Psychological Measurement of Coupled Human Balancing Tasks

Atsushi Higeta, Yoshida Katsutoshi, Shinichi Watanabe and Aki Nakatsuka

***Abstract*—In this paper, we investigate the relationship between human sense and motion in coupled human balancing tasks. We propose a measurement system to obtain the balancing error produced by two human subjects stabilizing a coupled inverted pendulum model in cooperation. After an experiment to measure the balancing error, each subject evaluated the performance of manipulation of both his own self and his partner. The factor analysis on sense and motion of the subjects implied that correlations can be found between the balancing error and the sense of aggressiveness and also between the motion delay and the sense of activity.**

I. Introduction

The inverted pendulum is among the simplest representatives of an autonomous entity (agent). Many studies have been performed on swinging-up control and stabilization in individual IPs. For example, Li et al. [1] studied playback and intelligent control of pendulums under a torque limitation, and Sekiguchi et al. [2] studied the stabilization control of an IP having two parallel independent driving wheels.

In real-world problems, the actual agents seldom function as isolated individuals, and it is therefore more realistic to consider circumstances in which coexisting agents influence each other. When agents share common resources and environments, it gives rise to the dynamic of timing in matching and conflicting interests [3]. Many studies have focused on the interaction between competition and cooperation in such circumstances. Cooperative transportation, in which agents must cooperate in order to transport a physical object, is a classic example. Representative studies include the cooperative transportation of a ladder by distributed control [4], the cooperative transportation system comprising humanoid robots using simulation-based learning [5], and the achievement of cooperative stabilization control by learning [6].

In a more fundamental approach, the authors of this paper proposed a Coupled Inverted Pendula (CIP) model as the simplest mechanical model representing competition and cooperation between agents [7][8], and have been engaged in investigation of the strategies that can be employed by the

Manuscript received October 11, 2011.

Atsushi Higeta is with Graduate School of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya-shi, Tochigi, 321-8585, Japan (e-mail: higeta@katzlab.jp)

Katsutoshi Yoshida is with Graduate School of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya-shi, Tochigi, 321-8585, Japan (e-mail: yoshidak@cc.utsunomiya-u.ac.jp)

Shinichi Watanabe is with Graduate School of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya-shi, Tochigi, 321-8585, Japan (e-mail: swtnb@cc.utsunomiya-u.ac.jp)

Aki Nakatsuka is with Tohoku Electric Power Co., Inc., 1-7-1 Honcho, Aoba-ku, Sendai, Miyagi 980-8550, Japan (e-mail: aki@katzlab.jp)

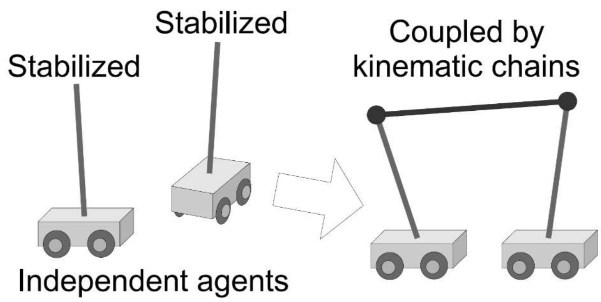


Fig. 1. Basic concept of mechanical implementation of competition and cooperation. The independent agents are coupled by kinematic chains.

pendula (i.e., the agents) in relation to mutual competition and cooperation [8][9]. In our initial studies, when we began to measure the competitive and cooperative strategies that emerge among humans, we found interesting results, such as the cooperative balancing movements that two humans develop when they work together, which increases their mutual stability and induces asymmetrical tracking sensitivity [10]. In human cooperative balancing movements, the effects of human emotion and sensitivity should naturally be considered. Because of our grounding in dynamic and control engineering, however, this aspect had remained unexamined.

In the present study, we are able to investigate this aspect by incorporating the Kansei engineering approach to elucidate the relationship of human sensitivities and emotions to human operations during cooperative balancing movements. More specifically, we develop a measurement system in which the human subjects actually operate the CIP model representing competition and cooperation, thus enabling measurement of the actual cooperative balancing performed by two human subjects. Following this measurement, each subject rates both himself and his partner in a sensory-based evaluation by the semantic differential (SD) method. We then apply factor analysis to the physical quantities obtained in the measurements and the rating values obtained in the sensory-based evaluation to elucidate the relationship between human balancing moves and human sensitivities and emotions.

With elucidation of this relationship, it may become possible to infer human sensitivities and emotions based on the measurement of human movements during a given operation. In cooperative movements or operations between a person and a robot or other autonomous system, this would provide a basis for the system itself to infer the human sensitivity and emotion from the human movement and perform system movement control accordingly.

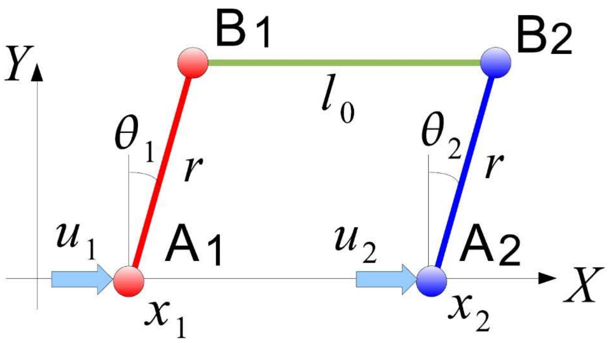


Fig. 2. Dynamic model of coupled inverted pendula model of competition and cooperation.

II. MECHANICAL SYSTEM REPRESENTING COMPETITION AND COOPERATION

A. *Coupled inverted pendulum model*

In the present study, we consider the mechanism shown in Fig. 1. This mechanism, consisting of two autonomous mechanical devices (agents) interacting via a mechanical linkage, represents a mathematical ecologically competitive model and the analogous competitive-cooperative dynamics, and also a model in which all system parameters are identifiable from the mechanical engineering viewpoint. In previous reports [7]-[9], we proposed the coupled inverted pendula (CIP) model, shown in Fig. 2. In the present report, we show the proposed CIP model together with its equations of motion.

The CIP model consist of two equivalent inverted pendula A_iB_i ($i = 1,2$) whose end points are jointed by the rigid link B_1B_2

B. *Penalty model*

The equations of motion of the dynamical model with the rigid-body link shown in Fig. 2 are differential algebraic equations (DAEs). As previously described [7]-[9], we therefore consider link B_1B_2 as a flexible link of natural length l_0 with a spring and damper, and apply the penalty method to derive the following ordinary differential equation equivalent to the DAEs. If the spring constant and damping coefficient of the flexible link are sufficiently large, they closely reproduce the behavior of the rigid-body model shown in Fig. 2. System parameters of the CIP model are shown in Table 1.

$$\begin{cases} (M+m)\ddot{x}_1^2 + mr\ddot{\theta}_1^2\cos\theta_1 + J_1 = u_1 \\ (M+m)\ddot{x}_2^2 + mr\ddot{\theta}_2^2\cos\theta_2 + J_2 = u_2 \\ mr\ddot{x}_1^2\cos\theta_1 + mr^2\ddot{\theta}_1^2 + L_1 = 0 \\ mr\ddot{x}_2^2\cos\theta_2 + mr^2\ddot{\theta}_2^2 + L_2 = 0 \end{cases} \quad (1)$$

where

TABLE I

SYSTEM PARAMETERS OF COUPLING INVERTED PENDULA MODEL

Sign.	Unit	Description
x_i	m	Horizontal displacement of cart A_i
θ_i	rad	Angular displacement of pendulum A_iB_i
M	kg	Mass of cart A_i
m	kg	Mass of pendulum A_iB_i
r	m	Length of pendulum A_iB_i
l	m	Length of link B_1B_2
c_x	N·s/m	Viscous damping coefficient of cart A_i
c_θ	N·s/m	Viscous damping coefficient of pendulum A_iB_i
k_l	N/m	Spring constant of ling B_1B_2
c_l	N·s/m	Viscous damping coefficient of link B_1B_2
c_{vis}	N·s/m	Air resistance coefficient of pendulum A_iB_i
g	m/s^2	Gravity acceleration
u_i	N	Control input

$$\begin{cases} J_1 := -mr\dot{\theta}_1^2\sin\theta_1 + k_l A\left(1 - lF^{-1/2}\right) \\ \qquad + c_l AGF^{-1} + c_x\dot{x}_1 + c_{vis}r\left(\dot{x}_1 + r\dot{\theta}_1\cos\theta_1\right) \\ J_2 := -mr\dot{\theta}_2^2\sin\theta_2 - k_l A\left(1 - lF^{-1/2}\right) \\ \qquad - c_l AGF^{-1} + c_x\dot{x}_2 + c_{vis}r\left(\dot{x}_2 + r\dot{\theta}_2\cos\theta_2\right) \\ \mathrm{L}_1 := -mgr\sin\theta_1 + k_l rH\left(1 - lF^{-1/2}\right) \\ \qquad + c_l rGHF^{-1} + c_\theta\dot{\theta}_1 - E_1 \\ \mathrm{L}_2 := -mgr\sin\theta_2 - k_l rI\left(1 - lF^{-1/2}\right) \\ \qquad - c_l rGHF^{-1} + c_\theta\dot{\theta}_2 - E_2 \end{cases} \quad (2)$$

and

$$\begin{cases} A := x_1 - x_2 + r\sin\theta_1 + r\sin\theta_2 \\ B := r\cos\theta_1 - r\cos\theta_2 \\ E_1 := c_{vis}r\{(x_1 + r\sin\theta_1)r\theta_1\sin\theta_1 \\ \qquad + (\dot{x}_1 + r\dot{\theta}_1\cos\theta_1)r\cos\theta_1\} \\ E_2 := c_{vis}r\{(x_2 + r\sin\theta_2)r\theta_2\sin\theta_2 \\ \qquad + (\dot{x}_2 + r\dot{\theta}_2\cos\theta_2)r\cos\theta_2\} \\ F := A^2 + B^2, \quad G := A\dot{A} + B\dot{B} \\ H := (x_1 - x_2)\cos\theta_1 + r\sin(\theta_1 - \theta_2) \\ I := (x_1 - x_2)\cos\theta_2 + r\sin(\theta_1 - \theta_2) \end{cases} \quad (3)$$

III. MEASUREMENT SYSTEM FOR HUMAN COOPERATIVE BALANCING MOVEMENT

To measure the human cooperative balancing movement, we next develop a measurement system for human operation.

A. *Input of human target positions*

To enable operation of the CIP model by humans, the control input u_i is taken as

$$u_i = -A(x_i - x_{hi}) - B\dot{x}_i, \quad (4)$$

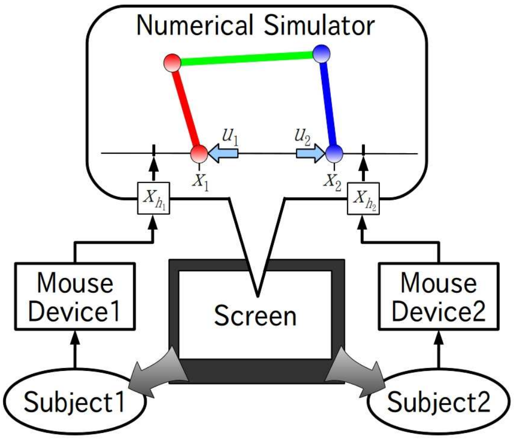


Fig. 3. Measurement system of human cooperative balancing

where x_{hi} represents the target position of x_i input by human operation.

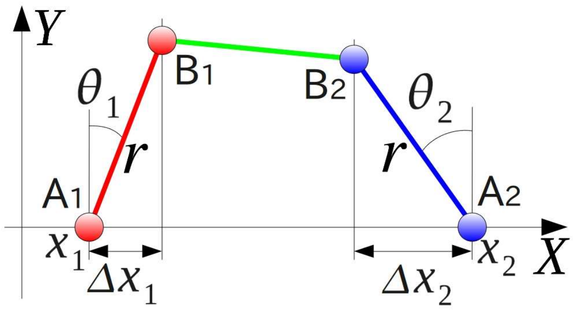
B. *Measurement system setup*

Fig. 3(a) is a schematic of the cooperative balancing movement measurement system. It comprises a CIP model numerical simulator, two mouse devices, and a screen for a dynamic animation of the CIP model. The human subjects input the target positions x_{h_i} by moving their respective mouse left or right while watching the CIP model. The dynamic animation of the CIP model occupies its central region without showing the target positions input by the subjects.

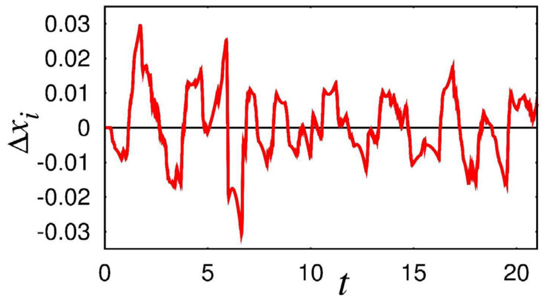
IV. EXPERIMENTAL MEASUREMENT OF HUMAN COOPERATIVE BALANCING MOVEMENT

We now perform measurement of the cooperative balancing movement performed by the two human subjects. In the present study, the measurements were performed with all possible pairing combinations of 10 subjects, who were healthy males in their early twenties. The subjects were first instructed in the method of operation of the measurement system, the number of moves to be performed per trial, the initial configuration, and the target time for continuation of the operation. Throughout the measurement, a partition was placed between the subjects so that they could not see each other.

Before the start of each trial, the subjects performed a certain number of practice runs until they became able to perform continuous operation of the CIP model shown on the screen for at least 20 sec without it falling over. In the actual trial, they began the operation upon hearing a signal and attempted to maintain the balance of the model by mutual cooperation for 20 sec. After a set of 5 consecutive trials was performed, their seating positions were reversed and they then performed a second set of 5 consecutive trials. If a pendulum left the screen or fell on the floor in less than 20 sec, the trial was repeated. After completing the 10 trials, each subject



(a) Definition of balancing errors Δx_i on CIP model.



(b) Balancing error Δx_i

Fig. 4. Definition of balancing error by self and other.

evaluated his own operation and that of his partner. All measurements were performed with the approval of the Bioethics Committee of Utsunomiya University.

V. OPERATIONAL AND PSYCHOLOGICAL MEASUREMENTS

In a previous report [10], we used the root mean square (RMS) of the balancing errors and the response delay time as indicators for evaluation of the stability and tracking sensitivity of human operations, respectively. The same indicators are used in the present study for the physical measurements of the operations by both human subjects in each trial. The impressions of each subject concerning his own and his partner's operation in the trials are scored by the SD method.

A. *RMS of the balancing error*

The RMS of the balancing errors is used as the indicator for evaluation of the human operation stability. Here, the balancing error is expressed in terms of the position of cart A_i relative to pendulum B_i in the horizontal direction, as shown in Fig. 4(a) and expressed as

$$\Delta x_i = r \sin\theta_i . \qquad (5)$$

Fig. 4(b) shows the typical measurement of the balancing errors by one subject pair. The horizontal axis represents the elapsed time t and the vertical axis represents the balancing error Δx_i . The operational stability is obtained as the RMS of these values. Small balancing errors indicate balance maintenance through relatively little movement of the mouse, and large balancing errors indicate the use of large mouse movements to maintain the balance.

B. Response delay time

To determine how promptly cart A_i performs corrective movement in response to the movement of pendulum B_i, we calculate the relative time of their movements [10].

If we take $x(t)$ and $y(t)$ as the objects of the time series comparison and Δt as the short-time average for the time intervals, then the short-time cross-correlation coefficient may be defined as

$$R(x, y; \tau)(t) = \frac{C(x - m_x, y - m_y; \tau, t)}{\sigma_x \sigma_y} \quad (6)$$

where

$$\begin{cases} C(x, y; \tau, t) := \langle x(s) y(s + \tau) \rangle_{[t, t+\Delta t]} \\ m_x := \langle x(s) \rangle_{[t, t+\Delta t]} \\ \sigma_x := \left\langle (x(s) - m_x)^2 \right\rangle_{[t, t+\Delta t]}^{1/2} \end{cases} \quad (7)$$

and $\langle x(s) \rangle_{[a,b]}$ is the temporal average $X(s)$ in the interval $[a, b]$, expressed as

$$\langle x(s) \rangle_{[a,b]} := \frac{1}{b - a} \int_a^b X(s) ds . \quad (8)$$

The cross-correlation coefficient is derived from the above with respect to the speed of cart A_i and pendulum B_i. To assess the response delay time, we observe the first peak value. A short response delay time indicates that the balance is maintained during rapid movement, and a long response delay time indicates that it is maintained during slow movement.

C. Psychological measurement by the SD method

As is commonly the case in the evaluation of ambiguous systems such as human impressions [11], language is used in the present study as the medium of measurement in the evaluation of human operations.

For this evaluation, we apply the semantic differential (SD) method commonly used in psychological studies and discussions of the relationship between words and impressions. In SD, several semantic pairs (pairs of semantically contrasting adjectives) are first selected for use as measures in the target object evaluation, with the adjectives in each pair separated by a scale having a given number of increments. In the experimental studies, the test subject chooses the position on each adjective pair scale that best describes his/her impression of the target object.

On the basis of preliminary SD experiments with the cooperative balancing measurement system using the 76 adjective pairs proposed by Osgood[12], the originator of the SD method, together with 14 other pairs devised by the authors, we selected 6 adjective pairs for use in the evaluations by each test of the subject's ("self") and the partner's ("partner") operations. The same adjective pairs were used in the self and partner evaluations to facilitate comparison between the two.

TABLE II
ADJECTIVE PAIRS IN SELF AND PARTNER EVALUATIONS.

No.	Self	No.	Partner
1	free – constrained	7	free – constrained
2	cooperative – uncooperative	8	cooperative – uncooperative
3	sharp – blunt	9	sharp – blunt
4	excitable – calm	10	excitable – calm
5	timely – untimely	11	timely – untimely
6	positive – negative	12	positive – negative

The selected adjective pairs are shown in Table 2. On each pair scale, the rating values assigned to the adjectives at the left and right ends of the adjective pair scale range from 1 to 6, respectively.

D. Factor analysis

Factor analysis is a method of discovering hidden factors that can explain data variability as part of a new concept. In the present study, we use principal factor analysis to obtain a factor loading matrix of the physical quantities obtained by the measurement and the rating values obtained by the SD method, and thus discover factors relating the physical quantities and the adjective pairs.

The factor analysis was performed with the statistical-analytical tool R [13] and using the self and partner rating values obtained by the SD for the 12 adjective pairs and the 4 physical quantities consisting of the self and partner RMS of balancing error and the self and partner response delay time obtained from the human cooperative balancing measurements. The number of factors was set at 4, with the condition that the eigenvalue of the correlation matrix equaled 1 or more. Axis rotation was performed by the promax method.

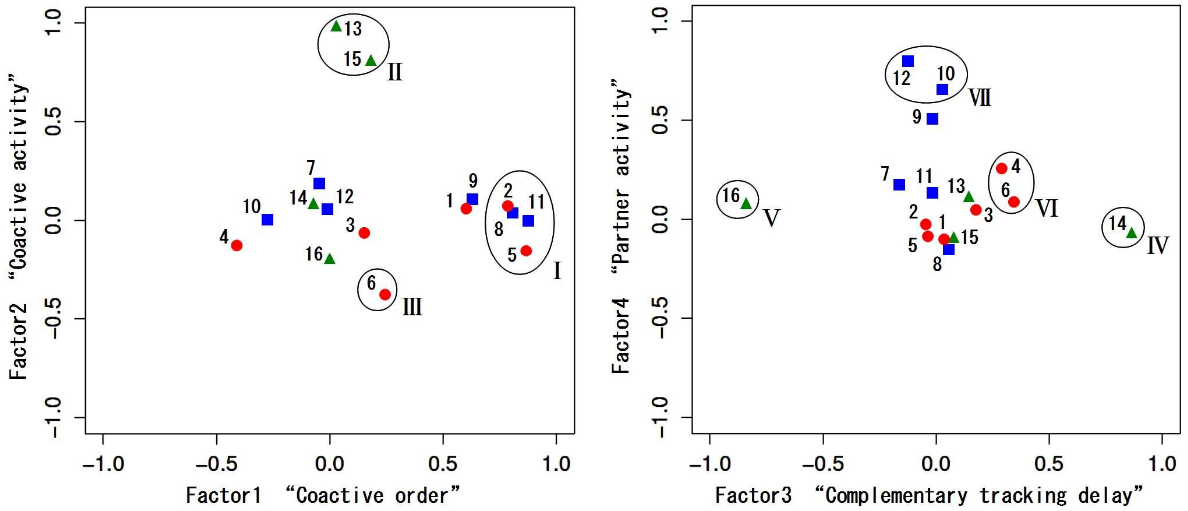
VI. RESULTS

A. Factor analysis

Fig. 5 shows the factor loading plots. The graph in Fig. 5(a) focuses on Factors 1 and 2 plotted along the horizontal and vertical axes, respectively, and the graph in Fig. 5(b) focuses on Factors 3 and 4 plotted along the horizontal and vertical axes, respectively. The circles (red) and the squares (blue) represent the self-evaluation and partner-evaluation adjective pairs, respectively. The relevant adjective pair number from Table 2 is shown next to each circle and square. The triangles (green) represent the physical quantities obtained in the measurements, with the relevant pair number from Table 3

TABLE III
PHYSICAL QUANTITIES OF SELF AND PARTNER.

No.	Self	No.	Partner
13	RMS of balancing error	15	RMS of balancing error
14	Response delay time	16	Response delay time



(a) Scatter diagram focuses on Factors 1 and 2.

(b)Scatter diagram focuses on Factors 3 and 4.

Fig. 5. Factor loadings of factor analysis results.

next to each triangle.

B. Factor interpretation

Focusing first on Factor 1 in Fig. 5(a), we find that the encircled Region I contains self-evaluation adjective pairs 2 (cooperative-uncooperative) and 5 (timely – untimely) together with partner-evaluation adjective pairs 8 (cooperative-uncooperative) and 11 (timely – untimely). The position of Region I indicates a strong positive correlation between all of these adjective pairs and Factor 1. This positive correlation of both self- and partner-evaluation adjective pairs of the same categories with Factor 1 indicates that it is a coactive factor. As these adjective pairs involve the evaluation of cooperativeness and timeliness, they may be regarded as evaluating orderliness, and Factor 1 may thus be deemed to concern “coactive order.” However, none of the measured physical quantities for self or other RMS of balancing error or response delay time shows a correlation with Factor 1. This result indicates that these physical quantities are not considered to be important with regard to coactive order.

Focusing next on Factor 2 in Figure 5(a), we find that the encircled Region II contains physical quantities 13 and 15 (self and partner RMS of balancing error, respectively). The position of this region indicates a strong positive correlation between these two physical quantities and Factor 2. As the values for both self and other in the same physical quantity category show this positive correlation, Factor 2 may be considered a coactive factor. Because the balancing error RMS is an indicator of the vigor of self and other, Factor 2 may concern “coactive activity.” It is also noteworthy that the adjective pair with the largest absolute value in its loading factor, self evaluation pair 6 (positive – negative), is located in encircled Region III, which indicates a weak negative correlation between this adjective pair and Factor 2, and thus a tendency for large self and partner balancing errors to result in the sense of the self as being strongly aggressive. It indicates further that, although achievement of a small RMS of balancing error is commonly deemed important in general control systems design, in human operation the human tends to attach relatively little importance to RMS of balancing error when acting aggressively. In contrast, no correlation was found for the partner evaluation adjective pair 12 (positive – negative).

Focusing next on Factor 3 in Fig. 5(b), we find that the encircled Regions IV and V contain physical quantities 14 (self response delay time) and 16 (partner response delay time). The relative positions show a strong positive correlation between the self delay time and Factor 3 together with a strong negative correlation between the partner response delay time and the same factor, all of which indicate a strong negative correlation between these two physical quantities. As self and other show a strong negative correlation in the same physical quantity category, Factor 3 may be regarded as a complementary factor. This shows that the partner response delay time lengthens as the self response delay time shortens, and thus an asymmetrical tendency is found in these response delay times. In short, Factor 3 may be deemed to be a factor concerned with “complementary response delay.”

Focusing finally on Factor 4 in Fig. 5(b), we find that encircled Region VII contains partner adjective pairs 12 (positive – negative) and 10 (excitable – calm), with the position of the region indicating a strong positive correlation between Factor 4 and both of these adjective pairs. The positive correlation of both of these pairs with Factor 4 indicates that it is a partner-related factor. As the two pairs concern partner aggressiveness and vigor, Factor 4 may be regarded as a factor of activity. In short, Factor 4 may be deemed to be a factor concerned with “partner activity.” With regard to physical quantities, in contrast, we find no correlation with Factor 4 by self or other RMS of balancing error or response delay time. This indicates that these physical quantities are not sensed as important with regard to partner activity.

VII. Conclusion

In this study, we were able to elucidate the relation between human operations, human sensitivities, and emotions by using a coupled inverted pendula (CIP) model representing competition and cooperation.

We first developed the CIP model in the form of a cooperative balancing movement measurement system that could actually be operated by humans in pairs. The system was used to obtain physical measurements of the operations by the two pendula ("self" and "other"), followed by sensory-based evaluation by each human operator of his own and his partner's balancing movements using the semantic differentiation (SD) method. Factor analyses of the measured self and other physical quantities and the self- and partner-evaluation SD quantities were then performed.

For the physical quantities of self and partner, the findings were as follows.

- A strong positive correlation was found between the self and other RMS of balancing errors. This result shows that an increase in balancing errors by the self tends to result in an increase in those of the other.
- A strong negative correlation was found between self and other response delay times. This result shows that a shortening in the response delay time of the self tends to result in a lengthening in that of the other, and vice versa. (The same tendency was ascertained in a previous report [10].)

These results and those of the sensory-based results taken together enabled us to identify Factor 1 as a "coactive order" factor, Factor 2 as a "coactive activity" factor, Factor 3 as a "complementary tracking delay" factor, and Factor 4 as a "partner activity" factor. Factors 1 and 4 are based on sensory-based quantities, and Factors 2 and 3 are based on physical quantities. Particularly, with regard to the factors based on physical quantities, we obtained the following results.

- Factor 2 (coactive activity) exhibits a strong positive correlation with the self and other balancing error and a weak positive correlation with the sense of self aggressiveness. In contrast, no correlation was found between the self and other RMS of balancing error and partner aggressiveness. These results reveal that in human cooperative balancing movements, contrary to general control systems design, a clear tendency exists to permit an increased self and partner RMS of balancing error in return for self-aggressiveness.
- Factor 3 (complementary tracking delay) exhibits a strong positive correlation with self response delay time, a strong negative correlation with partner response delay time, and a weak positive correlation with the sense of self activity, but no correlation of Factor 3 with a sense of partner activity was found. These results show that the sense of a short self response delay time is accompanied by the sense of strong self activity.

For Factors 1 and 4, no correlation with any of the physical quantities was found in the present study.

In a future work, the need exists to increase the number of subject participants to obtain heightened statistical significance. Also envisioned is the replacement of one of the two human subjects with a robot and experiments conducted with the substitute human-imitating controller to investigate more closely the relation between the sensory-based quantities and the physical quantities revealed in the present study.

Acknowledgment

We wish to express our gratitude to the members of the System Dynamics Laboratory of the Faculty of Engineering at Utsunomiya University for their participation and cooperation as subjects in this study.

References

[1] Li Zu-Shu, Takahashi Takayuki, Yu Kee-Ho and Inooka Hikaru, "Control of a Pendulum under Torque Limitation (Swinging-up Control by Intelligent Controller)," *Transactions of the Japan Society of Mechanical Engineers, Series C*, Vol.58, No.556, pp.3621-3626, 1992.

[2] Akio Sekiguchi and Masatoshi Tokita, "Control of Two Coaxial Wheeled Inverted Pendulum," *Journal of the Japan Association for College of Technology*, Vol.13, No.2, pp.15-20, 2008.

[3] Sigmund, K. and Hofbauer, J. "Evolutionary Games and Population Dynamics," Cambridge University Press, 1998.

[4] Li Chunyan, Asahiro Yuichi, Yamashita Masafumi, Suzuki Ichiro and Asama Hajime, "A Distributed Algorithm for Carrying a Ladder by Mobile Robots," *RIMS Kôkyûroku*, Vol.1093, pp.242-247, 1999.

[5] Inoue, Y., Tohge, T. and Iba, H. "Cooperative transportation system for humanoid robots using simulation-based learning," *Applied Soft Computing*, Vol.7, pp.115-125, 2007.

[6] Osamu Hoshino, Satoshi Morinaga, Masahiro Murakawa, Kazuyuki Hiraoka and Shuji Yoshizawa, "Spontaneous Formation of Language in Cooperative Control of Inverted Pendulum," *IEICE Technical Report, Artificial Intelligence and Knowledge-Based Processing (AI)*, Vol.99, No.95, pp.47-54, 1999.

[7] Katsutoshi Yoshida, Kazutaka Yokota and Shinichi Watanabe, "A Study on Mechanical System Representation of Competition and Cooperation," *Transactions of the Japan Society of Mechanical Engineers, Series C*, Vol.74, No.741, pp.1311-1316, 2008.

[8] Yoshida, K. and Ohta, H, "Coupled Inverted Pendula Model of Competition and Cooperation," Journal of System Design and Dynamics, Vol.2, No.3, pp.727-737, 2008.

[9] Katsutoshi Yoshida and Hiroki Ohta, "Coupled Inverted Pendula Model of Competition and Cooperation," *Proceedings of Dynamics and Design Conference 2008 (CD-ROM)*, No.143, 2008.

[10] Katsutoshi Yoshida and Atsushi Higeta, "Coupling Effects in Human Balancing Tasks," *Proceedings of 40th International Symposium on Stochastic System Theory and its Applications*, pp.264-269, 2009.

[11] Shinichi Watanabe, Koichi Ozaki, Yuuma Yamazaki and Sumio Yamamoto, "Recognition and Language Estimation of Fine Particles through Tactile Sensing with Fingers," J. Jpn. Soc. Precis. Eng., Vol.71, No.11, pp.1421-1425, 2005

[12] C. E. Osgood, G. J. Suci, P. H. Tannenbaum, "The measurement of meaning," University of Illinois Press, 1957.

[13] Tsuyoshi Yamada, Taketoshi Sugisawa and Junichiro Murai, "Easy Statistics by R Language (in Japanese), Ohmsha, 2008.