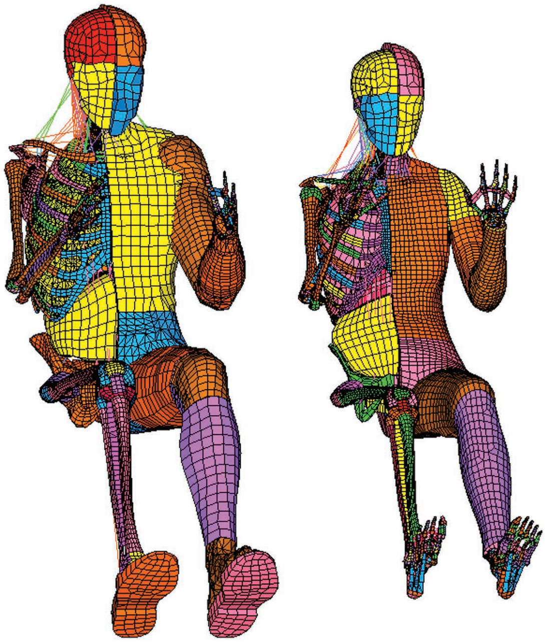
Courtesy of Toyota Central R&D Labs

4 Toyota's Thums model consists of more than 80,000 elements. The right half of the soft tissues aren't shown in this figure to expose the skeletal structure.[1-3]



Courtesy of Toyota Central R&D Labs

6 A virtual pendulum weight compresses the chest of the Thums model in this thoracic frontal impact simulation. The conditions of the test were created to match the conditions of existing cadaver tests that Charles K. Kroell and others conducted between 1971 and 1974.[6]



Courtesy of Toyota Central R&D Labs

5 The 5th percentile female model is shown here next to the 50th percentile male. The smallest member of the Thums family, a model of a 6-year-old, is in development as are pedestrian versions of the adult models.[4,5]

Prestressing your leg by slamming on the brakes may alter the outcome of a toe panel intrusion in a frontal car crash. Stiffening your arms by pushing against the steering wheel may modify the type and severity of your injury. How bracing changes the mechanics of injury is something engineers can explore with current models.

Although the mechanics of nonstructural organs are less clear, Haug feels there's enough information to build fairly representative human models with bone, flesh, organs, and fluids: "Of course, these models will be refined in the future. At any rate, impact biomechanics keeps us busy and will certainly evolve greatly in the coming years."

Toyota models

Toyota Central R&D Labs invests heavily in human modeling research and development. Using the existing information about the load-bearing structures of the body, they've assembled the Total Human Model for Safety, or Thums. They completed their first human model, a 50th percentile American adult male, in 2000 (see Figure 4). They've since improved the model, developing more detailed versions of the face, shoulder, and internal organs. Toyota has also developed a small female model and a 6-year-old model (see Figure 5).

The Thums male consists of more than 80,000 elements in a mesh of about 60,000 nodes. The model contains about 30,000 solid elements, 50,000 shell elements, and 3,000 bar or beam elements.[6] This is highly detailed, but still suitable for running crash simulations. In contrast, the Humos model consists of only 25,000 elements.

Toyota licensed WSU's head and thorax models for study. They used what they learned to create their own models. The Thums' skeleton skin and muscles are modeled in great detail, but the internal organs aren't because of their complexity. The heart and lung and the abdominal organs are modeled as a single continuum body with solid elements. Although the internal organs in the human body have different material properties, Toyota assigned homogeneous material properties to each continuum body. The current model can't be used to predict the response of internal organs accurately.

Toyota validated the Thums model by conducting simulations of published cadaver impact tests (see Figure 6). Most of these are pendulum tests, where a weight was swung into a cadaver and the results were recorded. By comparing the results of the simulation to the original impact test, Toyota was able to see where the model needed modification. However, as previously described, the current cadaver tests have their limitations. "We validate Thums using limited numbers of published cadaver test data," explained Masami Iwamoto, a Toyota Central R&D Labs researcher working on Thums. "The model is not validated for all directions or all speeds of impacts."

Now that they've validated the human body's overall frame, Toyota is replacing the simplified internal organ models with more realistic ones. Modeling soft tissues is much more difficult, however. Toyota's current model is based on linear isotropic equations. The viscoelastic properties of internal organs make them nonlinear. (Their stress isn't always proportional to strain.) The fibrous material in connective tissues, such as ligaments and tendons, alters the behavior of soft tissues under stress, making them anisotropic. (The mechanical properties of the structure depend on the direction of force.) Stressed in one way, the organ will behave differently than when stressed from another direction. To simulate the response of soft tissues more accurately, Toyota will need to alter the equations, using a nonlinear anisotropic viscoelastic material model.

Again, there are limits. "The living body has [such a] sophisticated and profound structure that injuries in real-world accident situations could not be sufficiently reproduced by the current Thums," Iwamoto explained. "Thums is still under development. We are still estimating how useful Thums is for practical application in research fields. Anyway, I think Thums will be used in research fields of automotive safety, medical application, and sports biomechanics in the near future."

Beyond crash testing

While designed for studying high-speed impact, human models are useful for other purposes. The ESI Group licensed WSU's head and chest models and used them in a North Atlantic Treaty Organization study on helmet design and medical applications. The US Army Research Laboratory licensed WSU's chest model to study how to design better body armor.

Although excited by the potential uses of human models, Yang has reservations about how widely the models can be applied. "I don't like to do work beyond what our tool is designed to do," Yang said. "I tend to be more conservative. In biomechanics, our first rule is 'do no harm.' If we start to overstretch what our model is designed for, it might be dangerous." The resolution and behavior of a model designed to study the impact of a car crash may not be valid when studying the impact of a bullet.

Haug pointed out that these additional uses in the medical and defense fields are "a welcome source of revenues in the highly investive field of occupant safety biomechanics." For researchers to get funding for the study of human models, the models need to be practical, and they need paying users now.

The future of cyberhuman models

"Certification of new car models for crashworthiness," explained Haug, "depends on their performance with legal dummies in legal crash tests. There is no direct legal incentive for car makers to use human models, since all cars must pass the legal crash tests using legal dummies not to exceed so-called legal injury criteria." When it comes to occupant safety, virtual testing isn't officially accepted. Dummies are the standard. It's a major obstacle for the adoption of human models in the automotive industry.

Before virtual testing can be made a legal requirement, it needs standards for model development. The Humos project is a step in this direction to build a uni-

Simulation and Crash Analysis Tools

The most common tools for simulation and crash analysis are LS-Dyna, PAM-Crash, and Radioss. While each has a rich history of contributions from other programs, they all share common ancestors in the finite element stress analysis tools created at Lawrence Livermore National Laboratories in 1976. The tools, Hemp and later Dyna, were designed to run on Cray supercomputers, about the only computers fast enough to perform FEA in 1976. LLNL's tools were developed in an open environment similar to many academic open-source projects. The ESI Group, a French company, quickly saw the commercial potential of FEA. In 1973, they began developing commercial applications to study hydrodynamics. This code eventually became the PAM family of programs, including PAM-Crash (see Figure C).

In 1985, several members of the ESI Group formed their own company, Radioss. By 1989, LLNL developers wanted in on the action. Dyna's speed and power had improved considerably and could now run on several systems, including MS-DOS, Unix, and VMS. Dyna developers formed the Livermore Software Technology Corporation and began developing their own commercial version of Dyna, called LS-Dyna, primarily for the automotive industry's crashworthiness studies.

The pivotal moment in crashworthiness studies came in 1985 when the ESI Group managed to run a full-frontal crash of a Volkswagen Polo overnight. Before this, only parts of cars could be feasibly studied. After 1985, the car industry began running crash simulations. The same software used to run car-crash simulations is used to run simulations of human models in crash situations or other tests.

Courtesy of ESI Software/IPS Int'l.

C **ESI's male H-Model (from PAM-Crash) is subjected to a frontal pendulum impact test. The massive pendulum (seen as a bluish square) has compressed the model's thorax.**

fied database that can serve as a model standard. This database will eventually need to contain

- human geometries and conventions for scaling, morphing, and aging those geometries;
- biomaterial information with the material properities for organs and mathematical descriptions of stress and strain;
- validation and certification procedures for components and models; and
- certified crash scenarios guiding the use of these models.

Essentially the same care given to the certification of crash-test dummies and the scenarios in which they're used needs to be brought to human model development. Without certification, testing with cybernetic models could even be seen as a liability.

Still, the industry pioneers continue to invest in human modeling R&D projects or test the emerging human models in private, often for nonstandard crash scenarios (dummies are primarily designed for front-end and side-impact testing). Haug pointed out that "a major incentive to use these models is the potential threat of liability suits." A victim or a victim's family could accuse a car maker of not using existing technology to make the car safer, regardless of whether it's prescribed by law. While testing may be as much of a liability as not testing, these simulations can help avert disaster on multiple levels. It's better to use all that we've learned about biomechanics and cyberhuman models to make cars safer. ■

References

1. A. Tamura et al., "A Tibial Mid-Shaft Injury Mechanism in Frontal Automotive Crashes," *Proc. 17th ESV Conf.*, Mira Digital Publishing, St. Louis, 2001, CD-ROM.
2. M. Iwamoto et al., "Development of a Finite Element Model of the Human Lower Extremity for Analyses of Automotive Crash Injuries," *SAE Trans. J. Passenger Car, Mechanical Systems*, vol. 109, no. 2000-01-0621, 2000, pp. 846-853.
3. M. Iwamoto et al., "Development of a Finite Element Model of the Human Shoulder," *Stapp Car Crash J.*, vol. 44, 2000, pp. 281-297.
4. H. Kimpara, M. Iwamoto, and K. Miki, "Development of a Small Female FEM Model," *Proc. Soc. Automotive Eng. of Japan (JSAE) Spring Congress,* no. 59-102, JSAE, Tokyo, 2002, pp. 1-4.
5. M. Iwamoto et al., "Development of a Finite Element Model of the Total Human Model for Safety (THUMS) and Application to Injury Reconstruction," *Proc. 2002 Int'l Research Council on the Biomechanics of Impact* (IRCOBI), IRCOBI, Bron, France, 2002, CD-ROM.
6. F. Oshita et al., "Development of a Finite Element Model of the Human Body," *Proc. 7th Int'l LS-Dyna Users Conf.*, Livermore Software Technology, Livermore, Calif., 2002, pp. (3-37)-(3-48).

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