The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

A Simple Control Design for Human-Robot Coordination Based on the Knowledge of Dynamical Role Division

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Abstract— **This paper discusses skillful role divisions of coordinated motion between two agents in a crank-rotation task. The roles for coordination, called "dynamical role division," emerge from dynamic interaction between the agents, through which each agent comes to play a specialized role without conscious understanding. This paper also proposes a novel approach to apply this latent skill in coordinated motions to human-robot coordination, and showing the following advantages of this method: 1) controls of each agent's actions are simplified; 2) task performances are improved in a simple manner.**

I. INTRODUCTION

A. Background and motivation

The human-robot cooperation would be a key issue as scopes of humans and robots working together are increasing in advanced-technological societies. An approach to unravel latent skills required for human-robot cooperation is to observe fruitful coordinated motions between humans, and apply acquired results to coordinated motions between humans and robots [1]. We empirically know that an appropriate division of roles often brings good performances to the whole work, resulting in an efficient completion of tasks done by a number of persons [2][3]. To apply this profitable knowledge to human-robot cooperation, however, it is necessary at least to interpret 1) how role divisions emerge in unbidden cooperative movement between persons, and 2) what merits can be obtained from the division of roles. In this paper, we focus on "dynamical role division" between a person and a robot, and propose a novel approach to human-robot cooperation to exploit the nature of humans utilizing intrinsic strategies to achieve effective performances in coordinated motions.

B. Related works and problems

Reed et al. investigated the cooperative movement between two persons standing face-to-face and turning a crank into certain target angles as quickly as possible [2][4]. Their fascinating findings can be summarized as follows: 1) the task performance was improved when it was executed rather by two persons than by one person; 2) the persons unconsciously shared the roles of acceleration and deceleration for coordinated crank movement; and 3) the persons unconsciously shared the roles of applying certain directed forces. The fact that such a sophisticated cooperation emerged unconsciously after several trials without any verbal communication or eye contact was very interesting. Reed et al. also analyzed the specialized-role division of acceleration and deceleration on the force related to the crank rotation (referred to as "tangential force"), and tried to apply this result to the coordinated motion between a person and a robot [5]. The robot, however, could not complete the coordinated task as quickly as two persons working together did. They cited an insufficient understanding of dynamical role division as the cause of the result.

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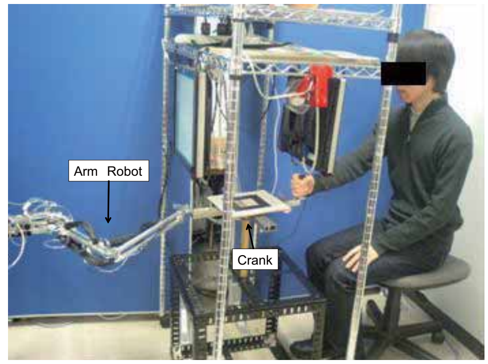

Fig. 1. Human-robot crank-rotation task.

C. Approach

The dynamical role division of the coordinated motion between two persons in the crank-rotation task includes not only "tangential force" but also "radial force". For a deeper understanding of the dynamical role division, we analyzed the role division on the force from another aspect: the "radial force". We demonstrate that the radial force is crucial to positioning of the crank. We also introduce a human-like arm robot equipped with pneumatic artificial muscles which is capable of rotating the crank together with a person(Fig. 1). A simple control strategy which exploits the knowledge of dynamical role division applied for human-robot cooperation is also proposed. Through analyses of coordinated motions between persons as well as the comprehension of successful coordinated motion between a person and a robot, this paper especially highlights following presumably advantages of the dynamical role division: 1) simplification of each agent's actions; 2) improvement of task performances between agents; 3) separate responsibilities of driving force and positioning to improve the performance of the crank-rotation task.

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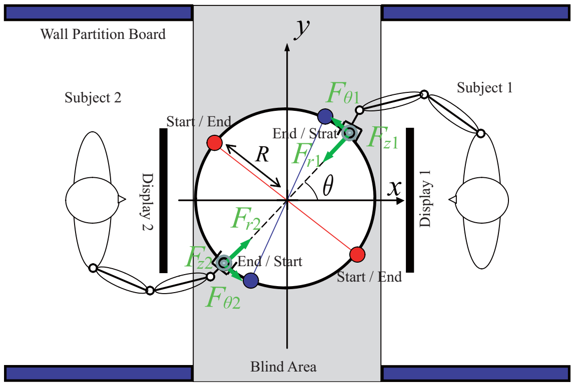

Fig. 2. General view of the human-human crank-rotation task.

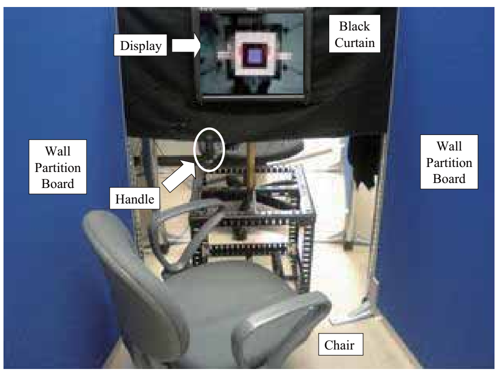

Fig. 3. Experimental setup with a crank equipment.

This paper is constructed as follows. Section II will explain the test apparatus configured and describe the task performed by subjects in detail. Section III will present the results of conducted experiments and discussion as well. Section IV will present a novel approach for the application of "dynamical roll division" in coordinated motions to human-robot cooperation. Finally, section V will summarize our results.

II. Experimental Apparatus

In this study, two subjects performed a task in which each subject pulled the crank into instructed positions in a number of times. A general view of test apparatus is shown in Fig. 2. The test apparatus consists of a machine part and a display part. The machine part includes a two-ends crank handle, and the display part shows the motion of the crank. We use the Cartesian coordinates (x, y) to express the configuration of the crank as shown in Fig. 2. The angular position of the handle, θ, is the angle between the handle and the x-axis with counterclockwise rotation. Hand forces created by each subject, the radial force F_r and the tangential force F_θ, were detected and measured by force sensors attached to each handle. The radial force F_r is positive when its direction is toward the center of the handle. The tangential force is positive if it applied toward the target. The length of the crank arm, R, is 350 [mm]. As shown in Fig. 3, in experiment the machine part is hidden by a blackout curtain, and two subjects control the crank together looking at the displays to see instructed targets. A camera is set on the metal frame hanging the curtain to capture the movement of the crank with attached markers. Library ARToolkit [6] for the C language is used and three-dimensional positions are calculated from camera viewpoint and the information of markers detected from the camera image. The monitors display target regions, number of attempts, and elapsed time based on calculated crank angle θ. During the experimental time, both subjects have no visual communication as well as exchange information but only communication by means of touching the freely spinning handle. The target of crank motion is a 20 [deg]-width region between two lines displayed on monitors. A target appears alternately with right and left, seeing from a subject. The right and left side targets can be varied from $\theta = 30$ [deg] to 40 [deg] and $\theta = -30$ [deg] to -40 [deg], respectively. If the crank is moved between these two lines and stays still for a while, a new target will appear. Standby time is set to be within $1.0 - 3.0$ [sec]. A trial is completed when subjects move the crank into target regions as quickly as possible and hold it there until a new target appears. The numbers of attempts were 40 trials.

TABLE I

Subject's data.

	Sex	Age	Height[cm]	Weight[kg]
A	Man	21	171	61
B	Man	21	172	57
C	Man	21	168	53
D	Man	21	177	65
E	Man	21	175	60
F	Man	21	170	62
G	Woman	20	152	45
H	Man	21	171	63
I	Man	22	175	48
J	Man	25	173	60
K	Man	21	170	52
L	Man	21	176	58
M	Man	21	173	63
N	Man	20	163	60
O	Man	29	168	77
P	Man	24	170	61

* Subject O is a left-handed person.

Eight groups (16 people) participated in the experiment. Each subject's sex, age, height, and weight are described in Table 1. A combination of two subjects forms a group, for example, the combination of Subject A and Subject B forms group AB. Each subject was asked to perform both individual and group tasks in order to compare performances in two cases. To be able to investigate any differences appeared in skills to complete the task, half of the subjects (group AB, EF, IJ, and MN) first performed the individual task, and then the group task. The remaining half (group CD, GH, KL and OP) performed trials in a reverse order.

III. Experimental Results and Discussion

A. Improvement through trial times

Fig. 4 shows the average trial time of the last ten of 40 trials in both cases, two subjects working together and one

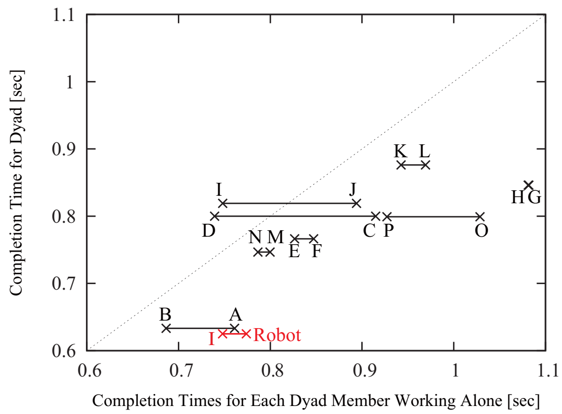

Fig. 4. Completion times of individuals and completion times of groups from 30-40th trial.

working individually. Horizontal axis shows the average trial time of each subject performing individually. Vertical axis illustrates the average trial time of that subject in work group. Robot's experimental results will be described in Section IV. Trial time starts to be counted when a task appears on the monitors until it is completed. The aim is to complete the task as fast as possible. In this figure, each subject is presented by an ×-mark accompanied with his/her corresponding alphabet letter. A group is identified by a line connected between the two subjects' marks. The dotted line represents the instant when the elapsed time of groups and individuals is the same. If data is located above the dotted line, the completion time of the group is longer than that of individuals. Contrarily, if data is below the dotted line, individual's trial time is longer. As shown in Fig. 4, 14 of 16 subjects' trial times are below the dotted line, thus expressing trial times of groups are shorter. This result implies an improvement in performance.

B. Hand force waveform of individuals

Tangential and radial forces applied by subjects to the crank show certain patterns from about 3rd-10th trials. The force waveform patterns of all individuals are similar. Data of subject A is plotted in Fig. 5 as an example. Tangential force is positive if it is applied toward the target, and radial force is positive if it bears to the center of the rotation. A crank task includes two kinds of motion, counterclockwise movement and clockwise motion. In Fig. 5, the left-handed side and right-handed side parts show counterclockwise and clockwise results, respectively. When the tangential force is positive (negative), the crank motion is in the acceleration (deceleration) phase. As shown in Fig. 5, there is one peak point in each phase of the tangential force. The radial force increases in the acceleration phase, and decreases in the deceleration phase. When the direction of the radial force comes out of the center of the rotation, the crank motion tends to reach a stable condition since radial force enlarges the tangential force toward an equilibrium position, thus decreasing the angle variation. Alternatively, when the radial force goes into the center of the rotation, it adds force to the tangential force in the direction that enlarges the change

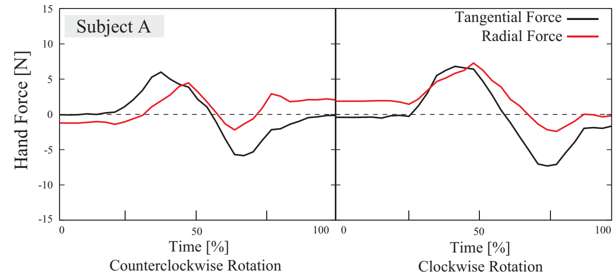

Fig. 5. The average force waveforms of individual in 30 - 40th trial.

of the shifted angle, thus, the trend of the crank motion is unstable[3]. Therefore, when the radial force is positive, the crank motion is accelerated and tends to reach an unstable condition as that of starting point. On the other hand, when it is negative, deceleration and crank positioning can be performed to achieve a stable condition as in the end position.

C. Hand force waveform of group work

The crank motions from left to right (counterclockwise) and from right to left (clockwise) have different characteristics as two separate tasks. Fig. 6 shows the average force waveforms of clockwise rotation of the last ten attempts (30rd-40th trials, like in section III-B) of groups AB, CD and EF. In each graph, the upper part displays the waveform of tangential force of each subject as well as the sum, while the lower part shows the waveform of each subject's radial force.

In clockwise rotation, the waveform of the sum of tangential force has two peaks, each in the acceleration phase and in the deceleration phase. This waveform is similar to the individual one plotted in Fig. 5. Although two subjects performed the same task, each subject played a completely different attempt. The waveform of group AB shows that there is a competition of the tangential force in the deceleration phase. All resultant waveforms of other groups (Group CD, EF, ...) show the same competition of the tangential force in the deceleration phase. On the other hand, the waveforms of the radial force shown in Fig. 6 are similar to those plotted in section III-B. The radial force tends to increase in the acceleration phase, and decreases in the deceleration phase. The whole strategy of groups, therefore, is presumably similar to that of individuals.

D. Dynamical role division

The experimental results of group EF show an interesting dynamical role division performance. The waveform of forces in the clockwise rotations of the last ten trials, is shown in Fig. 6. As shown in this figure, subject E chiefly provides tangential force while subject F prominently gives radial force. Thus, there is a coordinated strategy in which each subject is responsible for either tangential or radial force. To observe the process of forming a coordinated strategy of each subject, the temporal evolution of force vectors is plotted in Fig. 7. Waveforms of four trials, the 2nd (upper left), the 4th (upper right), the 10th (lower left),

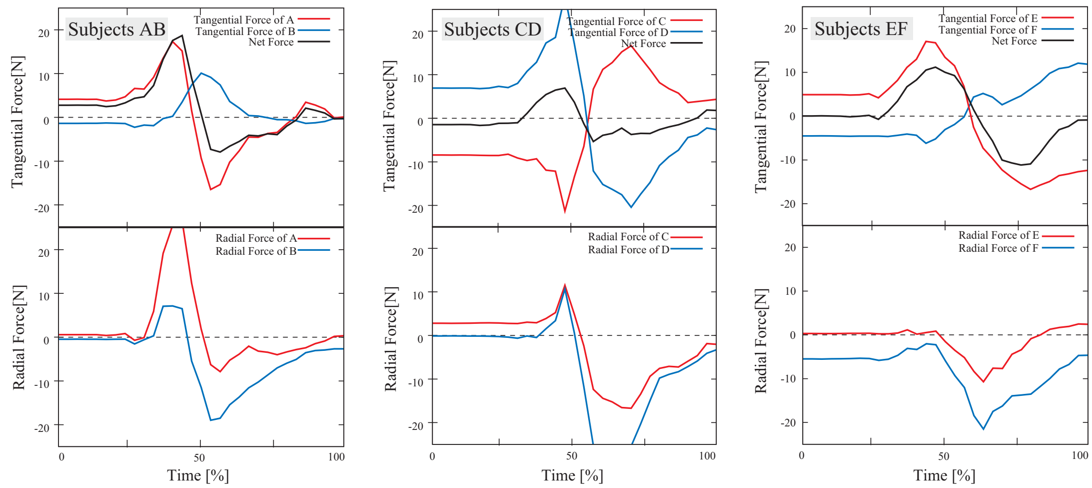

Fig. 6. The average force waveforms of group AB, CD, EF in 30 - 40th trial.

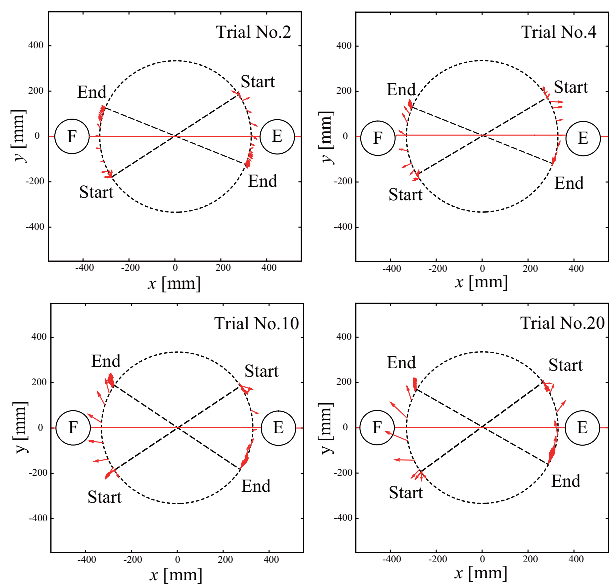

Fig. 7. Temporal evolution of force vectors yielded by two people.

and the 20th (lower right), are displayed. The length of an arrow indicates the magnitude of force. In the 2nd trial, both subjects' forces are small, and each person produces force in a similar way. In 4th trial, a difference in the force appears and increases. Since the 10th trial, patterns of the force waveform remain steads. According to Fig. 6 and Fig. 7, in a steady state subject E takes charge of producing tangential force, whereas subject F is responsible for supplying radial force. It is mentioned above that tangential force is the force of moving the crank, while radial force is responsible for positioning it. Concerning Reed's researches[2][4][5], the performance of group EF is said to be a "specialization" in which subject E takes charge of driving force, and subject F is responsible for positioning the crank. The improvement of task performace (completion time) is confirmed from the number of force vector arrows, because force vector is plotted by each time step. The dynamical role division has contributed to the simplification of each subject's action and the improvement of subjects' performances.

The experimental results show three skills in the cooperative crank-rotation task: 1) the competition in the tangential forces; 2) the regulation of the crank position by the radial force; and 3) the division of dynamic roles. It is interesting that such an advanced-coordinated movement is performed without any exchange of communication but with only force sensing via a freely spinning handle. These physically understandable skills would also be available to simplify complicated human-robot cooperation. In the next section, we focus on the skill of dynamical role division to verify how the simple control method improves the task performance between human and a robot.

IV. Application of Dynamical Role Division to Robot Control

A. Hypothesis of advantages of dynamical role division

From the consideration of dynamical role divisions, three following hypotheses can be considered as advantages in dynamical role division of tangential force and radial force.

1) Controls of each agent's actions are simplified.
2) Task performances are improved in a simple manner.
3) Since the tangential force is independent of the radial force, each subject does not need to adjust his timing finely with the partner (separate responsibilities of driving force and positioning).

To demonstrate that, we carried out a cooperative crank-rotation task with an arm robot which is able to perform dynamical role division. The experimental system is the same as one used in Section II.

B. Experimental apparatus

The experimental apparatus is shown in Fig.8. Participating subjects in each trial were a human and the arm robot. A human subject, like the subjects in Section II, got given tasks by watching the display. The arm robot, on the other hand,

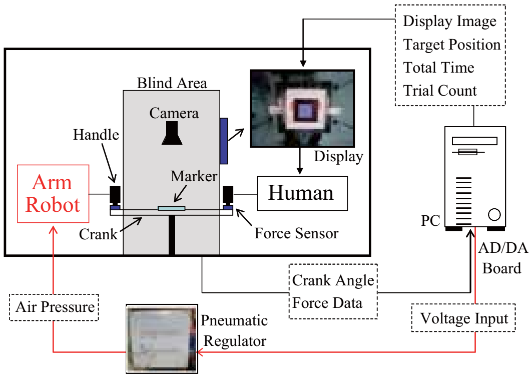

Fig. 8. General view of experimental system.

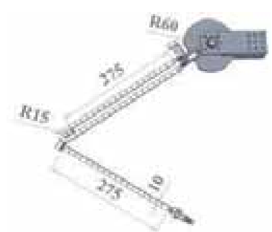

Fig. 9. 3D model of the robot arm.

Fig. 10. Pneumatic muscle robot arm.

directly processed measurement information from the PC control. Measurement information is the rotating angle of the crank, the forces of human subjects and the arm robot. Fig.1 shows an experimental test performed by a human subject and the arm robot. The arm robot, a replic of a human arm, is built up with pneumatic artificial muscles (made by Kanda Tsushin Kogyo Co., Ltd.). The 3D model with dimension in millimeters of the arm robot is shown in Fig.9. The height of the robot is fixed. Although the arm robot has five degrees of freedom, three of them, the horizontal rotation of the shoulder, the rotation of the elbow joint and free rotation of the wrist, are used. Supply pressure given to the pneumatic artificial muscle is controlled by voltage commands from PC to the air pressure control device (made by Hitachi Medical Corp.) which powers the pressure according to voltage changes via a proportional electromagnetic valve.

C. Method to control arm robot

In this experiment, "antagonist ratio control" is devised as the control approach of the arm robot. One degree of freedom of a joint is controlled by two parameters, antagonist ratio A_r and activity A_c. The antagonist ratio means the ratio of the pressure (Pre_a, Pre_b) given to the competitive artificial muscles a and b, respectively, ranges from 0 to 1. The activity is the maximum pressure given to artificial muscles according to the antagonist ratio. These relationships can be defined as follow.

$$\begin{cases} Pre_a = A_r \times A_c \\ Pre_b = (1.0 - A_r) \times A_c \end{cases} \quad (1)$$

$$A_r = \theta_d \times \frac{1}{\theta_{\max} - \theta_{\min}} \quad (2)$$

$$A_c = P[\text{MPa}] > \bar{P}[\text{MPa}] \quad (3)$$

where θ_d is the target angle, $\theta_{\max}$ and $\theta_{\min}$ are the maximum and minimum angles of the movable range of the joint, respectively. P represents the sum pressure of two artificial muscles a and b. $\bar{P}$ is the pressure to verify the dislodging of the joint at the maximum angle and the minimum angle. Since the antagonist ratio is independent of the activity, the arm robot can be in the condition which forces are added (high activity) or subtracted (low activity) with the same target angle.

D. Simple setting of the arm robot movement

Toward a simple design for robot control, we constructed the arm robot so that it mainly takes charge of producing the radial force. The robot was controlled in a manner that the instruction is "apply radial forces in the direction which go out of the center of the rotation". The applied radial force of the arm robot is about 5 [N]. The Bang-bang control signal is given to artificial muscles each time the position of targets changes. In human-human experiments, humans' forces tend to increase during trials from a not so strong initial force. In order to imitate that, in the first trial, the activity was set to be 50 [%] of the steady-state value (0.4 [MPa]), and raised 10 [%] for each following trial. From the sixth trial, supply pressure was constant. As mentioned above, the radial force is related to positioning, hence, in this setting of movement, it is expected that the robot side would contribute positioning the crank in the deceleration phase of each trial.

E. Experimental results and discussion

Subject I, whose improvement was the lowest in the work group of Section III, was asked to work with the arm robot in the coordination experiment. The experiment procedure is the same as that of Section III.

1) Shortening of trial time: As shown in Fig.4, shortening is found in the average trial time, and particularly, the performance of human-robot group is improved respect to human-human group (case of subject I). The robot was able to adapt to the human changes during trial time. Hence, the hypothesis 2 and 3 in Section IV-A were proved.

2) The hand force waveform: The force waveform of human-robot group differs from that of human alone. It can be seen from the waveform of tangential forces plotted in the upper part of Fig.11 that in the acceleration phase (the net force is positive), the tangential force (referred to as driving force) is dominantly produced by subject I, then in the deceleration phase (the net force is negative) the tangential force is mainly provided by the robot. This means that the subject I takes charge in the acceleration phase, while the robot is in charge in the deceleration phase. It shows that the robot cooperating with human can quickly perform the crank motion skillfully. It is also illustrated in the lower part of Fig 11 and in Fig 12 that the robot's radial force is larger than human's radial force. Thus, it can be said

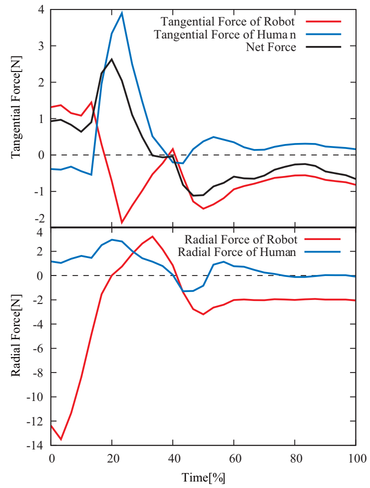

Fig. 11. Average force waveforms produced by human-robot group in 30-40th trials' clockwise rotations.

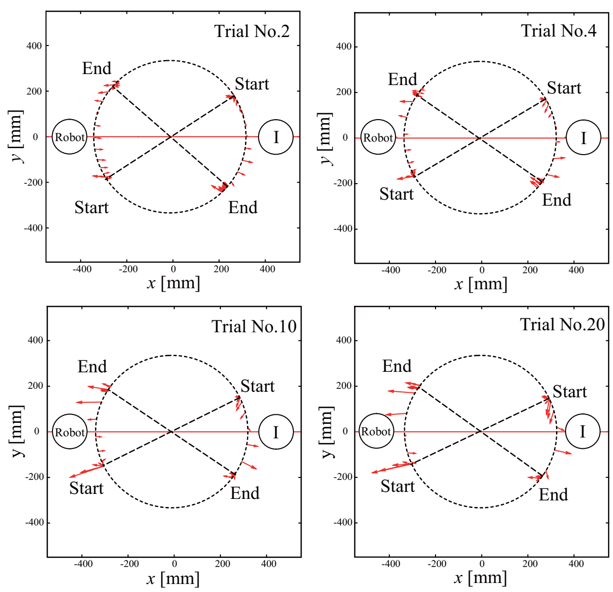

Fig. 12. Temporal evolution of force vectors yielded by human and robot.

that the role division of the tangential force and the radial force was performed. The improvement of task performace (completion time) is also confirmed from the number of force vector arrows in Fig. 12.

By referring to human's dynamical role division, in this experiment, the coordinated movement and the improvement compared with human-human group's performances were observed. It confirms the hypothesis 1 (in Section IV-A) that the robot achieves a good cooperation with human by a simple control. Moreover, this result has suggested that dynamical role division of the tangential force and the radial force is a very effective strategy.

V. Conclusion

In this paper, we investigated the dynamical role division in a cooperative crank-rotation task. The waveforms of force produced by individuals and those by two subjects working together were compared. Although there is a similarity in the waveform of the tangential force, individual tangential forces in group work tend to be different as time passes. It was also found that in a group each subject performed the same strategy to control the positioning of the crank by means of using radial force.

When two people work together, one primarily takes charge of tangential force (driving force) and the other mainly contributes to radial force (positioning), thus performing in a manner characteristic of cooperative tasks. Hence, in work group participants are separately responsible for dynamical roles of driving force or positioning to perform coordinated movement. This dynamical role division is thought to contribute to the simplification of each subject's attempt and the improvement of group performance.

Experimental results also show that in cooperated work, 1) the tangential forces competition, 2) the positioning of the crank by using the radial force, and 3) the separate dynamic role division were performed. This result is interesting since such a high-level cooperation is generated after only about 10 trials without any conscious understanding and visual communication.

We have developed a human-like arm robot which rotates the crank in a coordinated task with a person, and also proposed a novel control strategy to exploit the dynamical role division based on the effective performance in human-human cooperation. The excellent performances of coordinated motions between agents were realized when two agents unconsciously shared the specialized roles of adjusting the strength and directions of forces against the crank. The remarkable advantages of the proposed approach are summarized as below: 1) controls of each agent's action are simplified; 2) task performances are improved in a simple manner.

The knowledge gained from this study may lead to a deeper understanding of people's coordinated movement, and may serve as a foothold in designing control of robots in coordinated operating with people.

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