(2) Biological Information Interface Technology

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We are studying biological information interface technology with the aim of allowing people to interact with information in an expanded embodiment[*1] *of themselves.*
This article outlines the future possibilities of this interface technology, and introduces our research into the measurement, analysis and application of biological signals in nerves and muscles, which we are now starting to use as control signals for input operations.

1. Introduction

Advances in communication technology have made it possible to exchange a diverse range of different types of information. To communicate this information smoothly and efficiently, it is important to develop interface technology to allow different devices to be operated in different ways.

NTT DoCoMo is therefore building interface technologies based on the concept of using one's own body to exchange information in more natural ways. To do this we need to concentrate on what people say, see and feel and the movements they make, and to study how this sort of information can be reproduced for its intended recipient or within a communication system.

In this study, as the first step toward creating interfaces to biological processes of this sort, we have been focusing on the role played by nerves and muscles in human functioning and in the basic principles of movement, and we have been working on the implementation of "Biological Information Interface Technology" that uses the information thereby obtained.

In Chapter 2 of this article we describe the scope within which is envisaged with the use of biological information interface technology, and discuss the communication styles that can thereby be realized. In Chapter 3 we discuss the basic principles behind the action of nerves and muscles, and how their activity can be measured and analyzed. Finally, in Chapter 4 we introduce DoCoMo's research efforts.

2. Biological Information Interfaces and Their Future

2.1 Biological Information Interfaces

Biological information is information derived by measuring and analyzing the activity of living organisms with various types of measuring equipment. Technology to which biological information is applied is already being put into practical use in fields such as clinical medicine and psychological testing. For example, blood pressure measurements, brain wave readings, ElectroMyoGram (EMG) ,ElectroCardioGram (ECG), and ElectroEncephaloGram (EEG) are used to study the functioning of various organs and processes in the human body. Furthermore, the polygraph lie detector is able to record physiological changes associated with feelings such as anxiety and stress by monitoring characteristics such as eye movements and galvanic skin reflexes.

Thus, biological information has so far been used mainly for the purpose of checking the functioning and state of living organisms. On the other hand, at DoCoMo we aim to use biological information more actively by constructing user interfaces that operate in a more natural and stress-free way, even without the user's awareness. In this way, we aim to enhance the capabilities of users and augment their functioning and senses. For this purpose, we need to analyze, understand and control the activity of living organisms. Above all, we need to measure the information flowing into and out from the brain and its peripheral systems which form the core of these information processing functions, analyze it to understand the meaning of the information, predict the resulting activity by modeling these functions, and then find ways of controlling it. We studied biological information from the viewpoint of applying it to user interfaces of this sort.

2.2 Interfaces and Communications that Enchance Human Capabilities

The ultimate user interface technology that DoCoMo is aiming to develop as a biological information interface is technology that allows humans to input and output information according to their intentions and in a stress-free way. This means that the user's body information—e.g., the user's intentions and status—can be linked to environment information such as the contents and status of devices and sensors, and information on the environment side which is the external interface of the user.

That is, the user's embodiment is augmented so that all of the environment can be used as an extension of the user's own body.

As an example of a case where body information is transmitted to the environment side, it is possible to consider an intention input device that does not depend on operation devices or operation methods. With conventional input devices such as the keyboard and mouse, the intention that the user wants to input is expressed in the form of actions by converting it into operations specific to each input device. This can be an inconvenient process for the user, who has to select a suitable device according to the intention that he or she wants to input, and then has to operate this device by performing suitable actions. Another problem is that training is often necessary to operate input devices of this sort. With the biological information interface considered by DoCoMo, it should be possible for users to input their intentions without having to operate devices or learn operating methods. This can be achieved by tackling the problem from the viewpoint of biological information.

Conversely, as an example where environment information is transmitted towards the body, one might consider changing the condition of the body according to the status of the environment side. This could be achieved by transmitting various types of sensory information to the user from remote sensors. For example, a robot that is being operated in virtual reality by a user might provide the user with sensory feedback from its fingers when it picks up an object, or a personal navigation system could discourage the user from traveling in the direction of a congested area by detecting congestion information and making the user feel increasingly unwell and less able to continue the user to get closer to the congestion. Users could of course be urged to reconsider their actions in other ways, such as by displaying congestion information on a screen or giving audible warnings, but which approach is the more intuitive? In some cases users need to act based on carefully considered judgments. But in an advanced networked society, perhaps it will be worth studying systems that support this sort of intuitive status acquisition and judgment.

In the future, when information and devices exist ubiquitously, it will be very important to consider the issues of how information and devices should be operated, how they can be acquired by humans, and how they can be recognized. The biological information interface that DoCoMo is aiming for has the latent potential to solve these problems. We aim to create a new communication style involving interfaces that enchance human capabilities that can augment one's knowledge (including the five senses) or one's hands and feet in such a way that it becomes possible to operate on ubiquitous information or devices just as if they were one's own ideas, or parts of one's own body. This will lead to the realization of Human Centered Communication & Computing (HC^3) [1]. Biological information interfaces are thought to be important for achieving this goal.

2.3 The Use of Biological Information in Computer-Augmented Environments

To realize communication via a computer-augmented interface, it is necessary to use biological information. One of our aims is to detect the user's intentions and status from biological information, and to make use of it. Another aim is to use biological information to present information directly to the user in order to intuitivery present environment-side information to the user.

In the former aim, the reason why biological information is necessary is because the user's intentions are generated in the brain, where they are converted into movement commands for operating devices and are finally expressed as body movements. To communicate with an interfaces that enchance human capabilities, it is essential to detect the base information of the expressed action—i.e., the intention—rather than detecting the action that is expressed as a result.

Also, in the latter aim, the reason why biological information is necessary is because when transmitting information from the environment to the user, this information is converted into corresponding biological information which is directly presented to the user's body in such a way that the user can accept the information intuitively. In this way, environment-side information can be transmitted in the form of information that the user can relate to more directly. This is a very important aspect of communication with interfaces that enchance human capabilities.

3. The Measurement and Analysis of Biological Information

3.1 Types of Biological Information

Although there are many different types of biological information as mentioned in section 2.1, these can be broadly divided into two types. One is information derived from the detection of phenomena that occur as a result of information processing performed in the living body, and the other is information derived from the detection of the actual information that is processed and transmitted inside the body. Examples of the former include readings of blood pressure, ECG, and information observed by measuring devices such as Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI). With fMRI it is possible to measure the cerebral blood flow distribution which is associated with the brain activity. Since the former method involves measuring results associated with the body activity (e.g. blood flow), it is possible to observe the fact that a certain activity is occurring, but it is not possible to directly observe what sort of information processing is being performed.

On the other hand, examples of the latter include EMG signals, brain waves, magnetoencephalograms and nerve magnetic fields. Information is transmitted through the body by the electrical excitation of cells. To detect the actual information inside the living body, it is necessary to make direct measurements of the electrical excitations in the cells. Measurement methods that can be used for this purpose include detecting the electrical potentials caused by electrical excitations inside the cells, and detecting the magnetic fields produced by the currents resulting from this electrical stimulation. In order to realize a biological information interface it is necessary to directly detect the information processed and transmitted inside the living body, so we decided to use the latter method to detect the biological information.

Next, we investigated the different places where measurements can be made. The ideal way of ascertaining a user's intentions and emotions would be to measure the brain activity. However, the brain processes huge amounts of information, and even when information can be detected directly from the brain, it is difficult to understand its meaning straight away. On the other hand, the information processing performed in peripheral parts of the body such as muscles and nerves is much simpler than what is performed in the brain. Also, in the peripheral parts of the body it is easier to focus on a single measurement region because the sensory and motor functions become increasingly differentiated. Consequently, we decided to concentrate on the analysis of peripheral biological information, with a view to conducting further studies in the nervous system. If intentions and thoughts are expressed as actions and speech, then the activities of these peripheral nerves and muscles may also provide an effective means for discriminating between intentions and thoughts.

DoCoMo is planning to start by tackling the analysis of peripheral system activity. Then, based on our achievements, we will tackle the analysis of brain activity in order to develop user interfaces that based on neural transmission systems centered on the brain. The information transmitted between the brain and peripheral systems can be broadly divided into "downstream" information that is transmitted from the brain to the peripheral systems, and "upstream" information that is transmitted in the opposite direction. Downstream information is associated with the expression of actions—i.e., movement—and upstream information is associated with sensory perception. Regarded as a user interface system, the detection of movement corresponds to the input, and the presentation of feelings corresponds to the output. In this study we will deal with interface systems operating in both directions, but since we are focusing on the detection of intentions, we will concentrate on the study of downstream activity with the aim of developing an input interface. Accordingly, in this article we discuss the measurement of biological information in the downstream direction. Also, although this study is concerned with peripheral systems as a preliminary stage for the realization of user interface devices for neural transmission systems centered on the brain, it is thought that the research results into peripheral systems may themselves be useful either directly or indirectly for the development of practical applications. Direct applications include the recognition of actions. For example, our results may be applied to speech recognition by recognizing the action of the articulatory and vocal organs involved in the production of speech. It may also be possible to consider a virtual keyboard which recognizes the actions made when pressing keys with the fingers, or new coding techniques involving the transmission of muscular or neural information. Possible indirect applications include quantifying a user's feelings by quantitatively ascertaining the user's neural activity. In this way, it should become possible to objectively evaluate things that it has only been possible to evaluate subjectively hitherto, which would ease the use of user interfaces.

In the following, we discuss methods for measuring the basic principles and properties of neural activity which we are currently working on as well as ascertaining this activity in the form of electrical excitations in cells.

3.2 Muscle Activity and Measurement

(1) The Principles and Properties of Muscle Activity

Muscles generate forces according to commands from the brain which are transmitted via nerves. When a muscle generates a force, electrical stimuli are produced in its constituent muscle cells. These electrical stimuli can be detected as EMG, which shows the following characteristics:

① A change of electric potential of the order of μV to mV.
② Most frequency components are below 500 Hz,
③ As the generated force increases, the amplitude gets larger,
④ They are observed before the force is generated.

EMG is often used in medical tests. For example it is used to produce evoked electromyogram (evoked EMG). Evoked EMG can be used for purposes such as looking for abnormalities in the connections between nerves and muscles and for diagnosing injuries to the peripheral or sensory nerves by measuring the transmission speed or activity potential emitted from dominant muscles when peripheral nerves are electrically stimulated. They can also be used to measure the fatigue state of muscles based on the shift toward lower frequencies that is found to occur as muscles become tired. Furthermore, since EMG are correlated to the force generated by the muscle, they can be used to recognize actions. An example of where actions are recognized from EMG is a EMG prosthetic hand, which recognizes the movements of the fingers from EMG in the wrist.

(2) Measuring Myoelectric Signals (needle electrodes and planar electrodes)

EMG can be measured by inserting electrodes into muscles or by placing electrodes against the skin surface. A needle electrode is a type of electrode that can be inserted into muscles. This makes it possible to measure the EMG from a single target muscle, but the fact that needles have to be inserted into the body to achieve this is a definite drawback. On the other hand, taking measurements from the skin surface is a non-invasive*2 technique that simply involves attaching electrodes to the surface of the skin. However, it is much more susceptible to crosstalk whereby the EMG from other muscles in the vicinity of the measurement region are mixed in with the EMG from the target muscle. There are various types of electrodes that can be used to obtain measurements from the skin surface. The most common type is the plate electrode. Other types include disposable electrodes and active electrodes with built-in pre-amplifiers.

EMG can be measured with comparative ease compared with neural activity or brain activity. It therefore appears to be more practical for the implementation of user interfaces.

3.3 Neural Activity and Measurement

(1) The Principles and Properties of Neural Activity

The nervous systems of vertebrates can be divided into the peripheral nervous system (which includes the spinal cord) and the central nervous system (i.e., the brain). **Figure 1** shows the typical structure of a nerve cell. It consists of a cell body with a network of dendrites branching out from it, and usually a single axon, which is longer than the dendrites and branches out into multiple strands at its end. Nerve cells form a network by establishing connections between the ends of the axon of one cell and the dendrites of another cell—these connections are called synapses. Nerve cells receive information from other nerve cells via these synapses in the form of electrical signals. The cell assimilates this received information and enters an excited state due to this stimulus. This stimulus propagates along the axon as an electrical signal, and is transmitted to other nerve cells via the synapses. Synapses can be either excitatory or inhibitory, depending on whether they promote or inhibit the activity of the nerve cell. The electrical signal that propagates along an axon is called an action potential or nerve impulse and is caused by a flow of ions such as sodium and potassium ions that enter and exit the cell membrane. This generates a membrane potential that acts as a current source to produce waves of electrical current that travel at speeds of 100 m/s or more inside the cell. At the synapses, information is transmitted by converting the action potential from an electrical signal into a chemical signal mediated by neurotransmitters, which is then converted back into an electrical signal and propagated to other cells. The

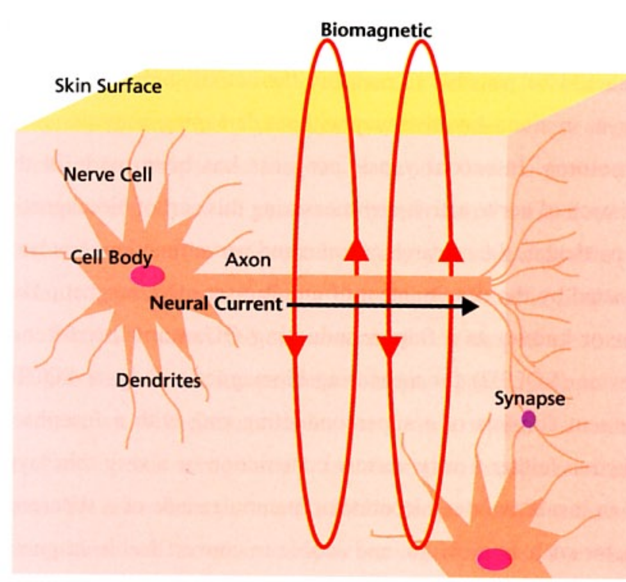

Figure 1 The Structure of Nerve Cells and the Generation of Biomagnetic

peripheral nervous system consists of large numbers of long nerve cell projections, and is broadly divided into sensory nerves which transmit sensory information from sensory organs (e.g., the eyes, ears and skin) to the central nervous system, and motor nerves which send motor information from the central nervous system to muscles and the like. The brain (central nervous system) is said to consist of a network of over 10,000,000,000 nerve cells which are interconnected by over 1,000 times as many connections as there are cells, resulting in advanced processing capabilities [2].

(2) Measuring Neural Information with Magnetic Fields

We have tried to make direct measurements of action potentials propagating through nerve cells with a view to construct new interface technologies as described above. For this purpose it is important to use a non-invasive technique to measure the action potential propagating through the nerves without damaging the living tissue in which the nerves originally exist or the network structure they constitute. Action potentials can be measured directly by implanting a minute electrode into the nerve cell. However, this destroys the tissue in the vicinity of the cell, making it impossible to understand the normal functioning of the cell. It also means that electrodes have to be inserted every time a measurement is made, resulting in damage to the specimen, which makes it difficult to be applied to user interfaces. On the other hand, according to the laws of electromagnetism, the flow of current inside a nerve cell induces a magnetic field in the outside world. If some way can be found of externally measuring the extremely feeble magnetic fields induced by the currents generated by action potentials in nerves and analyzing patterns such as the location and intensity of current flows, then it should be possible to measure the activity originating from nerves in a non-invasive way without damaging body tissues or structures. In recent years, progress has been made in the research of nerve activity by measuring this sort of biomagnetic. In particular, the research of brain and nerve functions has been assisted by the development of an ultra-sensitive magnetic flux sensor known as a Superconducting QUantum Interference Device (SQUID) for measuring biomagnetic [3,4]. A SQUID element consists of a superconducting ring with a Josephson junction (either a very narrow constriction or a very thin layer of an insulator or semiconductor material) made of a superconductor such as niobium, and is able to convert feeble magnetic field fluctuations into voltages with extremely high sensitivity. A SQUID magnetometer consists of a SQUID, a pick-up coil which senses the magnetic field to be measured, an input coil that guides the sensed magnetic field to the SQUID, and a feedback/modulation coil. The SQUID, pick-up coil and input coil are made superconductive by keeping them in a dewar, vacuum flask filled with liquid helium to keep them at cryogenic temperatures. A SQUID magnetometer is normally installed in a magnetically shielded room which shields out external magnetic fields to allow highly sensitive magnetic measurements to be made. Biomagnetic measurements made using SQUID magnetometer are characterized as follows:

① It is possible to measure the weak magnetic fields generated by nerve activity. It is over a billion times weaker than the earth's magnetic field.

② It is possible to make measurements with very high temporal resolution at sampling frequencies of the order of kilohertz.

③ By analyzing the magnetic data, it is possible to infer the position of electrical currents and analyze the action potential with millimeter order precision.

4. Research into Biological Information Interfaces

In this chapter we discuss the research we have so far conducted into biological information interfaces, and the issues for future study.

4.1 EMG Interfaces

In developing a user interface that uses EMG, the most important requirement is to be able to recognize the actions or movements that originate from the activation of different muscles. If the actions that are essential for communication can be recognized, then it will be possible to produce interfaces with high utility value. The research we are conducting at DoCoMo is based on the idea that body language, hand gestures and speech operation are particularly important in communication. Research into the recognition of body language and hand gestures is not only important for communication but also for the operation of robots. The research into body language and hand gestures is discussed in the chapter on "Avatar interface technology" [5]. In this article we will discuss the speech recognition.

By using EMG to recognize speech actions, it is possible to realize to recognize voiceless speech which is described below. However, the aim of this study is not just to create interfaces using EMG alone.

In the future, as research moves on to sensing information directly from the brain, it will become necessary to understand the meaning of the information thereby obtained. By observing speech operation—which are mainly an expression of intentions—from the viewpoint of muscles, it is possible to glimpse part of the information that is processed in the brain in the generation and expression of intentions, and it may even provide a foothold in efforts to sense information directly from the brain.

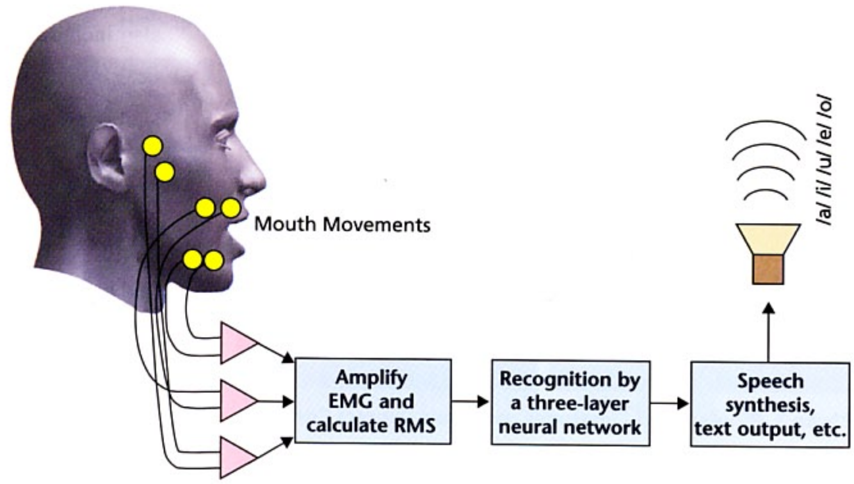

Figure 2 Voiceless Speech Recognition

(1) Voiceless Speech Recognition

By observing the activity of muscles when speaking, it is possible to perform speech recognition without using audio signals. Consequently, it is possible to recognize speech from oral articulations alone, and it is is not actually necessary to generate sounds. This form of speech recognition is called voiceless speech recognition. Since voiceless speech recognition is characterized in that a voice is not required, it is expected to be useful for applications such as speech recognition in places where speaking out loud is likely to annoy other people (e.g., on trains and in libraries) or where there is a lot of background noise, or as a speech support tool for people with impaired hearing or speech.

(2) Research Contents and Issues

Figure 2 shows an overview of the voiceless speech recognition process. EMG is measured from the muscles around the mouth which make a large contribution to speech. Speech patterns are then recognized from these signals, and the results are output in the form of text or synthesized speech. We are currently able to recognize the five vowels [6].

When this voiceless speech recognition technique is considered for use as a user interface, the method used for achieving contact with the electrodes is a very important issue. As mentioned above in section 3.2(2), EMG can be measured by inserting needle electrodes into the muscles or by attaching electrodes to the skin surface. If ease of use is taken into consideration, then the latter approach is more suitable. However, the attachment of electrodes to the skin surface also involves certain difficulties. For example, in the case of plate electrodes which have hitherto been the most popular choice, the electrodes are attached by coating them with conductive paste and fixing them to the measurement locations with adhesive tape or the like. This is not particularly user-friendly because the electrodes have to be coated with paste and taped into position before they can be used, and after they have been used there will be residues of paste left on the skin and tape left on the electrodes which has to be removed and discarded. Furthermore, when the electrodes are fixed with tape, sweating is promoted in the regions covered with tape, making the tape liable to peel away in regions around the mouth where there is a lot of movement, so it is difficult to use this method for prolonged periods. We therefore investigated electrodes that are easier to use. One possibility is to use a ring-shaped electrode. This involves Twisting an electrode around the user's finger, which is then pressed against the measurement position to measure the EMG. With this method it is possible to make measurements over prolonged periods even in positions where there is a lot of movement, and after the electrode has been used there is nothing to be thrown away. Furthermore, by using active electrodes where a pre-amplifier is incorporated into the electrode, there is no need to coat the electrodes with paste and the effects of noise from the surroundings can be reduced. By using this ring-shaped electrode, it is possible to realize a user interface that is simple to use. **Photo 1** shows the appearance of ring-shaped electrodes and how they are used to perform voiceless speech recognition.

Next we will discuss issues for further study. To realize voiceless speech recognition it is essential to recognize consonants. We have already started to tackle the problem of consonant recognition, and we plan to report on our work at a later date. Also, to study the links between neural activity and muscle activity, we are also making measurements with needle electrodes that

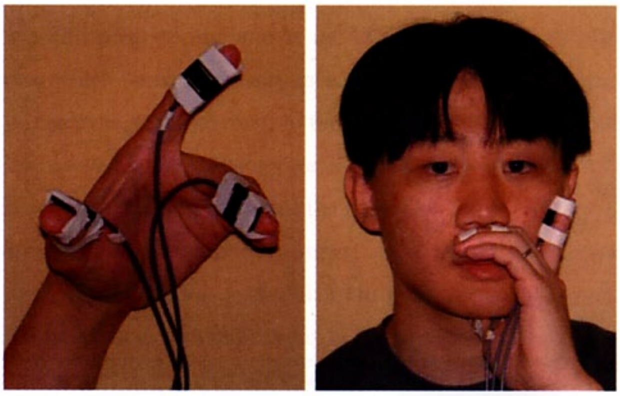

Photo 1 Ring-shaped Electrodes and Their Contact Positions

can isolate the EMG from individual muscles.

4.2 Biomagnetic Interfaces

As mentioned above, our aim is to make direct external measurements of information flowing through the biological information processing system that connects the peripheral nerves to the spinal cord and from there to the brain—i.e., the action potentials that constitute the biological signals flowing through these cells. Then, by analyzing patterns in these signals (e.g., their strength and timing, and the paths along which they propagate) we aim to determine the actions and feelings that are responsible for these signals with a view to develop user interfaces for communication involving interfaces that enchance human capabilities. For this purpose, the most effective measuring means currently available is a biomagnetism measurement system that uses SQUID magnetometer (in the following, this is referred to simply as a SQUID biomagnetic measuring system). As the first stage of research into interfaces that enchance human capabilities for communication, we need to clarify the information processing functions that re-performed in peripheral nerves, and the neural information that flows through them. For this purpose we designed, introduced and began operating the world's most advanced SQUID biomagnetic measuring system for peripheral nerves in 2002.

(1) The SQUID Biomagnetic Measuring System for Peripheral Nerves

An overview of this SQUID biomagnetic measuring system is shown in **Figure 3**, and the system appearance is shown in **Photo 2**. This system consists of the world's most advanced 71-channel planar SQUID magnetomater for taking measurements from peripheral nerves. It is installed in a high-performance large-scale magnetically shielded room approximately 22 m^2 in area (4.5 m wide × 4.8 m deep × 4.2 m high) with a magnetic shielding factor of over 90 dB (10 Hz). The system also includes a computer to control the system, a high-capacity file server for data storage, and a high-speed workstation for analyzing and visualizing the data. The control computer, file server and workstation are connected together by high-speed Ethernet links.

In this research, the important items as functions to be satisfied by the measurement system are thought to be the following:

① Spatial resolution,

② Temporal resolution,

③ Three-dimensional vector measurement of the magnetic field.

First we will discuss the spatial resolution. The excitatory response of a nerve can be regarded as a flow of sodium ions into the nerve cell. This influx of sodium ions causes the electric potential inside the cell to switch from its usual negative state to a positive potential (this is known as "depolarization"). Depolarization causes a sodium current to flow towards the interior of the cell membrane, thereby promoting further depolarization. The action potential propagates through the repeated feedback of this depolarization, thereby allowing neural information to propagate through the nerve cell as mentioned above. After a fixed amount of time has passed since the depolarization, potassium ions flow out from the nerve cell, and an outward potassium current flows. This is called "repolarization". The signal sources of the magnetic fields associated with the action potential can thus be regarded as consisting of two electric current dipoles with the depolarization and repolarization processes as current sources. In peripheral nerve magnetic field measurements, the distance between the measurement point and the signal source is usually about 15–40 mm, in which case the magnetic field attenuates in proportion to the cube of the distance, and the magnetic field behaves as if it is formed by a current quadrupole consisting of two current dipoles pointing in opposite directions. In biomagnetic measurements aimed at interface applications, it is necessary to analyze how the neural information propagates in detail. This requires sufficient spatial resolution to be able to see these complex changes in the magnetic field. One standard for obtaining this spatial resolution is the size of the spatial distribution region of the action potential (the source of the signal) with regard to the axon direction, which is thought to have a minimum value of about 20 mm. When the pick-up coil of a SQUID magnetic flux gage is larger than this, the spatial resolution is limited. At DoCoMo we have

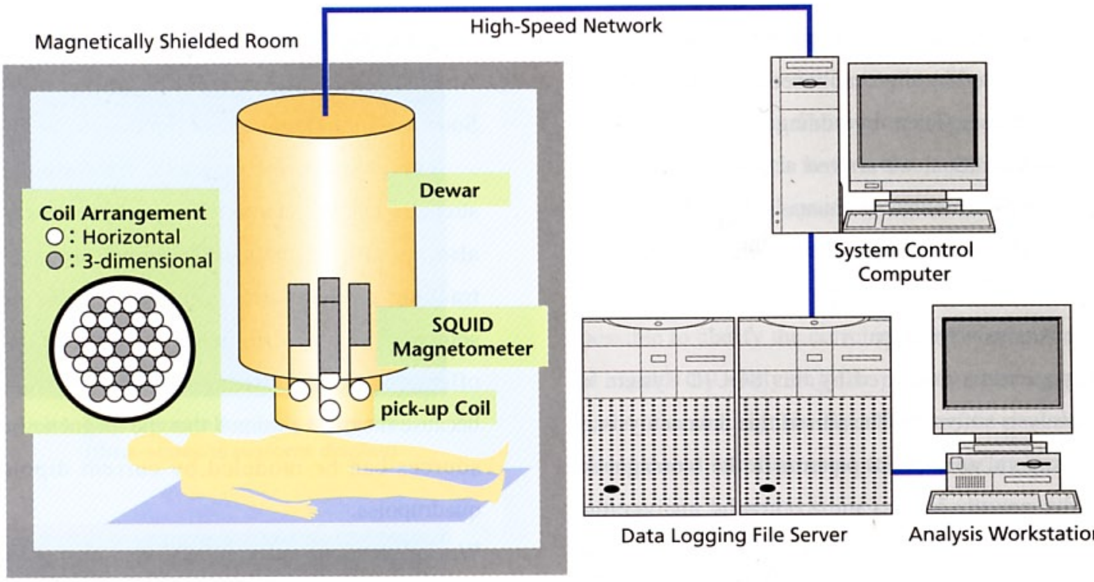

Figure 3 The SQUID Biomagnetic Measuring System for Peripheral Nerves

Photo 2 External Appearance of the SQUID Biomagnetic Measuring System (Seen from the entrance to the magnetically shielded room, the middle cylindrical object is the dewar)

therefore adopted a pick-up coil diameter of 20 mm to realize sufficient spatial resolution with respect to peripheral nerve magnetic field measurements. Also, since the magnetic field attenuates very rapidly in proportion to the cube of distance between the signal source and the measurement point as mentioned above, it is necessary to use highly sensitive low-noise magnetometer. For this system, we therefore employed dc-SQUID magnetometer in which the superconducting ring is excited at a relatively low frequency and the magnetic flux is extracted and amplified as a DC variation. The magnetometer we designed for this system has a dc-SQUID magnetometer with a three layer Nb/AlOx/Nb Josephson junction and a superconducting ring excitation frequency of 50 kHz. With this magnetometer, it is thought that it is possible to make measurements at distances of up to about 100 mm between the magnetic field measurement point and the signal source. Since most peripheral nerves are within 100 mm from the surface of the skin, this is a sufficient level of performance for peripheral nerve measurements.

Good temporal resolution is essential because the transmission of neural signals is one of the fastest biological processes, reaching transmission speeds of 100 m/s or more in humans. To adequately track the transmission of signals traveling at such high speeds, this SQUID biomagnetic measuring system for peripheral nerves supports high-speed sampling at 100 kHz, and is thus able to cope with all types of neural signals.

With regard to the three-dimensional vector measurement of the magnetic field, since this system is used for measurements of peripheral nerves, the pick-up coils of the SQUID magnetometer are arranged in a planar configuration. Considering the spatial distribution of action potentials and the size of the dewar suitable for measurements, we chose a hexagonal shape with sides of about 8 cm and a maximum diameter of 15 cm. Specifically, we configured a planar sensor with magnetic measurement directionality in the planar radial direction by arranging the pick-up coils with a coil diameter of 20 mm mentioned in (1) above in 37 channels in a hexagonal shape with a gap of 2 mm between coils. Also, at the positions of 13 distributed channels out of the 37 channels, two extra channels are allocated to SQUID magnetometer with pick-up coils oriented in two directions perpendicular to the planar sensor, making a total of three channels. In this way, we are able to make precise magnetic field measurements including the simultaneous measurement of three dimensional vectors. Then, by adding 8 reserve channels to this channel configuration, we arrived at a total of 71 channels, which is the highest number of channels that has ever been achieved in a SQUID magnetometer for peripheral nerve measurements.

(2) Biomagnetic Analysis Software

The biomagnetic data measured by this SQUID system is analyzed with analysis software. The aim of this data analysis is to analyze the temporal and spatial patterns in the biomagnetic fields induced by neural signals, and to thereby analyze the magnetic field generation sources (signal sources). The typical functions required of this biomagnetic analysis software are as follows:

① Improvement of Signal-to-Noise (S/N) Ratio by Processes such as Additive Averaging

Averaging proccess involves making repeated measurements in a single experiment and averaging the results together. This increases the S/N ratio by suppressing the noise generated by organisms or systems that contaminates the measurement data.

② Separation of Data by Signal Processing such as Filtering

Signal processing can be used to separate out useful signals by, for example, eliminating spurious trigger signals, correcting the baseline of waveforms and eliminating noise by applying various types of digital filter to data that has been cleaned up by Averaging proccess.

③ Visualization of the Analyzed Data by Methods such as Time-series Waveform Displays and Magnetic Field Contour Map

Visualization is a function that allows data to be displayed efficiently by combining the results of multiple measurements from different positions when an experiment is performed once, or by combining the data from multiple distributed channels obtained by the processes described above. Typical processes of this sort include displaying time-series waveforms of the data from a specific channel or from all channels, and producing magnetic field contour maps in which the positional data and magnetic field data of each channel is combined and displayed by searching for regions of equal magnetic field strength in the spatial distribution of the magnetic field. By forming time-series sequences of these magnetic field contour plots, it is possible to analyze the temporal variation of the magnetic field.

④ Analysis of Magnetic Field Generation Sources (Signal Sources) from Measurement Data

The positions of magnetic field sources and signal strengths can be determined by analyzing the field data. It is also possible to analyze the signal propagation paths by tracking the temporal variation of these magnetic field sources. The magnetic field contour plots described above offer one way of inferring the generation sources visually because it can be assumed that the magnetic field generation sources can be modeled by current dipoles or current quadrupoles.

We independently develop this biomagnetic analysis software to enable it to handle multi-channel data from the measuring system in individual and repeated measurements, to allow large amounts of data to be processed and analyzed (e.g., by high-speed data sampling), and to facilitate the feedback of results from biomagnetic measurement experiments and from research into analysis and evaluation techniques. **Figure 4** shows some of the waveforms recorded by this development system, and **Figure 5** shows a magnetic field contour map we produced.

In this software, the following issues need to be addressed in the future.

① Realization of high-precision signal analysis using data from multidirectional evoked magnetic measurements and functions for estimating the signal sources from magnetic measurement data and calculating induced magnetic fields from the estimated signal sources, thereby enhancing the analysis of this data.

② As research progresses in the future, we will aim to incorporate other advanced features such as images of the test subjects obtained by techniques such as fMRI and MEG.

③ We will continue in our efforts to achieve the real-time processing and analysis capabilities needed for the development of user interfaces.

(3) The Progress of Research

We are taking two approaches to the research into interfaces using biomagnetic from two directions. In the first approach, measurements are triggered when the test subject moves. The biomagnetic generated at this time is then measured and analyzed. By analyzing the transmission paths, timing and patterns of the neural signals emitted at the time of the movement and

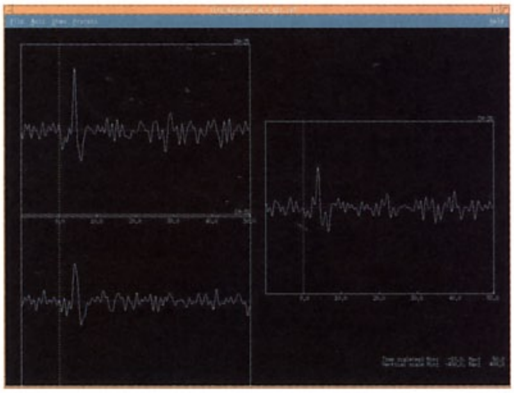

Figure 4 Biomagnetic Analysis Software (time-series waveform display)

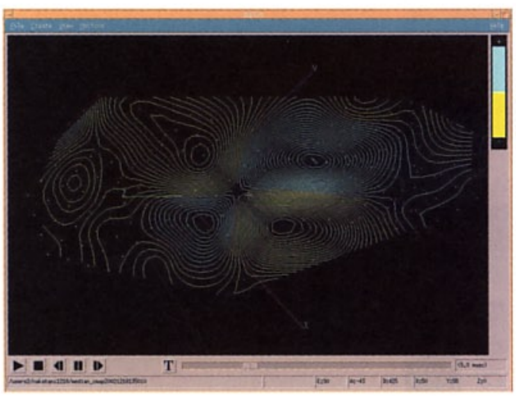

Figure 5 Biomagnetic Analysis Software (magnetic field contour plot)

during the preparation for the movement, we aim to clarify the correlation between movements and neural signals. In this way, it should be possible to analyze intentions about actions and the actions themselves based on the detected neural signals, and the results can be applied to the development of user interfaces. However, it may turn out to be impossible to achieve good results with this approach alone. This is because actions are generally caused by combination of large amounts of activity in the nervous system and muscles, and in voluntary movements or the movements of large parts of the body, the biological signals induced from these activities are intertwined in a very complex way. This makes it difficult to analyze the neural signals from measured biomagnetic data.

Our second approach involves inducing movement with neural stimulation as a trigger to clarify the correlation between movement and neural signals. As mentioned above, in the research into user interfaces mediated by movement it is essential to analyze the downward motor neural signals. However, with current technology it is very difficult to control movements produced by stimulating motor nerves in the downward direction, and with this method it is difficult to systematically analyze the relationship between neural signals and movement. Instead, movements can be induced by selectively stimulating nerves in the upward direction to generate upstream sensory nerve signals, which in turn result in the generation of downward motor nerve signals by reflex actions of these sensory nerve signals. By measuring and analyzing the magnetic fields induced by these downstream motor nerve signals, it should be possible to clarify the correlation between movement and neural signals by analyzing the patterns, timing and propagation paths of neural signals. By analyzing the neural signal propagation process in reflex response movements based on this sort of interaction between sensory and motor nerves, we aim to model the information processing performed by the nervous system with respect to simple motions, and to clarify the neural activity during simple motions such as the contraction of individual muscles. Then, by applying these two approaches in a complementary manner, we aim to clarify the neural signal model relating to the movement of larger body parts and more complex movements such as voluntary movements. In this way we hope to clarify the mapping between neural information and people's actions and feelings, which we will apply to user interface technology. In conjunction with this, we will also investigate procedures for obtaining objective results in situations where it has so far only been possible to obtain subjective evaluations (e.g., in evaluating how easy it is to operate electronic equipment).

With regard to the progress we have made in this research so far, we assembled, installed and aligned the measuring system, we prepared a test environment (including peripheral equipment), and we completed the first release of software production in the first half of 2002. Initial tests were started in the second half of 2002. One of these initial tests involved measuring the magnetic fields induced by the median nerve in the upper arm when stimulated by external electrical signals in order to obtain fundamental data for the second approach. In this test, a slight electrical stimulus was applied to the test subject's wrist, and then accurate measurements were made of the resulting upward signals propagating along the median nerve in the upper arm toward the shoulder. Figure 5 shows an example of a magnetic field contour map produced by analyzing the measured data. In the middle of this figure there are four large concentric circular patterns which correspond to a current quadrupole. Two of these (colored blue) represent magnetic field sources, and the other two (colored yellow) represent magnetic field sinks. In this figure, the wrist is off to the left side and the shoulder is off to the right side. By using our software to analyze the temporal variation of this magnetic contour map we were able to observe how the concentric patterns at the magnetic field sources and sinks travel from left to right, and we were thereby able to visualize the propagation of action potentials along the median nerve.

(4) Future Research Issues

This study crosses the boundaries between various fields such as engineering, anatomy, physiology and cognitive science. It is thus very important to actively partake in exchanges with researchers operating in areas different to DoCoMo, and we are continuously strengthening our efforts in this direction. Furthermore, with the aim of speeding up our research, we will study the introduction of fMRI in order to incorporate anatomical state information into the analysis of biological information, and the introduction of a MEG that will allow us to clarify the brain function in the central nervous system.

5. Conclusion

We have presented an outline of interface technologies that use biological information, and we have described our current research aimed at the realization of communication with interfaces that enchance human capabilities. In this study, we have shown that it is possible to use EMG for speech recognition. We have also introduced one of the world's most advanced SQUID biomagnetic measuring systems for measuring signals from peripheral nerves, and shown that it is able to measure signals from peripheral nerves. By continuing with this research, we eventually hope to develop new communication technologies with interfaces that enchance human capabilities.

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*1 **Embodiment**: The intelligence and functions incorporated into a body as seen from the outside, and the ability to interact with one's environment.

*2 **Non-invasive**: Causing no irreversible damage to the body's structures or functioning.