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Extended physiologic taction: Design and evaluation of a proportional force feedback system

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Abstract—In both robot teleoperation and prosthetics, the feeding back of touch information to the human operator in a physiologically compatible manner is an important problem. Most research in feedback systems for prosthetic devices has concentrated on electrotactile or vibrotactile stimulation of the skin. While these techniques can transmit information to the user, the user does not have the same sensation as if he were grasping an object in his natural hand. The present research investigates a third method of stimulation using direct force. In the sense of Simpson's Extended Physiologic Proprioception (EPP), it is called: Extended Physiologic Taction (EPT). The EPT system produces a one-to-one correspondence of touch sensation to user stimulation. The EPT system applies a force on the surface of the skin of the operator proportional to the grip force applied at the terminal device, or applies a vibration to the operator proportional to the vibration at the terminal device. A method of quantifying grip controllability has also been developed. A prototype was built and tested using a myoelectrically-controlled prosthetic terminal device as the remote gripping device. Quantifiable comparisons can be made between different feedback and gripping systems as well as comparisons between artificial terminal devices and the natural hand. Results are reported of improved grip control and of improved ability to manipulate objects when using the EPT system.

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INTRODUCTION

Tactile feedback is necessary for dextrous manipulation of objects by prosthetic terminal devices or teleoperated manipulators, so that objects can be manipulated without being broken or dropped. Research has shown the importance of touch feedback for successful dextrous manipulation (10). For robot teleoperation, it is important that the operator has the same sensation of touch of an object as he would if he were touching the actual object (9). For prosthetic use, it is important that the tactile feedback be compatible with myoelectric control and be as natural as possible.

Many tactile presentation methods have been investigated in the past, such as vibrotactile and electrotactile, with varying degrees of success. In this paper, a physiologically-based tactile feedback system is presented, called: Extended Physiologic Taction (EPT). The EPT method has a one-to-one or extended correspondence of sensation to stimulation. In essence, with an ideal EPT system, the user would exactly feel the object being grasped. For instance, if a cup were grasped in the terminal device, the user would feel a "cup," not a vibration or other stimulation that represents "cup." A portion of a complete EPT system is presented in this paper, where a one-degree-of-freedom force applied to the subject corresponds to a one-degree-of-freedom force at the terminal device. The basic idea of our simplified EPT is quite simple: for a given contact force on the terminal device fingers, a force proportional to the contact force is applied to the operator's skin. This idea is not new. The concept of force-to-force feedback was presented as early as 1916 by Rosset, and described by Childress (4). The system should respond to the dynamics of the force so that if a steady force is applied to the terminal device, a steady force should be applied to the user. If a vibration is applied to the terminal device, then a vibration is applied to the user.

By "physiologically compatible," the following is meant: it is postulated that the same type of neural receptors would be used with EPT as would be used by the natural hand when manipulating objects. It would have the same self-calibration and drift correction as the natural tactile system. In essence, an EPT system is a force teleoperation or telesensation system.

This name was applied to the approach because EPT is analogous to Simpson's Extended Physiological Proprioception (or EPP), which refers to a person's ability to extend his proprioception (knowledge of the position and motion of the person's limbs) beyond his limbs (22). Examples of EPP are a person's ability to feel the position and motion of a tennis racket held in the hand or skis on the feet. In the case of EPT, a contact or grip force is measured, and a proportional force is provided on the subject's skin, i.e., the subject's natural touch sensation is extended out to the prosthesis or manipulator.

A quantitative technique for evaluating manipulation of objects is also presented. It is important that any evaluation technique evaluate manipulation of real objects. The results from this technique are a simple success-failure ratio. The failures are catastrophic and easy to measure. There are two types of grip or manipulation failures to consider: 1) dropping the object; or, 2) breaking the object due to excessive grip force. An inability to control low grip forces would cause the object to drop, and an inability to control high grip forces would cause the test object to be broken.

One aspect of manipulation can be evaluated by grasping a brittle heavy object. The test object should not indicate any deformation before breaking, so that no other clues to grip force will be given to the subject other than those from the feedback system. A deformable object could give the subject visual clues on how hard he was gripping (13).

The breaking strength of the object determines the ease with which it can be grasped. If the breaking strength is too low compared to the weight of the object and coefficient of friction, the object cannot be lifted. If the breaking strength is high, the object could be grasped easily, with or without any force feedback. The frictional force, and the weight of the object, determines the minimal strength an object must have if it is to be grasped and lifted. The required lifting force applied by the terminal device is equal to the weight, and is equal to the normal force of the terminal device against the object multiplied by the coefficient of friction. If the normal force required is greater than the breaking strength of the object, the object cannot be lifted. Therefore, there is a lower threshold which can be used to compare the results between manipulation with the terminal device, and manipulation with a natural hand.

A perfect grasping system would be able to lift any object with a breaking strength at, or higher than, the lower threshold, and not be able to lift an object whose strength is below the threshold. The effectiveness of any real grip device or force feedback system can be determined by evaluating how successfully it can lift an object whose strength is near the lower breaking strength threshold. This is illustrated in **Figure 1**, which shows the threshold limit as a function of object-breaking strength.

PREVIOUS WORK

In the past, two approaches have been pursued the most: vibrotactile and electrotactile stimulation (3,8,15,24). Neither provides a physiologically-compatible stimulation of the natural tactile senses of the human operator. Systems similar to the EPT system have been investigated in the past. Rosset used a pneumatic means to transmit finger pressure to pressure pads on the residual limb (4). Conzelman (5) designed a similar system using hydraulic fluid. Goldman (6) used Bowden cables as the transmis-

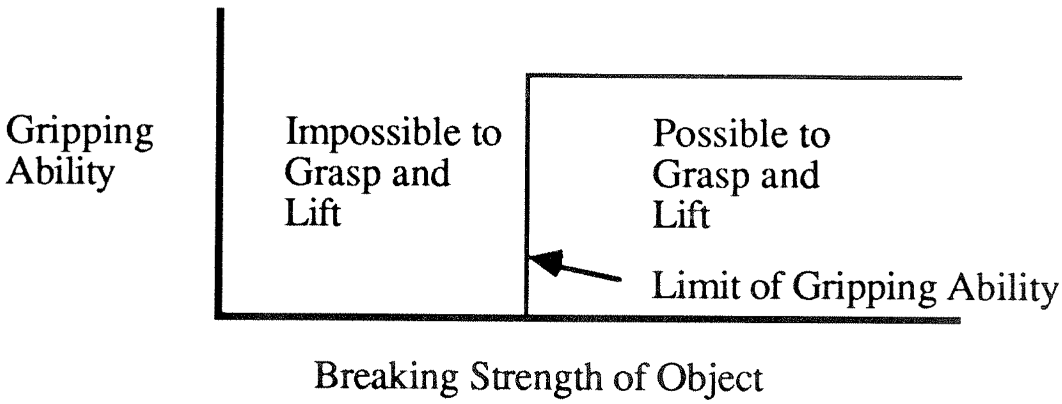

Figure 1.
Gripping ability of a perfect manipulation system.

sion. Some researchers have investigated closed-loop control of grip force. Notable is Salisbury's slip detection system (17).

Vibrotactile feedback uses a device to mechanically vibrate the skin of the operator. The vibration may be normal or transverse to the surface of the skin. The touch or grip force information is presented to the operator by a modulation of the amplitude, or of the frequency of the vibration (1,20,21). There is not a one-to-one correspondence of a steady grip force to vibrotactile stimulation. It has been shown that different skin receptors respond to vibration than respond to steady force or touch (12,14,26). With vibration (frequencies on the order of hundreds of Hz), the fast adapting (FA) receptors are being stimulated more than the slow adapting (SA) receptors. With a steady force on the skin, the opposite is the case; more SA units are stimulated than FA units.

Much of the past work has been directed toward finding thresholds of sensation in terms of amplitude and frequency of vibration in both normal and transverse motions of the skin (1,16). A low threshold of sensation is not necessarily the primary requirement for a force feedback system.

In electrotactile feedback, an alternating current is applied to the surface of the skin through a pair of electrodes. Since this requires only a pair of electrodes and some simple electrical circuitry, electrotactile stimulation is more easily packaged into a self-contained prosthesis and, therefore, has been researched more than vibrotactile stimulation. As with the vibrotactile system, both amplitude and frequency modulation have been used.

Early systems were annoying and sometimes painful, but some researchers claim to have these problems largely solved (20,21). There is still the problem of interference of the electrical stimulation system with the myoelectric signal detectors when the system is used with myoelectrically-controlled prostheses (2,8). As with the vibrotactile systems, electrotactile systems do not stimulate the same skin receptors as does touching an object with the natural hand. Johansson and Westling (14) have observed that weak electrical stimulation elicited motor responses similar to those elicited by slipping of the objects being grasped, and that the response declined with repeated stimulation. Thus, electrotactile stimulation does not have a one-to-one physiologic compatibility.

EPT test system

In order to test the EPT principle, a simple test system was built. The system is a servo of one degree of freedom: opening and closing of a terminal device, and one channel of EPT feedback: the grip force of the terminal device. However, the EPT technique could be used for many degrees of freedom.

The test system consisted of a myoelectrically-controlled terminal device with grip force transducers and proportional force application device. The terminal device was a Dorrance cable-powered hook modified to be electrically driven. The difference in the myoelectrical signals of a pair of antagonist muscles was used to proportionally control the terminal device (11). The hand controller and myoelectrodes from a Utah Arm (manufactured by

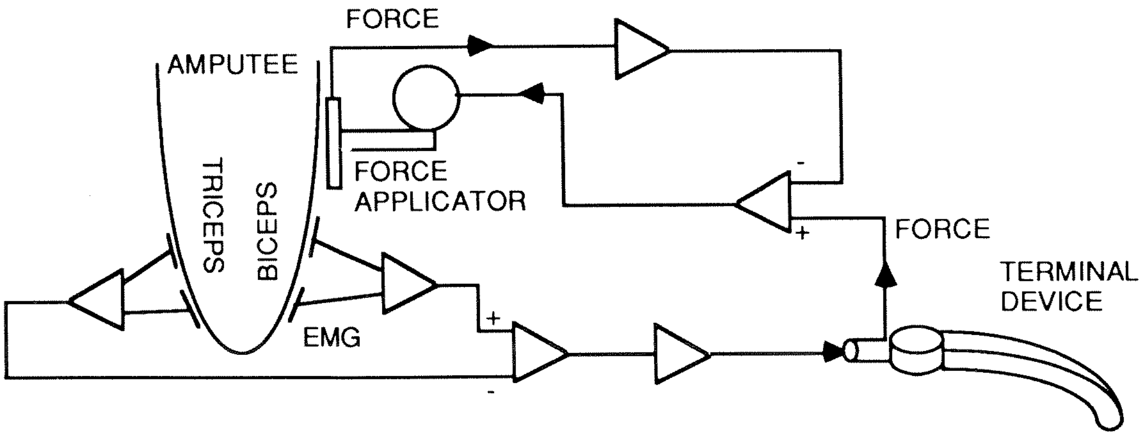

Figure 2.
Schematic of EPT evaluation system.

Motion Control of Salt Lake City, UT) were used for the controller.

Strain gauges connected in a Wheatstone bridge configuration were placed on the fixed finger of the hook. The gauges measured the deflection of the cantilevered finger. An apparent problem is that this configuration will measure the moment on the finger, not the force anywhere on the gripping surface. This is not actually a problem for testing the principle of EPT since the location of the gripping area can be controlled in the experiments. The output of the strain gauge bridge was calibrated to measure the force on the specified finger gripping surface in terms of pounds force. This signal was used as the input to the force application device. A schematic of the EPT system is shown in **Figure 2.**

The force was applied to the subject by means of a motor-driven pusher. A pinion on the motor drove a rack up and down against the skin. The force against the skin was measured by a small force transducer placed at the end of the pusher. The force on the skin was regulated by a closed-loop force feedback controller, so that the skin force was maintained no matter what position the device was in, or what movement of the skin occurred. **Figure 3** shows the test system. The force application device can push with a maximum force of three pounds and has a maximum frequency response of 10 Hz; the skin contact area was one square inch. The present system was intended only for laboratory testing and not for permanent application, so no attempt was made to miniaturize the system or to incorporate it into a self-contained prosthesis or teleoperation system.

The terminal device, controller, and pusher were mounted on a special prosthesis socket that could be worn by non-amputees. The force was applied on the mid-posterior forearm of the user.

Brittle, heavy test object

The test object was designed to "break" or release at preset levels. The resisting force drops to zero catastrophically. This was accomplished by having two parallel plates, one fixed and one hinged at the bottom and held by a magnet at the top. When too much force presses on the movable plate, it pulls away from the magnet and a spring snaps the plate away from the magnet, "breaking" the device. The magnet was adjustable up and down to adjust the "breaking" force. The force was adjustable from .75 pounds to 15 pounds. The test object exhibited brittle failure in that it would release itself at a preset force level and not visibly deform before it released. A diagram of the test object is shown in **Figure 4.**

The bottom of the test object was a hollow can which could be filled with lead shot to vary the weight. Whenever the subject snapped the plate on the object, it was considered a failure whether the subject dropped the test object or not.

Evaluation technique

The grip force feedback system is intended to inform the subject how hard the terminal device is

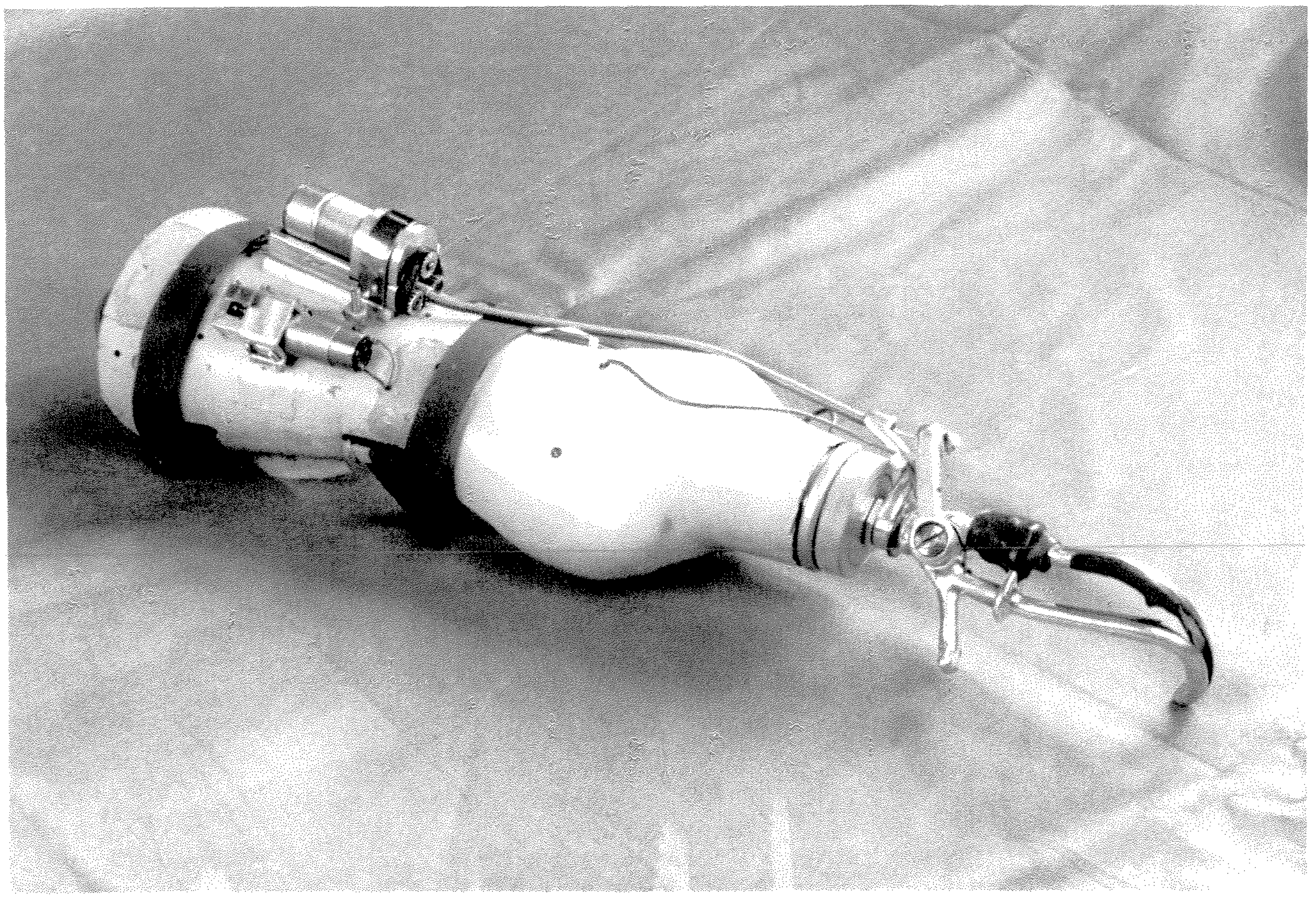

Figure 3.
EPT test system.

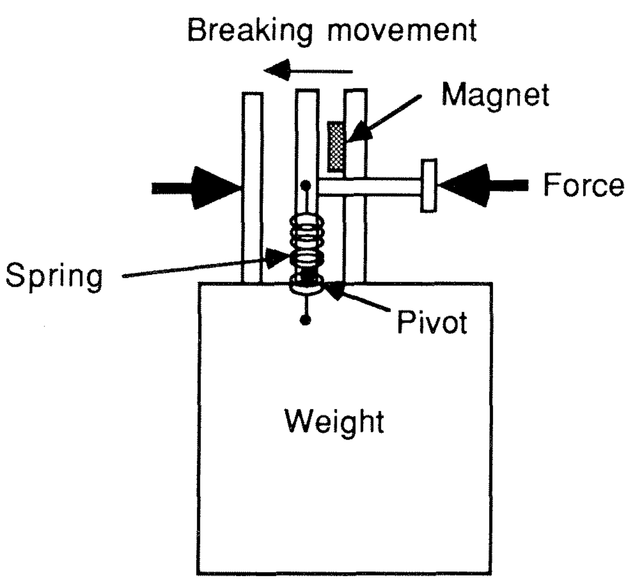

Figure 4.
Test object.

gripping the test object, so that the subject can control the gripping force (in the experiments, via the muscle contraction and therefore the EMG levels.) The ability of the subject to manipulate the object was measured as follows: the subject was required to grasp the test object, to lift it, to move it to a location one foot to the right of and one foot higher than the original location, to set it down, and, finally, to release the object. The process was then reversed, and the subject was required to move the object back to the original location. The number of successful manipulations and failed manipulations (by dropping or breaking the object) were recorded.

The manipulation experiments were begun by setting the test object to the minimum breaking strength for the terminal device. The subject tried to

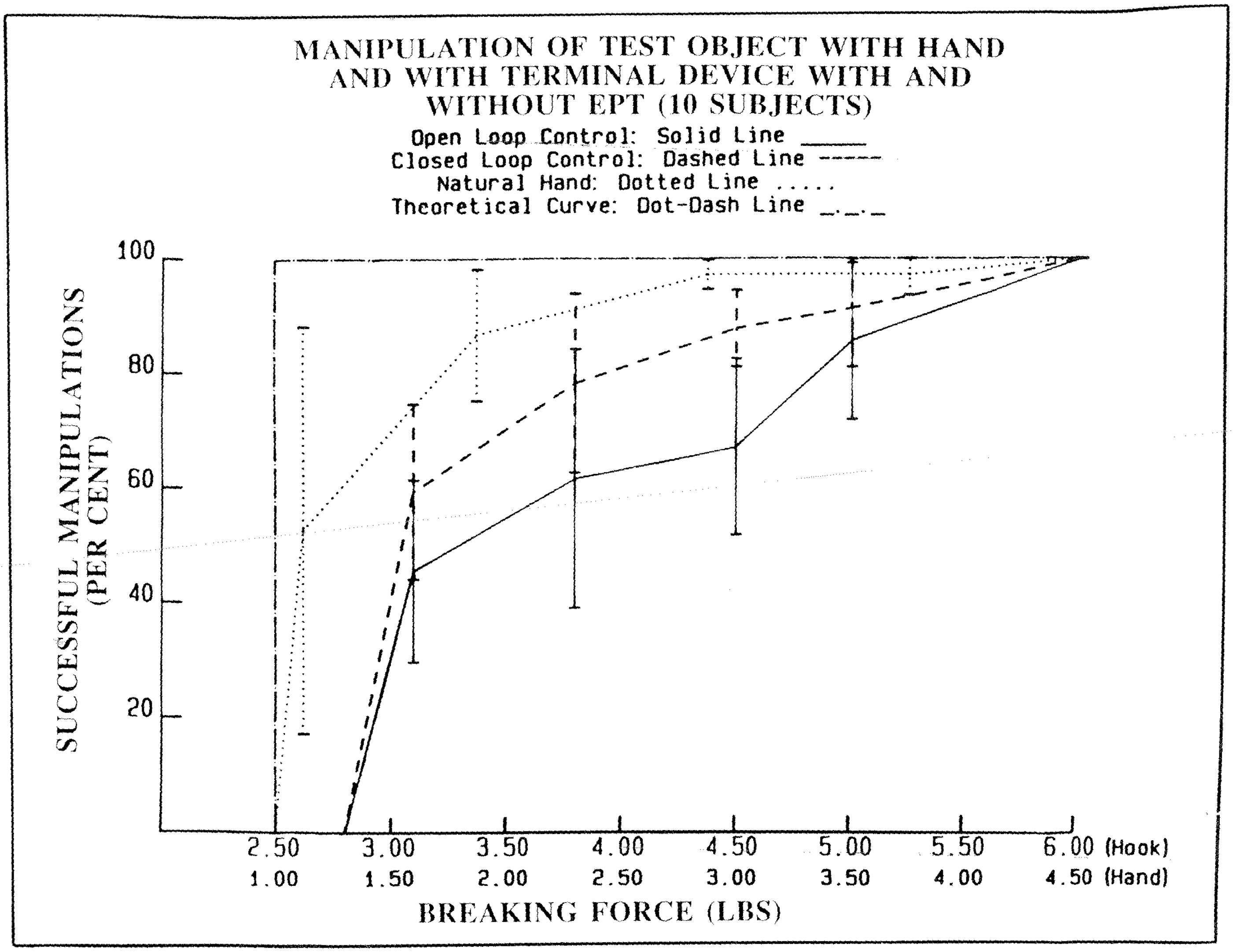

Figure 5.
Successful manipulations with EPT, without EPT, and with natural hand.

grasp and move the object ten times. The grasp on the test object was carefully monitored to ensure that the subjects used the same two-finger pinch grasp and that the prosthetic hook was gripping in the same location. The breaking strength of the test object was then increased by approximately a half-pound (approximately 50 percent minimum breaking strength) and ten more manipulation attempts were made. The breaking strength was increased another half-pound and the manipulation was repeated. The breaking strength was increased until the subject had 100 percent successful manipulation of the test object. The percentage of successful manipulations at different breaking strengths for a given weight test object indicates the effectiveness of the feedback system.

The subject was required to perform the series of manipulation tasks while using the terminal device with the EPT system. The series was repeated while the subject used the terminal device without the EPT system, and, finally, while the subject used his natural hand. A pinch grasp between the thumb and first digit was used with the natural hand in order to match the gripping of the terminal device. The only difference between gripping with a terminal device and with the hand was the different coefficients of friction.

The times required to complete the manipula-

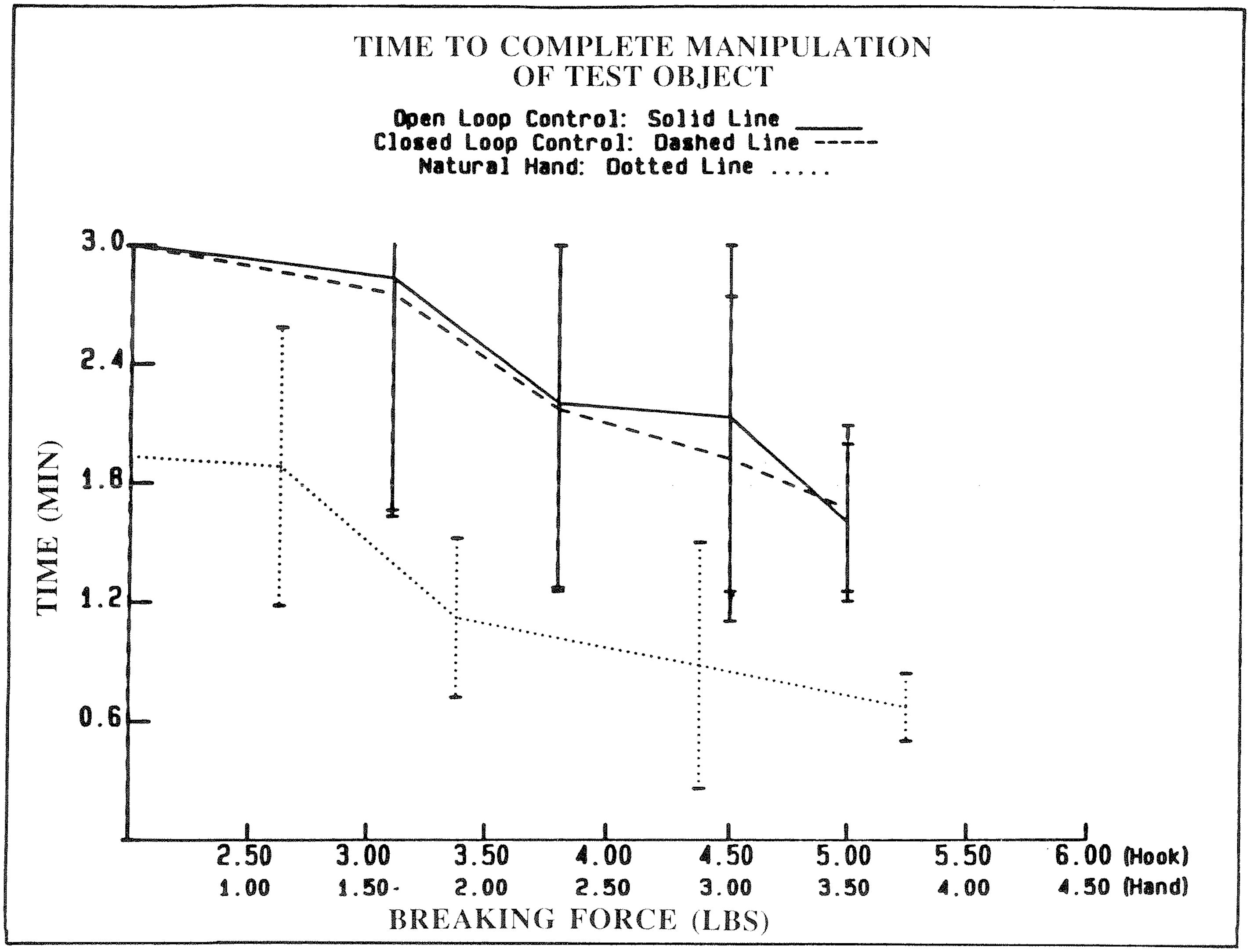

Figure 6.
Time to complete 10 manipulations of the test object.

tion tasks were also recorded. It was desired to see if the EPT feedback system affected the speed of the manipulation task.

RESULTS

The percentage of successful manipulations of the test object as a function of breaking force of the object for a typical experiment is shown in **Figure 5** (7). Many more experiments with different weights of the test object were performed. It is beyond the scope of this paper to present the entire body of test results. The horizontal axis is the breaking strength of the test object. It is shifted to reflect the different threshold limits of the terminal device and the natural hand caused by the different static coefficients of friction of the terminal device with the test object, and the hand with the test object. Therefore, the differences of friction of the terminal device and hand have been eliminated as a factor in the results, and the difference between the actual and the theoretical curves is the indication of the ability to control grip force.

The vertical axis is the success rate of ten manipulation attempts by ten subjects. The subjects were non-amputees using a myoelectric prosthesis on a special socket, as described earlier. Electrodes were placed over the flexor carpi radialis and flexor digitorum superficialis for the EMG signal for closure of the terminal device. Electrodes over the extensor digitorum and extensor carpi ulnaris recorded the EMG signal for opening of the terminal device.

The theoretical curve is the threshold of breaking strength of the object where it cannot be grasped and lifted. The ability of the subject to control the grip force is indicated by how close the curve of percent successful manipulations approaches the theoretical curve. The best manipulation success rate was obtained by the natural hand. The terminal device with the EPT system shows a significant improvement in manipulation control over that of the terminal device without the EPT system.

The time to accomplish the tasks was also recorded (7) and is shown in **Figure 6**. Note that there is no appreciable difference between the time required to accomplish the task with or without the feedback. The primary time delay is due to the control of the terminal device and is not affected by force feedback. This is probably because the major portion of the time is required to position and command the terminal device to close on the test object, which is unaffected by differences in sensing of the grip force. Also, the subject tended to close the fingers on the object slowly, in order to maintain a force control as precisely as possible.

SUMMARY AND CONCLUSIONS

Extended Physiologic Taction (EPT) is a grip force feedback system that uses the natural physiologic pathways to present terminal device contact force to the user of prosthetic limbs or teleoperation systems. The principle is to extend the user's natural tactile abilities out to an artificial terminal device. The operation of the EPT system is simple in principle: the user has a force applied to his skin (of the fingers in the case of a teleoperation system or of a residual limb in the case of an amputee) that is proportional to the contact force measured on the fingers of the terminal device. A myoelectrically-controlled terminal device was used as the manipulation system to test the EPT system. Evaluation results show improved grip control and manipulation when using the EPT system.

The use of the EPT system did not facilitate the speed of manipulation of objects. The time required to perform manipulation tasks was not changed with or without the EPT system, and was generally twice the time required to perform the task with the natural hand. The limiting factor for the speed of control of the terminal device was not the ability or inability to sense grip force, but was the myoelectric control system. This was probably due to the increased concentration required with the prosthetic system than with the natural hand, so the subject tended to be slow and cautious while using the system.

A quantitative method of measuring the ability to grasp and manipulate objects has been developed and used to evaluate the EPT principle. The ability to control grip force can be evaluated while grasping and manipulating objects. This was tested by measuring a person's ability to grasp and lift a brittle, heavy test object with a preset breaking strength and brittle failure behavior. If the object was grasped and moved to a new location without exceeding a set force, or without being dropped, it was considered a successful manipulation. If either the object was dropped, or the force limit was exceeded, the manipulation was considered a failure. The percentage of successful manipulations at different breaking strengths is used to compare different artificial gripping systems as well as the natural hand to a theoretical limit of grip force, determined by the minimum force normal to the surface that must be applied to an object by a gripper which will provide sufficient tangential force (because of friction) to overcome the weight of the object without exceeding the breaking strength of the object. How close a gripping system can come to the theoretical limit indicates the accuracy of each system's grip force control.

We have presented, herein, a laboratory study of a feedback system. To realize the system in a practical prosthesis or teleoperation system, several problems must be overcome. The present system, while useful in the laboratory, is too large to be used outside the laboratory. No attempt has been made to minimize the power drain which is critical on a prosthesis, but not as critical on a teleoperation system. Human factors questions of long-term use, such as skin pressure and irritation problems, have not been investigated.

The simple version of the EPT system investigated in this work was shown to be an effective force feedback system. Many problems must be addressed before such a system could be used as a practical system in prostheses such as: size, power drain, and tissue irritation.

Further studies will investigate multiple degree-of-freedom EPT systems where several contact force sensors would be used on each of the fingers of a teleoperated robot, and several force applicators would be used on each of the corresponding fingers of a human subject. The EPT force application system will require a redesign for a compact, efficient package, so that multiple forces can be applied to the fingers and hand in a teleoperation master. Areas of investigation will include: 1) the required spatial resolution of the force application; 2) the ability of the subject to recognize objects (shape and weight for example) using an EPT system; and, 3) the subject's ability to sense the slipping of a grasped object and other grasp instabilities.

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