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Review Article

Tactile and Slip Sensation Acquisition in Prosthetic Hands and Proprioceptive Feedback of Perception for Arm Amputees

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Abstract

Prosthetic hands are expected by upper-limb amputees as useful tools to restore lost hand abilities. Possible real-time and intuitive perception of touching and slipping through prosthetic hands would help amputees a lot in daily activities. In this review paper, the results of several surveys on user demands were firstly summarized, indicating the importance of tactile and slip perception feedback for prosthesis users. A possible way to build artificial sensation in prosthetic hands is to develop one or more sensor systems that can detect sensation signals of, for example, touching and/or slipping. In the second part of this paper, different sensing techniques for tactile and slip signal acquisition, which were especially investigated for the application in prosthetic hands, were reviewed. To transfer the sensor-detected sensation signals into users' nerve systems is very critical to realize a proprioceptive feedback of perception for amputees. The final part of the paper introduced some possible perception feedback modalities. Stimulations on residual limb surface, such as vibration, temperature, and pressure, are low-cost and easy to realize, but usually considered as distracting and still unintuitive. A direct neural interface may provide intuitive and accurate perception feedback. Electrical stimulations of both somatosensory cortex and peripheral never are possible approaches to regenerate perception feedback for limb amputees. But more research work and clinical verification should be performed before an actual application.

Keywords: Prosthetic hand; Limb amputee; Sensation; Perception; Feedback

Introduction

Dexterous prosthetic arms would be always necessary and expected for upper-limb amputees to restore their lost arm/hand functions. In order to improve the control performance of multifunctional prostheses, several control methods have been proposed and realized by using different neural signals related to motor commands, such as surface electromyogram (sEMG) [1], brain-computer interface (BCI) [2], peripheral nerve interface (PNI) [3], targeted muscle reinnervation (TMR) [4], etc. In addition, some control strategies based on fusion of multisource information have also been suggested and investigated [5]. For upper-limb amputees, an intuitive and real-time perception of external environments through their prostheses would be very helpful to enhance the prosthesis operation safety and satisfaction [6]. Up to now, however, almost all the commercially available prosthetic hands do not have this kind of sensation function, and they usually are operated only with a visual feedback. Thus users have to pay considerable concentration on the actions of their prosthetic hands and estimate the operation condition by means of eye observation, which is much less natural and cumbersome [7]. Without a proper feedback of tactile and slip perception, an "over-grasp" may occur where an object in hand may be deformed or damaged, or an "under-grasp" may occur where the object may slip down from hand. A basic schematic diagram of possible closed-loop control with perception feedback for prostheses is presented in Figure 1.

Several surveys have been performed on different user groups about their prior demands for prosthesis functions [8]. Biddiss et al [9] showed that a perception feedback was recognized as the design priority for motorized prosthesis by amputees. A survey on myoelectric prosthesis users by Pylatiuk et al [10] reported that more than 95% of questioned male individuals wanted force feedbacks in their prosthetic hands. In another survey specified on the demands for sensation feedback in upper extremity prostheses by Lewis et al [11], 88% of questioned persons placed different degrees of importance on acquiring perception feedback from their prostheses, where grip force was most absolutely important for amputees' demands, followed by proprioceptive information of prosthesis movement and position; perception of first contact during object grasping and end of contact during object releasing, as well as touching without grip, were also considered as very important and useful sensation information of prosthetic hands. Almost all the reported surveys have revealed a strong requirement for touching and/or grasping sensation feedback by prosthetic hand users, indicating the fundamentality of force-related perceptions inhuman hands. The information of touching, slipping, stress, or even material hardness, smoothness, and texture, might be elicited from the force-related perceptions. Although a temperature perception in prosthetic hands should also be useful for amputees in doing daily activities, it may be relatively less concerned by most of prosthetic hand users.

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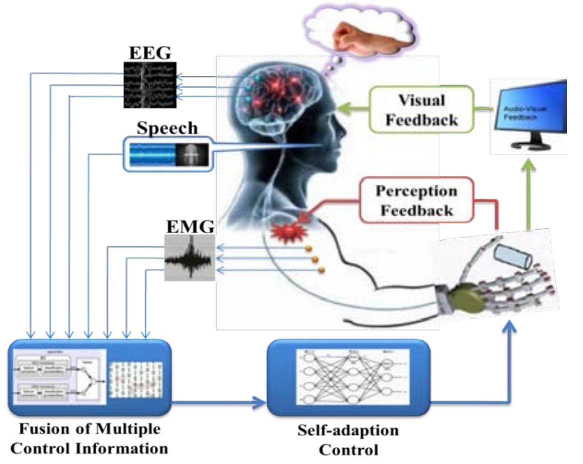

Figure 1: Closed-loop control with perception feedback for prostheses (EEG: Electroencephalography).

Tactile and Slip Sensation Acquisition in Prosthetic Hands

Generally, a tactile signal could be expressed as an acting force between a hand and an object, while a slip signal might be represented by the micro-vibrations that are generated due to the friction on contact surface. It is known that for an intact hand, the tactile and slip information is perceived with nervous system by detecting the sensation signals of force and vibration through glabrous skin receptors [12-13]. With an attempt to build artificial perceptions in prosthetic hands, some sensing techniques might be utilized to acquire the sensation signals.

Force-sensing resistors are a kind of widely used sensor with simple structure and interface, which show advantages of small thickness (usually less than 0.5 mm) and low cost. In the studies of Mingrino et al [14], Kyberd et al [15], and Tura et al [16], static sensors based on force-sensing resistors were designed and mounted in prosthetic hands to measure touching and/or grip strength signals. However, force-sensing resistors normally have relatively low measurement precision, which limits their further application in prosthetic hands where accurate signal detections are required. Strain gages are another type of commonly applied approach for force sensing. Wang et al [17] used a linkage to connect the thumb and finger of a prosthetic hand, in which the grasp force could be calculated by measuring the force acting upon the linkage with strain gauges. Maeno et al [18] developed a strain-distribution sensor for elastic fingers that was made of silicone rubber, where strain gages bonded on thin plates were arranged at uniform intervals inside the curved surface of fingers. Strain gages may achieve a good detection precision, but at the cost of relatively complicated structure design. In addition, both force-sensing resistors and strain gages may be suitable only for touching but not for slipping detection because of their working principles.

Some other force-sensing methods have also been investigated for applications in prosthetic hands. Hashimoto et al [19] proposed a tactile sensor for multi-fingered robot hands. The sensor had a silicone rubber cap with a cavity full of incompressible fluid, and the contract forces were transferred by the fluid to a semiconductor pressure gage. Shen et al [20] tested a fingertip tactile sensor based on the optical total reflection principle for applications on a five-fingered hand system. Curcie et al [21] reported the use of myo-pneumatic sensors for measuring three-dimensional mechanical dynamics in a biomimetic finger control. Schmidt et al [22] presented a dynamic tactile sensor that consisted of a capacitive-sensor array for dexterous grasping with applications in human-robot interaction and object exploration. All the above sensing approaches may realize an acquisition of high quality tactile signals, however, the complicated operation principle and elaborated sensing structure would result in a lower reliability and increase the fabrication cost.

Recently, several new sensing techniques have been developed and considered as appropriate candidates for sensation signal acquisition in prosthetic hands. Heo et al [23] described two kinds of force sensor arrays using fiber Bragg gratings for distributed normal force detecting, one of which was with good sensitivity and spatial resolution, similar to human finger skin. Noda et al [24] exhibited a tactile sensor with standing piezoresistive cantilever array that could detect the directions and magnitudes of shear stress applied on its surface. Wisitsoraat et al [25] showed a thin-film based piezoresistive MEMS tactile sensor with optimized sensitivity for displacement and force sensing. Wen et al [26] demonstrated a three axes polymer tactile sensor. The sensor consisted of polymer membrane and four sensing cantilevers with piezoresistors to measure in-plane and out-of-plane loads.

The measurement of slip signals is more complicated compared with that of tactile signals due to the difficulty in micro-vibration detection, and thus there are less research reports on this aspect. Miniature microphone was used by Kyberd et al [15] and optical sensor was applied by Tura et al [16] to acquire vibration signals in their prosthetic hands, respectively. Shang et al [27] developed a slip sensor based on photoelectric technology to detect micro-vibrations in prosthetic hands. Yamada et al [28] illustrated an artificial elastic finger skin that had ridges on surface to divide the stick/slip area, and slippage of the ridge could be detected. These slipping sensing approaches measure the micro-vibrations indirectly by means of voice, optical or some other signal types, which would increase the complexity of system and the difficulty in device design.

Piezoelectric materials can transfer mechanical signals directly into electric signals, which have a promising potential in sensation signal acquisition in prosthetic hands. Piezoelectric polyvinylidene fluoride film is a thin and soft polymer-based sensing material that can measure forces both in normal and tangential directions. In a prosthesis-applied sensor system suggested by Mingrino et al [14], slip signals could be successfully acquired by means of a piezoelectric polyvinylidene fluoride film. Although it is possible to collect both tactile and slip signals with a single piezoelectric polyvinylidene fluoride film, the low sensitivity and high cost prevent the further development of this material in signal acquisition for prosthetic hands. Polymer-based piezoelectrets are another type of novel piezoelectric material [29-30]. They are flexible and very thin, with a thickness of a few dozen micrometers, and show a strong piezoelectric response which is more than ten times larger than piezoelectric polyvinylidene fluoride. In addition, piezoelectrets are stretchable and low-cost. The polymer-based characteristics make them very suitable for embedding on artificial skins. Combined with their promising sensing and material properties, piezoelectrets have been experimented to acquire both tactile and slip signals in prosthetic hands [31], and more researches are in progress for possible actual applications.

Proprioceptive Feedback of Perception for Arm Amputees

It would be essential that a prosthetic hand could accurately detect possible tactile and/or slip information with some elaborate sensing techniques; more importantly, the arm amputees would be desired to proprioceptively perceive sensations from their prosthetic hands. It is a big challenge to transfer the sensor-detected sensation signals into users' nerve systems, and many efforts have been made in previous studies with an attempt to develop appropriate modalities for sensation message transmission.

For currently developed techniques, stimulations on residual limb surface, including vibration, temperature, pressure, or even more, are identified as the well-received feedback means based on amputees' personal acceptance and sensitivity of their residual limbs [11]. Among them, the vibration feedback is mostly of interest for applications [32], because it can easily be realized by mounting a low-cost consumer vibration motor on residual limbs. However, these feedback methods would be unintuitive and indirect because a vibration or temperature feedback is a different sensation from touching or slipping. Thus the amputees have to take a long-time training to be accustomed to these indirect feedbacks. In addition, they are often described as distracting due to the possible interference on regular body activities.

A direct neural interface may provide intuitive and accurate perception feedback instead of the stimulations on body surface such as mechanical vibration. It has been reported that electrical stimulation of somatosensory cortex [33-34] may elicit reproducible perceptions for amputees. By using microneurographic technique of intraneural microstimulation, Moore et al [35] studied the functional consequences of topographic reorganization within the human somatosensory cortex. A brain-machine-brain interface was set up by O'Doherty et al [36] for active tactile exploration, which allowed the signaling of artificial tactile feedback through intracortical microstimulation of primary somatosensory cortex. Their experiments on two monkeys suggested that the intracortical microstimulation feedback might generate somatic perceptions associated with mechanical, robotic or even virtual prostheses. Berg et al [37] implemented and tested a somatosensory prosthesis with sensorized finger on rhesus macaques. By means of intracortical microstimulation, perceptions were delivered to primary somatosensory cortex through chronically implanted multi-electrode arrays, and the perception feedback magnitude was graded according to the force applied on finger.

Electrical stimulation of peripheral never [38] is another possible approach to regenerate perception feedback for limb amputees. Dhillon et al [39] implanted longitudinal intrafascicular electrodes within individual fascicles of peripheral nerve stumps in amputees. Their work demonstrated that electrical stimulation through the electrodes could produce graded, discrete, and distally referred sensory feedback of touch or movement. In a recent work conducted by Raspopovic et al [40], transversal multichannel intrafascicular electrodes were utilized to stimulate median and ulnar nerve fascicles, according to the sensation message obtained by artificial sensors mounted on a prosthetic hand. It was shown that real-time and near-nature perceptions could be restored for an amputee during the prosthetic hand operation for various grasping tasks. In addition, the results demonstrated that the user could identify the stiffness and shape of objects by exploiting the different characteristics of restored sensations. Tan et al [41] also implanted peripheral nerve interfaces in two human subjects with upper-limb amputation. By electrical stimulation through non-penetrating peripheral nerve cuff electrodes, natural and repeatable touch perceptions of tapping, pressure, moving touch, and vibration were reproduced in the subjects and stable for more than one year. The correlation between perception types and stimulation patterns was investigated in the work, as well.

Compared with the indirect sensation feedback on residual limb surface by means of vibration or temperature, both electrical stimulation of somatosensory cortex and peripheral never could provide a proprioceptive sensation feedback for limb amputees. In addition, the feedback through stimulation of peripheral never might be more accurate than that through stimulation of somatosensory cortex, as demonstrated by the up-to-date researches reviewed above. On the other side, however, the electric stimulations of cortex and never require a second surgery, and thus the risk and cost should be taken into account. The bio-compatibility of stimulation electrodes might be another issue, which should be considered before the wide acceptance of these feedback techniques.

Summary

Natural perceptions of external environment are necessary for arm amputees to operate their prosthetic hands independently of visual and/or auditory feedback. Various developed artificial sensing techniques may be integrated in prosthetic hands to acquire sensation information of, for example, touching and slipping. Proprioceptive perception feedback for prosthesis users is very critical to achieve an intuitive control of prostheses. Feedback through the stimulation on residual limb surface such as vibration or temperature is easy to realize, but still unintuitive. Both electrical stimulation of somatosensory cortex and peripheral never may achieve a direct and intuitive perception feedback for arm amputees, as already proved by several pilot studies. But more research work and clinical verification should be performed before actual applications.

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