Bodies in Motion

Scientists bring analytical models to bear on sports

By RICHARD LIPKIN

Snow crystals settle on a frozen track that snakes between jagged boulders and frosted pines. A pistol shot echoes among mountain peaks. Four daredevil bobsledders heave their sled forward, leap into its shell, and plummet down an icy slope.

Frigid winds blast goggled eyes as the sled hurtles along at 80 miles per hour, its steel runners carving grooves into the track's ice. Pitching, rumbling, and slamming against curves, the bobsled barrels at mind-numbing speed, forcing the sledders to heighten their awareness of every sensation and nuance, harmonizing the sensory rush with orchestral precision.

One glitch or missed cue and the half-ton dynamo could crest its frozen banks and splinter on an unforgiving precipice. Victory or disaster hinges on split-second reactions.

The human body, from a purely mechanical point of view, sees its finest hour during competitive athletics. Whether running, jumping, or somersaulting—much less careening down a mountainside at high velocity—human beings can, through practice and training, push themselves to remarkable physical extremes.

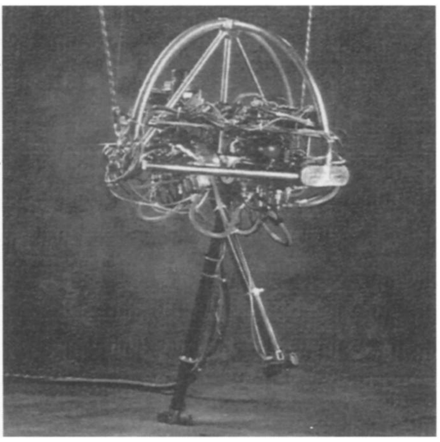
To understand more deeply the physics of human motion, scientists are bringing a wide variety of mathematical models, computer programs, and robotics to bear on what they call "human dynamical behavior."

Body motions, whether as simple as walking or as complex as airborne pirouettes, depend not only on the fine control of a well-tuned nervous system but also on simple physics. To learn more about how the human body acquires the skills to manage high-speed maneuvers—and to help train Olympic bobsledders—Mont Hubbard, a mechanical engineer at the University of California, Davis, and his colleagues have built a bobsled simulator.

Resembling an arcade ride, this saddle-up-and-sled simulator recreates the perceptual experience and many of the physical sensations of competitive bobsledding on specific courses. A bobsledder in training hunches into the driver's seat of the simulator, a replica of a competition vehicle mounted on a motorized platform. Steering posts in hand, the driver watches the track speed toward him in three dimensions on a color monitor, navigating the rushing course and feeling the rumbles, twists, and turns of each high-speed maneuver.

The simulator computes the driver's position 100 times a second and refreshes the high-resolution graphics monitor 30 times a second.

Hubbard says that the simulator produces four types of sensations. Most important in provoking the sensation of motion are the visual cues. To make the three-dimensional display seem authentic, Hubbard recorded visual subtleties from existing Olympic bobsled courses—including those at Calgary, Alberta; La Plagne, France; Salt Lake City; and Lillehammer, Norway, site of the 1994 Winter Games.


Photos: Playter/Boston Dynamics

A two-legged robot prepares to run, jump, and somersault.

"After visual input, the next most important factors in a realistic simulation are motion cues," Hubbard says. "You need to create a feeling of movement through sensations coming from the motion base. But you have to be careful. If the motion cues are not synchronized exactly with the moving visual scene, the person will get motion sickness." To simulate those sensations, a computer guides a set of small motors that tilt and shake the shell.

"The third most important factor is the way the steering feels," Hubbard says. "When the simulator's driver pulls the steering handles, they must feel like real bobsled handles, with realistic resistance." To mimic that feeling, the simulator computes the sled's position on its fictitious course, calculates the forces on the sled's runners, and figures out how those forces would feel coming through the steering mechanism. Tiny motors in the simulator's base replicate sensations of steering resistance at different angles and speeds, creating tactile feedback.

The capper of this Olympic illusion comes in the form of bobsled sounds recorded during actual runs. Hubbard says, "The sounds make the experience seem very real."

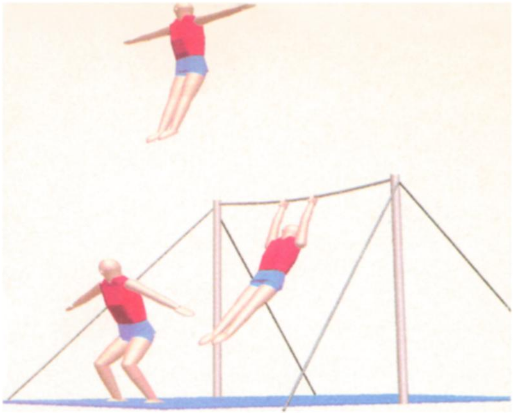
Hubbard maintains that simulators can potentially tell athletes much about how they become more skillful. "We want to understand, characterize, and quantify the way that human beings acquire the types of coordination skills demonstrated in sports," he says. "How do people control dynamic tasks? How do they use perceptual cues? How do they integrate feedback to master a skill and exert control over a dynamical task?"

Do simulators actually improve performance? "It's hard to say," says Hubbard. "The answer turns out to be difficult to measure." For example, the U.S. Olympic bobsled team used a simulator to train for the 1992 Winter Games in Albertville, France, and for the 1994 events in Lillehammer.

Despite positive reviews from the bobsledders, who contend that the simulator did improve their performances, the team, alas, captured no medals. "We did lousy," said one training participant. "We even lost to Jamaica."

Nevertheless, the U.S. Bobsled Federation has enough faith in the new technology to install a simulator in its training facility in Lake Placid, N.Y. "This is the way to go," says Matthew S. Roy, the federation's executive director. "Simulators can help bobsledders hone their driving skills and fine-tune their reactions. We're going to see much more of this type of training during the next few years."

Roy believes simulators can augment practice sessions in a cost-effective way, particularly since actual mountain runs can cost over $700 apiece. "We think these systems have great potential," says Mari A. Tollaksen, coordinator of the International Olympic Committee World Congress on Sports Sciences in Atlanta. "The simulators could help the bobsledders learn particular courses while keep-



A gymnast can stabilize a somersault by relaxing the shoulders and letting the arms swing free.

ing down training costs."

At the September convention of sports scientists in Atlanta, several non-Olympic bobsledders hopped into the simulator to try a virtual run. "Most seemed to really like it," says Tollaksen. "Even Prince Albert of Monaco."

"Sports scientists generally want a deeper understanding of what goes on physically and psychologically when an athlete refines a dynamic task," Hubbard says. "They want to know what factors enhance or limit performance, whether it's muscle strength or sensory overload."

Understanding the mechanics of an athletic performance well enough to model it mathematically, says Hubbard, may help athletes hone their training. For example, a bobsledder, high jumper, or pole vaulter who wants to perfect his or her performance practices repeatedly, adjusting techniques after noting what does and doesn't work. That process requires extremely subtle coordination and muscle control. During each maneuver, an athlete integrates a flood of sensory data to execute a set of complex actions.

"We want to put performance questions into an objective, scientific context," Hubbard says. "Athletes have always sought answers in an empirical mode of trial and error. But if you have a model that tells you exactly what's going on, it's easier to get clear, unambiguous answers to subtle questions that are often difficult to test in the real world."

The urge to grasp the biomechanics of many sports movements has led Hubbard's research team to derive mathematical models for a wide variety of events, from pole vaulting, ski jumping, and javelin throwing to skateboarding and, most recently, golf.

"Sports are about optimization," he adds. "They're about learning to do something better than you did it last time or better than your opponent has done. Ultimately, our aim is to use scientific methods to help athletes improve their performances." □

Gymnastics: Active or passive control?

Poised and balanced, in deep concentration, a gymnast eyes the mat. Gingerly, she steps into her aerobatic dance: a hop, a skip, a jump, and a leap into a tucked somersault. Thump go her feet as she lands triumphantly, with arms open and chin high.

Such airborne maneuvers, done with so much finesse, appear to be feats of superhuman control. But to what extent do these acrobatics depend not on active control but on the mere mechanics of a body in motion?

"The layout [straight body] somersault, for instance, is an inherently unstable maneuver," says Robert R. Playter, a mechanical engineer at Boston Dynamics in Cambridge, Mass. Any rigid body has two axes about which it can rotate stably and a third—the middle axis (which runs from hip to hip in the somersaulting gymnast)—about which rotation becomes unstable, he explains. A body forced to spin about that middle axis "wants to flip-flop, as a way of conserving energy and momentum."

To demonstrate, Playter tosses into the air a video cassette spinning end over end and watches it twist rhythmically from front to back as it somersaults.

How, then, do gymnasts who perform layout somersaults rotate around their middle axes without wobbling? "Do they actively steer themselves when airborne or rely on the passive control of a body in motion?" Playter asks. "No one yet has fully answered this question."

To investigate the problem, Playter—a former all-American gymnast—built a family of robots and dolls designed to execute airborne gymnastic maneuvers. Working with Marc Raibert, an engineer at the Massachusetts Institute of Technology, he devised tests to determine the roles of active and passive control during somersaults.

In one experiment, a two-legged robot waddles down a track, jumps into the air, pitches itself forward, tucks its legs, somersaults, extends its legs, and lands on its feet—finishing up with a victorious run.

The experiment's goal involves teasing out the components of a somersault. Playter says, "The somersault is challenging because the performer has limited control over his or her body while airborne."

Gymnasts, once aloft, can do little to influence motion other than bending their torsos or moving their limbs. Conservation of momentum largely determines how the maneuver will turn out. An act as simple as extending the arms—as pirouetting figure skaters do—can alter the performer's inertia, changing the rate of spin. Timing such arm or leg extensions, a method of active feedback control, plays a pivotal role in determining a somersault's success.

In the case of the somersaulting doll, Playter has found that simply relaxing the shoulder joints, to let the arms hang loose, stabilizes an otherwise unstable maneuver. So the doll either somersaults gracefully or wobbles, depending on the tension in the shoulder joints.

"Biomechanics researchers previously assumed that a gymnast actively stabilizes a somersault by compensating with arm and body motions," Playter says. "What if passive arm movements, arising from body rotation and shoulder joint tension, stabilize the somersault without active control?"

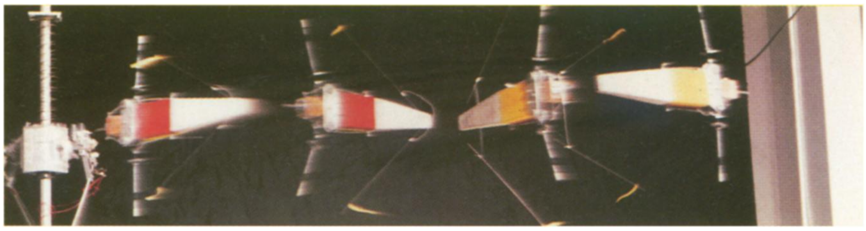
Passive stabilization appeals to Playter because it "relieves the performer of sensing variations in movement and responding quickly enough to prevent instability." The athlete has merely to start off properly, maintain proper shoulder tension, and then let the maneuver unfold. "The doll experiments show that active steering isn't necessary," he says.

Through similar studies, Playter hopes to find basic principles of locomotion and dynamic balance that enable animals, including human beings, to walk around. "Each body has certain inherent movements that occur without the control of a nervous system and brain," says Playter. Scientists are exploring to what extent the bodies move and balance simply in response to their design.

Why have they begun their studies with gymnastics? "It's full of complex motions," Playter says. "Trained gymnasts learn to make movements happen on their own, without much active control.

"Let the body do what it knows how to do," Playter recalls his coaches saying. "Let it do what it's designed to do, without consciously getting in the way."

— R. Lipkin



A doll, its arms swinging free, executes stable somersaults.