Pressures Measured in Live Hip Joint

The first in vivo pressure measurements in a human hip joint reveal large, unexpected effects from muscle contraction; these results have important clinical implications and may lead to new rehabilitation practices

IN June 1984 a 73-year-old woman had a partial hip repair operation at Massachusetts General Hospital, one of 50,000 such procedures completed that year nationwide. The woman, Mrs. F, had fractured the neck of her right thigh bone and elected to have the head of the bone replaced by a metal prosthesis. Now, 2 years later, she is doing fine, with the metal, ball-shaped head of the femur articulating perfectly with the cartilage-lined socket, the acetabulum. In addition to being a perfect patient, Mrs. F has been the source of a unique set of experimental data on the pressures exerted within the hip joint during the immediate postoperative and recovery phases of her treatment.

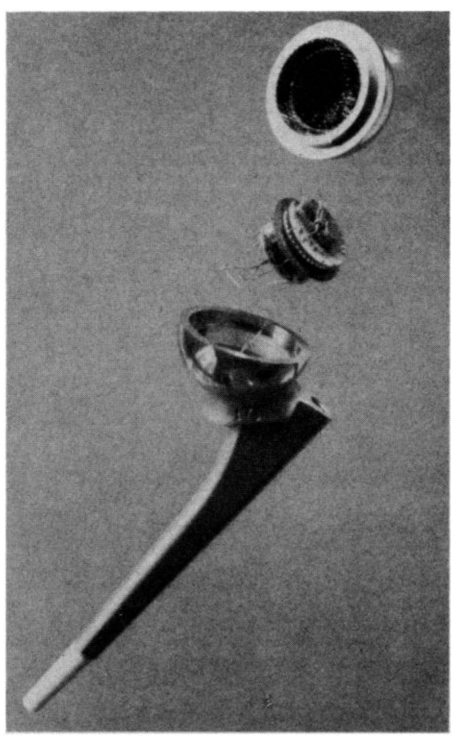
The artificial femoral head that was inserted into Mrs. F's thigh bone was not a standard, off-the-shelf model. It had been carefully engineered by Robert Mann and his colleagues at the Massachusetts Institute of Technology, so that it carried ten pressure sensors, an induction coil, and a small transmitter. In collaboration with William Harris and W. A. Hodge, at Massachusetts General Hospital, Mann and his colleagues have thereby been able to monitor the pressure 253 times a second at ten discrete locations within the joint socket as Mrs. F walked, jogged, jumped, climbed stairs, and rose from a sitting position. Such in vivo measurements from an intact hip have never been obtained before.

The results confirmed quite strikingly two aspects of hip joint pressures that had been indicated from in vitro experiments and calculations. First, the pressure is not uniformly distributed within the joint, but varies significantly from point to point. Second, pressures are much higher than had been predicted from an assumption of uniform pressure distribution. But perhaps the most significant, and surprising, result was the discovery of extraordinarily high pressures that are exerted during the rise from a sitting position.

"These are interesting and important findings," comments Thomas Brown of the University of Iowa. "They will contribute to a better understanding of the loading of cartilage through activity during life."

One area where this improved understanding will be particularly significant is in the etiology of osteoarthritis, in which the hip-joint cartilage partially or completely deteriorates. Close to 50 million people suffer this painful and debilitating condition in the United States.

"There is evidence that as much as 90% of osteoarthritis of the hip is caused by some kind of structural abnormality in the joint," says Harris. "These abnormalities, some of which are quite subtle, may be the result of one of several developmental problems." In any case, the upshot of these abnormalities appears to be an exaggeration of normal focal pressures, with the consequent erosion of the cartilage. Hence the importance of a closer understanding of the normal microenvironment of the hip joint.



Instrumented femoral head.
Pressure sensors are inserted into recesses that are electron-discharge-machined from inside the top of the femoral head: a diaphragm of less than 0.5 mm is left over the sensors. The antenna is located in the narrow end of the prosthesis. [Courtesy of *Proceedings of the National Academy of Sciences of the U.S.A.*]

This line of research, which Mann initiated in the late 1960's, was, he now says, "driven by an engineering interest in understanding how skeletal bearings perform as well as they do." A great deal of mechanical analysis of cartilage as an articulating surface has been, and still is, carried out with round "plugs" of material cut from joints. Such experimental systems are extremely limited, argues Mann, not least because they typically do not replicate the ebb and flow of water from the cartilage when it is under pressure. This water flow is key to the high performance of cartilage as a low-friction bearing. As a result, says Mann, "people who work with cartilage plugs rarely use pressure over 100 psi (6.8 atm), whereas we see pressures ten times that in our system."

Mann teamed up with Harris some years ago to develop more realistic experimental models. Eventually they employed an instrumented femoral head like the one they implanted in Mrs. F, but in cadavers. By loading the hip joint as it would be during walking and other exercises, they were able to determine that, contrary to general belief, pressure distribution within the joint was extremely uneven and involved unexpectedly high peaks. They also showed that an ill-fitting femoral head generates immensely high pressures, which could explain the rapid failure of some partial hip repair operations. As a result, manufacturers began to produce a range of metal femoral heads with closer intervals between standard sizes so that surgeons could achieve a better fit between the ball and socket.

Although Mann and Harris' analyses with the cadavers were instructive, they lacked the component that turns out to be so crucial in loading joints. This is muscle contraction, specifically contraction of opposing muscles that leads to stability rather than movement of the joint.

Traditionally, much of the analysis of hip-joint function has centered on walking on a flat surface, which is an efficient, dynamic process. Although there is some cocontraction of opposing muscles to ensure stability, particularly in the stance phase, the resulting load is limited and transient. This is not the case, it turns out, when one rises from a sitting position. "This involves a huge cocontraction in what is an essentially static process," says Harris.

For comparison, peak focal pressures during walking are in the range of 6 megapascals (MPa, where 1 MPa = 10 atm) but can be as high as 18 MPa in rising from a sitting position. "Many people were surprised to see such high pressures from this kind of activity," comments Brown. Clinically, this discovery is extremely important, particularly in improving total hip replacement procedures, in which the pelvis is partially reconstructed.

Harris and his colleagues are just completing a 5-year retrospective study of total hip replacement. They find that if the acetabulum cracks or fails, it often does so toward the back of the joint. "The reason for this is now clear," says Harris. "Not only is the pressure from cocontraction very high during rising from a sitting position, but it is directed posteriorly." There has generally been the assumption that most pressure on the joint would be on the top, not at the back, again because of the concentration on the mechanics of walking. Bone remodeling during total hip replacement has therefore often neglected a point where the highest pressure is exerted.

Because Mann and Harris have been able to monitor pressures in Mrs. F's hip joint throughout the recovery phase they are now in a position to evaluate more critically some of the rehabilitation regimes. For instance, it turns out that loading of the joint when the patient uses a cane for support is only 5% greater than if a single crutch is used. This also is contrary to conventional wisdom, and it means that it might be possible to move patients from a crutch to a more convenient cane sooner than is currently done, thereby accelerating their progress.

Dramatic and important though these results undoubtedly are, they of course represent only one case and will therefore have to be replicated to improve their value. And the data are limited to pressures within the microenvironment of the joint and do not give total resultant force across the joint, which remains a separate and equally important piece of information for orthopedic surgeons. ■ ROGER LEWIN

ADDITIONAL READING

W. A. Hodge *et al.*, "Contact pressures in the human hip joint measured in vivo," *Proc. Natl. Acad. Sci. U.S.A.* **83**, 2879 (1986).

Atoms in Strong Laser Fields Obey the Rules

Experimentalists and theorists now agree that the multiple ionization of rare gas atoms by infrared, visible, or ultraviolet laser light takes place one electron at a time

WHEN the intensity of laser light reaches 10^{16} watts per square centimeter, the strength of the light wave's electric field is comparable to that of the field binding the electron and proton in a hydrogen atom; that is, the light is no mere perturbation as assumed in the conventional theory of the interaction of electromagnetic radiation with matter. Since this intensity can now be easily reached with the focused light from a laser with picosecond pulses, it is hardly surprising that atomic physicists have been finding seemingly out-of-the-ordinary behavior as they crank up the power of their light sources.

An unresolved question is, At what laser intensity is a new theoretical approach necessary? Over the past 4 years, for example, atomic physicists have been puzzled by the apparent ease with which rare gas and some other atoms can be multiply ionized by absorption of laser light over a wide range of wavelengths from the infrared to the ultraviolet. Naive application of conventional thinking results in much lower probabilities for stripping away subsequent electrons than for removing the first one.

A series of ultraviolet experiments by Charles Rhodes and several co-workers at the University of Illinois at Chicago, who were able to generate such highly charged ions as U^{10+}, has provoked the most excitement during the period, partly because the researchers proposed a new, highly efficient collective excitation process in which an entire shell of electrons could be simultaneously removed. The group also argued that such an efficient excitation process might provide a way to overcome the principal difficulty in making an x-ray laser, selectively and quickly pumping enough energy into the laser medium to generate a so-called population inversion before the excited atoms spontaneously relax to lower-energy quantum states.

The most recent ultraviolet findings at Chicago, reanalysis of infrared and visible experiments at the Saclay Nuclear Research Center in France, and several new theoretical studies, however, are converging on the proposition that such novel atomic physics notions are not needed to explain any of the results up to now. In particular, the ionization process is almost always a sequential one with electrons coming off one at a time.

Interest in the multiple ionization of rare gas atoms grew after a 1982 publication by Anne L'Huillier, Louis-André Lompré, Gérard Mainfray, and Claude Manus of Saclay, who observed the production of singly, doubly, triply, and quadruply charged krypton ions after irradiation with 50-picosecond pulses from a high-power near-infrared laser (mode-locked Nd:YAG emitting at 1.06 micrometers). The results were surprising, not only because of the multiple ionization, but also because higher charge states occurred at comparatively low intensities, ranging from 10^{13} to 10^{14} watts per square centimeter, where the laser's electric field is still much weaker than the internal field binding the outer electrons.

During the next 2 years, the Saclay researchers reported similar findings with other rare gases, including xenon, argon, neon, and helium, irradiated with 1.06-micrometer infrared laser light. And they saw the same kind of behavior with xenon and neon irradiated with 0.53-micrometer visible light, also obtained from their Nd:YAG laser by the standard nonlinear optics technique of second harmonic generation or frequency-doubling. Finally, for xenon, the group studied the effect of varying the length of visible laser pulses between 5 and 200 picoseconds.

To see more explicitly why these results were surprising, consider the multiphoton absorption of visible light by which ionization occurs in xenon. For this atom, it takes 12.1 electron volts to remove one electron, 33.3 electron volts to shake off two electrons, 65.4 electron volts for three electrons to be stripped away, and 111.4 electron volts for four electrons. Since each visible photon has an energy of 2.34 electron volts, the number of photons needed to make these ions ranges from 6 to 48.

If only one photon is needed to ionize the atom, there is no particular difficulty, and the difference between the photon energy and the photoionization threshold is carried away as kinetic energy by the photoelectron. However, if several photons are needed, one must visualize a stepladder of successive transitions between atomic quantum states