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SCIENCE

Instrumentation for Bioengineering

Wallace E. Frank

Bioengineering is the field of applied science which is concerned with the application of the physical science techniques to problems in medicine and biology. Bioengineering also applies to the general area of the extension of normal and abnormal limits of human physical capabilities. While bioengineering encompasses much that requires instrumentation, one of the major divisions of the field is instrumentation development per se.

Perhaps we can best explore this general field by considering specific examples of instrumentation for bioengineering. As a matter of fact, most of those which I have chosen are ones on which my own group has actively worked.

Intraocular Pressure Measurement

Consider the problem of measuring the pressure inside the eye, which is of great importance in the detection of glaucoma. It is not practical to put a pressure probe inside the eye. Usually this intraocular pressure is measured by means of a tonometer, a special form of indentation-hardness tester that is placed over the eye, loaded with a given force, and indicates the depth of penetration. The reference plate rests on the rigid front of the eye and the moving plate, on the cornea. Although it is a very useful instrument, the tonometer nonetheless has many drawbacks, and there is need for a better method of measuring intraocular pressure. We are working to develop such a method. A technique devised by Karl Sittel of our laboratories involves measurement of vibration of the eye. Nothing will touch the eye but a fluid column. Preliminary experiments indicate the feasibility of this method, and we are just starting a more ambitious program to develop and evaluate the technique fully.

Endoscopy

Another instance of a physical limit that must be overcome by an instrument is exemplified by the problem of the endoscope. Endoscopes can be thought of as periscopes which are used to examine interior body cavities. Typical of these are the gastroscope for examining the stomach, the bronchoscope, and the cystoscope. These devices do not always permit the physician to view the entire area of interest. For instance, an important area of the stomach is frequently beyond the field of view of a gastroscope. Present endoscopes are not always as easy to place as both physician and patient would like them to be; they are neither flexible nor controllable enough.

An entirely new principle of image transmission is now being applied to endoscopy, and the press has recently carried a number of news stories telling of some work, at the Institute of Optics in Rochester, directed toward the use of the fibroscope, a flexible cable which consists of a bundle of fine, light-transmitting filaments. Fibroscopes are much more flexible than present gastroscopes and provide images of good quality. We, too, have been working on this problem. But we have extended our work beyond the optical features of the design and have developed a technique for controlling the configuration of the fibroscope so that the physician may easily view what would otherwise be very inaccessible places.

Also, in the field of endoscopy there is a need for better light sources which will permit photographing these body cavities in true color and at high speeds so that the motion may be "stopped." Such photographs would be useful in record-keeping, diagnosis, and teaching. Present light sources are not brilliant or long-lived enough for the job.

Reading Device for the Partially Sighted

Much work has been done in prosthetic and sensory aids to help handicapped individuals to perform normal actions in a more nearly normal manner. For instance, for the partially sighted we have developed the projection magnifier (Fig. 1). This is an opaque projector which produces a magnified, high-contrast image that can be read by a great number of the partially sighted who cannot comfortably read with other instruments. This device is an image magnifier, but many design problems of screen size, magnification, contrast, illumination, control of field of view for scanning, and material insertion had to be solved, in terms of the needs of the partially sighted, before the development was completed. A large-scale research and test program was undertaken for the purpose.

The first projection magnifier that we made was a walk-in model which required 18 automobile head lamps of 32 candlepower each and, naturally, a large blower to keep the reader from being baked alive. In tests of this model, with a number of subjects, relationships between visual acuity, reading speed, and magnification were determined. We came to the conclusion that for people who needed 10 times or more magnification, reading required considerable effort, and not many of them were sufficiently interested to take the trouble.

We also learned—and this seems obvious in retrospect—that persons with poor visual acuity tend to press their eyes close to the screen and move their heads as they read across the line. Even when manual control of scan was provided, many preferred to leave the material alone, scanning as much as possi-

The author is chief of the bioengineering section, Chemistry and Physics Division, of the Franklin Institute Laboratories for Research and Development, Philadelphia, Pa. This article is based on a paper presented 26 Dec. 1956 at the annual AAAS meetings in New York.

Fig. 1. Use of the projection magnifier, reading device for the partially sighted.

ble by head rather than by hand motion. This was even more likely to be true as visual acuity decreased. Finally, we concealed all but a small portion of the screen and determined the reading speed and comprehension of children with the small screen as compared with the large. The differences were small, and the economic advantages of the small machine and the small screen far outweighed the minor improvement in performance with the large machine.

The small-screen projection magnifier was then developed and subjected to preliminary test with partially sighted individuals of all ages. Thereafter, 50 test units were constructed and carefully evaluated in a 2-year test program. The results of the evaluation revealed a need for this type of device and pointed out the advantages and deficiencies of the test models. Since that time, a commercial producer has been licensed to manufacture and distribute projection magnifiers of an improved design, thus bringing the partially sighted a new reading aid. The same optical principles are being applied to an industrial inspection device. Thus, this work not only has benefited the class which we originally set out to help but is serving industry as well.

Guidance Devices for the Blind

Several programs of development of devices for the blind are also currently under way. One phase of the problem, navigation, is being worked on in several places. Guidance devices based on more sophisticated principles than the principle of an ordinary cane have been undergoing development since World War II.

These devices are intended to permit a blind traveler to get about more safely, more rapidly, and with less stress than is possible with a guide dog or an ordinary cane (Fig. 2). They employ ranging and proximity principles. They use ambient and self-generated radiations. They use sound, light, radio, and radar. While none have yet gone very far beyond the development laboratory, these instruments are good examples of bioengineering developments which involve adapting known engineering techniques to a new setting. At all of the meetings of those working in this field the most significant discussions are likely to be about the requirements for such guidance devices, the characteristics of the people who are to use them, the situations in which each device is or is not suitable, and the many intangibles, rather than about engineering features. The basic philosophic design problems are much more difficult to answer than the engineering problems, and frequently it is very difficult to formulate the design problems in any satisfactory way.

Reading Devices for the Blind

Other groups are striving to develop reading machines that will enable the sightless to comprehend ordinary printed material. These projects are not yet complete, but they are building an understanding of the requirements, and this is necessary before we can proceed with the proper development.

The crux of most bioengineering instrumentation problems is in setting the specifications; the development of reading machines for the blind illustrates this point.

The means for converting ordinary printed material into a code is well within the competence of those working in the field of commercial reading machines. Converting a letter-by-letter translation of the text into any other reasonable code is possible with modern computers. For instance, the converter could use the contractions used in advanced Braille. All this would be expensive, and whether it is worth while depends on how many of the blind read Braille or, more important, on how many would read Braille if there were a greater range of material available.

Or is the problem of reading one's own mail even more important? How many of the blind would go to how much trouble to learn to use a device that would let them read their own mail, labels, and so on? Just to read a cookbook might mean a great deal to someone.

Prosthetic and Protective Equipment

In recent years a great deal of scientific work has been done on the development of prosthetic devices. The Veterans Administration-sponsored artificial-limb program has brought an engineering approach to an important problem of device development and fit, and with notable success. Our own part in this work has been largely to develop pressure-sensing devices which can determine the pressure pattern between the stump and the stump socket, both at rest and during motion. Studies of the pressure pattern are expected to lead to a more rational basis for fitting, as well as designing, the attachment between prosthesis and man.

The basis of this work in prosthesis began some years ago when we were asked by the Government to develop instrumentation which could be used in measuring the pressure between man and his environment. The immediate application was to the design of sleeping bags. The problem was to develop a pressure-sensing element which would be so thin and flexible that it would cause no discomfort or alteration of the pressure pattern and yet would have adequate sensitivity and be able to operate either through telemetering or with long cables, so that the motion of the individual being tested would be unhampered. A survey revealed that no existing instrument small enough, thin enough, and flexible enough to suit these requirements was available.

A number of people had made thin pressure-sensing devices, but these all suffered from operational defects which made them unsuitable for our purpose. For instance, R. Plato Schwartz and Arthur L. Heath, at the University of

Fig. 2. Use of the sensitive cane, guidance device for the totally blind.

Rochester School of Medicine, had developed resistance-type pressure patches, which they used with some success in gait studies, and had also worked on strain-gage transducers. Strain-gage transducers, unfortunately, seem to require some sort of reference structure and a diaphragm which is stressed under load. The problem of making a thin, flexible, strain-gage transducer that would not be felt against the body and would not, of itself, alter the pressure distribution pattern seemed almost insurmountable. Bulk-resistance gages presented a number of problems, chiefly lack of stability. Hydraulic capsules have many attractive characteristics, but if a long tube is used, high-frequency response is difficult to attain.

We decided to work on a capacitance gage and, with the support of the Quartermaster Research and Development Center, pursued that development for more than 3 years. We now have devices called Filpips (Franklin Institute Laboratories pressure indicating patches) which are made of thin embossed steel plates separated by mica (Figs. 3 and 4).

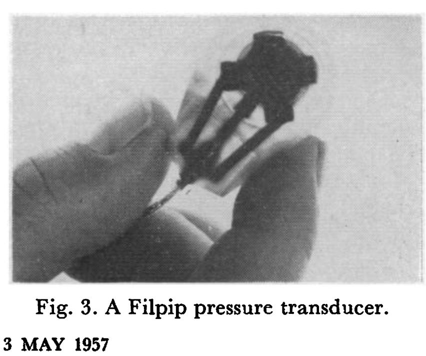

Fig. 3. A Filpip pressure transducer.

A typical Filpip is made of 0.001-inch steel, and seven plates, in an airtight cover, present a total thickness of about 1/32 inch. The change in capacity under load is very substantial, and the auxiliary instrumentation is simple. The devices are flexible and can be used successfully against the body.

These same pressure-sensing elements are also being applied to studies of gait in man; in this case they are placed inside the shoes. Another application of the same technique has been suggested as a means of following, quantitatively, the progress of disease—in this case, one that affects gait.

We have used the same sort of pressure-sensing instrument to evaluate crash-protective helmets, and another group has used it to evaluate protective helmets used in sports. Crash-protective helmets present many interesting bioengineering problems, and a good deal of work has been done in this field. Test procedures have been set up which measure such things as the momentum of a standard projectile which the helmet is able to withstand, the energy of impact of sharp and blunt projectiles which a helmet can absorb without failure, the momentum transmitted through the helmet to a simulated head after a blow. (Devices which project the helmet, pendulums which drop hammers on helmets, and hard steel balls which drop on helmets have been preferred by most experimenters.)

These criteria give a good deal of information about the structure of the helmet and the point at which it fails. However, our interest is not in designing an indestructible helmet but, rather, in designing a helmet which will provide adequate protection against head injury. This, we feel, can best be done by determining the forces and force-time pattern exerted by the helmet on the skull, since, after all, it is the forces on the skull which will cause the injury. We have actually begun applying the aforementioned pressure-sensing elements to a dummy head form covered with a helmet and are using various masses and accelerations to establish force and force-time patterns.

Of course, this neglects one very vital bit of information. We simply do not have data on what forces and force-time patterns the skull can absorb without injury. To this end, we hope to undertake a program that will provide such data. Actually, our plan is concerned less with skull fracture than with brain injury. We propose to insert pressure-sensing instruments inside an animal's skull to measure the effect of various head blows. Measurement of these internal pressures would establish the physical basis of both cerebral concussion and gross brain injury. If such data could be extrapolated to human beings, the bioengineer would

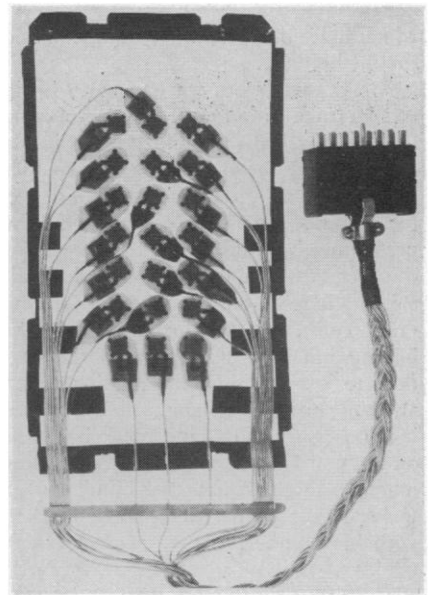

Fig. 4. A Filpip array.

be in a good position to design and evaluate crash-protecive gear.

Another application of the pressure-sensing instrument is in measuring the blast forces which are exerted on the body of a pilot who is being ejected from an aircraft at very high speed. These blast forces can cause considerable damage, and it is necessary that they be known and that limits of tolerance be established, so that protective gear can be designed and built.

In addition to the bioengineering problems to which we have applied these Filpips, we have found them useful in other applications. At the moment, for instance, we are measuring aerodynamic pressures of the order of inches of water and are considering applications in heavy machinery where the pressure would go up to many pounds per square inch. The development of these Filpips may serve to illustrate the point that even such a simple problem as a thin, flexible, pressure transducer may require many years of work and a great deal of money, but it is quite possible that the final product of all this effort will have far wider application than was originally intended.

Sensory Substitutes

Fitting the physically handicapped to take useful places in industry is another field of great interest to the bioengineer. Our own experience has been limited to the problems of the blind, but we have developed sensory substitutes which enable blind workers to perform tasks which would not otherwise be possible. Substitutes may range from very complex devices to the very simple, such as a conducting brush and conducting plate used to find holes in a thin mica sheet.

Much more of this kind of thing can and should be done.

Along these lines we expect to begin an extensive program of job engineering for the physically handicapped. Simple devices would be of the type that enables a blind person to read a gage. There are, for instance, many jobs that could be performed by a blind worker except for the fact that a dial must be read. Optical, inductive, or capacitative sensing units could be developed, which the blind worker would apply to the dial face to convert the dial reading to an auditory or tactile signal. In other jobs it is necessary that some mark be made on a record slip, and a simple reading machine might enable the blind worker to locate the proper place to be marked with his number.

Effort Measurement

Studies of the motion and energy expenditures of lower animals and of man may be of considerable interest in designing more efficient techniques of work, in studying disease, and in developing equipment. We have been interested in studies of sleep in human subjects and found it necessary to devise equipment to measure the energy the subject expends during slumber. This may be related to the individual's physical and emotional condition and to the characteristics of the surface upon which he rests as well as to external physical and environmental factors such as temperature and humidity. Since existing equipment could not make these measurements, we have developed special sensing and recording techniques which not only record the frequency of these motions but also integrate energy. In addition, we measure the pressures exerted.

The development of instruments for biomechanical analysis involves many challenging problems. Here we must measure motion and determine velocity and acceleration and a variety of forces and momentums. Such studies are of interest, not only in evaluating prosthetic devices, but also in designing equipment and procedures for use by normal people.

Summary

A tremendous range of physical science problems and techniques, from all branches of engineering, are involved in bioengineering instrumentation. The examples I have cited typify the problems that arise, but the techniques we have used represent only an infinitesimal fraction of the resources that we must exploit. The main challenge to the bioengineer is that of defining the problem in terms of what is useful and economically justified. One must understand the possibilities of engineering development and the probability that an effort will reach any assignable goal within a given time. Only then is it possible to work out a practical solution to the instrumentation problem. It is very easy to become so absorbed in the engineering development that we lose sight of the final goal and the purpose of the development. It is also easy, in working out an experiment, to become obsessed with the need for a particular bit of data, or of too great a degree of precision, without considering that the cost of obtaining these data might not be justified by their value to the full development. Thus, the only principles that can be generally applied to a bioengineering problem are those which would apply to making any decision that leans heavily on judgment.

Biological Clock in the Unicorn

LaMont C. Cole

A physiologist colleague has urged me to examine some of the rapidly accumulating mass of evidence for the existence of rhythms of activity and of various physiological functions. This subject, it seems, is attracting increasing interest among physiologists, and new "cycles" are rapidly being discovered in such remotely related material as intact mammals and slices of living vegetables.

It is postulated that there are two fundamental types of cycles. On the one hand, organisms may exhibit exogenous rhythms and have their periods of activity adjusted to correspond to changes of light intensity, temperature, humidity, phase of the moon, height of tide, or, allegedly, to fluctuations in the intensity of cosmic radiation and of the earth's magnetic field. Presumably, the organisms may respond to several such factors simultaneously so that the raw data from experiments present an appearance of complexity. On the other hand, organisms may possess endogenous rhythms that persist for long periods, if not indefinitely, in the apparent absence of external stimuli. These rhythms may originally have been synchronized with environmental rhythms, but, possibly, some of the endogenous cycles are innate properties of the organisms.

It is not very difficult in theory to conceive of mechanisms for generating persistent rhythms in the absence of external stimuli. For example, a hormone might accumulate until it reaches some threshold value that initiates the activity in question and simultaneously begins to exhaust the store of hormone. It is, however, very difficult to insulate organisms from cosmic radiation and from the earth's magnetic field. Hence, innate rhythms and exogenous rhythms of different periods may be intermingled and lend a further appearance of complexity to the raw data.

Time Series

It would appear that the physiologist faces a major problem of recognizing the cycles in his data and of disentangling the components when several cycles are present simultaneously. Considerable ingenuity has been exercised in the analysis of such data, and the justification for some of the procedures used must lie in some particularly obscure statistical theory. Since this subject seems to be of such current interest, it may be worth while to warn the uninitiated that there is a possibility of being misled in the analysis of complicated time series. This is the purpose of the experiment to be described in the next section.

One approach that could be used for simplifying the experimental data would be to seek correlations between the series of observations and some environmental rhythm. The principal difficulty here is that time series sometimes exhibit the

The author is professor of zoology at Cornell University, Ithaca, New York.