# Human Motor Control Mechanism

*Hiroaki Gomi*†

**Abstract**

This paper introduces a hierarchical structure of information processing for generating movements and an experimental test of a major hypothesis of the human movement production mechanism called 'equilibrium-point control' from the viewpoint of stiffness control. It also presents experimental observations of stiffness control of the human arm in interactions with the external world and of coordinative speech articulation. This research has future applications in the design of new types of man-machine interfaces for communication devices and of artificial brain processing mechanisms for humanoid robots.

## 1. Introduction

Humans are not consciously aware of the cognitive computation that is performed to produce motor commands for their physical movements, such as grasping objects like cups and doorknobs. When we learn new sports, we never imagine the processes occurring in our brain as our performance improves. Infants cannot smoothly reach out their hands to grasp an attractive toy placed in front of them. Older children, however, can easily extend their hands and take hold of any object without any practice; they can also speak fluently through the unconscious coordination of multiple speech organs, including the jaw, upper and lower lips, tongue, and vocal cords. These fine motor skills are honed through unconscious improvements in their information processing as they learn how to coordinate many muscles to generate smooth and complicated movements. Understanding these computational mechanisms for human movements will enable us to design new types of man-machine interface for communication devices and of artificial brain processing mechanisms for humanoid robots.

† NTT Communication Science Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: gomi@idea.brl.ntt.co.jp

## 2. Hierarchical motor control

It has been reported that the hand trajectory is almost straight for any directional arm reaching

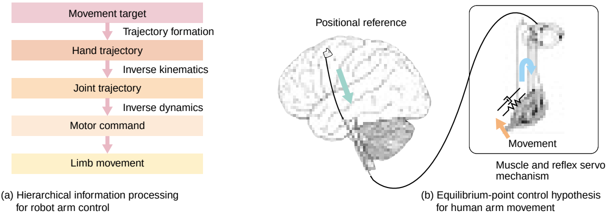


Fig. 1. Computational framework for arm control.

movements [1]. From the computational viewpoint, it is known that the trajectory planning and the nonlinear coordinate transformation from hand (or Cartesian) coordinates to muscle coordinates must be understood to generate such a straight trajectory.

Figure 1(a) shows an example of the computational processing for controlling a robot arm. When a movement target is represented in the hand coordinates, there are three computational problems to be solved to extend the hand to the object: (1) trajectory formation, (2) coordinate transformation from the hand to joint coordinates (*i.e.*, inverse kinematics), and (3) motor command generation to produce the joint trajectory (*i.e.*, inverse dynamics). In the robotics field, much research has been done to design efficient algorithms to solve these computational problems related to the smooth movement of robotic limbs [2].

## 3. Computational mechanism of arm movements

Because a robot's arm has a similar dynamical structure to the human arm, there could be similarities between the way humans process information that results in motor control and the steps necessary for smooth movement of robotic limbs. The hypothesis of movement control, called 'Equilibrium point control hypothesis' [3], however, explains that the human brain plans a simple pattern of arm movement and sends these commands via the nervous system to the musculoskeletal and reflex systems that control arm dynamics. This explanation means that hierarchical computation is not necessary for generating arm movement. According to this theory, as shown in Fig. 1(b), the brain sends a time series of equilibrium positions from start to target positions, then actual movement is generated by the spring property of muscles and reflexes. This mechanism corresponds to 'feedback control' in the engineering field. If a human uses this control mechanism, then accurate movement control can be attained without any complex computation for controlling arm dynamics. This hypothesis was supported by several computer simulations and has become a standard explanation of the functioning of the musculoskeletal control mechanism.

This hypothesis does, however, assume a high degree of arm stiffness during movement. Muscle activity increases during movements for generating joint torque, creating an increase in stiffness. Thus, because of this muscle characteristic, the equilibrium-point control hypothesis has been widely accepted by many researchers. If the arm stiffness is not large enough to reduce the error between the desired (*i.e.*, equilibrium) and actual trajectories, then a smooth straight trajectory will not be obtained because of nonlinear arm dynamics.

To test this hypothesis, we measured arm stiffness during multi-joint movement [4]. Small perturbations were applied by a manipulandum (Fig. 2(a)) at several times and directions during arm movement. Stiffness values of the elbow and the shoulder joints were estimated by computing the relationship between force and positional responses to these perturbations. Figure 2(b) shows stiffness ellipses measured at nine different times during the left-to-right movement of the arm. The diameter of the ellipse represents the magnitude of stiffness in each direction. The major axis of the ellipse represents the greatest stiffness at that hand position.

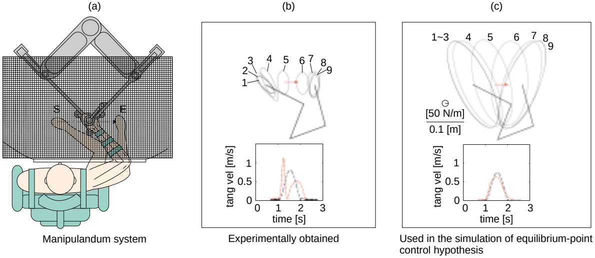


Fig. 2. Stiffness & velocity pattern of estimated equilibrium trajectory.

Comparing the measured stiffness with that used in the simulation of the equilibrium-point control hypothesis illustrated in Fig. 2(c), we found that the measured stiffness was much lower than the value predicted by the equilibrium-point control hypothesis. If this experimentally observed low stiffness is used to try to generate a smooth straight hand-trajectory, then according to the hypothesis, the equilibrium position should lead the actual position in the accelerating phase and then fall behind it in the decelerating phase.

The bottom panel of (b) shows the velocity profiles of equilibrium trajectory estimated from the measured stiffness and actual trajectory. The equilibrium-point velocity (red line), in particular, increased rapidly and peaked just after the initiation of the movement, whereas the velocity pattern predicted by the equilibrium point control hypothesis (red line in the bottom panel of (c)) has a single peak and is close to the actual velocity pattern (black dashed line). These results indicate that the equilibrium point control hypothesis is insufficient for describing the arm control mechanism that the human brain uses.

## 4. Interaction with the external world

Based on these kinds of experimental and theoretical studies, it is clear that the human brain controls and computes the internal dynamics of limbs in producing smooth and straight-reaching movements. Additionally, the computational model of the learning mechanism has been formalized [1] to explain performance improvement. Let us now further consider the practical situation of motor control in interactions with external objects. Many researchers are interested in improving the computational model by using an ‘internal model’ of the controlled objects for describing the dexterous manipulation of many kinds of objects and tools human limbs [5]. However, it may be difficult to explain the mechanism that controls human limbs during unstable movements such as drilling and screwing and during constrained movements such as door and window opening. Such movement tasks, as shown in Fig. 3(a), may require reflex reactions rather than planned movements.

To investigate such reaction control mechanisms, we measured human arm stiffness during a constrained movement. The movement chosen in this experiment was similar to the opening and closing of a window (Fig. 3(b)). The manipulandum system shown in Fig. 2(a) was used to impose this constraint and the perturbations for measuring stiffness on the arm. Figure 3(c) compares stiffness ellipses during a free movement (black) and a constrained movement (pink). The stiffness during constrained movement decreased in the constrained direction compared with the stiffness during free movement. Stiffness decrease in the constrained direction is advantageous in responding to external forces caused by constraints such as the window rail or the shutter hinges. These experimental results indicate that arm stiffness is actively controlled according to external dynamics. In other words, the brain regulates motor commands not only by using the internal model of limb dynamics but also by taking into account the body’s interaction with external forces.

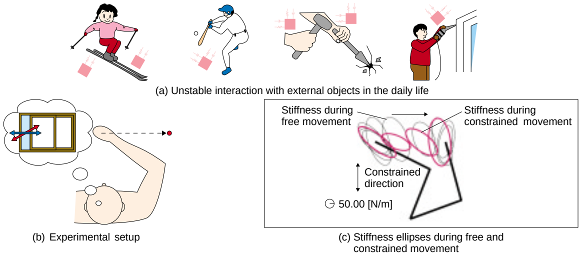


Fig. 3. Stiffness change during constrained movement.

## 5. Articulatory coordination embedded in muscle dynamics

Stiffness characteristics play an important role in speech articulation control as well as in arm control. In articulatory movements, we produce various kinds of sounds by coordinating several organs such as the tongue, upper and lower lips, jaw, vocal cords, and lungs. In assuring smooth coordination, not only feedforward motor commands from the brain to each organ, but also dynamical interaction among organs, and maintenance and modification of coordination by sensory and auditory feedback may be used at each different stage of control.

To investigate the mechanism for coordinating the human jaw and lips during utterances, we developed the jaw perturbation system shown in Fig. 4(a) [6]. Because the jaw closes in order to configure labial constriction or closure for labial consonant production such as "fu" (phonetic symbol: /Φ/), "pa," "ba," and "ma," jaw perturbation could disturb this phoneme production. However, when we supplied jaw perturbations at several different times during the utterance "kono/aΦaΦa/mitai," the /Φ/ sound was not impaired. Figure 4(b) shows temporal variations of the upper lip, labial distance, and jaw positions during utterances with two different perturbations. Even when the jaw was pulled down at /Φ/ production (green lines in the bottom graph), the labial distance (middle graph) was not altered by the compensatory downward movement of the upper lip (top graph). On the other hand, when the perturbation was supplied during the /a/ production (red line), the labial distance increased because the downward movement of the upper lip was not enough to maintain that distance. This difference indicates a functional change of the upper lip compensatory movement. It was previously considered that this kind of compensatory movement was caused by a regulation of motor commands initiated by sensory feedback. However, we found that the downward shift of the upper lip preceded the increase in the muscle activity of the upper lip associated with the perturbation. This suggests that compensatory movement of the upper lip was not induced by the sensory feedback.

To clarify the mechanism of this compensatory

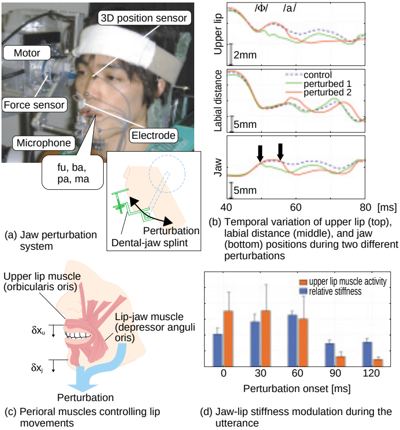


Fig. 4. Jaw-lip coordination for labial consonant production.

articulation, we quantified the stiffness of the linkage between the upper lip and the jaw. The measured stiffness of the muscle lips during the utterance (blue bars in Fig. 4(d)) increased at the /Φ/ production and then decreased during /a/ production. Additionally, this stiffness variation nicely correlates with the muscle activity of the upper lip (orange bars in Fig. 4(d)). This result suggests that the compensatory movement for maintaining the labial constriction is achieved by stiffness regulated by muscle activation according to the speech tasks. A major advantage of mechanical linkage (namely stiffness) is a fast reaction time, which is crucial for real-time control, whereas the latencies of neural transmission and mechanochemical dynamics cannot be avoided in the responses as caused by sensory feedback.

For speech motor control, several kinds of mechanisms such as muscle dynamics and sensory and auditory feedback may be combined hierarchically. By organizing multi-level regulation mechanisms according to speech tasks, we can build a computational model of speech motor control, which will contribute to the design of new voice communication interfaces.

## 6. Conclusion

This paper introduced basic studies of human information processing for generating movements. Although we tend to think that 'perception' occurs though 'sensation', actually 'production' as well as 'sensation' is important for configuring perception. Continued exploration of the interaction between these information-processing mechanisms will lead to various new techniques for advancing telecommunications.

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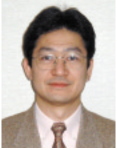


**Hiroaki Gomi**

Senior Research Scientist with NTT Communication Science Laboratories.

He is an Adjunctive Professor of the University of Tokyo Institute of Technology and is working on a CREST project of the Japan Science Technology Corporation. He received B.E., M.E., and Ph.D. degrees in mechanical engineering from Waseda University in 1986, 1988, and 1994, respectively. He was involved in biological motor control research at ATR Laboratories in Kyoto from 1989 to 1994, where he developed computational models of human motor control, novel robot learning mechanisms (demonstration learning), and a manipulandum system for investigating human arm movement. His current research interests include human arm/speech motor control and motor-learning mechanisms. He is a member of the Society for Neuroscience, Society of Neural Control of Movement, Society of Instrument and Control Engineers, Institute of Electronics, and Information and Communication Engineers.