2.
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A DESCRIPTION

The Boston Elbow looks like a whole arm, extending as it does from the wrist (to which various hooks and artificial hands may be attached) to a socket that fits the stump, but only the elbow joint moves.[1] In engineering terms, the arm has one degree of freedom. It reproduces the active movement of the human elbow flexion and extension, but not, of course, other forearm movements such as pronation, supination and flexion or extension at the wrist.

The Boston Elbow is, like some other elbow prostheses (see ch. 3), battery powered. Like a few of them, it is also myoelectrically controlled. This means that electrodes located in the socket of the prosthesis detect, on the surface of the wearer's skin, the electrical charges that accompany contraction of the stump muscles. These electromyographic (EMG) signals are transmitted to and interpreted by a computer housed in the prosthesis, and the battery-powered motor "takes orders" from the computer to flex or extend the elbow. Although any muscle can provide an EMG signal, the Boston Elbow is designed to tap residual biceps and triceps muscles, precisely those that would ordinarily flex and extend the arm. Thus an amputee's control of the prosthesis imitates control of the natural elbow.

The Boston Elbow is both myoelectric and proportional. As such, it moves at speeds directly proportional to the intensity of muscle contraction by the amputee. Proportional control depends on the fact that muscle contraction produces an electrical signal the magnitude of which varies with contraction intensity. This relationship is a continuous one, so by contracting more or less intensely, the wearer of a proportional-control prosthesis produces a full range of signal magnitudes and, after electronic processing, is able to flex or extend the elbow at a full range of speeds.

Fitting a Boston Elbow involves making a cast of the amputee's stump and then a mold to which socket material is shaped. The prosthetist works down from the above-elbow socket with layers of foam and attaches a prosthetic elbow unit that includes a battery-powered motor. The Boston Elbow's forearm houses the batteries and electronics and offers the wearer a choice of terminal devices: a mechanical hook or hand controlled with a roll of the amputee's shoulder, or an electric or myoelectric hook or hand with switch control. The prosthesis is designed so that hook and hand are interchangeable and may be used by the same wearer at different times.

The current Boston Elbow weighs 2.5 pounds. It will lift 5 pounds and hold something over 50 pounds in a locked position. A fully charged battery will power the device for about 8 hours. The prosthesis has a range of 145 degrees, i.e., full flexion is 145 degrees from full extension, and this distance is traveled in a minimum of a second. The Boston Elbow has a 30-degree free swing that lends it a more natural appearance. Even so, the device is not easily mistaken for a human arm, especially because the forearm, which houses batteries and electronics, is noticeably boxy. But neither is the Boston Elbow unpleasant to look at, and its variable speed reduces the robotic aspect. Like many machines, it hums, but the addition of auditory to visual feedback can be advantageous. The prosthesis does not provide tactile feedback, a widely acknowledged (and as yet unrealized) feature of the perfect upper extremity device.

[1]*A Description* was compiled from interviews with Liberty Mutual officials and MIT faculty.

A HISTORY[2]

The Boston Elbow is a cybernetic limb prosthesis, and mathematician Norbert Wiener is considered its "godfather. " Having raised the possibility of cybernetic applications to prostheses in the late 1940s (6), Wiener was moved to reconsider electronic limbs, when, in 1961, he was hospitalized for a broken hip. Wiener's orthopedist at Massachusetts General Hospital was Melvin Glimcher, who also headed the amputee clinic at the Liberty Mutual Insurance Co., a major carrier of workers' compensation policies.

Glimcher had found in his work for Liberty Mutual that below-elbow amputees were using prostheses to recoup much more of their lost functioning than were above-elbow amputees. Even with the most advanced body-powered prosthesis, the above-elbow amputee had to: 1) position and 2) open or close the terminal device sequentially. The single-cable design did not allow for simultaneous execution of these two functions, and the result was unnatural body movements that were unattractive and inefficient. Glimcher visited the Soviet Union where he observed a myoelectric hand prosthesis. When he returned to Boston, he took advantage of Wiener's temporary disability to discuss with him the feasibility of surpassing Soviet technology with a myoelectric elbow. To Glimcher's mind, myoelectric control seemed less necessary for below-elbow amputees, who could function well with conventional devices. As one collaborator on the Boston Elbow project explained, the mission of its creators was and continues to be to make above-elbow counterparts, that is, to allow above-elbow amputees to use a terminal device well.

Weiner encouraged Glimcher's interest in the elbow and put him in touch with two Massachusetts Institute of Technology (MIT) professors, Amar Bose, an electrical engineer, and Robert Mann, a mechanical engineer. By 1965, two graduate theses had been written about the possibility of a myoelectric elbow prosthesis. Both were supported in part by Liberty Mutual, and, in 1966, the company hired two of Mann's former students to develop a real prosthesis from the MIT research. The Boston Elbow Version I was produced in 1968 and made its debut that fall with a press conference at Massachusetts General Hospital. Eighteen Version I Elbows were manufactured. They were by all accounts failures. Every amputee fitted rejected the prosthesis, and a National Academy of Sciences evaluation found the device unsatisfactory (15). The most serious problem was that the first Boston Elbow ran on a battery so large it had to be mounted on the wearer's belt.

At about the same time, another MIT graduate student was modifying the Elbow's design to incorporate a battery into the prosthetic forearm. Liberty Mutual hired this engineer when he finished his training, and he went on to build 25 Boston Elbow prototypes during his l-year tenure with the firm. In 1973, Liberty Mutual added a production engineer to the project, and in 197'4, 25 working prostheses were manufactured. Twelve of these are still being worn. A batch of 100 Boston Elbows followed in 1976; these featured a slimmer forearm and more reliable electronics. One hundred still slimmer and more reliable prostheses are being sold at this time. Liberty Mutual itself manufactures the Boston Elbow. The electronic components are supplied by small firms in the Boston area.

Neville Hogan, a mechanical engineer at MIT, conducts further research on the Boston Elbow. He maintains that the usefulness of the device is limited by the fact that, unlike the natural arm, the Boston Elbow is rigid. It is not, in Hogan's words, "floppy" or "springy" and so does not respond to the press of other objects the way the intact arm does, i.e., with variable force. Hogan proposes to design a Boston Elbow with the same viscosity, stiffness, and inertia as the natural limb. In addition to imitating more exactly the characteristics of the human arm, a floppy Boston Elbow might be positioned more accurately without tactile feedback. Recent research in neurophysiology (4) suggests that animal subjects deprived of all sensory information about a limb are able to return it to its resting position when a human investigator pushes it away. Presumably this occurs because the muscles return the limb to the posi-

[2] *A History* was compiled from interviews with Liberty Mutual officials and MIT faculty.

tion dictated by the balance of normal tension of opposing muscles. Although tactile data are widely thought to be critical to positioning an artificial limb, such feedback continues to elude bioengineers. Hogan believes that floppy arms will enable amputees to function well without it.

AN ASSESSMENT

In 1983, approximately 100 amputees wore Boston Elbows, and, for them, as Glimcher had hoped, elbow flexion and operation of the terminal device were simultaneous. But the Boston Elbow might have been expected to have been more widely diffused by now, and skeptics wonder about the value of the device.

Assessing the diffusion of the Boston Elbow requires knowledge of its clientele. Unfortunately, data specifically about above-elbow amputees are relatively scarce. The number of upper extremity amputees (both below- and above-elbow) in the United States is usually set at 75,000 to 100,000 (19). It has been estimated from data collected in 1967 (9) that 43 percent of the total number of upper extremity amputations (in some cases bilateral) are above-elbow, and the 1977 National Health Interview Survey (43) found the number of arm (as opposed to hand) amputees to be about 53,000, or 58 percent of all upper extremity amputees. More plentiful and timely data are available about limb amputation generally, but lower extremity amputation is far more common—at least three times as common—as upper extremity amputation, making combined statistics unrepresentative of the latter. Loss of an upper extremity usually results from trauma and that of a lower extremity from disease. Thus, above-elbow amputees are likely to be younger than their lower extremity counterparts and to be in better general health.

Amputation denotes loss of an extremity from any cause. It is estimated that 9 percent of the above-elbow amputations in this country are congenital (see table 1). Eight percent result from tumors, 6 percent from disease, and 77 percent from trauma. There were 773 trauma-related, upper extremity amputations identified in a sample drawn from case records provided by 44 prosthetics facilities in 30 States. (Only amputees fitted with prostheses were included.) Industrial, farm, and automobile accidents accounted for almost all amputations in women and 68 percent of amputations in men, who are far more likely than women to lose an arm for any reason (9). The typical above-elbow amputee, then, is a young male who has been injured in some way (see table 2).

As in all evaluative undertakings, asking the right questions about the Boston Elbow is critical, especially in this case study, because, surprisingly, the objectives of prosthetic technology are not obvious. "It is manifestly unrealistic to think one could write down all the criteria and performance specifications of the normal arm and hope even to begin to be able to reproduce them in a man-made device" (23). Any prosthesis, then, will embody only some subset of the original functions of the human arm; choosing among them is a complex process. Judgments must be reached again and again as new needs materialize, and the

Table 1 .—Causes of Upper Extremity Amputation

Congenital	8.9°\0
Tumor	8.2°/0
Disease	5.8°/0
Trauma	77 °/0

SOURCE E. J. Davies, B R. Fnz, and F. W Cl!pplnger, "Amputees and Their Prostheses, " *Artificial Limbs* 14(2) 19-48, 1970

Table 2.—Traumatic Amputation by Cause

	Male	Female	Total
Car	73	12	85
Industrial	253	10	263
War	58	0	58
Farm	164	7	171
Train	18	1	19
Gunshot	46	5	51
Thermal	19	3	22
Lawnmower	5	2	7
Other	87	10	97
Total	723	50	773

SOURCE E J Davies, B R Friz, and F W Cllpplnger, "Amputees and Their Pros. theses, " Artficial Limbs 14(2) 19-48. 1970

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real priorities may be evident only after a provisional device has been fitted (20).

The variety of possible approaches to the design of an arm is startling. First, there is the gross dichotomy between efforts to start from first principles and those directed at improving existing prostheses (12). A more specific list includes simulation of normal arm movement, recreation of command outputs and sensory inputs, and design for specific tasks (23). Goals of functional and cosmetic replacement frequently conflict, and the goal of economy further complicates the choice.

Evaluating the results of the design process means raising these issues again. Should evaluation focus on how well the prosthesis is engineered, how much functioning it restores, how easy it is to use, or simply how satisfied its users are? Even the most comprehensive study entails choosing how to weight the several factors. One engineer notes that because explicit evaluation of prosthetic limbs means attending to so many factors, design decisions are often made intuitively (14). Another anticipates that in the face of all the things a natural arm can do, "each worker will seize on a particular feature he wishes to sustain . . . and a multiplicity of attempted 'solutions' is inevitable" (23). It would be difficult to overstate the divergences of viewpoint expressed by the prosthetics experts interviewed for this study. What was a critical feature for one was a red herring for another, and, although some disagreements rested on data, others concerned ideas about what an artificial arm should be expected to do.

The Boston Elbow is one attempted solution to the problem of amputation. The overriding concern of those who created it seems to have been what Mann calls "innateness" (20) —i.e., the extent to which control of the device imitates control of the natural arm. As described above, the Boston Elbow taps the amputee's residual biceps and triceps muscles—the very muscles that control the human elbow. Innateness is further served by the proportionality of the Boston Elbow, which gives the wearer control of the speed of the elbow movements, and by the independent operation of the elbow and terminal device. Theoretically, innateness makes a prosthesis easier to use. To the extent that it mimics the natural arm, amputees already "know" how to use it. A prosthesis that acts like an arm is also arguably more assimilable into the amputee's body image.

On the other hand, innateness often trades off against "access" (20), the latter meaning accessibility to the user—how easy it is to understand and maintain, how safe and convenient it is to use. The Boston Elbow is less accessible than it is innate. Although it is perfectly safe, the device is technically complex and requires specialized components and personnel for maintenance. An Elbow needs attention on the average once a year, and on these occasions the prosthesis must be returned to Liberty Mutual. Because the Boston Elbow is **a** battery-powered device, it must also be recharged after about 8 hours of use, and complete recharging is a 2-hour process (see table 3).

Anecdotal data seem to confirm this mixed evaluation. All of the several Boston Elbow owners contacted for this study found the device useful, some extremely so, and those who had used other prostheses as well found the Elbow a significant improvement. Users reported that they could do more things more easily with the myoelectric device, although two owners who were not wearing their Boston Elbows had experienced mechanical failure and were unable to return to Boston for repairs. Apart from this, the most common complaints were about the Elbow's noisiness and weight, both of which were said to be greater than those of a conventional prosthesis. Still, neither of these factors deterred any of the owners from using their Boston Elbows, and most owners considered the devices to be helpful to them in doing their jobs. An accountant and lawyer found the Elbow to be of some importance; a benefits examiner, a technician at a utility company, and a machine operator said it was very important; but a janitor gave up wearing his Boston Elbow for heavy work because this activity drained the battery too quickly. It should be noted that almost every owner contacted was a worker's compensation client and therefore did not pay for his prosthesis directly.

The cost of the Boston Elbow is $3,500. When it has been fashioned into an artificial arm and fitted to an amputee, the cost rises to an average

Table 3.—Elbow Prostheses[a]

	Boston Elbow	Cable Elbow	VA Elbow	Utah Arm
Power	battery	body	battery	battery
Control	myoelectric	mechanical	switch	myoelectric
Proportional	yes	yes	no	yes
Number of powered joints	1	o	1	1
Weight	2.5 lb	1.51b	1+ lb	2 lb 1 oz
Lift	51b	very variable	31b	2+ lb
Hold	50 lb	very variable	10lb	50 lb
Speed	1 second	very variable	1.5 seconds	0.5 seconds
Range	145°	165°	135°	135°
Free swing	30°	total	120'	total
Repair cycle	l/yr	Ilyr	1.51yr	2/yr
Repair local	no	yes	some	yes
Time without recharge	8 hours	NA	8 hours	8 hours[b]
Recharge time	2 hours	NA	2 hours	16 hours
costs:				
Elbow	$3,500	$ 400	$ 900	$10,000
Fitting and other costs	$6,000	$1,100	$1,100	$10,000
Total (includes socket, fitting, etc)	$9,500	$1,500	$2,000	$20,000
Annual repair	$ 250	$ 25	$ 100	$ 150
Service Life	5 years	10 years	10 years	6 years

[a]Data for powered arms provided by manufacturers Data for cable arm provided by independent prosthetist Alldataar eapproximate Experts disagree about the importance of these features
[b]But Immediately replaceable so can run 24 hours per day

SOURCE S J Tanenbaum, Brandeis University, 1983

of about $9,500. The cost effectiveness of the Boston Elbow is harder to determine. An engineer at the National Institute of Handicapped Research describes the prosthesisas “essentially overkill,’ i.e, an unnecessarily complex technology at a cordespondingly high price. Is the extent to which the Boston Elbow outperforms conventiona! pros thesesso great as to warrant the difference in its cost? He believes not. But proponents of the Boston Elbow and other myoelectrically controlled arms assert that the enhanced innateness of the devices more than justifies their high price.

Whether the marginal benefits are worththe extra costs is ultimately a very personal calculus. Functional loss is idiosyncratic and contextual; loss of an arm means different things to different people and to the same individuals over time. Thus a long and elaborate evaluative study of below-elbow prostheses concludes:

> The mental load, gain in function and acceptance cannot be described with one single scalar quantity. It is therefore not possible to”give a general rule for selection of a prosthesis on the basis of these variables, because of the fact that each individual amputee appreciates and weights the various aspects of these quantities differently. . . (32).

These remarks apply as well to the above-elbow amputee’s alternative responses to functional loss.