11

Quantitative Evaluation Methods of Therapeutic Effects of Sanding Training in Patients with Hemiplegia

Yoshifumi Morita and Hiroyuki Ukai
Nagoya Institute of Technology
Japan

1. Introduction

In the year 2013, the percentage of elderly people is forecasted to be 25 percent of the total population in Japan. Moreover, the number of elderly people who have a disease or a physical disability is increasing. So, the need of new rehabilitation methods and systems having high therapeutic effect is also increasing.
For this reason many rehabilitation support systems and robots have been developed for upper limbs (Kerbs et al., 1998, Reinkensmeyer, et al., 2000, Jezernik et al., 2003, Colombo et al., 2005, Furusho et al., 2005, Furusho et al., 2007, Kikuchi et al., 2007, Beer et al., 2008). The advantage using the robots and the systems are that the patients can perform effective rehabilitation trainings and the therapeutic effect can be evaluated quantitatively.
We also have developed a rehabilitation support system for various resistance trainings of upper limb motor function as shown in Fig. 1 (Morita et al., 2007a, Morita et al., 2009). This system supports the occupational therapy for recovering physical functions. This system equipped with the teaching/guided function for personalized rehabilitation. The teaching/guided function enables the therapists to easily make not only training trajectories but also training programs to suit the individual needs of the patients. Moreover, we have proposed a quantitative evaluation method of the therapeutic effect of sanding training (Morita et al., 2007b, Morita et al., 2008). This method is used to evaluate the cooperative movement of forearm and upper arm that is one of the therapeutic effects. In the future the final aims of our research are to quantitatively evaluate the therapeutic effect of upper limb motor function during the training from the standpoint of the establishment of EBM (Evidenced Based Medicine) and to develop a new rehabilitation training support system with the quantitative evaluation function of therapeutic effect.
In this chapter three kinds of evaluation methods of upper limbs during sanding training are proposed. These evaluation methods are used to evaluate the achievement level of sanding training, the cooperative movement of healthy and paralyzed arms, and the cooperative movement of forearm and upper arm. In order to verify the effectiveness of the proposed methods, we measure the upper limb motion of healthy people and patients with hemiplegia during the sanding training by using Shape Tape and the force/torque sensor. Then we examine the validities of the proposed evaluation methods using the patients' data, and the relationship between the evaluation results and the Brunnstrom Stage.

Fig. 1. 3-Dimensional rehabilitation training robot for upper limbs with measuring function

Fig. 2. Conventional sanding training tool

2. Sanding training and measurement

2.1 Measurement of upper limb motion during sanding training

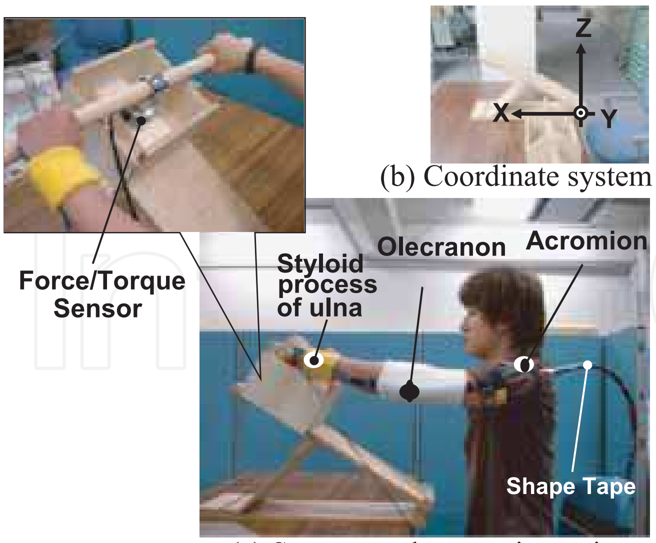
Sanding training, which is one type of resistance training for upper limbs widely performed in occupational therapy in Japan. This training is usually performed using a sanding training tool as shown in Fig. 2. This training is performed for ROM (range of motion) training of joints, muscular reinforcement of upper limbs, improvement of the cooperative movement between flexor muscles and extensor muscles, endurance training and so on.

We evaluate the therapeutic effects of the sanding training by using the data acquired during the sanding training. For this purpose we use two kinds of sensors, namely the 6-axes force/torque sensor (NITTA CORPORATION, IFS-67M25A 15-I 40) and Shape Tape (Measurand Inc.).

As shown in Fig. 3(a), the force/torque sensor is attached to the conventional sanding training tool in order to measure the force and torque exerted by patients. The sensor signal is acquired using a personal computer with the sampling frequency 1[kHz].

By using Shape Tape, we measure the 3-dimensional positions of the wrist, elbow and shoulder joints of the upper limb during the sanding training. In the coordinate system of measurement, let the X, Y and Z axes be horizontal, right-left directions and vertical, respectively as shown in Fig. 3(b). The sampling frequency is 100[Hz]. The measuring points are the styloid process of ulna, olecranon and acromion as shown in Fig. 3(a).

The subjects are ten healthy male students who are between 22 and 25 years old and fifteen patients with hemiplegia. All the healthy persons are right-handed. All patients have one paralyzed arm and one healthy arm. The Brunnstrom Stages (Br.stages) of all the patients are from I to VI. Br.stage I score is the highest of paralysis. Br.stage VI score is the lowest of



(b) Coordinate system

(a) Sensors and measuring points

Fig. 3. Measurement system

Fig. 4. Sanding training and clinical measurement

paralysis. In the case of patients, Shape Tape is attached to their paralyzed arm as shown in Fig. 4. In the case of healthy persons, Shape Tape is attached to their right arm. All subjects perform the sanding training for 25[sec].

As shown in Fig. 4, the subject takes a seat, holds the grips of the sanding tool with both hands and moves the grips up and down on the slope. If the subject cannot grasp the grip by himself/herself, the subject's hand is fixed to the grip. The range of movement of training is 40cm. The angle of the tilting rotary board is 20[deg]. The therapist chose the loads of training according to the patient's ability from among no weight, 1[Kg] and 2[kg] weight and the angle of inclination of 0[deg], 10[deg] and 20[deg]. The healthy persons performed four cases, namely no weight–10[deg], no weight–20[deg], 2[kg]–10[deg] and 2[kg]–20[deg].

2.2 Measurement data and consideration

For example the time histories of the measured data of a patient of Br.stage II and a healthy person during the sanding training are shown in Fig. 5 and 6. Fig. 5 and 6 show the joint positions of the X axis, the joint velocities of the X axis, the forces of the X, Y and Z axes, and the rotational moment torque of the grip. The joint velocities are obtained by differentiating the joint positions. The conditions of the loads of training are without a weight and the angle of inclination of 10[deg].

The followings are found from the results of the healthy person in Fig. 5. The time necessary for an alternating motion is about 3.0[sec]. The force is large in the upward motion as compared with the downward motion, because the subjects utilize the gravity force in the downward motion. Among the three joint velocities, the amplitude of the wrist joint velocity is large. The shape of the wrist and elbow joint velocities is almost the same. But the shoulder joint velocity is different from them. In the upward motion the shoulder movement starts after the wrist and elbow movements. In the downward motion the shoulder movement finishes before the wrist and elbow movements. This kind of motion can be found in the motion of all the healthy persons. Therefore the characteristic of cooperative movement of upper arm and forearm is found from the three joint velocities.

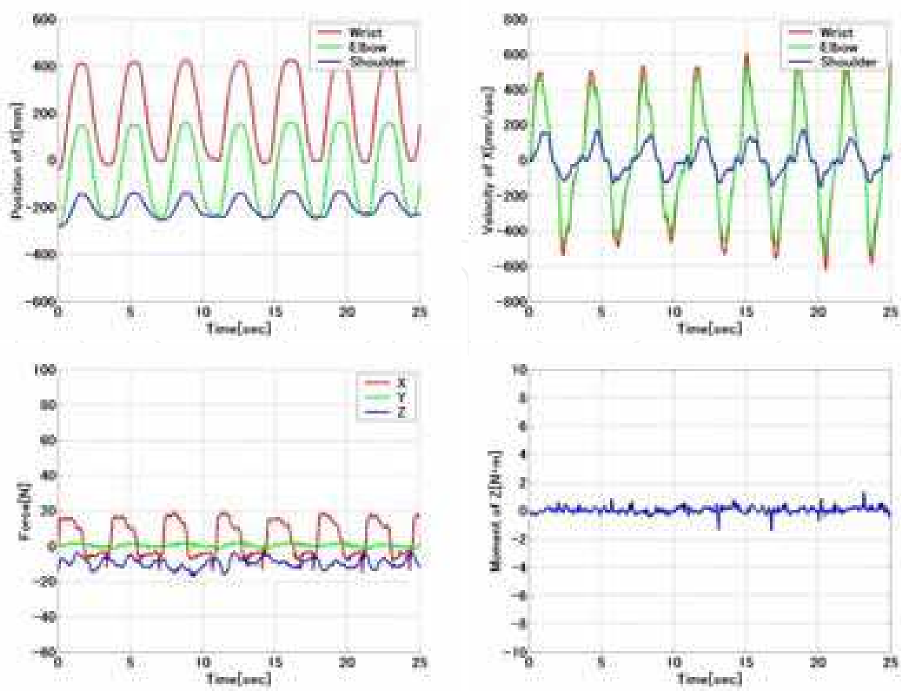


Fig. 5. Time histories of measured data of healthy person during sanding training.

The followings are found from the results of the patient in Fig. 6. It is seen from the time histories of the joint positions and velocities that the motion of upper limbs of the patient is small and the patient can hardly perform the sanding training. The cooperative movement of an upper arm and a forearm found in the motion of a healthy person cannot be found. When a patient with hemiplegia performs the sanding training, the healthy arm pushes the sanding tool and the paralyzed arm is moved along with the healthy arm. In this case the z axis component of the rotational moment torques occurs as shown in Fig. 6, which is called the moment in this chapter. Then the friction between the mover and the board of sanding tool becomes larger due to the moment. Therefore the sanding training becomes more difficult. On the other hand, in the case of healthy persons the measurement of moment is almost zero. The cooperative movement of both arms found in the motion of a healthy person cannot be found in the patient's motion. Therefore the cooperative movement between the healthy upper limb and the paralyzed upper limb of a patient with motor hemiplegia can be evaluated from the measured moment.

3. Evaluation methods and their verification using patients' data

The therapeutic effect of the sanding training can be evaluated quantitatively by analyzing the difference between a healthy person and a patient. In this chapter three kinds of evaluation methods for (1) Achievement level of sanding training, (2) Cooperative movement of healthy and paralyzed arms, and (3) Cooperative movement of forearm and upper arm of the paralyzed arm are proposed.

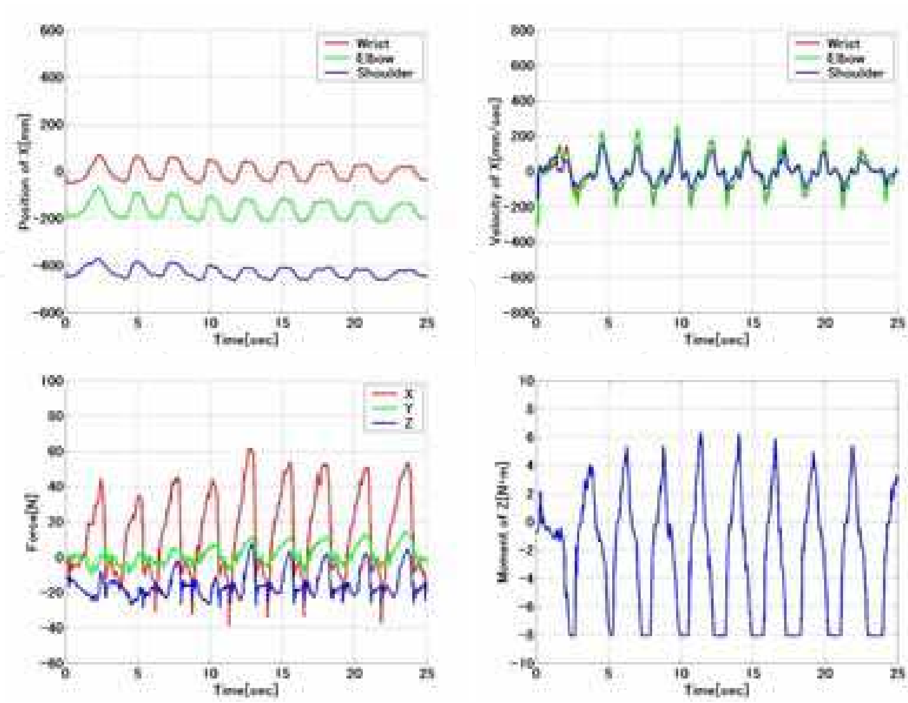


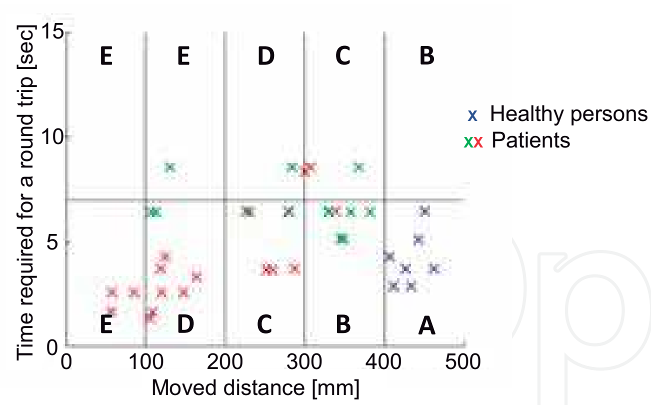
Fig. 6. Time histories of measured data of patient during sanding training.

3.1 Achievement level of sanding training

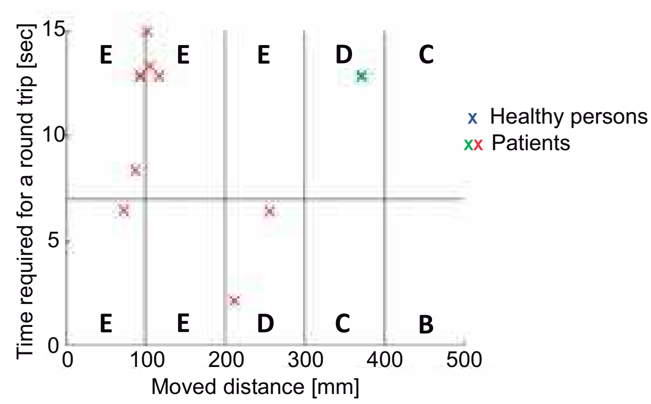
In order to evaluate the therapeutic effect of the sanding training, the moved distance, the time required for a round trip, the number of round trips per the specified time and so on have been used. In this chapter a new evaluation method is proposed by calculating the three kinds of evaluation indices, namely the moved distance, the time required for a round trip and the number of round trips per 25[sec], from the measurement data and using the classification charts of Fig. 7. The threshold values between healthy persons and patients are determined from the healthy persons' data. The therapeutic effect is evaluated in 5 levels from A to E. Level A is the highest achievement. All the healthy persons are classified in level A. Level E is the lowest achievement. This evaluation index is called achievement level of sanding training. The achievement levels of the fifteen patients and the ten healthy persons are plotted in Fig. 7. The relationship between the achievement level and the Brunnstrom Stage is investigated. The results are shown in Fig. 8. The dashed curve denotes the curve for second order approximation. Although the patient of Br.stage I can not move the paralyzed arm, the patient can perform the sanding training by using only the healthy arm. It is similar to the sanding motion of a healthy person. The paralyzed arm of the patient of Br.stages II and III moves involuntary due to associated movement and stereotyped of motor synergy. So, the patient can not perform the sanding training smoothly, because the paralyzed arm disturbs the smooth motion. Consequently, in the case of Br.stages I, IV, V and VI, the achievement level is high, and in the case of Br.stages II and III, the achievement level is low.

3.2 Cooperative movement of healthy and paralyzed arms

The quantitative evaluation method is proposed for the characteristic of cooperative movement of healthy and paralyzed arms. In the case of a patient with a right paralyzed arm, the



(a) More than 3 round trips per 25[sec]



(b) Less than 3 round trips per 25[sec]

Fig. 7. Achievement level

left healthy arm mainly pushes the sanding tool. In the case of a patient with a left paralyzed arm, the right healthy arm mainly pushes the sanding tool. In order to evaluate the cooperative movement of the healthy and paralyzed arms, we measure the moment. The relationship between the peak value of the moment and the Brunnstrom stage are shown in Fig. 9. The higher the level of the paralysis is, the larger the measurement of the moment is. The two dashed lines denote the lines for first order approximation. It is found from Fig. 9 the plus and minus peak values of the moment correspond to the left hemiplegia and the right hemiplegia, respectively. Consequently the cooperative movement of healthy and paralyzed arms can be evaluated using the peak value of the moment.

3.3 Cooperative movement of forearm and upper arm

The quantitative evaluation method is proposed for the characteristic of cooperative movement of forearm and upper arm. The therapeutic effect is evaluated by comparing healthy persons' models with the patient's data. The healthy persons' models are constructed by using the NN (Neural Network) modeling approach(Morita, 2006a).

3.3.1 Evaluation method using Neural Network

The characteristic of cooperative movement of forearm and upper arm of healthy persons is modeled using NN. The three joint velocities of a healthy person are plotted in a 3-dimensional

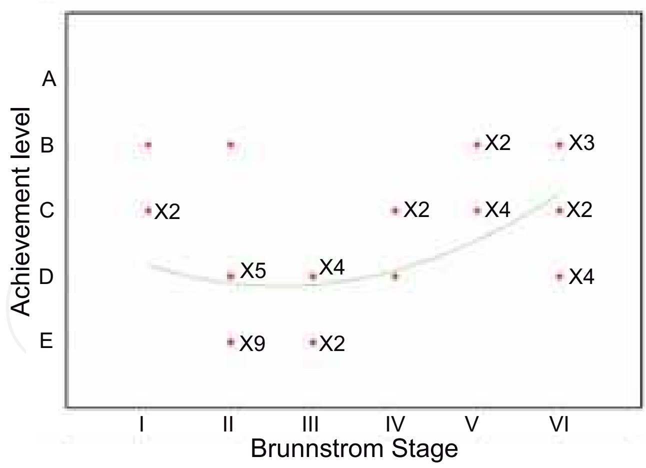


Fig. 8. Relationship between achievement level and Br.stages

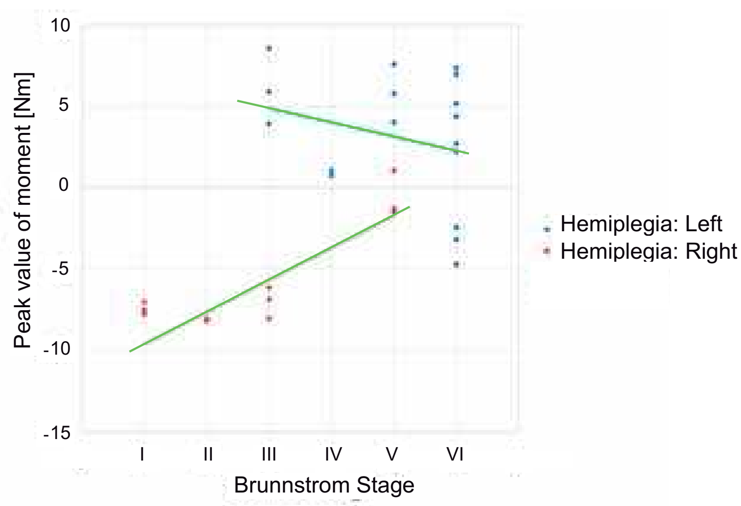


Fig. 9. Relationship between peak value of moment and Brunnstrom stage

phase space as shown in Fig. 10. The mutual relation of the velocities is seen in Fig. 10, as mentioned in Section 2.2.
The structure of NN shown in Fig. 11 is used, where the input signals are the X axis components $(v_W(k), v_E(k))$ of velocities of the wrist and elbow joints, and the output signal is the X axis component $v_S(k)$ of velocities of the shoulder joint. It is important to determine the inputs and outputs. These inputs and the output are determined by comparing the results of all other cases. For example the wrist and shoulder joints are used as input signals and the elbow joint is used as an output signal. The number of the inner layer is one, and the number of neurons is 100.
Since there are individual differences in upper limb motion, it is difficult to model the cooperative movement with only one model. So, the ten healthy persons are classified in two groups on the basis of the individual differences. For this purpose the NN modeling technique and the cluster analysis are used. The dendrogram is obtained as shown in Fig. 12. The horizontal

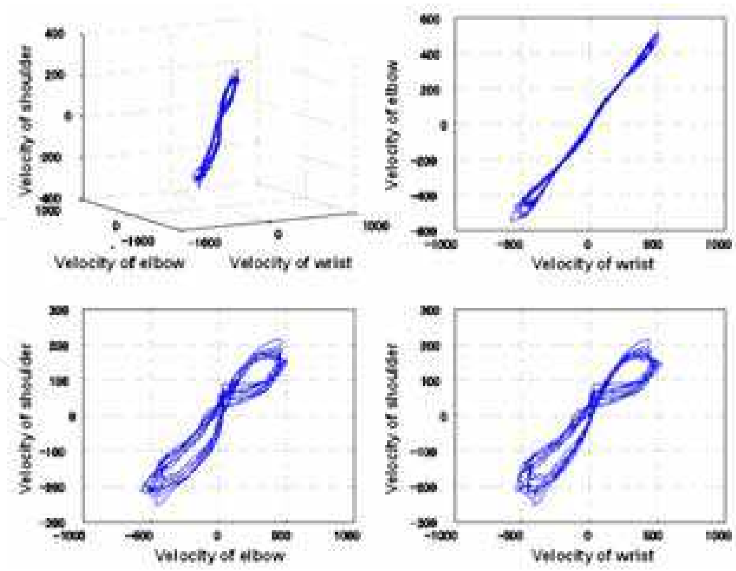


Fig. 10. Joint velocities in 3-Dimensional phase space

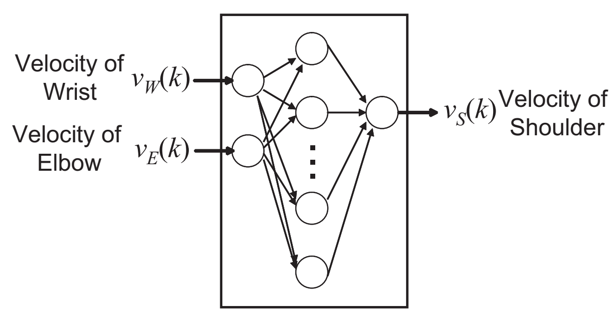


Fig. 11. Structure of neural network

axis is the subject number. The vertical axis is the MSE. The dendrogram shows the similarity between subjects or a subject and subject group. For example, Subject 6 is similar to Subject 10 in upper limb motion. And the group of Subjects 2, 3, 7 and 9 is similar to the group of Subjects 4 and 5. In this study the MSE of 0.015 is used as the threshold of discrimination. As a result, all the subjects are classified into two groups.

Moreover, some patients are not able to move the sanding tool the maximum distance of 40[cm]. So we prepare models of 40[cm] and 20[cm]. We choose one model from the models of 40[cm] and 20[cm] owing to the moved distance performed by a patient.

The difference of the two groups is investigated. We found from the time histories of joint velocities of all subjects that the two groups differ in the amount of shoulder movement in both the cases of the moved distance of 40[cm] and 20[cm]. In one group, the amount of shoulder movement is large, which is called Group 1 and Group 4 in the cases of the moved distance of 40[cm] and 20[cm], respectively. In the other group, the amount of shoulder movement is small, which is called Group 2 and Group 3 in the cases of the moved distance of 40[cm] and 20[cm], respectively. Models 1 to 4 are constructed using the data of Groups 1 to 4, respectively. By using four types of healthy persons' models and by comparing them with the patient's data we can evaluate the therapeutic effect.

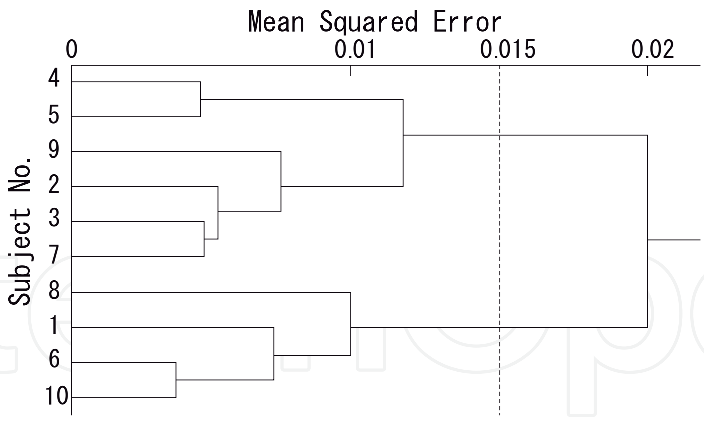


Fig. 12. Dendorogram

The quantitative evaluation method for therapeutic effect of cooperative movement is proposed on the basis of Models 1 to 4 as shown in Fig. 13. The procedure is as follows;
Step 1: The models of 40[cm] or 20[cm] is chosen owing to the moved distance performed by a patient, namely Model 1 and 2 in the case of the moved distance of 40[cm] or Model 3 and 4 in the case of the moved distance of 20[cm].
Step 2: The data of the velocities of wrist and elbow joints of a patient is input to the models chosen in Step 1. The two errors of the velocities of shoulder joint of a patient are output from the two models. The errors, namely $\bar{e}_1$ and $\bar{e}_2$ in the case of the moved distance of 40[cm] or $\bar{e}_3$ and $\bar{e}_4$ in the case of the moved distance of 20[cm] are evaluated using the Mean Squared Error(MSE). The MSE is calculated by

$$\bar{e}_i = \sqrt{\frac{1}{N}\sum_{k=1}^{N} e_i^2(k)}, \quad (i = 1, 2 \text{ or } 3, 4), \tag{1}$$

where $e_i(k) = \hat{v}_{Si}(k) - v_S(k)$, $(i = 1, \cdots, 4)$, N is the number of measured data.
Step 3: The data ($\bar{e}_1$, $\bar{e}_2$) or ($\bar{e}_3$, $\bar{e}_4$) is plotted in the $\bar{e}_1$-$\bar{e}_2$ plane or the $\bar{e}_3$-$\bar{e}_4$ plane, respectively as the quantitative evaluation score.
The data of the ten healthy persons is analyzed. The scores $(\bar{e}_1, \bar{e}_2)$ and $(\bar{e}_3, \bar{e}_4)$ are calculated by applying each subject's data to Models 1, 2, 3 and 4, respectively. The scores $(\bar{e}_1, \bar{e}_2)$ and $(\bar{e}_3, \bar{e}_4)$ of all the subjects are plotted in the $\bar{e}_1$–$\bar{e}_2$ plane and the $\bar{e}_3$–$\bar{e}_4$ plane as shown in Figs. 14 and 15, respectively. The blue marks denote the results of healthy persons. The blue lines denote the threshold between the patients and the healthy persons.
It is seen in Fig. 14 that the marks of healthy persons are in the region ($\bar{e}_1 > 0.006$ and $\bar{e}_2 < 0.006$) and the region ($\bar{e}_1 < 0.006$ and $\bar{e}_2 > 0.006$). The former region contains the subject with short shoulder movement. The latter region contains the subject with large shoulder movement. The similar results are seen in Fig. 15. When the moved distance is smaller, a decreasing tendency is seen in the shoulder movement.

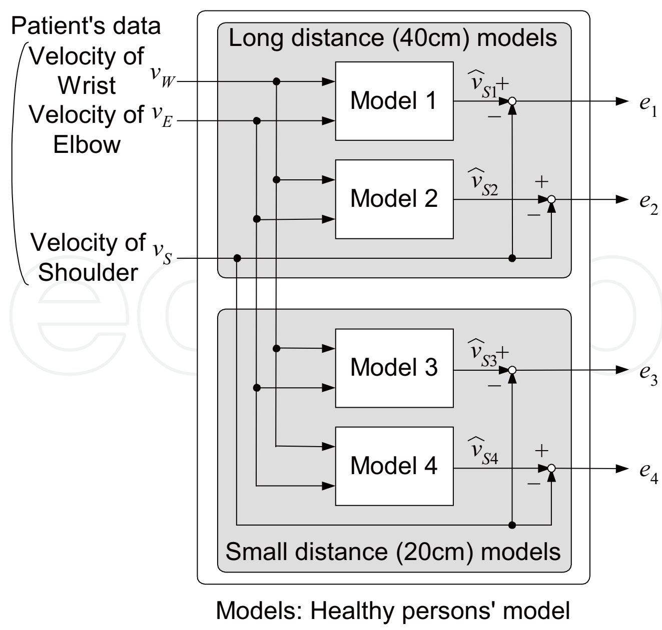


Fig. 13. Block diagram of quantitative evaluation method

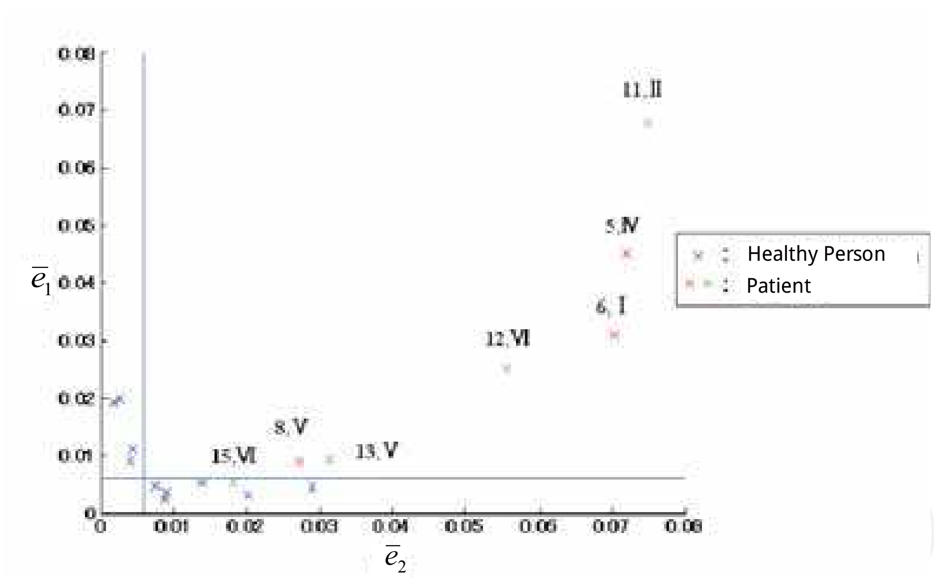


Fig. 14. Distribution charts of quantitative evaluation scores (Moved distance: 40[cm])

3.3.2 Verification of the proposed method using patients' data

Only the data of the achievement level A through D is applied to the proposed evaluation method. The conditions of the loads of training are without a weight and an angle of inclination is 10[deg].

The models of 20[cm] or 40[cm] are chosen owing to the moved distance performed by a patient. The scores of the patients that moved the sanding tool around 40cm and 20cm are plotted in Figs. 14 and 15, respectively. The cardinal number on the left is the patient number.

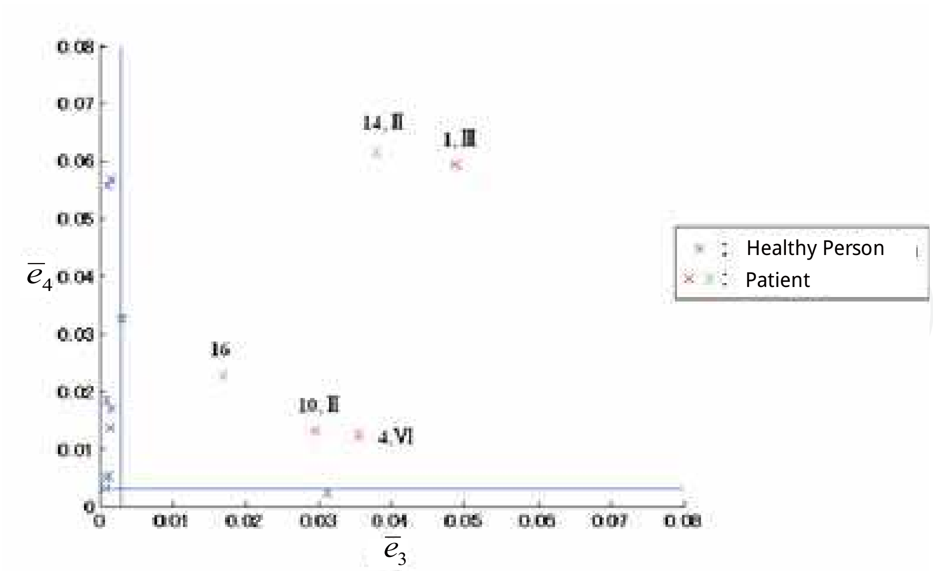


Fig. 15. Distribution charts of quantitative evaluation scores (Moved distance: 20[cm])

The Roman number on the right is the stage number of Brunnstrom stage. The red and green marks denote the results of the patients measured on 5 June, 2007 and 7 November, 2007, respectively. Patient 6 and patient 11 are the same person. The Br.stage of Patient 6 increases from 1 to 2 after performing the sanding training for 5 months. It is seen from Figs. 14 and 15 that the marks of all the patients are out of the region of healthy persons. This implies that the movement of all the patients is different from that of a healthy person. It is seen from Fig. 14 that the marks of the patients 8, 13 and 15 are close to the region of healthy persons. This implies that the movement of the patients 8, 13 and 15 is similar to that of a healthy person.

The relationship between the quantitative evaluation scores $\bar{e}_1$ through $\bar{e}_4$ and Br.stages is examined. The marks of the patients of Br.stage I are close to the region of healthy persons in Fig. 14, because muscle contraction and involuntary motion do not occur on the paralyzed arm, and only the healthy arm can move the sanding tool smoothly. The marks of the patients of Br.stages II and III are far from the region of healthy persons in Fig. 14 or are plotted in Fig. 15, because involuntary motion due to associated movement and stereotyped of motor synergy occur on the paralyzed arm, and the patient can not move the sanding tool smoothly. The marks of the patients of Br.stages IV, V and VI are plotted in Fig. 14. Some of them are close to the region of healthy persons.

Consequently the followings are suggested. By observing the mark for its change with time in the distribution chart, the effect of training can be found. The patients need to do rehabilitation training so that the personal mark approaches the region of healthy persons. Moreover, the proposed evaluation method can be used to evaluate recovery.

4. Conclusions

In order to evaluate the therapeutic effects of sanding training, we proposed three quantitative evaluation methods for the achievement level, the cooperative movement of the healthy and paralyzed arms and the cooperative movement of the upper arm and forearm. The validities of the proposed methods are confirmed by applying the patients' data to them. Moreover, the relationships between the evaluation results and the Brunnstrom stage were examined. It

is suggested that the proposed evaluation methods can be used to evaluate recovery in the sanding training.
The future works are to install the proposed evaluation methods to the rehabilitation training support robot(8), and to perform the clinical demonstrations using the proposed system in cooperation with medical facilities.

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Population ageing has major consequences and implications in all areas of our daily life as well as other important aspects, such as economic growth, savings, investment and consumption, labour markets, pensions, property and care from one generation to another. Additionally, health and related care, family composition and life-style, housing and migration are also affected. Given the rapid increase in the aging of the population and the further increase that is expected in the coming years, an important problem that has to be faced is the corresponding increase in chronic illness, disabilities, and loss of functional independence endemic to the elderly (WHO 2008). For this reason, novel methods of rehabilitation and care management are urgently needed. This book covers many rehabilitation support systems and robots developed for upper limbs, lower limbs as well as visually impaired condition. Other than upper limbs, the lower limb research works are also discussed like motorized foot rest for electric powered wheelchair and standing assistance device.