ARTIFICIAL SENSORY FEEDBACK FOR PROSTHETIC LIMB

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ABSTRACT

We are investigating various kinds of sensory feedback systems for upper and lower limb prosthetics since 1964. Our research points that:

1) Artificial sensory feedback is needed more in above-knee prothesis than the arm and hand prosthesis;
2) Modalities of artificial sensation should match the function of the prosthesis and should be similar to the natural sensation;
3) Cutaneous transmission, like the mechanical vibration and/or surface electrical stimulation, is not suitable. This type of transmission is not reliable and fast enough, and the phantom sensation prevents the multichannel transmission. The cutaneous sensation in not the most natural one. The sound is the most practical way of transmission at present; and
4) Evaluation of artificial sensation for prosthesis should be performed with visual and incidental feedback. "Simulated prosthesis" is very useful tool for the evaluation.

KEY WORDS: Artificial sensory feedback, upper-limb prosthesis, Lower limb prosthesis, Simulated prosthesis

INTRODUCTION

The research on artificial sensory feedback for prosthetics started in our center in 1964. We investigated artificial arms, at first and artificial legs latter on. At the starting stage we considered this task as a simple one. Although various kinds of devices have been experimentally produced and tested. our systems up to now are only in a developmental phase. allowing routine clinical use outside the laboratory. In this paper, we would like to report on our research and experience in the development of artificial sensory feedback for prosthetic limb.

EXPERIMENTALLY PRODUCED AND TESTED SYSTEMS

We will present eight different feedback systems developed and tested by our group.

1.Feedback system for the conventional below-elbow prosthesis

Strain gauges and potentiometer, installed at the base of the hook, detect pinching force and opening angle of the hook. These signals are transmitted as vibration to the skin of the stump by two mechanical oscillators (Figure 1). Results of test performed with closed eyes showed that the accuracy of pinching force was improved by this system (Figure 2)

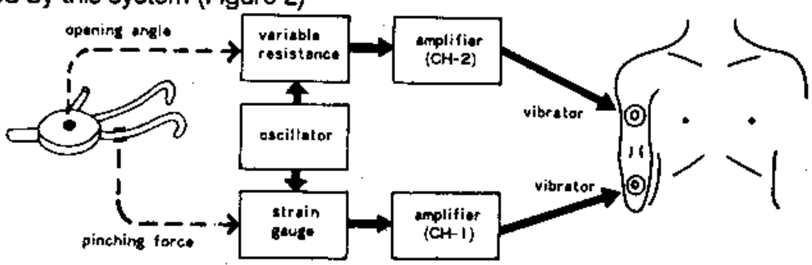

Figure 1. The feedback system for conventional below-elbow prosthesis

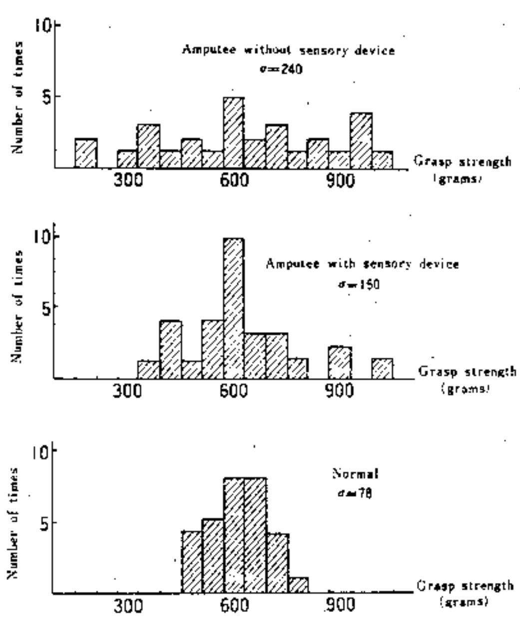

Figure 2. The accuracy of pinching force.

The task was to pinch with 600 g (6 N). Lowest graph presents the normal subject, middle one the hook equipped with the described sensory feedback system, and the upper one the hook with open-loop control.

Furthermore, the clinical tests in three amputees, who used the hook for three months in their daily living activities showed, showed that a great deal of confidence was developed. However, none of the subjects wanted to continue to use the feedback system, because of difficulties in donning and doffing of the feedback system, its heaviness and its fragility.

2.The system for powered below-elbow prosthesis

The similar feedback system to the one described above, was installed in the powered elbow prosthesis (Figure 3). Results of this system in powered arm prosthesis were poor. One of the reason for this was associated with the motor noise serving as incidental feedback, the second with low controllability of the powered elbow.

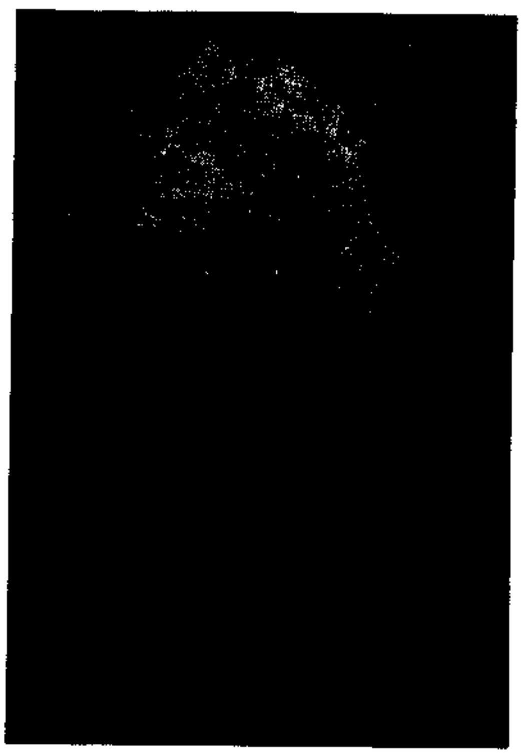

Figure 3.The powered below-elbow prosthesis with the feedback controller

3.Photo-electric effect feedback system

A small electric bulb and photo transistor were embedded inside opposite tips of the hook. When the object was placed between these tips, the light scan is discontinued, begininig transmission of vibrations to the stump (Figure 4). Results of "pick-up" test carried out with no visual feedback showed that this system remarkably increased the number of objects that were picked-up.

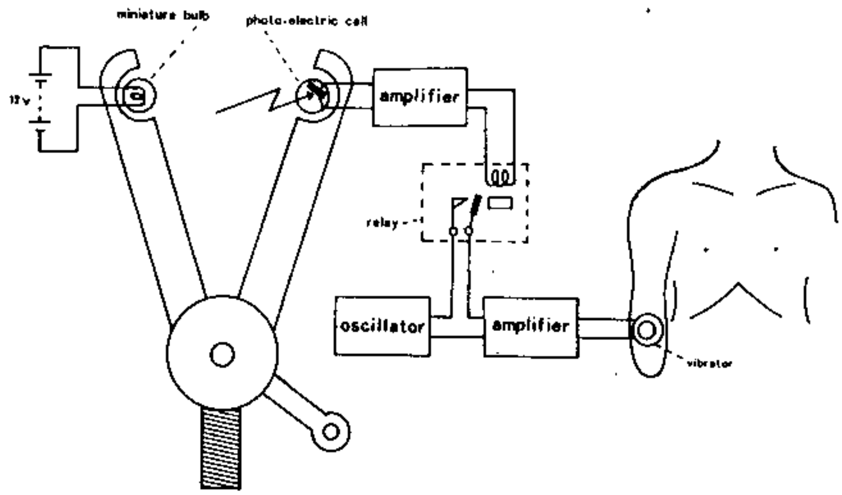

Figure 4. The feedback system utilizing photo-electric effect

4.Foot sole pressure feedback system for artificial leg

Four tape-type switches were installed on the sole of artificial foot and electrical signals were transmitted through surface stimulation to the amputee thigh (Figure 5). The accuracy of sensing tilted floor was improved (Figure 6)

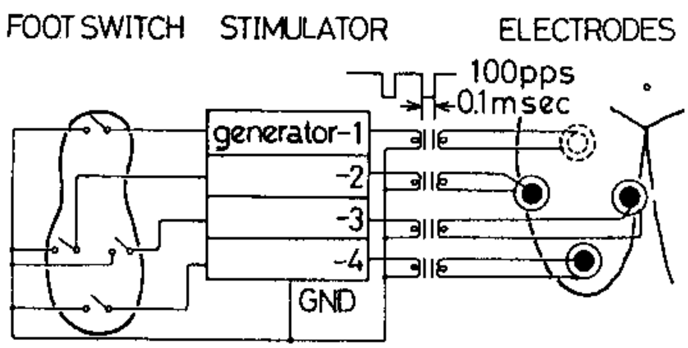

Figure 5. The foot-sole pressure feedback system (FPF)

We tested the FPF system in gait. There was no appreciable difference between temporal factors with and without feedback system. The tests were performed in 6 subjects "simulated prosthesis" (See Appendix) (Figure 7).

5.The knee-angle feedback system for above-knee prosthesis

A potentiometer was attached to the knee axis of above-knee prosthesis to detect knee angle. Four electrodes were positioned at the thigh of the amputee. The

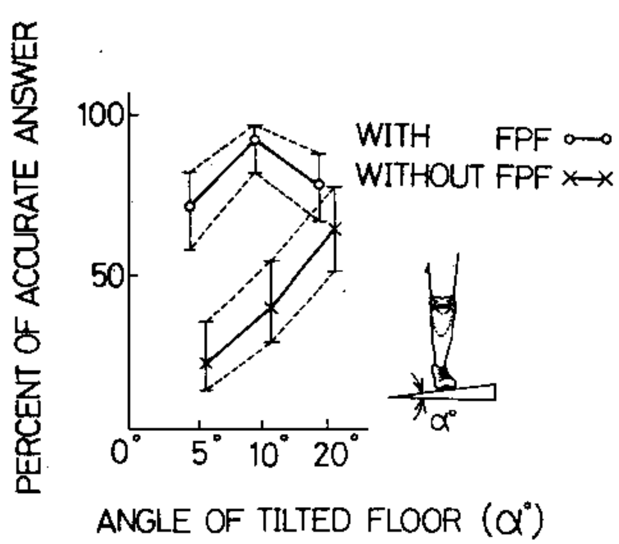

Figure 6. The efficacy of the FPF feedback system in artificial leg. The improvement of the accuracy is exposed very much for smaller angles, while the exteroception and proprioception of the stump provides almost equally good results for bigger tilt angles.

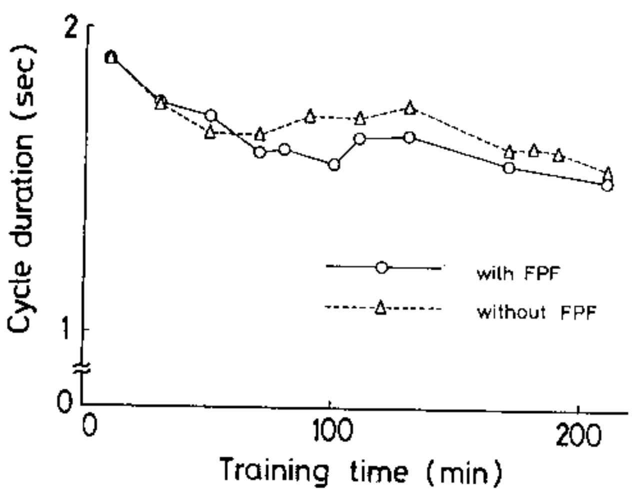

Figure 7. The change of the gait cycle duration during the gait training

knee angle was coded to start the stimulation through only one of the four electrodes. We tested the system in knee-disarticulation amputee. The subject could hardly notice which of the electrodes is active accurately. Therefore, the number of electrodes was reduced to three (Figure 8). Patient could recognize the knee angle when slow motion was performed. However, he could hardly sense the knee angler during the gait.

6.The simulated stimulation of knee-angler feedback system

The simulated stimulation using microcomputer on non-amputee subjects was carried out in our laboratory (Figure 9). Transverse arrangement of electrodes attached on lateral side of the thigh showed more accuracy in response compared to the oblique or longitudinal arrangements. However, shortening the stimulation period decreased the response accuracy in all arrangements (Figure 10). As the movement of stimulating electrodes became faster, area of stimulation sensation became closer and eventually fused. Furthermore, when the speed of movement is rapid, the sensation area became shorter as well (Figure 11).

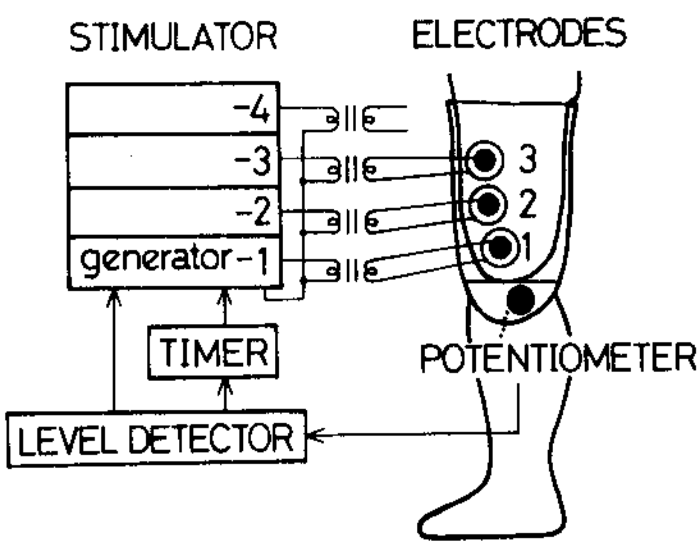

Figure 8. The knee-angle feedback system

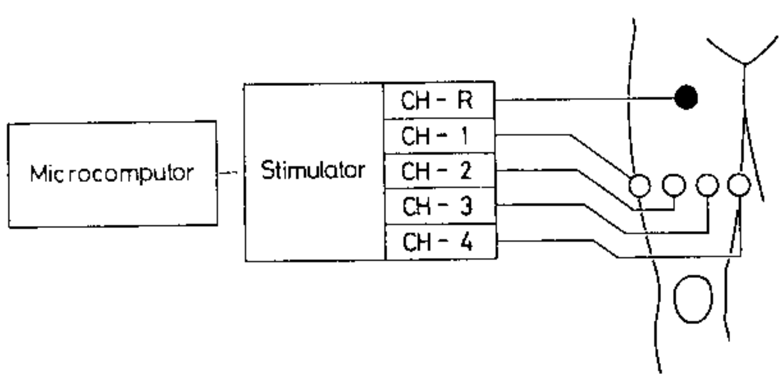

Figure 9. The stimulator of the knee-angle feedback system

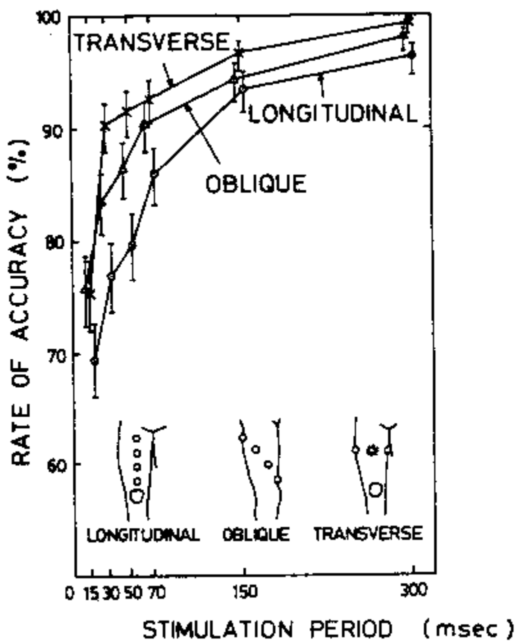

Figure 10. The effect of direction of electrode arrangement

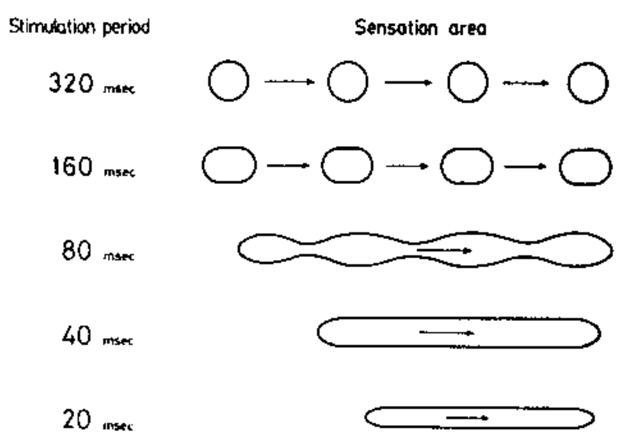

Figure 11. The effect of stimulation period vs. sensation area

The use of reference electrode did not improve the response accuracy in both cases, when reference and active electrode were stimulated simultaneously or alternately (Figure 12)

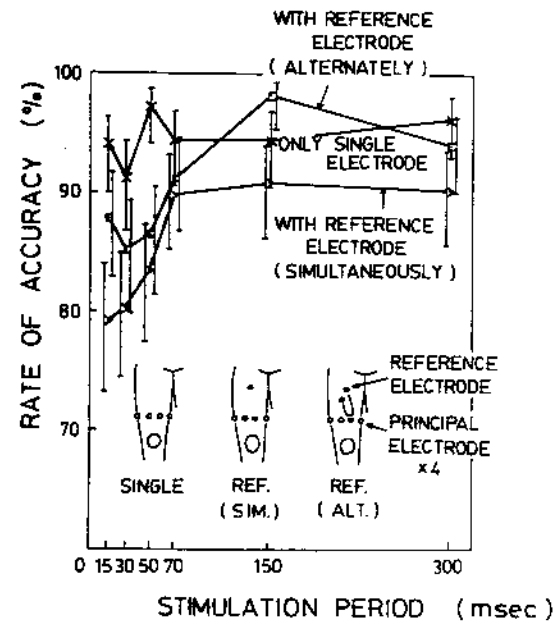

Figure 12. The effect of the reference electrode to the response accuracy

7.The knee angle and knee velocity feedback system using the sound

Frequency modulation was carried out based on knee angle and knee angular velocity using voltage to frequency converter. Amputee can sense the changes in the knee-angle and/or knee angular velocity by listening the sound coming through a small loudspeaker (Figure 13).

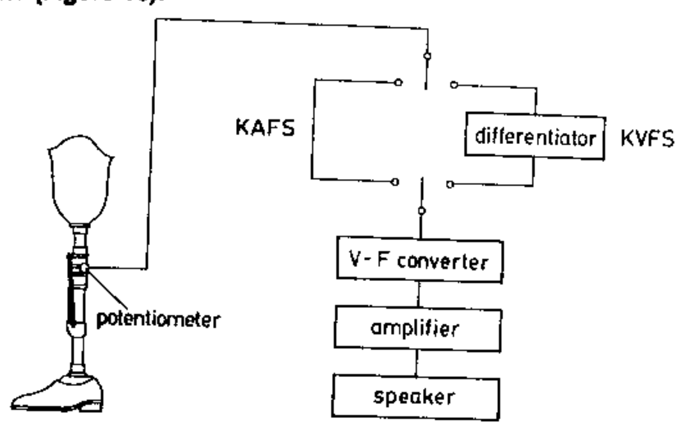

Figure 13. The knee-angle and knee velocity feedback system using the sound (KAFS & KVFS)

Our clinical tests with KAFS & KVFS were done in six "simulated prosthesis" subjects. Results with this feedback system showed the change in temporal distribution of the gait cycle (Table 1). KVFS may increase the gait velocity.

	Without FS	KAFS	KVFS
Walking speed (cm/sec)	96.4	99.7*	97.3
Cycle duration (sec)	1.36	1.30*	1.31*
Swing phase (sec)	0.61	0.59*	0.59*
Period from complete knee extension to heel contact (sec)	0.19	0.17*	0.17*

Table 1. Effects of the KAFS and KVFS. (* $p < 0.05$)

8."Advance signal to full knee-extension" system

This system is meant to provide the signal to the amputee before the full extension of the knee joint. The angle can be selected within broad limits: 10°, 30° and 50° (Figure 14).

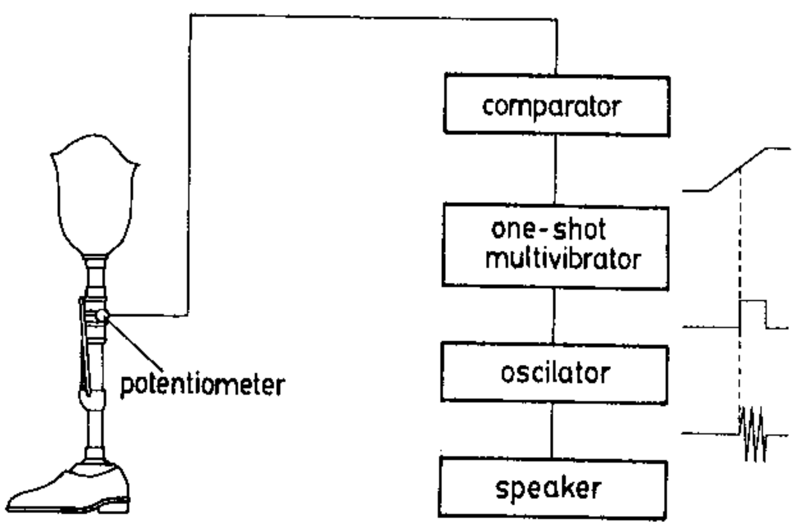

Figure 14. The scheme of "Advance signal to full knee extension" feedback system

Temporal factors were measured using "simulated prosthesis". All temporal factors were shortened for all values of angles, but there was no significant increase of the gait speed (Table 2).

	Without FS	10°	30°	50°
Walking speed(cm/sec)	130	133	127	129
Cycle duration (sec)	1.27	1.19*	1.21*	1.19*
Swing phase (sec)	0.59	0.55*	0.55*	0.54*
Period from complete knee extension to heel contact (sec)	0.19	0.17*	0.18	0.18

Table 2. Effects of the "Advance signal to full knee-extension" system (* $p< 0.05$)

DISCUSSION

The provision of useful sensory feedback signals to the amputee was considered somewhat as an exclusive goal [22]. Most research activities in artificial sensory feedback for prostheses concentrated to and prostheses up to now [1 - 5, 9 -11, 13, 15 - 23]. The feedback systems were developed only in few research centers [6 - 8, 14] besides the work of our group [12]. Experience in building of controllers and clinical trials imposed several questions:

1. What type of prosthesis needs sensory feedback system ?

It was thought generally that arm and hand prosthesis need more artificial sensory feedback than leg prosthesis. However, there are visual and incidental feedback, and artificial exteroceptor provided by the control cable on use of upper limb prosthesis. On the contrary, it is very difficult to control visually the leg, and there is no artificial exteroceptor in lower limbs prosthetics. Therefore, the real need for artificial feedback is associated with above-knee prosthesis (Figure 15).

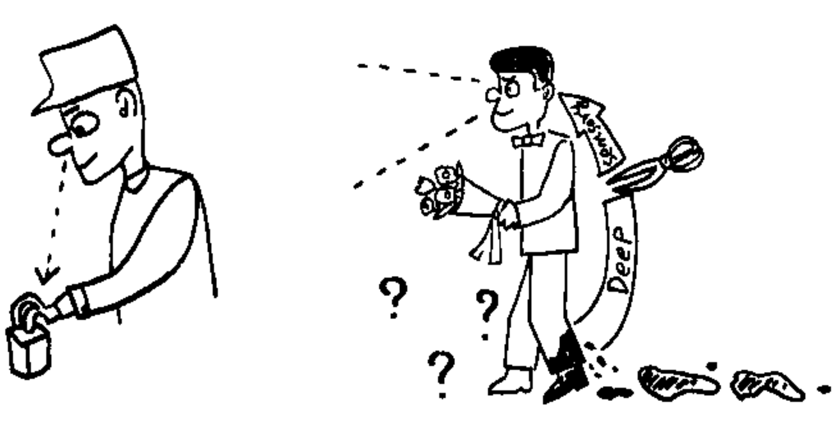

Figure 15. The needs for artificial feedback system is bigger in leg than in hand prosthesis

2.What modality of sensation is needed in artificial feedback systems ?

There are big differences in needs in upper and lower limb prosthetics. Although pinching or grasping force feedback is very important, the information on the ground force reaction and knee angle is essential for reliable function of the above-knee prosthesis. Our experience shows that the full extension information is significant fro the amputee. This information serves the amputee to place the foot down safely and confidently.

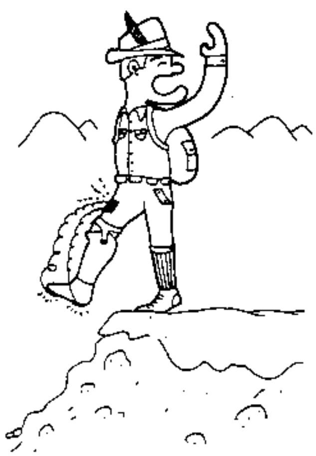

Figure 16. The balance between controllability and sensory feedback is important for the design of reliable and practical prosthetic device.

Modalities of sensation must match the prosthetic function. The controllability of the device should be able to use the sensory information, other wise the sensory system will serve only for provision of information on the failure of use (Figure 16). The powered elbow prosthesis is a good example where sensory feedback and controllability does not match, thus the device can't be used efficiently.

The system using photo-electric effect was very effective. We are considering some other possibilities to match natural type of sensory information. One of possible techniques will be ultrasound proximity sensors for the sole of artificial leg.

3.How to transmit the sensory signals to the amputee ?

Cutaneous stimulation, like mechanical vibration and surface electrical stimulation are not suitable fro the transmission of sensory signals. Reliable and rapid transmission of signals using cutaneous sensation is difficult because to the frequency limit (d Hz). This frequency limit is imposed of the noise and uncomfortable sensation of higher frequencies. Multichannel transmission of signals using multiple vibrators or electrodes is also difficult because multi channel cutaneous stimulation may produce one point sensation as a result of phantom sensation. Another disadvantage of cutaneous transmission is that this sensation is not natural. While we can agree with the opinion [1] that the best way of transmission is the afferent nerve stimulation with implanted electrodes Figure 17), we think that the sound is the most practical means at this stage.

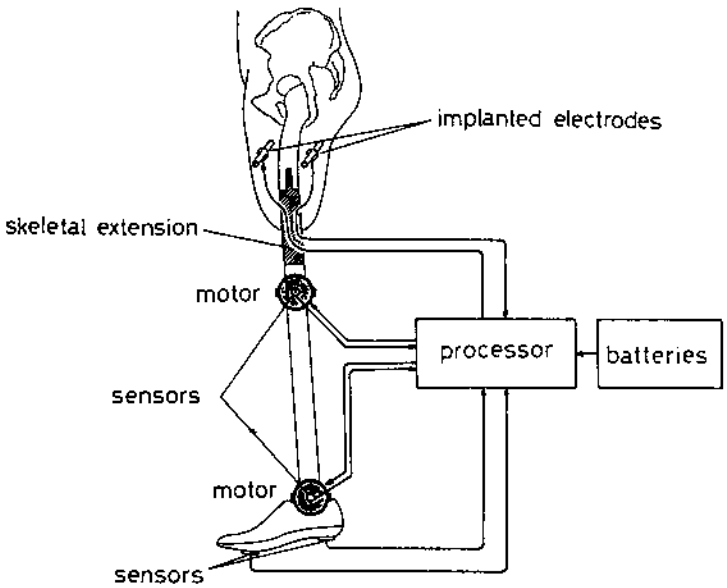

Figure 17. Neural feedback for the above-knee prothesis

4. How to evaluate the sensory system ?

The evaluation of the sensory system gives better results if combined with visual and incidental feedback. The use of "simulated prosthesis" is a very effective tool in development or reliable and practical feedback systems.

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APPENDIX - SIMULATED PROSTHESIS

We have developed the simulated prosthesis with which non-amputee subject can walk. Normal individuals can wear the prosthesis with his flexed knee. The body weight is supported at the anterior surface of the shank. The plastic socket is adjustable, therefore the same prosthesis fits many subjects. The knee alignment is adjustable. The prosthesis simulates the behaviour of the knee disarticulation and above knee prosthesis. The time needed to learn how to use the prosthesis is one hour, in average (Figure 18).

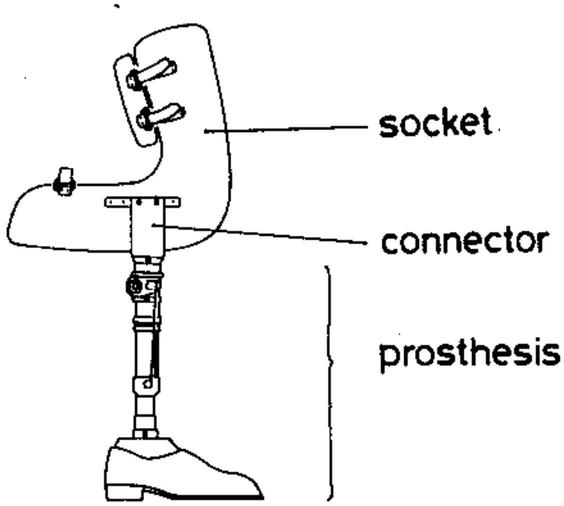

Figure 18. The sketch of the simulated prosthesis

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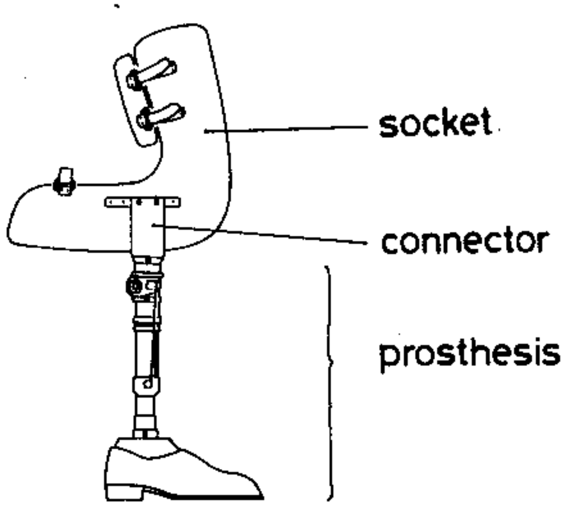

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