Multimodal Sensor Controlled Three Degree of Freedom Transradial Prosthesis

Kengo Ohnishi
Division of Electronics and Mechanical Engineering
Tokyo Denki University
Hatoyama, Hiki, Saitama, Japan
ohnishi@mail.dendai.ac.jp

Isamu Kajitani
RT-Synthesis Research Goup, Int. Syst. Research Inst.
National Inst. of Adv Industrial Science & Technology
Tsukuba, Ibaraki, Japan
isamu.kajitani@aist.go.jp

Toshiyuki Morio, Tomoo Takagi
Dept. Mechanical and Information Systems Engineering
Okayama Prefectural University
Souja, Okayama, Japan

Abstract—**This paper describes the basic concept of our multimodal sensor control system for 3-Degree-of-Freedom transradial prosthesis. The target of developing the controller is to reduce the mental effort of planning operating multiple joints in the conventional multifunctional myoelectric controller and reduce the compensating motion of conventional myoelectric prosthesis. An accelerometer is installed in the socket and the angles of the gravitational force are computed to drive the pronation/spination joint and the palmar flexion/dorsifelxion joint of the prosthesis. A threshold On/Off control using the posture information is implemented with the triggering of a co-contraction EMG signal. Through experiment with able-body subjects, we confirmed that this controller has a potential of reducing compensating shoulder movements for pick-raise-place tasks, when compared to the task conducted with conventional locked-wrist prostheses. Yet modification is required for stability.**

Keywords—Upper Limb Prosthesis, Multimodal Sensor Control, Myoelectric Sensor, Acceleration Sensor

I. INTRODUCTION

Myoelectric control is one of the clinically practical interfaces for transradial amputees to operate powered upper limb prostheses. However, the practical composition of transradial prosthesis does not include an externally powered wrist and the operational freedom is limited to opening-and-closing of the DC-motor driven hand unit. Therefore, multifunctional and multiple degree-of-freedom (DOF) upper limb prosthesis has been a demand from the upper limb amputees. From the engineering approach, number of research projects [1-5] has been conducted to propose new mechanical structure. Though the researches on multiple DOF hand and arms made clear that the main reason of this arrangement is due to the difficulty of retaining multiple DOF appropriate independent myoelectric signal sources within the socket to control multiple joints. The complex constraints that limit the selection of signal source are related to the properties of socket structure, surface myoelectric sensor, controller, and therapeutic training program. To overcome the challenge of improving the controllability of multijoint and multifunctional upper limb prosthesis, groundbreaking researches, such as Implantable Myoelectric Sensors[6], neural electrodes for biofeedbacks, and neural surgical methods such as Targeted Muscle Reinnervation[7] are currently in progress. Furthermore, approaches of implementing signal processing and filtering technologies combined with soft-computing technologies[8] and LSI design[9] for feature extraction and multifunction control are also reported to overcome the bottleneck of limited signal channels. Though, these innovative approaches promise high potential for improving the prosthesis's function in the near future, revolutionary technologies commonly lack consideration on irregular deficit, especially in durability, stability and implementation, and also the cost of implementing the technology. Another limitation of the proposed soft-computing technologies with short numbered signal source is that limited simultaneous control of the joints. These problems tend to draw back the technology to be fully reliable in daily use.

For this reason, we considered an approach of benefiting the superiority of myoelectric signal and supplementing the shortage. We target to develop a technology which enhances the operability with minimum addition to the existing myoelectric control method. Myoelectric signal has superiority in representing motor command signal, but on the other hand, have a major problem of lacking sensory feedback and rely significantly on vision. As a solution, research attempting to feedback the motion or tactile information to substituting sense are reported [10,11]. The biofeedback methods are effective, however, if not being natural sense, the method cannot overcome the drawback of extra process of decoding the signal which is a mental load to the prosthesis user.

Furthermore, this research focused on the prosthesis user's point of view of considering upper limb prosthesis as an effective but a practically wearable tool. To meet this goal, the design target was concentrated to enhance the hand-elbow coordination of repeated joint motion in table-top task, e.g. dinning. In addition the system was designed so that all components of the control system to be embedded in to the prosthesis and the software are executable on a controller with general purpose microprocessor .

II. Technical Challenge in Developing Myoelectric-control Transradial Prosthesis

One of the commonly used control algorithm of a marketed myoelectric control prosthetic hand is a two-site two-function ON/OFF Control, known as Digital Twin or Myoswitch method [12]. The problem for transradial amputees on using transradial prosthesis is the lack of joint movement of palmar flexion and dorsiflexion. The lack of wrist joint requires compensation by the shoulder and trunk posture when orientating the fingertip for prehension. The unnatural posture are energy consuming and unfavorable for aesthetic reason especially in formal cases. Furthermore, it requires additional training to perform tasks with quality and/or tools to reduce the amputees operational burden. Therefore, in this research, we target to apply myoelectric control of a 3-DOF transradial prosthesis while reducing the compensative movement and refraining additional operational burden of the fingertip orientation control. Adding joint mechanism causes additional weight and complexity for system integration. One of the major conflicts in assembling a myoelectric prosthesis is to balance the ability of self-suspension and the arrangement of the multiple surface-mounted myoelectric sensors within the socket structure. We, thereby, propose an approach of not adding myoelectric sensor, but to apply acceleration sensor to compute the forearm orientation angles as additional signal source to seek multi-DOF control of the prosthesis.

To apply acceleration sensor signal to control the joint, the concept was set as to create a digital version of a Bowden control cable system in body powered prosthesis[13]. The activation of prosthetic wrist joint movement is linked to the residual elbow joint movement. The significant advantages of control-cable based interface system are not only the straightforward and easy motor command signal, but the sensory feedback of the residual limb condition that enables intuitive estimation of the artificial joint to adjust precise control of the device motion. Our interest was to understand the effect of combining a very simple acceleration sensor-based interface with the current state of the art of myoelectric upper limb prosthetic control for transradial prosthesis.

This paper discusses on the first prototype of our multimodal sensor control method for transradial prosthesis. Our multimodal sensor controller and software are developed on an embeddable microcomputer system and tested as a quasi-prosthetic device, which are assembled to be donned by non-amputated subjects. The research platform system and sensor control, experimental setup, and the first pilot test results are described in the following chapters.

III. Research and Development Platform and Multimodal Sensor Control

The quasi-prosthetic device assembled for non-amputated subjects is shown in Figure 1. The device consists of prosthetic hand unit, controller unit, myoelectric sensor, acceleration sensor, and a thermoplastic socket. DC stabilized power supply and personal computer is connected to the device to power it and to monitor the sensor outputs. Figure 2 shows the hand unit: AIST prosthetic hand. The hand was developed as a R&D platform for multifunctional prosthetic control research projects at National Institute of Advanced Industrial Science and Technology. The hand unit has 3 DOF: hand open/close, wrist palmar /dorsi-flexion, and forearm pronation/supination. The controller consists of a 16-bit single chip microcomputer (Renesas Electronics, H8/3067), peripheral circuits and interface connector sockets for 2 RS-232C serial communications, 3 relays, 4 A-D inputs, 3 PWM outputs. The controller is designed to write and verify control algorithms on desktop environment and not for installing within the socket, so the controller was placed in a belly bag for the experiments and wired to the power supply. As for the 4 ports of the A-D inputs, 2 myoelectric Sensor's (ottobock, 13E125=50) signal lines and the X- and Y- axes of the 3-D acceleration sensor (Kionix, KXM52) are attached to the ports. The myoelectric sensor has a built in signal processing circuit of band-pass filter, notch filter, full-wave rectifier, and smoothing, therefore no additional processing of the myoelectric sensor signals are applied after the A-D conversion. For the acceleration sensor, capacitors were arranged in the circuit to set the upper limit of the frequency band of the on-board filter to 10Hz.

Two-site two-function on/off control is applied for the

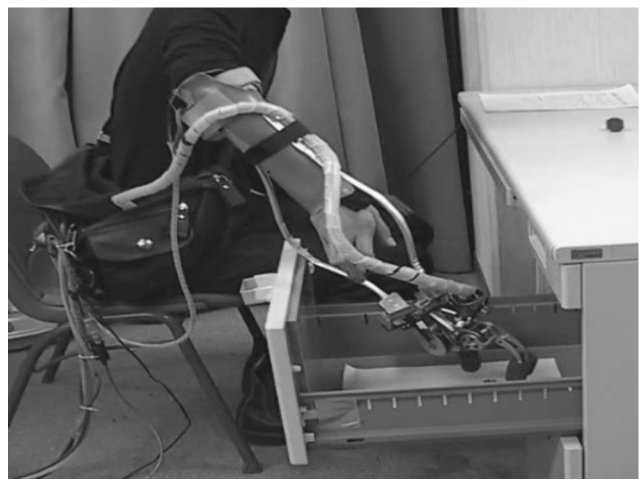

Fig. 1. Experimental condition of 3-DOF Transradial Prosthesis

Fig. 2. AIST 3-DOF prosthetic hand, controller, and myoelectric sensors

myoelectric signal based motion decision algorithm for the hand open/close. This algorithm compares the myoelectric sensor signals' amplitudes to the threshold values. When it detects the first crossing of the rising signal, it locks out the motion detection of other signal until the selected signal descends and crosses the threshold. A constant speed motor driving signal is generated while the first detected signal amplitude exceeds the threshold.

Figure 3 is the diagram describing the acceleration sensor mounted on the forearm socket surface and the setting of the axes and orientation angles of the upper limb. The coordinate system origin is offset distal to the elbow joint while the x-axis is arranged to direct from medial to lateral side, the y-axis from the elbow to the wrist, and the z-axis from posterior to anterior, respectively. The orientation angles α and β are computed from (1), where g_x and g_y are the x and y axis sensor output, G is the preliminarily confirmed sensor output for gravitational acceleration for 1G.

$$\alpha = \cos^{-1}(g_x/G)$$
$$\beta = \cos^{-1}(g_y/G\sin\alpha) \tag{1}$$

The orientation angles α and β are ratio scale of the forearm socket posture, however when following a protocol for initialization, the sensor outputs can be converted to interval scales which are equivalent to the forearm abduction and forearm flexion inclination angles. The forearm abduction angle is assumed to be equivalent to shoulder abduction. And forearm flexion inclination angle is a composition of shoulder and elbow flexion. As described in (1), the computation requires running inverse trigonometric function, and furthermore, a chance of zero-divide for angle. However, floating-point arithmetic is not efficient for general-purpose processors in real-time control. We therefore implemented a precomputed equally spaced data table and a linear interpolation algorithm to suppress the processing delay. In our pilot study we tested the performance of the acceleration sensor and the angle estimation algorithm under static combined angle conditions. See Figure 4. The result indicates that the errors are under 10 degrees and durable for computing α and β while the sensor is tilted less than 75 degrees from the horizontal plane.

IV. Control of a Externally Powered Prosthesis with Myoelectric and Upper Limb Posture

The time-series data of upper limb posture of the intact arm motion in table top tasks were measured and studied to consider and to extract featuring pattern of coordinating forearm posture state and wrist joint motion. The trail data were then used to select a suitable control algorithm. The goal of this process was to develop a control interface which are 1) naturally performable with minimum error to perform the targeted tasks, 2) effective for reducing the compensation motion, and 3) simple and easy to code and to adopt for usage and to be repeatable. The selected targeted task was to move the arm donning the prosthesis to A) start at a hanging position, B) reach and pick up a target object from the table, C) carry the object to the mouth and back to the table, and D) finally, release the object and reposition to the initial arm posture. This task motion protocol was selected since it is one of the motions

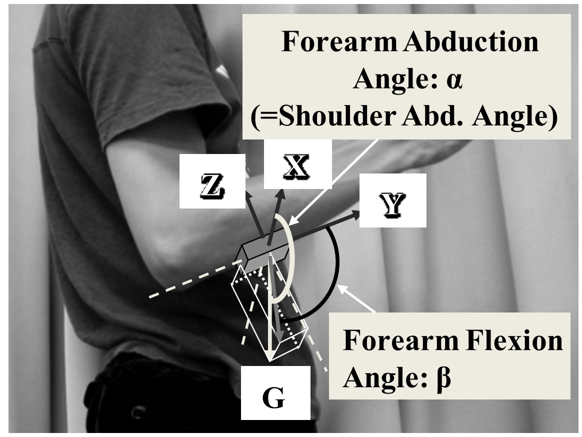

Fig. 3. Definition of the coordinate system and the angles for computing the upper limb posture from the acceleration sensor

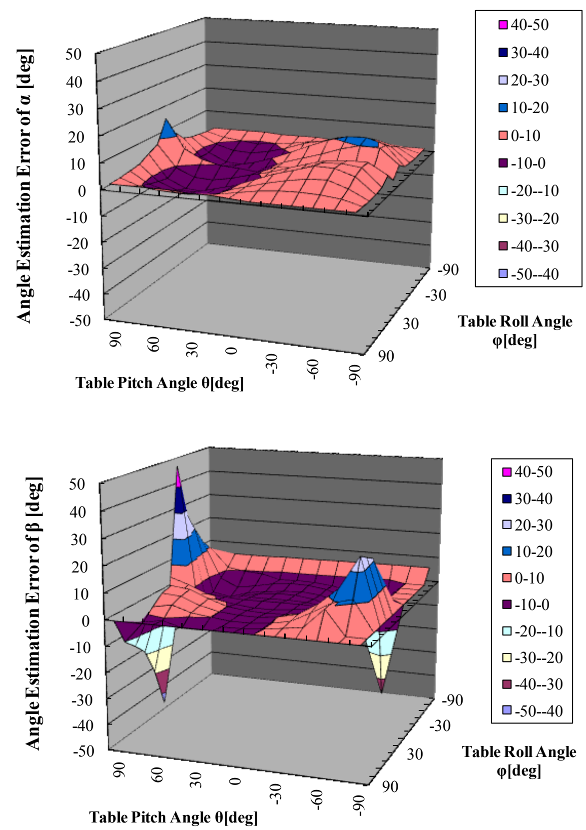

Fig. 4. Experimental result of numerical computation of angle α and β from the acceleration sensor in static posture. The angle estimation error of α(top) and β (bottom) are shown in relation to the table posture pitch and roll angles.

for fitting and evaluating the setting of the Bowden cable system for body-powered prosthesis.

First, acceleration sensor signals were tested to confirm that the sensor location being on the skin or on the socket surface does not cause error to the data. It was confirmed that signal did not differ within the range of motion. Therefore, the acceleration senor was placed on the tentative socket in the experiments. The motion data of intact arm movements was recorded from a single subject wearing the tentative socket. The target task motions were performed standing, and seated for comparison. Furthermore, motions of picking up an object from inside a drawer in a seated position were recorded to compare the influence of the body posture. From the observation and comparison of the collected data, we selected to use a simple state machine logic and threshold values to control the 2-DOF of the wrist joint motions in the prosthetic hand as next.

A. Wrist pronation/supination motion control

The state of the wrist joint motion is switched based on the relation of the threshold values and the forearm flexion inclination angles β, reference angle β_0, and minimum angle β_{min}, as next. First, as to initialize the joint control algorithm to the user and environment, when both of the myoelectric sensor signal exceeds the threshold value (which is a state called co-contraction) for a short period of time, the state is initialized and the forearm flexion inclination angle β is assigned to the reference angle β_0 and minimum angle β_{min}. This operation is expected only at the beginning of using the acceleration sensor control in the target task period. Else then the co-contraction state, β_{min} is assigned as next.

$$\begin{gathered} \beta_{min} = \beta(t) \quad [\beta(t) \leq \beta_0] \cap [\beta(t) < \beta_{min}] \\ \beta_{min} = \beta_0 \quad [\beta(t) \leq \beta_0] \end{gathered} \tag{2}$$

After the initialization, the pronation and supination of the prosthetic wrist joint is controlled by the following logic (3), where $S_{wr}(t)$ is the state of the wrist motor driving direction, $S_{wr}[SP]$ is the state of wrist motor driven in supination direction and $S_{wr}[PR]$ the state of wrist motor driven in pronation direction. This logic is terminated and shifted by logic (4) at the time forearm flexion inclination angle β becomes smaller then the reference angles β_0 and β_{min}. By setting phase 0 and 1, the wrist pronation/supination is selected based on the forearm flexion inclination angle. Pick-raise-place ask motions conducted on the tabletop are controlled under phase 0, whereas the same task conducted under the table surface is controlled under the logic of phase 1.

$$\begin{gathered} S_{wr}(t) = S_{wr}[SP] \quad [\beta(t) \geq \beta_0 + 60] \\ S_{wr}(t) = S_{wr}[PR] \quad [\beta(t) < \beta_0 + 60] \end{gathered} \tag{3}$$

$$\begin{gathered} \text{Phase}(t) = 0 \quad [\beta(t) \leq \beta_0] \\ \text{Phase}\ (t) = 1 \quad [\beta(t) \leq \beta_0] \cap [\beta(t) < \beta_{min} + 20] \end{gathered} \tag{4}$$

Phase 0:

$$\begin{gathered} S_{wr}(t) = S_{wr}[PR] \quad [\beta(t) \geq \beta_0 - 20] \\ S_{wr}(t) = S_{wr}[SP] \quad [\beta(t) < \beta_0 - 20] \end{gathered} \tag{5}$$

Phase 1:

$$\begin{gathered} S_{wr}(t) = S_{wr}[SP] \quad [\beta(t) \geq \beta_{min} + 20] \\ S_{wr}(t) = S_{wr}[PR] \quad [\beta(t) < \beta_{min} + 20] \end{gathered} \tag{6}$$

B. Wrist palmar flexion/dorsiflexion motion control

The states of the wrist palmar flextion($S_{wr}[PF]$) and dorsiflexion($S_{wr}[DF]$) joint motion are switched based on the range of forearm flexion inclination angles β as next, and the motor is driven in the direction.

$$\begin{gathered} S_{wr}(t) = S_{wr}[DF] \quad [\beta(t) \leq 80] \\ S_{wr}(t) = S_{wr}(t-1) \quad [80 < \beta(t) < 100] \\ S_{wr}(t) = S_{wr}[PF] \quad [\ \beta(t) \geq\ 100] \end{gathered} \tag{7}$$

The AIST prosthetic hand unit does not have sensors mounted for joint angle detection, and therefore, the motors are all driven in constant speed at open loop control. The motor is halted with a mechanical switch to maintain within the range of motion of the joint and also monitored by the processor not to run in single direction for more than the determined time limits. Furthermore, the acceleration sensor signal based motion control logic can be silenced/activated with a long co-contraction signal of the myoelectric signals, which can be created by maintaining the co-contraction for a briefly longer period. To avoid unexpected switching, this discrimination is applied in the hanging posture of the arm.

V. Experiment and Results

Pilot tests were conducted on 4 subject to confirm the concept model and the prototype control logic. The pilot evaluation test was conducted with the same subject, platform, and task as the initial data collection, and the later 3 subjects were tested with the setting of the first subject. The myoelectirc sensor data and acceleration sensor data were recorded as the subject donned and used the hand installed in the quasi-prosthetic assembly. The subjects were asked to perform a pick-raise-place task with a small wooden block placed on top of a desk. The subjects performed the task while standing by the table and operating the prosthesis. The task was conducted under two control interfaces: the conventional two-site two-functions on/off control of the hand with a locked wrist and forearm, and our multimodal sensor control. The two myoelectric sensor signals and the x- and y-axis acceleration sensor signals were instrumented, computed, and recorded. The sensor signals are processed on the microprocessor to control the prosthetic hand unit while the recorded sensor signal and motor command logs are monitored and recorded to the personal computer. The recorded data are transmitted to the personal computer through serial communication (RS232C) port in real time.

Figure 5 shows the results of sensor data of the two control logic of the first subject's pilot tests. The left diagrams describe the result of the two-site two-functions on/off control. The right describes the multimodal sensor control. Both top diagrams describe the time-series behavior of the forearm abduction angle α and forearm flexion angle β in gray line and black line, respectively. The bottom diagrams show the myoelectric sensor signals of the flexion muscle and extension muscle in gray and black lines, respectively. The rising of the extensor muscle signal are recorded when opening the hand, and the rising of flexor muscle signal are recorded at closing the hand. Both myoelectric sensor signals show the timing of the hand closing and opening related to the shoulder and elbow joint movement. By comparing the abduction angles α of the right and left figures, the data for the multimodal control has a suppressed variation. This indicates our target of reducing the shoulder compensation motions is successful and the latter two targets we put up for system integration are met.

Within the following three subject's test result, one subject with similar body characteristic was capable of operating the prosthesis to pick-raise-place the block. The abduction angles of the multimodal sensor control were smaller than the locked-wrist conventional control method. However the other 2 subjects, that were taller or heavier than the first subject, had major problem of a continual hunching wrist pronation/ supination motion during the reaching phase and the task was not performable at the same experimental condition. The hand opening/closing operated by the myoelectric signal was not interfered, yet was not useable without the positioning control of the wrist.

VI. DISCUSSION

A concept of multimodal sensor control for 3-DOF transradial prosthesis is proposed and tested with a prototype device under 4 subjects. The method combines the conventional myoelectric control of the prosthetic hand with the control based on acceleration sensor signals. The acceleration sensor signals are filtered and processed to represent forearm orientation angle and the component of the longitudinal direction is read as the forearm flexion angle. Based on this information, the wrist flexion and forearm pronation/supination is triggered in relation to the forearm posture. Data were collected to study the pick-raise-place task of a subject and simple state-machine logic was implemented to test the wrist motion control concept. The data gained using multimodal sensor control showed reduced shoulder abduction angle, when compared to conventional locked-wrist myoelectric hand control in the target table top task for two subjects. These result showed that the method has potential to reduce the compensation motion of the shoulder and allows additional elbow joint motion. However, the 2 other subject's results, showing that the task is not fully performable, indicate that the control system is not stable to simply apply to arbitrary user.

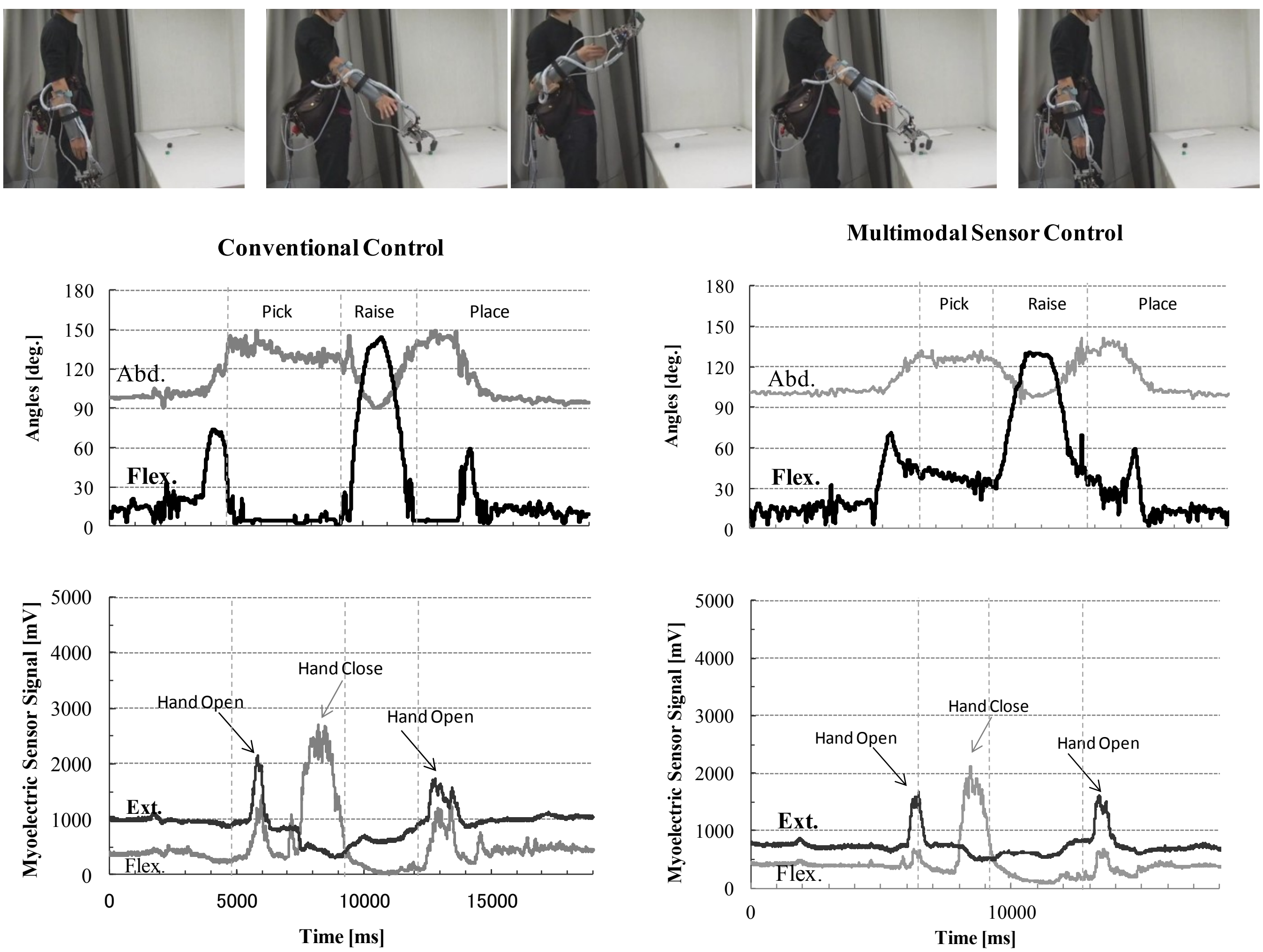

Fig. 5. First subject's experimental results comparing the conventional myoelectric control of the hand with locked wrist (left) and the multimodal sensor control of 3DOF prosthesis (right). The gray lines in the top graphs are the orientation angle α, representing the forearm abduction angle, and black lines are orientation angleβ, which represet the forearm flexion inclination angle. The gray and black lines in the bottom graphs are the myoelectric sensor signals of flexor muscle and extensor muscle, respectively.

Further research is required to confirm whether this simple logic is capable of satisfying multiple subjects with different body characteristic within resembling task environment. The tests should be first conducted by able-body subject and then by amputees, for safety reason. Task motion data without the test prosthesis should also be collected to evaluate compensation of the abduction and flexion angle. In the proposed method, only the flextion inclination angles were used to control the wrist, but the abduction angle can also be used in combination. The control algorithm should be then tested under real user environment with tasks which the use of the wrist joint may significantly assist on reducing compensating movement and unnatural body posture. The reduction of sequence in rotating the prosthetic wrist with the sound hand should also be observed to fully evaluate the influence of the control. Finally, practical modification should follow based on the findings in the field test.

As a future research topic, adding sensor(s) in the joint(s) and composing a closed-loop feedback control may lead to a more useful and natural control of the prosthetic wrist as in the interface with Extended Physiological Propioception [14-16]. Furthermore, quantitatively evaluating the combination of other interface, such as tactile switches and FSRs[17], with microcomputer based control would be an important study for preparing a clinical guideline for upper extremity prosthetic interface fitting and evaluation.

Finally, with the limited number of data collected in a specific condition, the result of this experiment should be interpreted with caution. Additional confirmation experiments are to be conducted and modifications based on the experiments should also be reported in the near future.

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