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A Study on Dynamical Role Division in a Crank-rotation Task from the Viewpoint of Kinetics and Muscle Activity Analysis

Hang T.T. Pham, Ryohei Ueha, Hiroaki Hirai and Fumio Miyazaki

***Abstract*— This paper focuses on dynamical role divisions of cooperation interaction between two human subjects in a typical cooperation task, the crank-rotation task. The dynamical role division in which each subject plays a specialized role without conscious understanding is a key issue that brings the efficiency to the performance of the crank-cooperation work. By investigating kinetics and muscle activities, we found out interesting results about the correlation between the muscle activities and the hand motion, thus, suggesting a method to design control of robots which involve in the crank-cooperation task and presumably in other cooperative interaction with humans.**

I. INTRODUCTION

A. Background and motivation

As the number of robots, especially the robots working in cooperation task with humans, such as rehabilitation robots, surgical robots, entertainment robots, is constantly increasing, the human-robot cooperation would be a key issue nowadays. An understanding of the cooperation between humans thoughtfully benefits to the control design of robots which work cooperatively with humans. From empirical understandings of the facts that an appropriate division of roles often improves work performances [6][7][8][9][10], and muscle activities have an effect on movement [1], this research focuses on "dynamical role division" of two persons in a crank-rotation task by examining the correlation between kinetics and muscle activities.

B. Related work

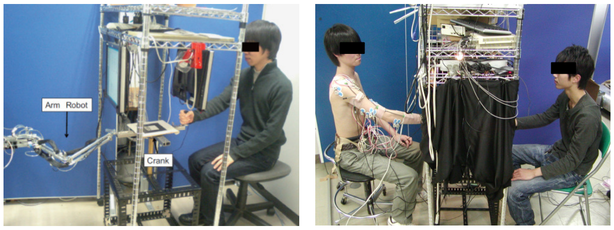
K. Reed *et al.* [6][7] investigated the cooperative movement between two persons standing face-to-face and turning a crank into certain target angles as quickly as possible. They reported that the dyads "specialized" temporally such that one member took on early parts of the motion and the other late parts. This strategy resulted in a more efficient performance. The interesting finding was that such a sophisticated cooperation emerged at a level below the awareness of the participants only after several trials without any verbal communication or eye contact. K. Reed *et al.* [8] 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. The robot, however, could not complete the coordinated task as quickly as did two persons working together. They cited an insufficient understanding of dynamical role division as the cause of the result.

There is an increasing concern in studies involving the kinematics and muscle activities of arm movements. It is likely that there is a high correlation between muscle activities and arm movements. O. Levin *et al.* [5] reported a different role of the shoulder and elbow muscles in the manipulation of the hand end-effector trajectory. He also reported the co-variation of muscle activity during multi-segmental control with the orientation of arm movements and inter-segmental interaction torques. These results suggest a way to approach reaching movements and/or drawing task by observing arm speed, joint dynamics and muscle activities.

C. Approach

In the previous work, we examined the dynamical role division between two persons in a crank-rotation task by studying the hand forces (tangential and radial forces), and applied the results into a human-like robot arm which was expected to perform a similar role sharing with human subject [10]. Though we did observe a cooperation strategy in which the human subject took charge in the acceleration phase while the robot was in charge in the deceleration phase, the strategy was mainly caused by the human subject since the arm robot was constructed to produce only the radial force. The performance was improved when the human subject produced tangential force by chance. Therefore, it is necessary to improve the robot in a manner that it is adjustable to cooperate with human subject, particularly, to perform division roles in the crank-cooperation task. It should be able to mimic the dynamics of human arm that are consequently controlled by central nervous system through muscles and joints. In order to do that, we again considered the dynamical role division in the 2-person cooperation task with an expectation of achieving better results to apply to the robot-human cooperation task. Specifically, we have investigated not only the kinetics but also muscle activities since an understanding of the correlation between these two aspects is thought to clarify the mechanisms of dynamical role division performance. We studied muscle activities by examining electromyographic (EMG) features of subjects' arm muscles. The results showed off a high correlation between the muscle activities with the hand force and hand movement, therefore, this study provides an idea to design the robots involving in the cooperative interaction with humans based on that interesting correlation.

This work was performed at Osaka University. All the authors are with the Department of Mechanical Science and Bioengineering, Graduate School of Engineering Science, Osaka University, Japan. The authors email addresses are: phamhangtt@robotics.me.es.osaka-u.ac.jp ueha@robotics.me.es.osaka-u.ac.jp hirai@robotics.me.es.osaka-u.ac.jp miyazaki@robotics.me.es.osaka-u.ac.jp



(a) Robot-human (b) Human-human

Fig. 1. Experiment view: a) Experiment between the robot arm and a human subject, b) experiment between 2 human subjects.

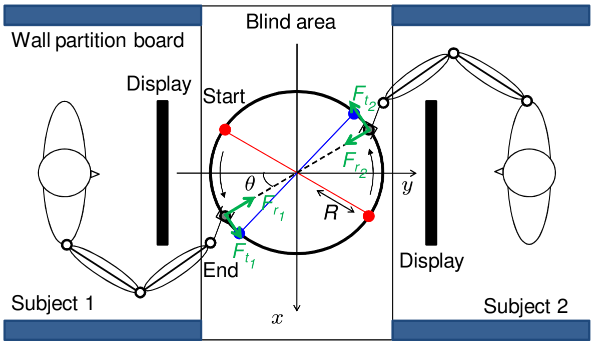


Fig. 2. General view of the crank-rotation task. Hand forces of both subjects were measured. EMG signals were recorded from Subject 1.

This paper focuses on kinetics and muscle activities of one human subject in the 2-human crank-cooperation task. After describing the test apparatus, performed task and data measurement, section III presents the results of conducted experiments with discussion. Section IV summarizes our results and states the future plan.

II. EXPERIMENTAL APPARATUS

A. Experimental setup

Four subjects (male, right-handed) with no known neuromuscular deficits and no experience about the experiment participated in the test. The experimental procedures complied with the rules of the local ethical committee. In this paper, we call the 4 subjects “A”, “B”, “C” and “D”, respectively.

The general view of the experimental apparatus is shown in Fig. 2. The experimental apparatus consists of a 2-handle crank with the length R of 350 mm, force sensors (USL06-H5-200N) mounted on each end of the handle to measure hand forces exerted by each subject, a camera (QCam Pro 9000, Logicool) to capture the motion of the crank, 2 displays to show the targets and information, and a blackout curtain hang between 2 subjects to prevent visual communication. Camera setup and real-time crank tracking were programmed by using Library ARToolkit for C language. A computer was used to transfer targets to the displays as well as to get measured data. EMG signals of target muscles (see Fig. 3) were recorded by using surface electrodes. After cleaning the skin by skin pure gel, surface

TABLE I
SUBJECTS' DATA

Subject	Age (years)	Height (cm)	Weight (kg)
A	22	171	63
B	22	168	54
C	22	173	63
D	22	173	62

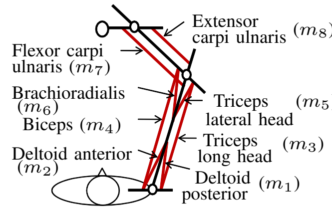


Fig. 3. Target muscles

TABLE II
AGONIST-ANTAGONIST MUSCLE PAIRS

Pair	Muscles	Function
r_1	m_2/m_1	Shoulder extension
r_2	m_3/m_4	(Shoulder extension) & Elbow flexion
r_3	m_5/m_6	Elbow extension
r_4	m_7/m_8	(Elbow extension) & Wrist flexion

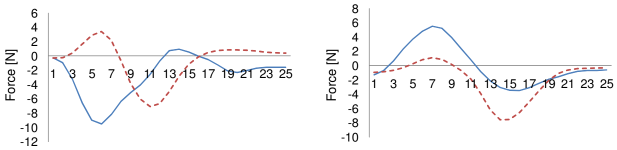
electrodes were placed on the skin according to the EMG guidelines by Hislop *et al.* [3].

We use the Cartesian coordinates (x, y) to express the configuration of the crank. The angular position of the handle, θ, is defined as the angle between the handle and the y-axis with counterclockwise rotation. The tangential force $\mathbf{F}_t$, perpendicular to the crank shaft, is positive if it is counterclockwise. The radial force $\mathbf{F}_r$, whose direction goes along the crank shaft, is positive if it is toward the center of the handle.

The target of crank motion is a $20°$-width region between 2 lines displayed on monitors. It varies from $(-40° : -30°)$ left to $(30° : 40°)$ right. A target appears alternately with right and left, seeing from a subject. If the crank is moved into the target area and held there for a while, a new target will appear. Standby times for a new target appearing was set to be within $(1.0 : 3.0)$ sec. Given targets and standby time were programmed by using C language.

B. Data recording

The only instruction given to subjects was to move the crank into target areas as quickly as possible. Subjects sitting comfortably in the opposite side controlled the crank together to complete the given targets on the displays. Visual and verbal communications were not allowed during experiments. Subjects performed and completed the task only by haptic sensing in terms of touching the freely-spinning handle. Subjects participated in both individual and group tasks. The number of tests was 12 for each group, including 6 individual tasks and 6 group tasks. Initially, subjects were asked to perform maximum voluntary isometric contractions (MVC) of 8 target muscles in order to normalize EMG data. EMG data used to analyze were recorded during each test. After amplified, the analog EMG signals were converted to digital signals (AD Logger LX-110 (TEAC)) and transmitted to the computer at a sampling rate of 1 kHz.



(a) Clockwise rotation (b) Counterclockwise rotation

Fig. 4. Hand forces of individuals in the crank task. Solid lines: tangential force, dashed lines: radial force.

C. Data analysis

Kinetic data are time-normalized to 100% of the movement so as to allow for graphic representations of handle motion (x, y) and hand-force profiles $(\mathbf{F}_t, \mathbf{F}_r)$. We define muscle activity index of a muscle pair as the sum of EMG signals of agonist and antagonist muscles. Agonist-antagonist ratio is defined as the ratio of EMG signals of agonist and antagonist muscles. EMG signals are band-pass filtered at (10-150) Hz, full-wave rectified, amplitude normalized, and time-normalized. Time-normalization divides 100% of the movement into 25 periods, from t_1 to t_{25}. The EMG signals then are compressed by using Principal Component Analysis (PCA), a method to reduce the dimensionality of variables in a way that the maximum amount of information is preserved (Vallery *et al.* [11]). Principle components (PCs) are found from correlation matrix whose elements are agonist-antagonist ratio.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Role of hand forces

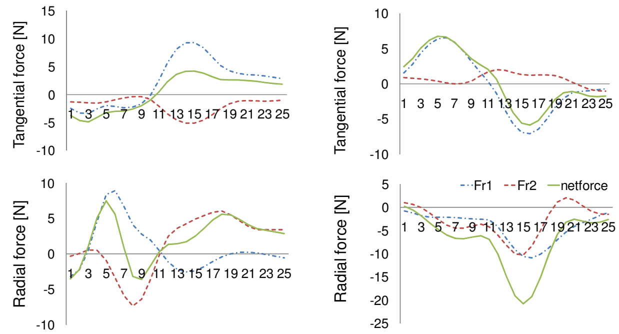
A crank task includes 2 kinds of motion: counterclockwise and clockwise rotations. All individuals produced a similar hand-force profile. Fig. 4 plots the hand-force profiles of individual tasks. The horizontal and vertical axes show normalized time and subject's hand forces (F_t, F_r), respectively.

In the clockwise rotation, the crank is accelerated (decelerated) when the tangential force is negative (positive). Conversely, in the counterclockwise rotation, when tangential force is positive (negative), the crank motion is in the acceleration (deceleration) phase. The tangential force, then, is thought to be responsible for driving the crank.

The radial force, on the other hand, increases in the acceleration phase and decreases in the deceleration phase. When the radial force is positive, the crank tends to reach an unstable condition. When it is negative, the crank tends to reach a stable condition. The radial force, therefore, is referred to as the positioning force [9][10].

B. Dynamical role division

There is a role sharing between subjects in group tasks. All of group tests provided similar performances. As an example, Fig. 5(a) and Fig. 5(b) plot hand forces of group task in the clockwise and counterclockwise rotations, respectively. Horizontal and vertical axes are normalized time and forces, respectively. Net force is the sum of component forces. As



(a) Clockwise rotation (b) Counterclockwise rotation

Fig. 5. Hand forces of 2-person crank task. Dashed-dotted lines: Subject 1's force, dashed lines: Subject 2's force, solid lines: net force. Above 2 graphs are tangential force profiles, below are radial force profiles.

shown in Fig. 5(a), in the clockwise rotation, Subject 1 mainly took the role of producing tangential force through the trials. This subject also mainly gave radial force in the early part of the test. Subject 2, otherwise, chiefly contributed radial force in the later part of the test. In the counterclockwise rotation, similarly, Subject 1 again produced most of the tangential force. Subject 2, however, was responsible for producing the radial force. As shown in these graphs, one chiefly provided force as tangential force during the trials while one prominently gave radial force throughout trial times (counterclockwise rotation) or in the later parts of the trials (clockwise rotation). Thus, there was a coordinated strategy in which each subject was responsible for either tangential or radial force. This performance is called "dynamical role division" [9].

There was an interesting performance when the dynamical role division occurred. The net force of the tangential force in the clockwise rotation was associated with the "bang-bang type control", the optimal control of the system with bounded control signals. This evidence supports the simple way to control the human-like robots by using the bang-bang control [10].

Another interesting fact is that all of groups performed the role division without reflexive understanding. This important point suggests that the dynamical role division has contributed to the simplification of each subject's action and the improvement of group's performance. Additionally, the completion time of groups was much shorter than that of individuals, implying an improvement in performance when two persons working cooperatively. The experimental results also showed an existence of competition of tangential forces. This, together with the feeling of each subject about an increase of competition forces, suggests a development in role divisions through trial times by means of producing competition forces to control the crank.

C. Correlation between muscle activity index of two-joint muscle and hand force

Two-joint muscles (m_3 and m_4) seem to have interesting effects on the hand motion. By using multiple regression analysis, we got a model which can reasonably estimate

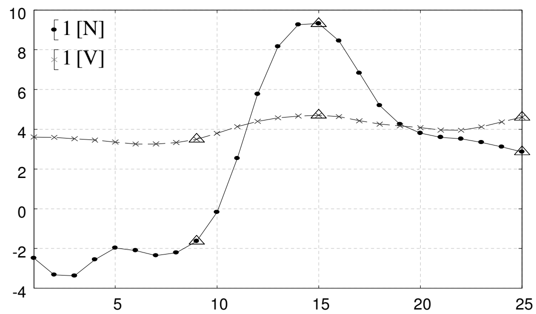


Fig. 6. Correlation between muscle activity index $(m_3 + m_4)$ and tangential force F_t (clockwise rotation). Horizontal axis: normalized time; vertical axis: tangential force F_t [N] (pointed-solid line), muscle activity index $(m_3 + m_4)$ [V] (marked-dashed line).

TABLE III
PCA RESULTS OF AGONIST-ANTAGONIST RATIO

	PC 1	PC 2
Eigenvalue	2.8	0.97
% variation	70.09	24.22
Cumulative %	70.09	94.31

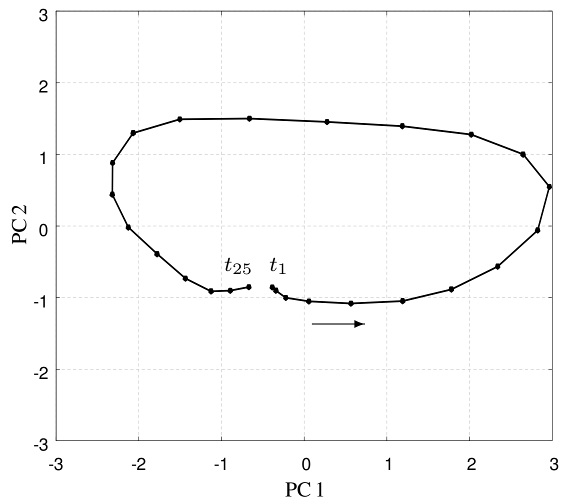
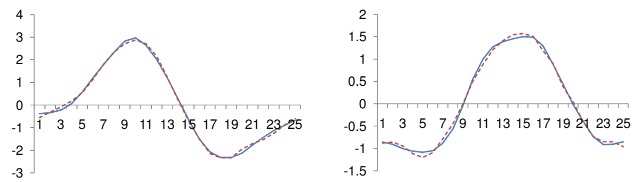


Fig. 7. Observation of the first 2 PC scores plotted against each other (clockwise rotation).



(a) Estimation of PC 1 (b) Estimation of PC 2

Fig. 8. Estimation of the first 2 PC scores by hand position and tangential force (clockwise rotation). Solid lines: analyzed PC scores, dotted lines: estimated PC scores; horizontal axes: normalized time, vertical axes: value of PC scores.

the muscle activity index $(m_3 + m_4)$ from the tangential force F_t. The correlation coefficient of determination, R^2 (ranges from 0 to 1), was 0.93, indicating that the model fitted very well. A high correlation of $(m_3 + m_4)$ and F_t can also be concluded as the probability value (p-value) was very low at 0.001. This result leads to a hypothesis that a pair of two-joint muscles plays a major role in generating the tangential force.

This hypothesis also can be proved by observing the trend of $(m_3 + m_4)$ and F_t (see Fig. 6). They begin to increase from t_9, suggesting that $(m_3 + m_4)$ initiated F_t. The plots then reach a peak point at t_{15}. At the end of the motion, $(m_3 + m_4)$ increases again while F_t decreases. This implies a high effect of the muscle activity index on the stiffness. At the peak point, there was a high stiffness to generate F_t while at the end point, there was a high stiffness to stop the motion.

D. EMG data

As the performance in the clockwise rotation was interesting, EMG signals of the clockwise rotation were used for further analysis. Since the first 2 PCs (PC 1, PC 2) accounted for over 90% of the total variation of the data set (see Table III), they were reasonable to represent the agonist-antagonist ratio. Fig. 7 illustrates the variance of PC 2 with respect to PC 1. Our objective was to understand the meaning of the muscle ratio represented by PCs as well as theirs correlations with kinetics, which may be helpful for understanding the mechanisms of the dynamical role division between two persons in the crank-cooperation task.

E. Correlation between kinetics and PC scores

Assumed the motion occurred in a very short period, we have observed a linear relation between the agonist-antagonist ratios represented by the first 2 PCs scores $(\mathbf{w}_1, \mathbf{w}_2)$ and kinetics. The model achieved R^2 values of 0.997 and 0.995 for $\mathbf{w}_1$ and $\mathbf{w}_2$, respectively, hence, it fitted the data very well. The prediction based on the multiple linear regression analysis is plotted as in Fig. 8. It shows a matching between predicted values with measured values, impressing the fitness of the model. The model also showed a high correlation between $\mathbf{w}_1$ with $(x, \dot{x}, \ddot{y})$, and between $\mathbf{w}_2$ with $(x, y, \dot{y}, F_t)$.

Moreover, the hand forces with respect to the Cartesian coordinates, $(\mathbf{F}_x, \mathbf{F}_y)$, can be reasonably estimated by using linear model of PC scores. Let $(\bar{\mathbf{F}}_x, \bar{\mathbf{F}}_y)$ be the average of $(\mathbf{F}_x, \mathbf{F}_y)$ over one clockwise rotation task. The deviation of the hand forces is given by

$$\begin{cases} \Delta\mathbf{F}_x = \mathbf{F}_x - \bar{\mathbf{F}}_x, \\ \Delta\mathbf{F}_y = \mathbf{F}_y - \bar{\mathbf{F}}_y. \end{cases} \tag{1}$$

$(\Delta\mathbf{F}_x, \Delta\mathbf{F}_y)$ can be predicted as follows:

$$\begin{aligned} \begin{bmatrix} \Delta\mathbf{F}_x \\ \Delta\mathbf{F}_y \end{bmatrix} &= \begin{bmatrix} -2.09 \\ 2.05 \end{bmatrix} \mathbf{w}_1 + \begin{bmatrix} 1.77 \\ -0.3 \end{bmatrix} \mathbf{w}_2 \\ &= \mathbf{p}_1 \mathbf{w}_1 + \mathbf{p}_2 \mathbf{w}_2, \end{aligned} \tag{2}$$

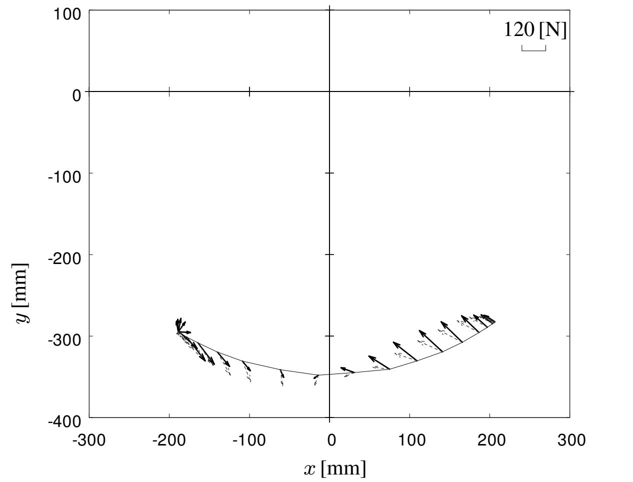


Fig. 9. Hand force vector (solid vectors) and its estimation (dotted vectors) plotted along the handle trajectory (arc) in the clockwise rotation.

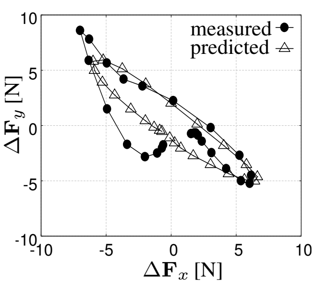


Fig. 10. Hand-force deviations ($\Delta\mathbf{F}_x$, $\Delta\mathbf{F}_y$) plotted against each other (clockwise rotation).

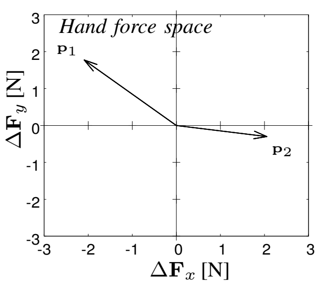


Fig. 11. Synergy vectors corresponding to scores of the first 2 PCs (clockwise rotation)

where $\mathbf{p}_1$ and $\mathbf{p}_2$ are synergy vectors corresponding to $\mathbf{w}_1$ and $\mathbf{w}_2$, respectively.

The R^2 values of $\Delta\mathbf{F}_x$ and $\Delta\mathbf{F}_y$ models are 0.96 and 0.81, respectively. The PC scores, hence, gave an acceptable evaluation model for $\mathbf{F}_x$, but a slightly lower reliable estimation model for $\mathbf{F}_y$. In general, the models by PC scores can predict the deviation of hand forces and consequently estimate hand forces quite accurately as shown in Fig. 10 and Fig. 9, respectively.

The effect of vectors $\mathbf{p}_1$ and $\mathbf{p}_2$ on the hand motion can be explained in the hand force space (Fig. 11). The vector $\mathbf{p}_1$ has an oblique direction of about $45°$, thus likely resulting in stretching motion while $\mathbf{p}_2$ has a horizontal direction, corresponding to the fact that the tangential force $\mathbf{F}_t$ had a high correlation with $\mathbf{w}_2$.

F. Joint torque contribution by muscle synergies

It is considered that the central nervous system may use muscle synergies to manage controlling a high dimensional structure using low dimensional control space. Each individual muscle force defines a sub-space of torque space whose axes are the torques about the joints [4]. Referring to our target muscles, let $\boldsymbol{\tau}_{r_p}$ $(p = 1, \ldots, 4)$ be the generated torque with respect to the p-th agonist-antagonist muscle pair, particularly, $\boldsymbol{\tau}_{r_p} = \boldsymbol{\tau}^1_{r_p}$ or $\boldsymbol{\tau}^2_{r_p}$ depending on the command of the first or second synergy. We can define the direction of $\boldsymbol{\tau}_{r_p}$ in the torque space diagram as illustrated in Fig. 12. Assumed that the generated torque is proportional to the muscle activities which are reasonably represented by the first 2 PCs, it can be estimated by

$$\begin{cases} \tau^1_{r_p i} &= d^1_p \alpha_{pi} w_{1i}, \\ \tau^2_{r_p i} &= d^2_p \alpha_{pi} w_{2i}, \end{cases} \quad (i = 1, \ldots, n), \tag{3}$$

where d^1_p and d^2_p are values of the p-th elements of the eigenvectors corresponding to the first and second synergies, respectively; $\alpha_{pi} = a_{pi}/\sqrt{a^2_{1i} + \cdots + a^2_{4i}}$ is the weight of normalized muscle activity index representing the command of the synergy to muscle pairs, a_{pi} is the muscle activity index of the p-th muscle pair and $n = 25$ is the total of observations. The torques $\boldsymbol{\tau}_{s_1}$ and $\boldsymbol{\tau}_{s_2}$ are the sum of component torques generated by the first and second synergies, respectively. Fig. 13 shows the average joint torque contributions of muscle synergies corresponding to the first 2 PCs. In the beginning of the trial, during (t_1, t_3), the first synergy generated a joint torque that made the shoulder extended and the elbow flexed. In the middle of the trial, from t_4 to t_{15}, it produced a joint torque oriented between the shoulder flexor axis and the elbow extensor axis, causing the shoulder flexed and the elbow extended. During the remaining time, the first synergy again generated a joint torque that made the shoulder extended and the elbow flexed. The torque generated by the first synergy made "shoulder flexion - elbow extension" or "shoulder extension - elbow flexion", which on the whole results in stretching motion. PC 1, therefore, played a major role in producing stretching force. The second synergy, however, in the early and late parts of the trial, (t_1, t_9) and (t_{20}, t_{25}), respectively, generated the torque pointing into the area between the elbow and shoulder extensor axes, inducing both the shoulder and elbow extension. In the middle of the trial, from t_{10} to t_{19}, the generated torque oriented between the shoulder and elbow flexor axes, making both the shoulder and elbow flexed. The joint torque generated by the second synergy, therefore, resulted in rotating motion. PC 2, hence, played a role of producing rotating force. This result agrees with the result in Section III-E. The PC 1 (first muscle command) caused stretching motion while the PC 2 (second muscle command) resulted in rotating motion. Moreover, in the beginning and at the end of the motion, muscle synergies produced joint torques oriented in the same direction. This implies a similar skill to control the crank in the beginning and at the end of the motion.

IV. CONCLUSIONS

We have investigated the dynamical role division in the crank coordinated movement by examining both kinetics (represented by hand forces and hand position) and muscle activities (represented by PCs of EMG signals) of two persons in the crank task in order to achieve a deeper investigation of human-human cooperation to re-apply to the proposed robot control and improve the robot's performance.

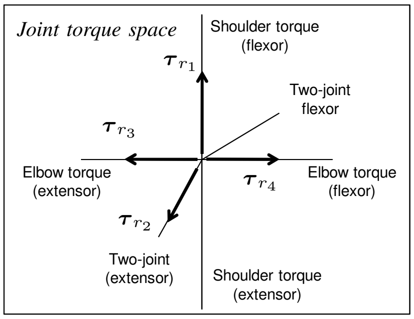
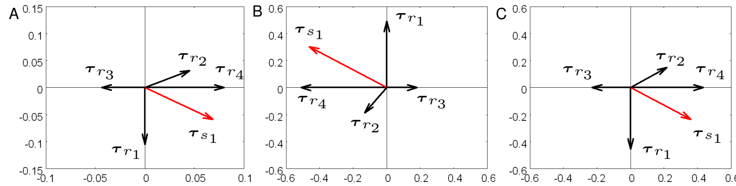
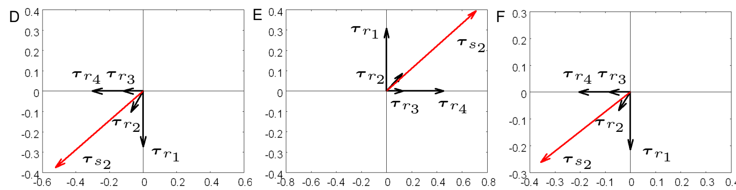


Fig. 12. Definition of joint torque orientations



(a) Average joint torque contributions by the first synergy



(b) Average joint torque contributions by the second synergy

Fig. 13. Average joint torque contributions by the first synergy (A: during $(t_1,\, t_3)$, B: during $(t_4,\, t_{14})$, C: during $(t_{15},\, t_{25})$); and by the second muscle synergy (D: during $(t_1,\, t_9)$, E: during $(t_{10},\, t_{19})$, F: during $(t_{20},\, t_{25})$) in the clockwise rotation. Horizontal and vertical axes are elbow torque and shoulder torque axes, respectively.

The dynamical role division in which two participants performed a characteristic of cooperation tasks, is thought to contribute to the simplification of each subject's attempt and the improvement of group performance. The interesting point is that after several trials, the dynamical role division was unconsciously performed between the two participants without visual nor verbal communication.

The analysis showed a high correlation between the deviations of average hand forces with muscle activities represented by the first 2 PCs. It was observed from the kinetics of the dynamical role division that there was a synchronization between the two subjects' forces. Since one subject's hand force had a high correlation with the first 2 PCs, it suggests a similar correlation in the other subject's.

The analysis also showed a high correlation between the first 2 PCs with the hand motion and the hand forces. The two-joint muscles have a high effect on the hand motion. In the clockwise rotation, the first PC played a major role of stretching motion while the second one filled the role of rotating motion. This result is thought to benefit to the design of the robot built up with pneumatic air muscles. The control algorithm based on these characteristics could make the robot behave as flexibly as does a human in the cooperation interaction.

The findings of this research are probably productive for unraveling the mechanisms of humans cooperation movement, and suggest an idea to control the robots working cooperatively with humans. We are now on the way to transfer them to the robot's control and experimental verification of achieving the human-robot crank-cooperation task.

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