Motion Analysis of Human-Human Cooperative Task and Its Application to Robotic Control

by

Ahmad Faizal bin Salleh

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in

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Advisor: Professor Dr. Ryojun Ikeura

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Alhamdulillah and praises to him for the compliment of this thesis.

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CHAPTER 1

INTRODUCTION

1.1Research Motivation

Ideas of robotic originated from many and various cultures around the worlds [1]. The term ‘robot’ which was originally proposed by Josef Capek was brought to public in 1921 by his brother, Karel Capek a dramatist, in his play Rossum’s Universal Robots [3]. With the advancement in digital computing, the first digitally operated and programmable industrialized robot, the Unimate, was installed by General Motor in 1961 in its assembly line to lift a hot piece of metal from a die casting machine and stack them. Since that, robot had been used extensively in industry to carry out a repetitive task that demanding volume, speed, precision and dependability better than human. Also, the robot was used to relieve human from bad working condition such as in dangerous, dirty, hazardous environment, etc. In most applications, the robots were separated from human for safety reasons e.g. kept in a cage to avoid life-threatening collision with humans [4].

In advanced countries, the elderly population is increasing rapidly due to low fertility and low mortality rates, see Fig. 1. This has created some other problems including the shortage of labor especially in the age of 20-65 years old. Figure 2 shows the reduction of working age due to ageing society in most industrialized nation [5]. Such problem had encouraged the used of robotic technology to substitute human workers as an alternative solution to the reduction of labors. This had induced new robotic trends which eliminated the separation and required the robot to work closely and cooperatively with human.

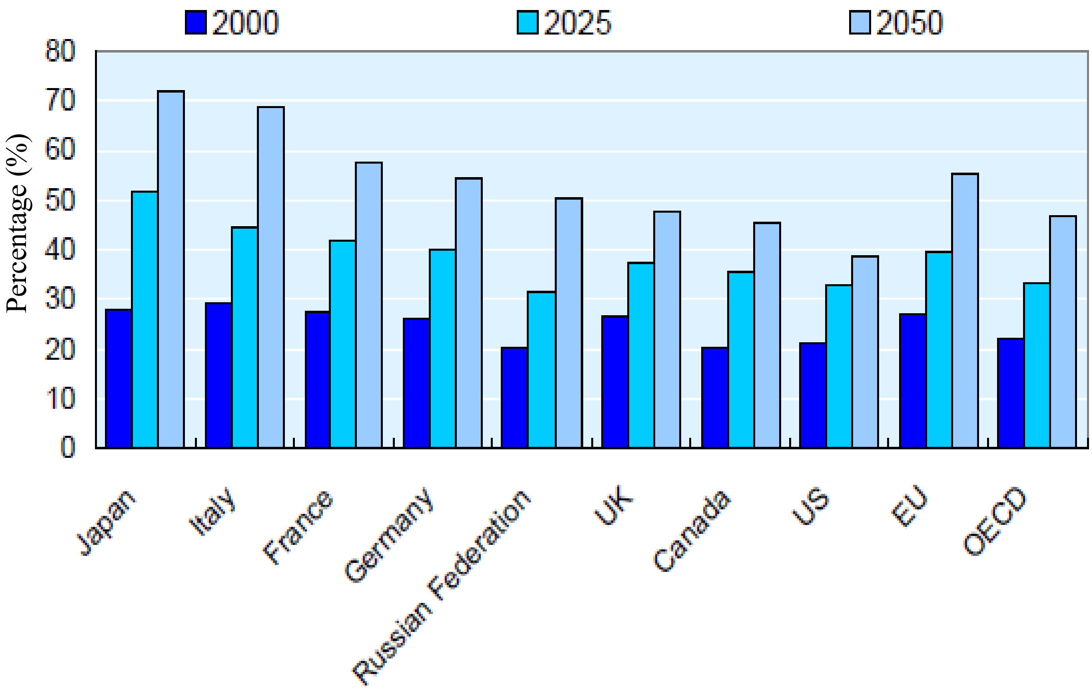


Fig 1 Ratio of the population aged 65 and over to the population aged between 20 to 65 years old.

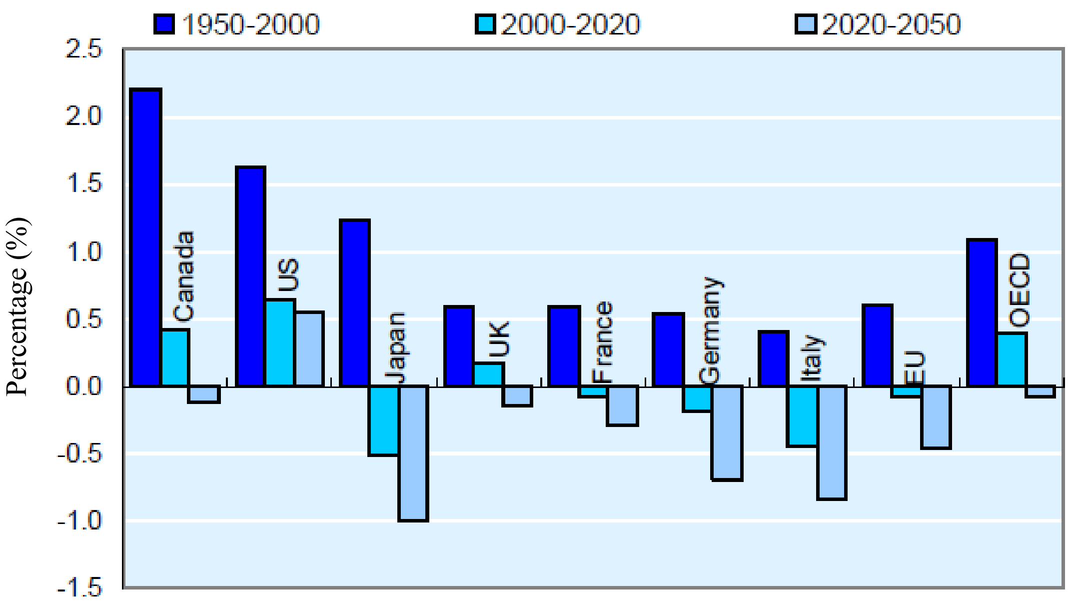


Fig. 2 Labor force growth, past, current and future in some advanced countries.

1.2 Human-Robot Cooperation

As mentioned previously, the reduction in numbers of workers has pushed the robotic technology towards human occupied environment where robot was required to work closely and cooperatively with human. The cooperation between human and robots will complement each other strength and weakness and generated an efficient system towards achieving same objective. In cooperative task involving two agents, communication between agents has significant role for successful task accomplishment [6-8]. In human-robot cooperative task, human acts as a teammate to a robot and interact/communicate towards each other in accomplishing a common mutual objective [9]. The communication occurs during the task could be classified as synchronous and asynchronous. The terms synchronous could be explained as the communication that occurs in real-time between the two agents. In contrary, the asynchronous mean that the message issued by one agent will be received by the other agent at some other time. Another classification for human-robot cooperation was based on either both agents performed the cooperative task in the same space (collocated) or not (non-collocated) and also being in the same constituent or not (attached to human's body or not attached to human's body i.e. either side by side or separated at certain distance) [10]. Table 1 and Fig. 3~5 show the classification and its example. Human-robot cooperation with synchronous, collocated and attached to human's body like power assist system was investigated by few researchers [11-19] whereby cooperation with synchronous, collocated with side by side power assist system was investigated by [20-29]. Cooperation with synchronous, non-collocated and side by side constituent as in space exploration, tele-operated robot, etc was investigated by [30-34]. Some researchers investigated synchronous, collocated, side by side cooperative object transfer between human and mobile robot [20, 35]. In this thesis, we will focus on synchronous, collocated and side by side cooperation as in arm-manipulator cooperative object transfer [36].

Table 1. Characterization of Human-Robot Cooperation

Time Characterization	**Space Characterization**	**Constituent Characterization**	**Human-robot cooperative system**
Synchronous	Collocated	Attachable	Power assist system
Synchronous	Collocated	Non-attachable	Human-robot cooperative transfer system, Power assist system
Synchronous	Non-collocated	Non-attachable	Nuclear reactor, Space exploration tele-operated robot
Asynchronous	Non-collocated and Collocated	Non-attachable	Industrial Robot.

Fig. 3 HRP-2 carrying a panel with a human (Yaskawa Electric, Shimizu Corporation, Kawada Industries, AIST)[2]. Example of Synchronous, Collocated, Side by Side human robot cooperative motion.

Fig. 4 Robot HAL suit, introduced by Professor Yoshiyuki Sankai and produced by Cyberdyne Inc. is an example of synchronous, collocated and attachable to human's body as in human robot cooperation.

Fig. 5 Fourth generation QinetiQ's Talon robot for detecting radiation level at Fukushima power plant is an example of synchronous, non-collocated, and non-attachable human robot cooperation.

http://www.crazyengineers.com/tag/talon-robot-specifications/

1.3 Arm-Manipulator Cooperative Research

Many researches have been carried out under arm-manipulator cooperation [37-44] and some focus on a safe [45-52] and comfortable interaction which provides human trust and acceptance of robot technology in human environment. This encompassed the generation of a smooth and natural motion of arm and manipulator cooperation for hand over task [53], motion assisted task like rope turning [54], microsurgical operation [55], object positioning, handling and assembly [56, 57], drawing task [58], etc. Some other researchers investigated the arm-manipulator cooperation for carrying an object from one position to another [7, 37, 39, 42, 43, 59-63]. Only few of them included humans' cooperative behaviors in their studies to generate smooth and natural arm-manipulator cooperation [64-66]. In their experiment, some information were exchanged or communicated between subjects to achieve the objective of the cooperative motion.

Hayashibara et al. [64] investigated cooperative behaviors of two humans in raising and lowering an object in vertical direction. They *focused* on maintaining the object's posture parallel to the horizontal plane during the cooperative task. One of the subjects was blindfolded and he exchanged *the object's position and posture, cooperative task initiation signal and cooperative task stop location information* with non-blindfolded partner using haptic sense to moved and keep the object parallel to the horizontal plane. Hayashibara et al. found that human's arm velocity during raising or lowering the carried object was proportional with the tilt angle of the object with respect to the horizontal plane. Finally, a controller that maintained the object's posture was proposed in arm-manipulator cooperative system.

Miossec et al. [65]investigated the cooperative behavior of two humans when lifting an object from start location and reaching the stop location. The start and stop locations of the cooperative task were placed on the same horizontal plane and 300mm distance apart from each other. They compared the cooperative lifting and reaching actual velocity profile with the minimum jerk velocity profile of the subjects. They found a more suitable velocity pattern than the minimum jerk model to resemble the cooperative motion between two humans. Both human subjects exchanged *the cooperative task starting signal, stop location, and the object position and orientation information* during the cooperative task.

Chris et al. [66] studied cooperative behaviors of a human cooperating with manipulator in raising and lowering a cylindrical long object in vertical direction too. Human subject followed the robot trajectories using either visual or tactile or both of the senses in feedback manner while maintaining the object posture parallel to the horizontal plane. Although their research had some similarity with Hayashibara et al., their research *focused* was to understand which senses human used when cooperating with a partner to carry an object from start to stop position in vertical direction. Human and robot exchanged *the object's position and posture, cooperative task initiation signal and stop location information* of the cooperative task using visual and/or tactile senses. They found that both visual and tactile were important for realizing cooperative motion between arm and manipulator.

Based on the reviews, we understood that most of the researchers included the exchanged of the *cooperative task object's position or orientation, task initiation signal and stop location information* between subjects (human-human or human-robot) towards realizing a safe and smooth arm-manipulator cooperative carrying of an object. However, *none of them investigated the effect of possessing or not possessing the cooperative task initiation signal and stop location information on generating smooth cooperative motion*. Thus, we investigated the effect of possessing or not possessing the cooperative task initiation signal and stop location information on generating smooth cooperative motion.

In our previous research [67-74], we had also investigated human cooperative behavior in carrying a rigid object prior to the development of human-robot cooperative system. In human-human cooperative system, we focused on the effect of *completely possessing or partially possessing or not posses*sing *at all* the cooperative task initiation signal and stop location information on generating smooth cooperative motion.

In the researches [67-74], if subject possessed both information before executing the cooperative task, he/she was defined as a Leader. If the subject possessed only one of the two (partially) or did not possess both information, he/she was defined as a Follower. The definition of Leader and Follower were merely based on either possessed or not possessed the information. The methods to possess the information did not influence the definition of Leader and Follower e.g. whether the Follower understand the signal to initiate and stop location through visual or aural is not matter. Based on the Leader and Follower definition, there were cases of the Leader and Follower type cooperative motion and also, Leader and Leader type cooperative motion. The former is the case where one subject knew both information and the other subject did not know both or only one of the two information. The latter is the case where both subject knew both information.

When both subjects knew both information (Leader & Leader case), each subject's trajectory was found to be overlapped with their own Minimum Jerk Model trajectory which indicated a smooth motion was generated in each subject. Also, it was understood that both subjects moved towards the target location in *feed-forward manner (independent hand rhythm) i.e. without the requirement to feedback each other motion*. Although both subjects were found to move with independent hand rhythm; both subjects' trajectories were almost overlapping, indicating a good cooperative motion. Therefore, the motion characteristics of robot in human-robot cooperative system could be programmed with the motion characteristic of one of the human subject and should be based on the subject's motion Minimum Jerk Model.

1.4 Shortcomings in Our Previous Research

In previous research, both subjects did not perceived directly on the object to understand each other motion, however, they perceived at an image (displayed on the LCD in front both of them) resembling the real object motion. Each subject were asked to perceive at the different parts of the image i.e. the image's end (it was similar for both of them to perceive at the end part of the experimental object which closest to their own hands) during the cooperative motion.

In actual cooperative motion, it is unknown on which part of the experimental object that human perceive to generate smooth motion. Thus, in this research, we compare the effect of perceiving at the End and the Center part's of the object on cooperative motion smoothness. Also, the effect of these two cases on experimental object rotation was investigated. The details of the experiment were explained in the second chapter.

In previous research, the motion smoothness of each subject was evaluated using the error value, ER_v which is the difference between actual velocity and the velocity calculated using a well-known Minimum Jerk Model. Flash T. & Hogan N. [75] had mentioned that maximizing smoothness of human's arm motion is actually equal to minimizing the jerk generated during the arm's motion. Thus, we assumed that it was better to evaluate the cooperative motion smoothness using the jerk value rather than the error value.

Jerk is the third derivative of position; which means, it consisted of distance and time parameters. In this research, the cooperative tasks were carried out for short and long distances. Since jerk consisted distance and time parameter, longer distance generated more jerk compare to short distance cooperative motion. Therefore, the effect of distance and time should be eliminated to compare the cooperative motion smoothness for short and long distance. Thus, in this research, the normalized jerk value was used for calculating the cooperative motion smoothness. Thus, we re-evaluated all the experiment conducted by previous researchers [70] using the normalized jerk.

In previous research, it was reported that in forward/backward direction, when starting signal and stop location information were not available through aural means to the human Follower, the cooperative task smoothness was found to be smooth and similar with the case where both information were available [72, 76]. Thus, we had inferred that in forward/backward direction, tactile means (force interaction) between subjects was used to understand the two information during the cooperative task [72]. Nevertheless, the analysis of interaction between force and cooperative task smoothness indicated that force was not significant in generating smooth motion for all cooperative task directions [74]. Thus, in this thesis, force data capturing and analysis was neglected. The next section explained clearly on the objective of the thesis.

1.5 Research Objectives

In this thesis, the following objectives were set:

1. Further the studies of previous researcher [74] to understand more on the characteristics for generating smoother cooperative motion in human-human cooperative system.
2. Proposed a control method for human-robot cooperative system based on the characteristics from human-human cooperative system.
3. Verify the results from human-human system in human-robot system.

In human-robot cooperative system, one end of the object was held by the robot and the other end was held by human as shown in Fig. 6 [77]. Several experiments were carried out for achieving each sub-objective. The objective of each experiment was explained in their respective chapter.

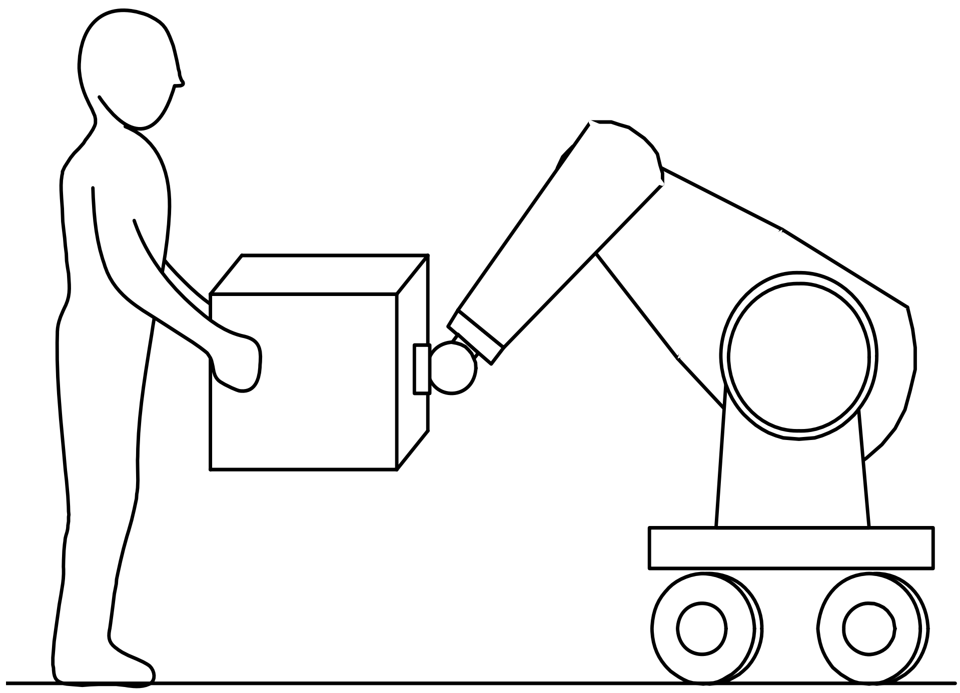


Fig. 6 Human-robot cooperative task.

1.6 Limitations

1. The research did not produce any prototype of robot with audio and visual devices to work cooperatively with human. The final stage only verified the cooperative characteristics obtained from human-human system with human-robot system.
2. The carrying motion only involved the movement of the subject's arm and the robot's manipulator. The motion of other human bodies was not considered in the experiment. Robot manipulator does not have tires.

1.7 Thesis Structure

The article was arranged in the following manner. This chapter provides overview of the thesis which includes the background, motivation, literature reviews, objective, scope and the use of Minimum Jerk Model as smoothness indicator.

The second chapter elaborates on the experiment involving the effect of perceiving either different or same part of the object on cooperative task smoothness. The third chapter explained on the investigation of the relationship between traveled distance and movement time during the Center case of cooperative task in human-human system. The fourth chapter described the experiment for selection of the best regression line from human-human system into human-robot system. Chapter 2, 3 and 4 includes the experimental equipment, procedures, analysis and result, and summary of each experiment. Finally, the fifth chapter is the concluding chapter of the thesis.

CHAPTER 2

PERCEIVING DIFFERENT OR SAME PART OF THE OBJECT AS MEANS OF COMMUNICATION

2.1 Introduction

The effect of having two critical information i.e. signal to start and location to stop the cooperative task on the cooperative motion smoothness was evaluated by previous researchers [74]. However, both subjects only perceived at the end part of the image displayed on the LCD monitors in front of them (this imaged resembled the real experimental object's motion) to understand each other motion. Perceiving the image's end was similar as perceiving at the end part of experimental object closest to each subject's hand. One subject perceived at experimental object's end part near to his hand, and similarly, the other subject perceived at experimental object's end part near to his hand. Thus, both subjects perceived at different location on the experimental object. Moreover, in their research, cooperative motion smoothness was indicated by an error value obtained from the difference between actual and minimum jerk velocity of each subject motion.

In this experiment, the following items were set as objectives:

1. The effect of perceiving different or same location on a two dimensional image (the image resembled the experimental object) on cooperative task smoothness. This differed from previous research [74] where they only perceived at different location on the image. In this

chapter, the experiment was conducted in two different manners. In one experiment, the subjects were asked to perceive at different location on the image i.e. by looking at the image's end. In another experiment, the subjects were asked to perceive at the same location on the image i.e. by looking at the image's center. Henceforth, the former and the latter will be known as End and Center case, respectively.

2. In either perceiving different or same location on the image, this research reevaluated [74] the effect of having or not having or having only one of the two critical information by one of the subject on cooperative motion smoothness. However, in this thesis, instead of error value, the normalized jerk value was used as smoothness indicator. The reason was mentioned in section 1.4.

3. Additionally, the effect of End and Center case on the object rotation during smooth cooperative task was investigated. This was based on hypothesis that less object rotation was expected during smooth cooperative task. The analysis on the object rotational motion was based on the following formula,

$$\theta_{ave} = \frac{1}{t_f}\int_0^{t_f} abs\big(\theta(t)\big)\, dt \tag{1}$$

where θ_{ave} and $\theta(t)$ is the average and instantaneous angle of the object during the cooperative task, respectively.

2.2 Minimum Jerk Model as smoothness indicator

Some researchers have utilized the Minimum Jerk Model for generating smooth and human friendly robotics motion in their studies [78-81]. Minimizing jerk not only for generating smooth motions but also it reduces the actuator's mechanical strain and wear [82]. Thus, in this research, the model was utilized to evaluate cooperative motion smoothness quantitatively and finally, to generate a smooth robotic motion in human-robot system. The model adapts the optimal control methodology which has been proven to be the smoothest movement of human arm that can be achieved by minimizing jerk during the motion. Jerk is defined as the change of rate of acceleration; thus, it is a third temporal derivative of position. In other words, the model can be used to predict the kinematics aspect of smooth human arm motion which includes the arm position, velocity, acceleration and jerk. Assuming that *x* and *y* are the time varying hand positions in Cartesian coordinate, the magnitude of the jerk to be minimized can be shown as,

$$\text{Jerk} = \sqrt{\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2} \tag{2}$$

In moving a human hand from an initial to a final position in a given time t_f, the cost function C to be minimized is the time integral of the square of the magnitude of jerk:

$$C = \frac{1}{2}\int_0^{t_f} \left[\left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2\right] dt\,, \tag{3}$$

In our experiment, a one dimensional movement is considered; therefore the above minimum jerk formula can be simplified as,

$$C = \frac{1}{2}\int_0^{t_f} \left[\left(\frac{d^3x}{dt^3}\right)^2\right] dt \tag{4}$$

Since jerk is the third temporal derivative of position, a difference in traveled distance results in a difference jerk value (a longer distance may produce more jerk than a shorter distance). Thus, in the analysis, the actual jerk value was normalized with distance and time before it was used to calculate the minimum jerk value. By doing this, the effect of distance and time on the calculation of minimum jerk value was eliminated. Assume that X is the normalized position, $x(t)$ is the actual position data at each sampling time, t. t_0 is the time at task initiation and t_f is the time at task termination. The normalized position, normalized time, normalized jerk and normalized minimum jerk is shown in the following formulas.

$$\text{Normalized Position}, X = \frac{x(t)}{x(t_f)-x(t_0)} \tag{5}$$

$$\text{Normalized Time}, T = \frac{t}{t_f-t_0} \tag{6}$$

$$\text{Normalized Jerk} = \frac{\mathrm{d}X^3}{\mathrm{d}^3T} \tag{7}$$

$$\text{Normalized Minimum Jerk}, C_{Normalized\_Jerk} = \int_{t_0}^{t_f} \left\{\frac{\mathrm{d}X^3}{\mathrm{d}^3T}\right\}^2 \mathrm{d}T \tag{8}$$

2.3 Experimental Equipment

The experimental equipment consisted of a position measurement system (Optotrack Certus 3020 camera, System Control Unit and Personal Computer), two Liquid Crystal Display (LCD) monitors and a rigid experimental object as shown in Fig. 7. Figure 8 shows the experimental object dimensions and configuration. The dimensions of the experimental object were 60 mm (H) x 180 mm (W) x 460 mm (L) and weighed about 3 kg.

It was equipped with small infrared light emitting diode (IR LED) markers on its sides. When both subjects moved the experimental object in any directions, a three dimensional (3D) camera in the position measurement system detected signal from the diode marker and sent it to the main computer. The computer processed the signal and converted it to a two dimensional (2D) rectangular image mimicking the experimental object`s motion in real time. The image was displayed on the LCD monitors in front of both subjects. Figure 9-14 shows the image perceived by both subjects in each cooperative task direction. The rectangular image size was

10 mm (W) x 100 mm (L). In leftward/rightward task, the image (10 mm x 100 mm) represented 180 mm x 460 mm surface area of the real object. In upward/downward and forward/backward task, the image (10 mm X 100 mm) represented 60 mm x 460 mm surface area of the real object. The start and four targets position were presented as two parallel lines and if its centerline coincides with rectangular image's centerline, it provides 3 mm gaps to tolerate the image positioning. The targets were positioned at two distances in each direction namely, short and long distance. The short distance was set between 75 to 100 mm and long distance was between at 150 to 200 mm based on the subject suitability. Position data (X, Y and Z coordinates with origin at the center of the 3D camera) from each marker was recorded into the computer at every 10 ms of sampling interval. Each data was low-pass filtered by using a second order dual-pass Butterworth filter with a cut-off frequency of 5 Hz.

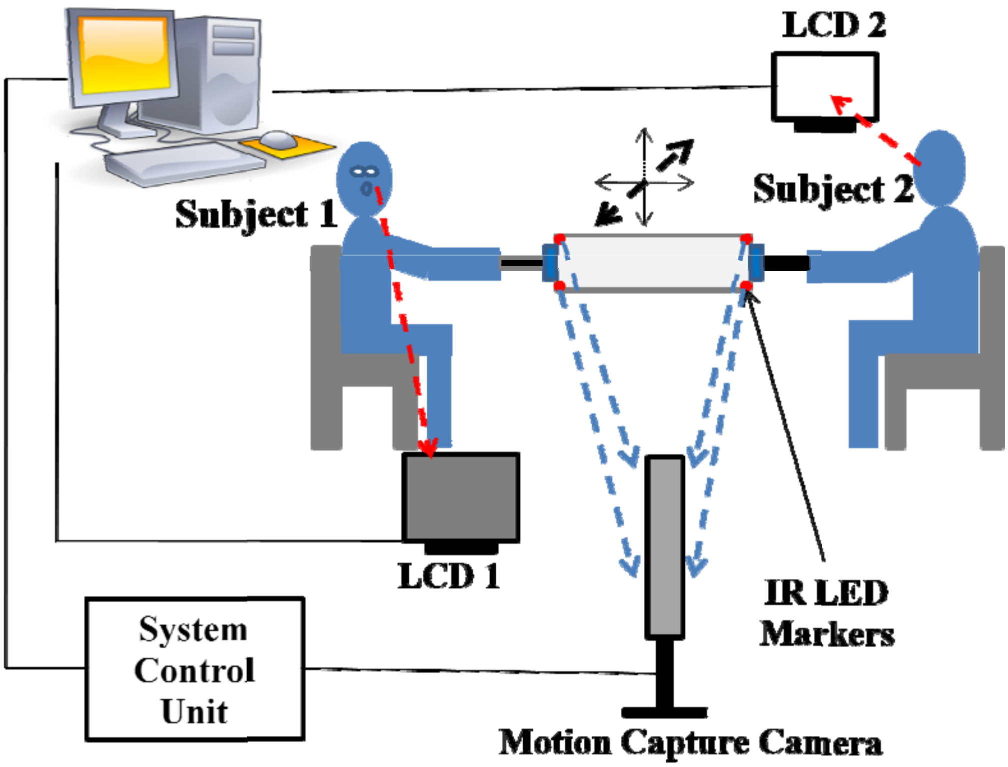


Fig.7 Experimental Equipment

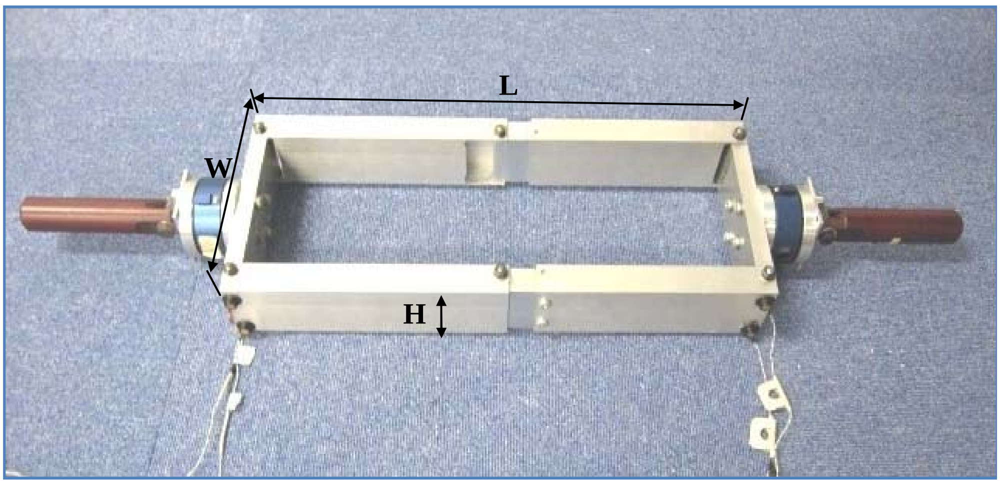


Fig. 8 Experimental Object

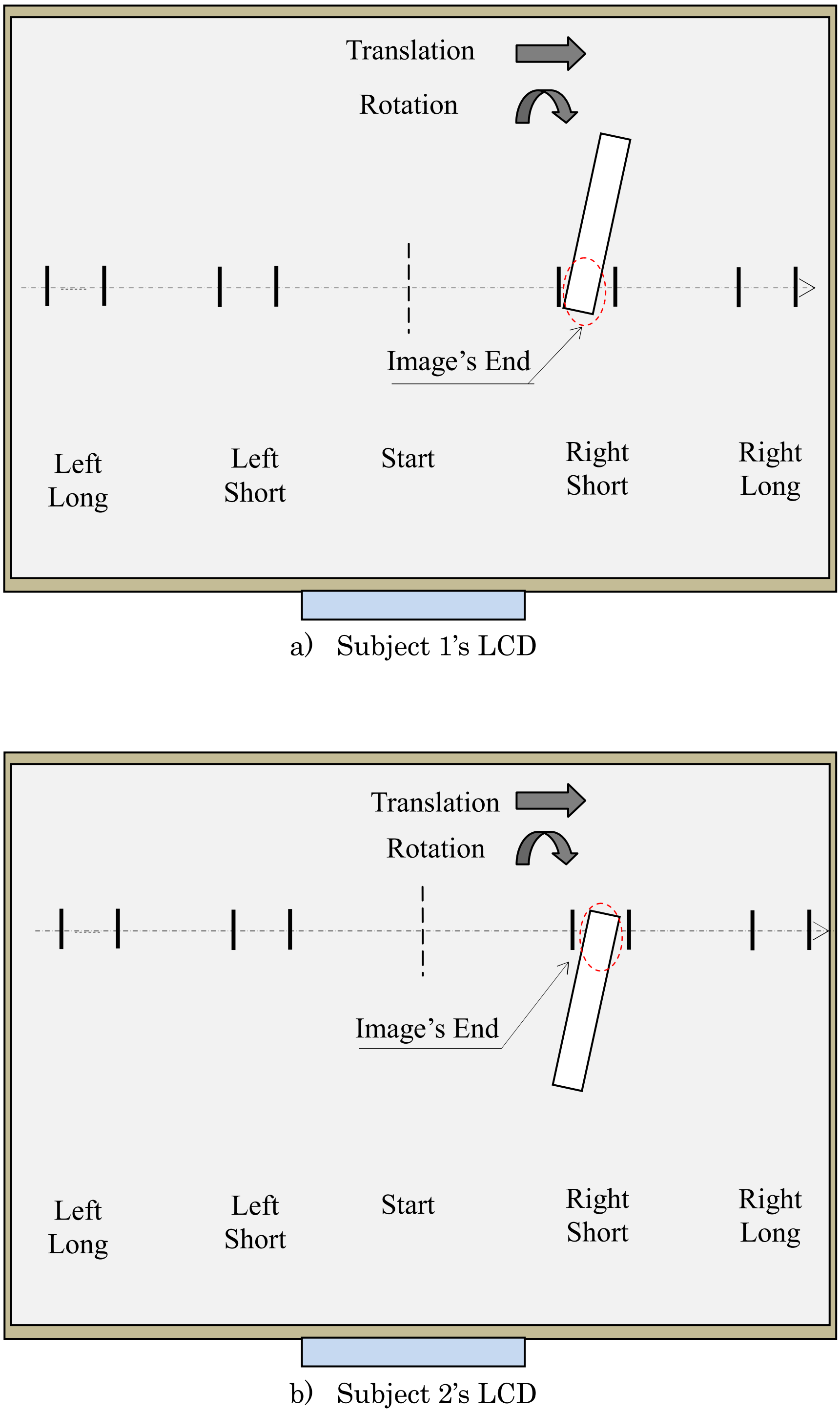
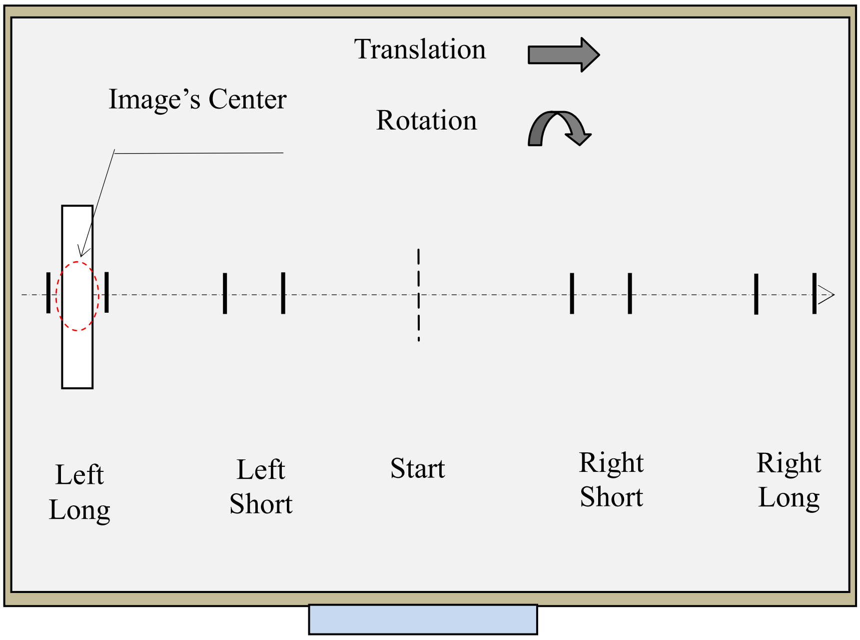
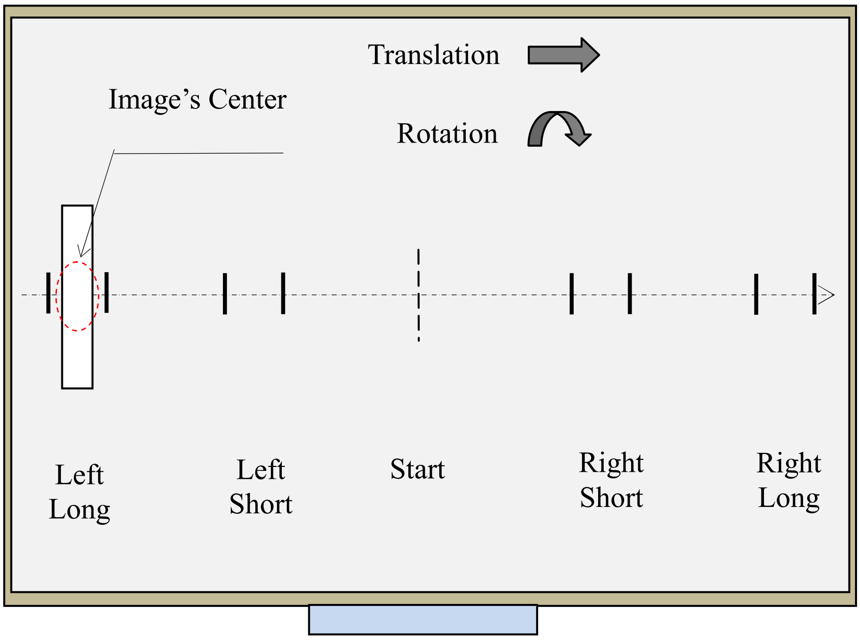


Fig. 9 A 2D rectangular image displays on the LCD monitors in front of both subjects for End case cooperative task in leftward/rightward direction. Although it was provided independently in each LCD, it was the same image to be perceived by both subjects.

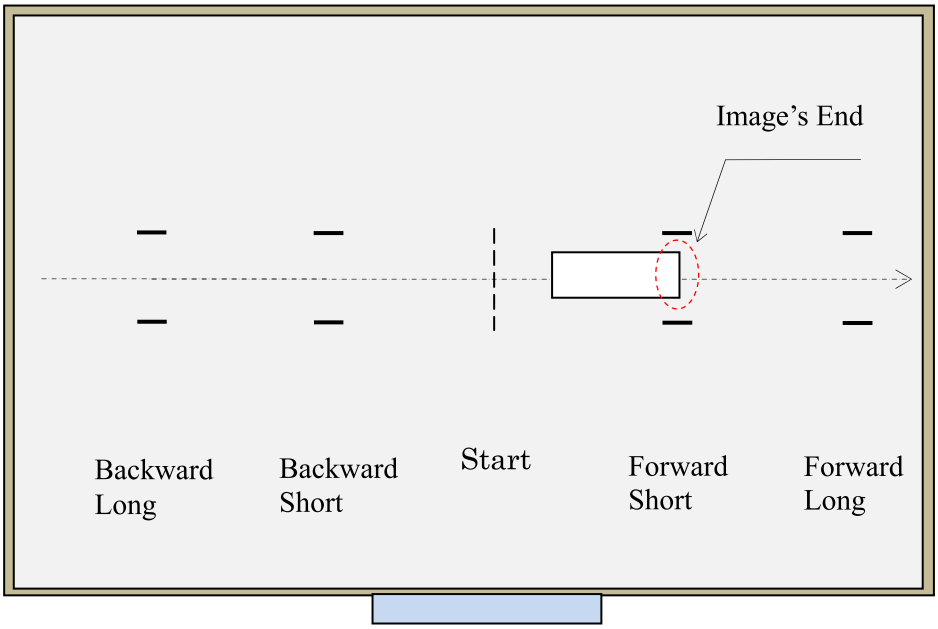


a) Subject 1's LCD

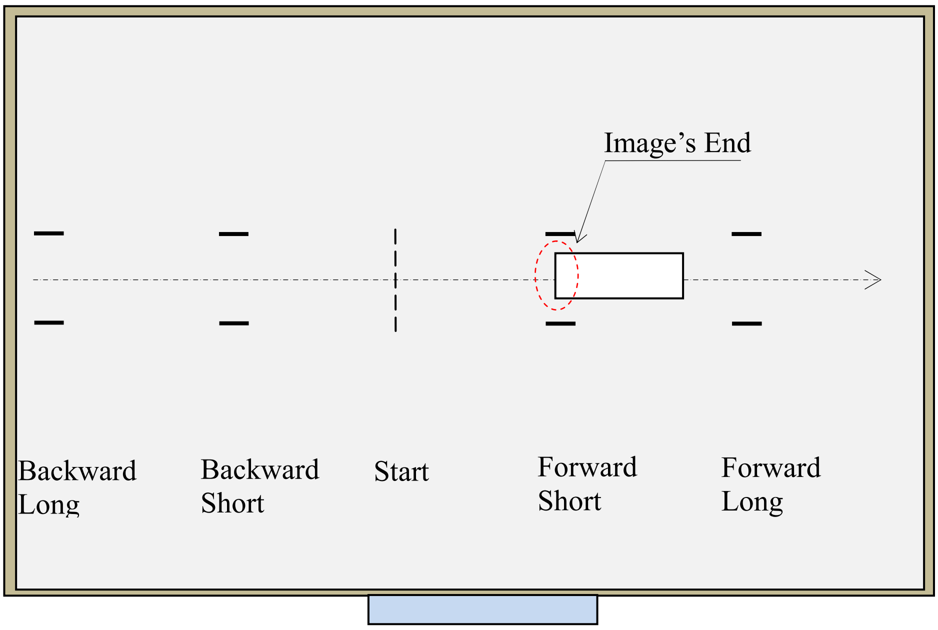


b) Subject 2's LCD

Fig. 10 A 2D rectangular image displays on the LCD monitors in front of both subjects for Center case cooperative task in leftward/rightward direction.

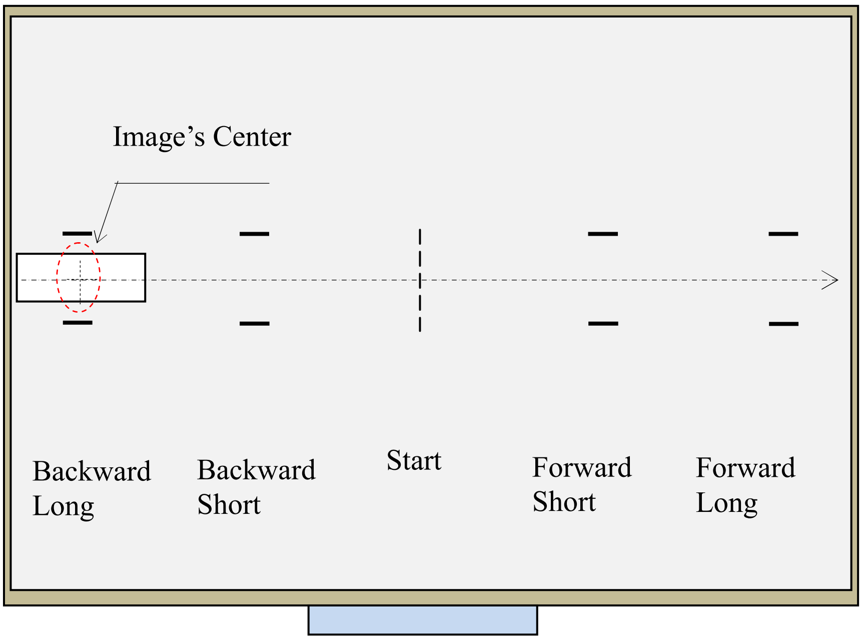


a) Subject 1's LCD

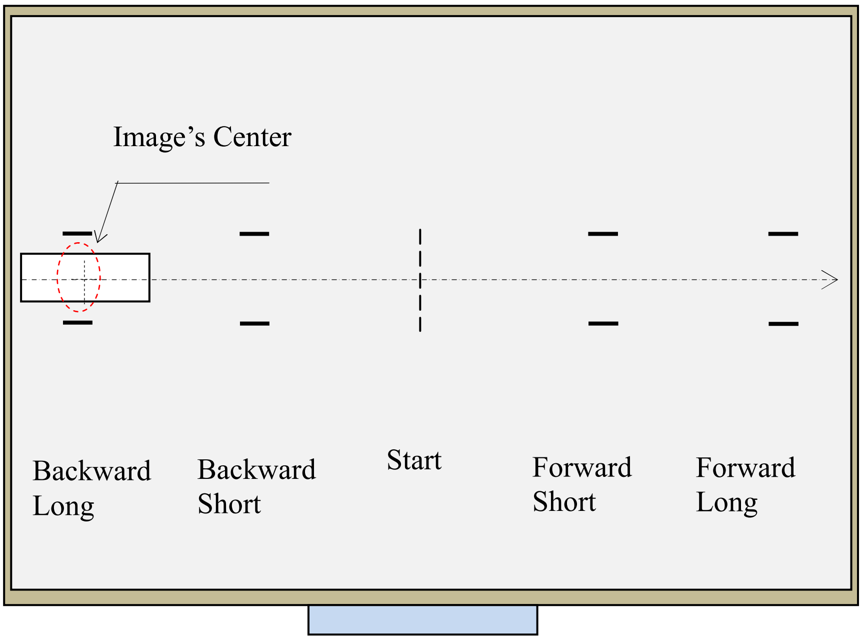


b) Subject 2's LCD

Fig. 11 A 2D rectangular image displays on the LCD monitors in front of both subjects for End case cooperative task in forward/backward direction.

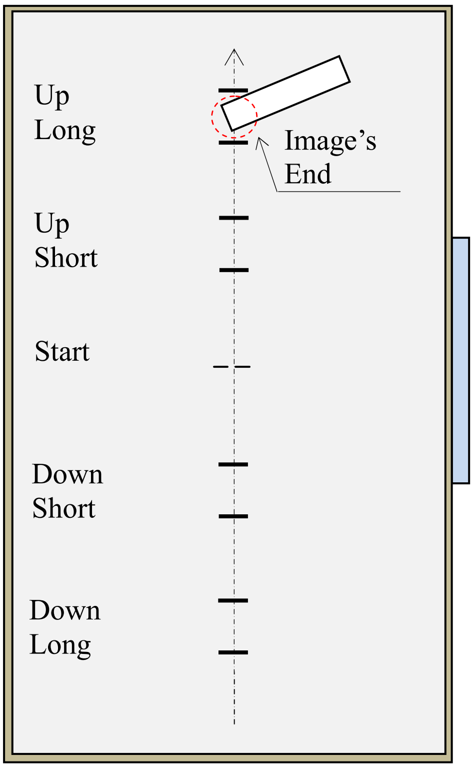


a) Subject 1's LCD

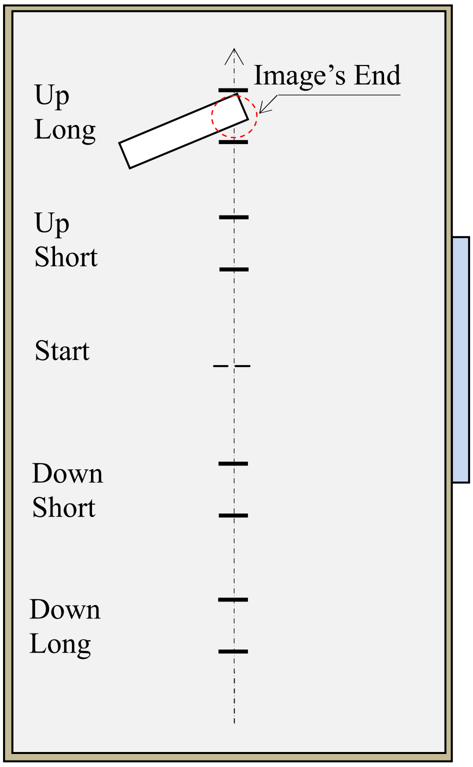


b) Subject 2's LCD

Fig. 12 A 2D rectangular image displays on the LCD monitors in front of both subjects for Center case cooperative task in forward/backward direction.

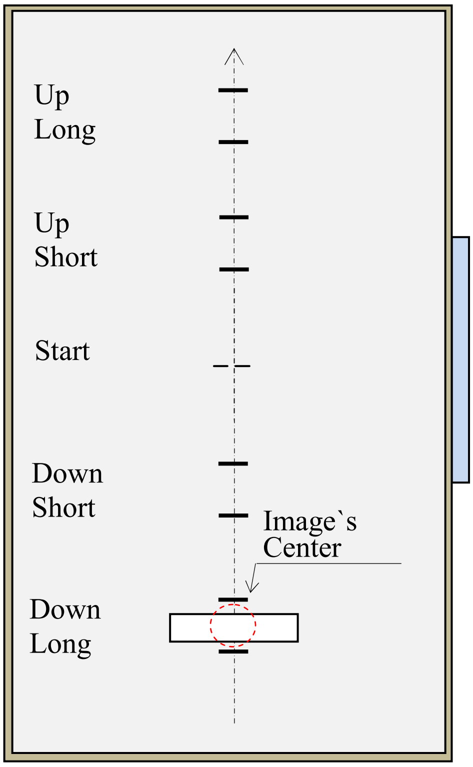


a) Subject 1's LCD

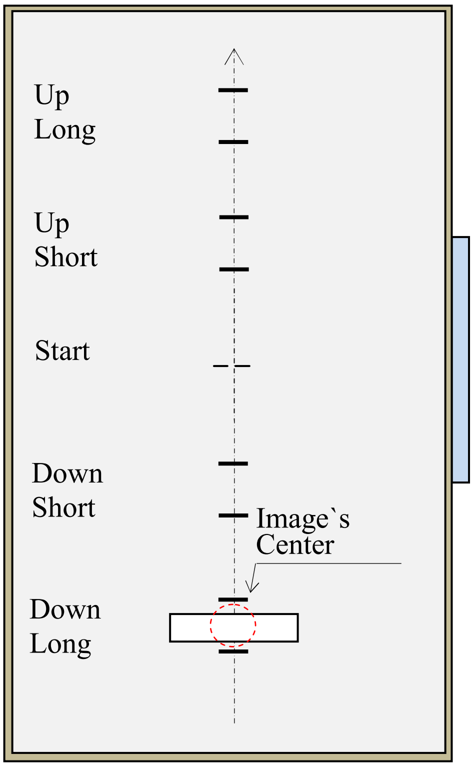


b) Subject 2's LCD

Fig. 13 A 2D rectangular image displays on the LCD monitors in front of both subjects for End case cooperative task in upward/downward direction.



a)　Subject 1's LCD



b) Subject 2's LCD

Fig. 14 A 2D rectangular image displays on the LCD monitors in front of both subjects for Center case cooperative task in upward/downward direction.

2.4 Experimental Method

2.4.1 Subjects

We have selected 10 engineering students as experimental subjects, aged between 22 to 35 years old, who are physically and mentally healthy (no sensory, neurological, muscular, cutaneous or other impairment related problems). All of them have had no prior experiences in executing the current experiment. All subjects were provided with informed consents and instructions on the experiment. The subjects were classified into 5 groups, and each group consisted of two persons, subject 1 and subject 2. Only one group has a female participant, all the rest being males. Subject 1 knows two critical information i.e. signal to start the cooperative task and location to stop the cooperative task, thus he/she was defined as Leader. Subject 2 may know both or may not know both or may know only one of the two information . When he/she knows both information, he/she also known as Leader; however, when he/she only knows one of the two information, he/she is known as Follower. This was discussed in detail in procedural section.

2.4.2 Procedure

The experiment was executed to achieve the objective mentioned in section 2.1. During the experiment, one subject known as Host, worked at the computer (start up the software, recording, etc) and other two subjects known as subject 1 and subject 2 worked at the experimental object area. Subject 1 was appointed as a Leader and he knows both critical information i.e. task starting signal and task terminating location prior to the cooperative task. Subject 2 based on cases, may know both or may not know both or may know only one of the two information. This has generated four modes of information possessing through as shown in

Table 2. It was understood that in mode 4 the Leader-Leader cooperative motion was formed.

Table 2 Mode of Information Possessing and Type of Cooperation

Mode	**Does Subject 2 posses this information**		**Type of cooperation based on the definition of Leader & Follower**
	Start Signal	**Stop Location**	
1	No	No	Subject 1 (Leader) Subject 2 (Follower)
2	Yes	No	Subject 1 (Leader) Subject 2 (Follower)
3	No	Yes	Subject 1 (Leader) Subject 2 (Follower)
4	Yes	Yes	Subject 1 (Leader) Subject 2 (Leader)

On the signal to start the cooperative task; in mode 1 and 3, subject 2 was not given any verbal instruction. However, in mode 2 and 4, he/she was informed loudly through verbal means (3, 2, 1, Start) to start the cooperative motion. On the target location to stop the cooperative task, in mode 1 and 2, subject 2 did not have the target information. Only, subject 1 knew the target position and he selected them randomly to avoid subject 2 from understanding his desired stopping position. In contrast, in modes 3 and 4, both subjects have the target location information and it was in an orderly manner to facilitate them during the experiment. For example, in leftward/rightward direction, the targets were in the order of left-short, left-long, right-short and finally, right-long. Mode 1, 2 and 3 were lacked of explicit information, therefore, subject 2 was asked to follow or predict subject 1 motion by using the available implicit information, i.e. by looking visually and feeling the object motion by hand. However, in Leader-Leader type cooperative motion as in mode 4, both subjects moved towards target with his/her own rhythm [74] and generated smoother cooperative task without the needs to follow either subject motion.

The variables of the experiment were shown in Fig 15. First, let's consider the End case. In each mode of experiment, there were six directions which the subject should execute the cooperative task. In each direction, the cooperative motion must be executed in two distances namely, short and long. The short and long distance was set between 75mm to 100mm and 150mm to 200mm, respectively, based on subject suitability. In each distance, 10 cooperative motions were executed.

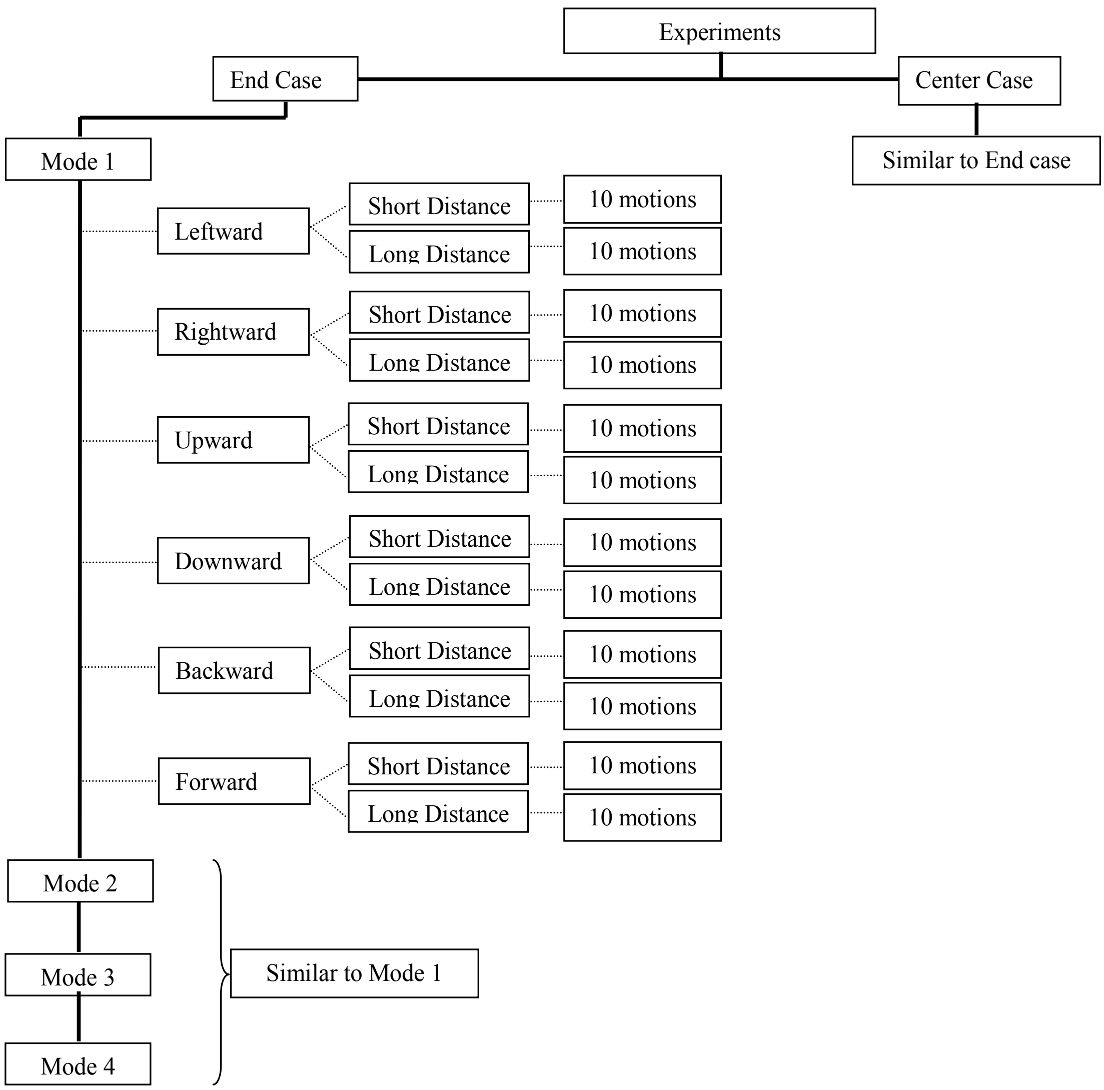


Fig. 15 Experimental Variables

In executing the cooperative task for End case, both subjects sat on their respective chair facing each other as shown in Fig. 7. The distance between the chairs was fixed for each group and it was decided so that all subjects could move their hand smoothly from the start to the farthest target position on the screen in all cooperative task major directions i.e. leftward/rightward, upward/downward and forward/backward. The major directions were defined relative to subject 1.

Before executing the task, Host started up the software and a 2D image resembling the experimental object appeared on the screen in front of both subjects. Host instructed both subjects to hold the experimental object with their right hand and matched the 2D image’s end (End case) portion to the start position. The start position on the screen was similar to the middle point located between both subjects. Subject 1 decided, informed or may not informed subject 2 on the target position to stop the cooperative task based on mode of information understanding. Host started capturing the cooperative motion and informed both subjects to be ready for executing the experiment. Subject 1 (Leader) based on mode of information understanding, informed or may not informed subject 2 to initiate the cooperative task. Then, subject 1 simultaneously cooperated with the subject 2 in bringing the experimental object to the target position. Near to the target location, both of them perceived at the 2D image’s end portion and matched it to the target position. The cooperative motion data were saved in the computer. Then, Host instructed both subjects to return to the start position. In Center case cooperative motion, similar procedure was repeated; however, both subjects matched the 2D image’s center portion to the start and target position.

Although the hand movement towards target consisted of two motion phases[83] (i.e. the transfer phase from start to target position and the precise positioning phase at target), the precise positioning phase was excluded from this research. This phase was excluded to resemble the natural hand motion for a non-precise positioning cooperative task (e.g. carrying task at home, office, etc). Moreover, the accuracy of the hand movement at target was neglected when confirming the application of Minimum Jerk Model to generate smooth arm motion[75].

Both subjects were required to practice by moving the object for several times before proceeding with the experiments. The practice was very important in order for both subjects to adjust to the changes of the experimental conditions and familiarized with each other's motion. Furthermore, it resembled a trained motion (as it was done daily) performed by the industrial workers.

Statistical analyses were performed using the Statistical Packages for the Social Sciences (SPSS). For each Mode, the normalized mean jerk was computed to evaluate the cooperative motion smoothness. Differences between the levels of each variable were detected using repeated measure ANOVA. Significance level for all statistical tests was set at $p < 0.01$. The measured position data were filtered with Butterworth filter at a cut-off frequency of 5 Hz programmed in Matlab software version 2007b.

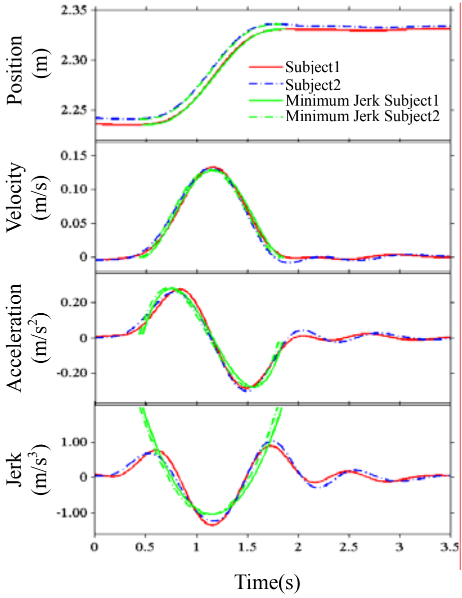
2.5 Results & Discussion

2.5.1 Kinematics profiles during cooperative task

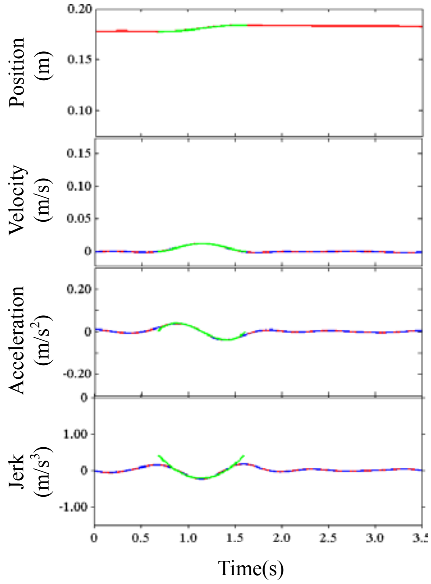
Figure 16 shows the example of a smooth and an awkward cooperative task, in terms of position, velocity, acceleration and jerk profiles. The task was executed in leftward/rightward direction with a same distance and direction by the same subjects. The red and blue lines indicated the kinematics profiles based on the actual motion data of subject 1 and subject 2, respectively. The green solid and dash-dot lines indicated the kinematics profiles based on the minimum jerk model of subject 1 and 2, respectively. In each plot, the kinematics profile based on the Minimum Jerk Model (refers to green solid and dash-dot lines) has the same dimension as the actual motion profile (refers to red and blue line). As for example, the position profile based on Minimum Jerk Model has the same dimension as actual position data, i.e. meter. This is also true for velocity, acceleration and jerk.

In smooth cooperative task (Fig. 16(a) was obtained from Mode 4 where both information was possessed by both subjects), each subject actual hand's motion was almost similar to the pattern of their own minimum jerk profiles. The result indicated that each subject generated a smooth hand motion during the cooperative task. Also, it could be observed that both subjects showed different actual kinematic profiles. This indicated that each subject moved the object with different hand's rhythm [74] towards the target location. Another observation is that both subjects' kinematic profiles were almost overlapping indicating a good cooperative motion. Thus, it could be understood that both subjects moved the object in feed-forward manner (moving the object with own hand's rhythm) to achieve a smooth cooperative motion. The results were in agreement with the previous researcher [74]. Each kinematics profiles were calculated based on the position data in the same direction of the cooperative task (i.e. moving leftward/rightward, the position data in leftward/rightward direction was used to calculate other profiles).

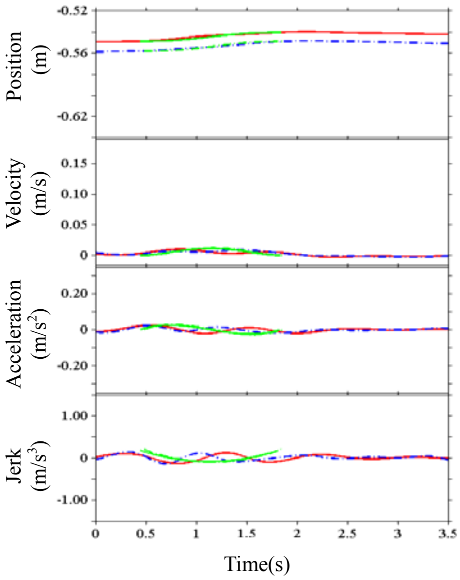
Figures 16(b) and 16(c) show the kinematics profiles for the cooperative task in the same direction of 16(a). However, the profiles in 16(b) and 16(c) were calculated in the direction perpendicular to the cooperative task direction of 16(a) (i.e. moving leftward/rightward, using either forward/backward or upward/downward position data to calculate the other profiles). The kinematics profiles calculated in forward/backward direction (Fig. 16(b)) was smooth with a small jerk value. In contrast, the kinematics profile calculated in upward/downward direction (Fig. 16(c)) was not so smooth. However, with a relatively small jerk value, the motion was considered smooth. Therefore, in one dimensional motion, representing the jerk profile in the same direction of the cooperative task direction was sufficient to indicate the cooperative motion smoothness. In contrast to the smooth cooperative task (referring to 16(a)), in awkward task (Fig. 16(d), all profiles was calculated in the same direction of the cooperative task), such similarities were not found especially in the acceleration and jerk profiles. The jerk profile shows more fluctuation during the task execution.



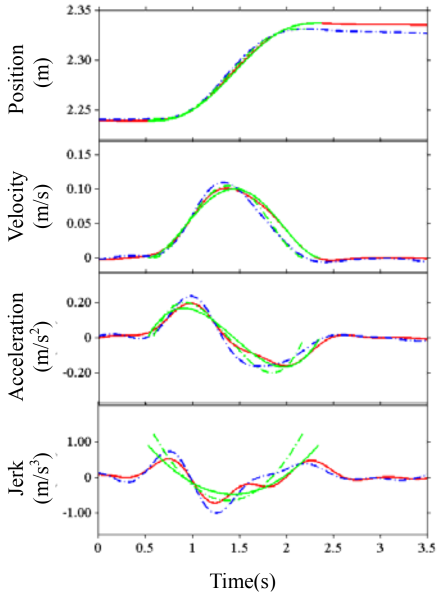
(a) Profiles of a smooth leftward/rightward cooperative task.



(b) Profiles calculated in the direction perpendicular (forward/backward) to cooperative task in (a).



(c) Profiles calculated in the direction perpendicular (upward/downward) to cooperative task in (a).

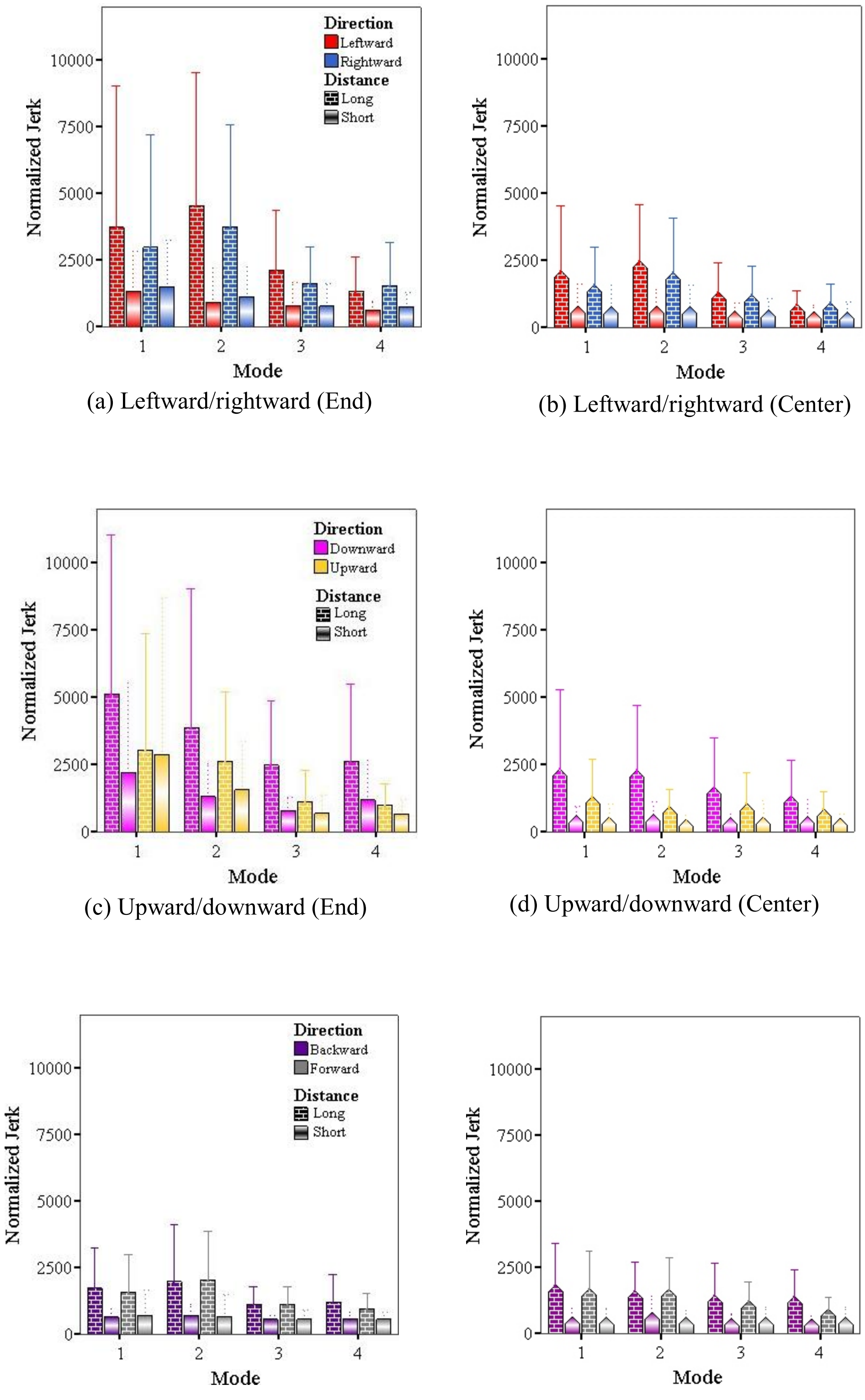


(d) Profile of an awkward leftward/rightward cooperative task.

Fig. 16 Profiles of position, velocity, acceleration and jerk during cooperative task

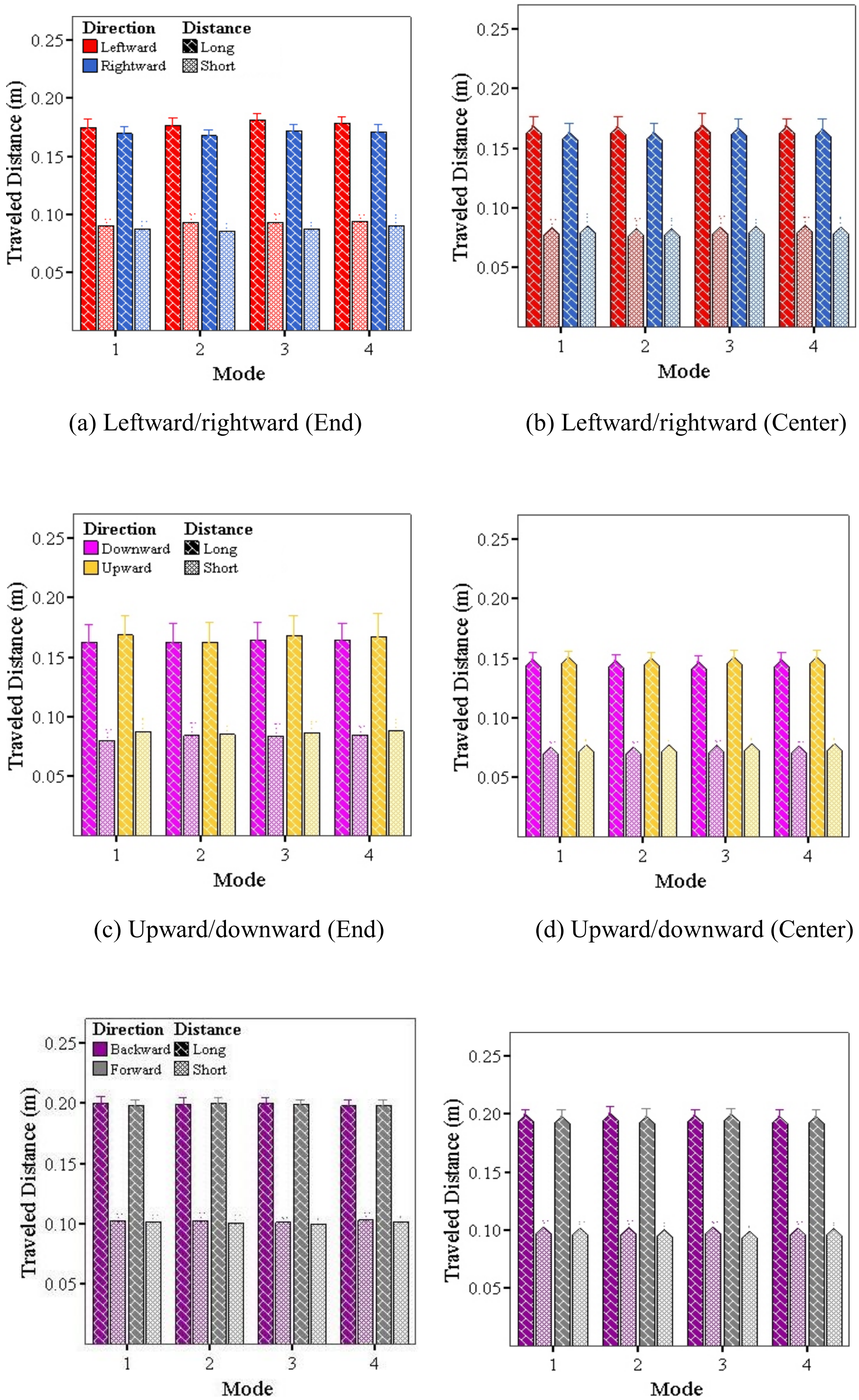
2.5.2 Smoothness versus modes of information possessing by subject 2

Figure 17 shows the motion's smoothness of subject 2 with regards to the cooperative task in leftward/rightward, upward/downward and forward/backward direction over the aforementioned four modes (refer to Table 2) of information possessing for End and Center cases, respectively. Each bar in each mode represents the average normalized jerk of 10 repetitions of all groups' motions. The average normalized jerk was calculated based on the experimental object's end motion (position data based on IR LED markers). These repetitions consist of a same direction and distance variables combinations. In each mode, the first bar indicated the long distance with a first direction (which referred to the order of the direction in each graph, i.e. in leftward/rightward direction, the first direction is leftward, in upward/downward is downward, and in forward/backward is backward) of the cooperative task, and the second bar shows the short distance with the first direction of the cooperative task. Subsequently, the third and fourth bars represented the cooperative task in long and short distance with a second direction (which refers to rightward in leftward/rightward, upward in upward/downward, and forward in forward/backward), respectively. The error bars indicated the standard deviation of the normalized jerk. A smaller mean normalized jerk value indicated a smooth cooperative motion and vice versa. The distance traveled during each cooperative direction was within the range mentioned in §2.3.2 and shown in Fig. 18. Some variation of distances existed as the precise positioning phase was excluded from the research and subjects were asked to stop the object at the vicinity of the target area.



(a) Leftward/rightward (End)
(b) Leftward/rightward (Center)
(c) Upward/downward (End)
(d) Upward/downward (Center)
(e) Forward/backward (End)
(f)Forward/backward (Center)

Fig. 17 Smoothness over the mode of information possessing for the cooperative task in each direction for End (Left column) and Center (Right column) case.



(a) Leftward/rightward (End)

(b) Leftward/rightward (Center)

(c) Upward/downward (End)

(d) Upward/downward (Center)

(e) Forward/backward (End)

(f) Forward/backward (Center)

Fig. 18 Traveled distance in each cooperative task direction.

The effect of mode on the mean normalized jerk was investigated. Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of mode in each direction (leftward/rightward, χ^2 (5) = 35.76; upward/downward, χ^2 (5) = 45.51,; forward/backward, χ^2 (5) = 30.15, all *p*s < 0.01), therefore degrees of freedom were corrected using Greenhouse Geisser estimates of sphericity (leftward/rightward, ε = 0.745; upward/downward, ε = 0.586; forward/backward, ε = 0.723). The result shows that there was a significant effect of modes on mean normalized jerk in each direction (leftward/rightward, F (2.23, 100.5) = 59.81, upward/downward, F (1.76, 79.10) = 24.09, forward/backward, F (3, 97.6) = 23.64), all *p*s < 0.01). Obviously, regardless of the cooperative task directions, the mean normalized jerk value reduced towards mode 4 and furthermore, this mode was associated with the least standard deviation.

Thus, regardless of which part of the image was being perceived, if humans have both information on the target destination and signals to initiate motion, a natural and smooth cooperative motion is frequently generated. Therefore, for a smooth human-robot cooperation, both information must be made available to the robot. The effect of distance on mean normalized jerk was found significant in all directions (leftward/rightward, F (1, 45) = 282.25, upward/downward, F (1, 45) = 142.58, forward/backward, F (1, 45) = 403.87, all *p*s < 0.01). This means that the long distance cooperative motion generates a higher mean jerk and standard deviation compared to the short distance motion. The higher standard deviation in each bar shows that, for 10 trials of motion, some generate smooth whilst some produce awkward cooperative motion. The difference of cooperative task smoothness between sub-direction (e.g. between leftward and rightward in leftward/rightward cooperative task) was shown in the graph. In leftward/rightward direction and forward/backward direction, the statistical test indicated that the differences of cooperative task smoothness in these two directions were not significant, F (1,

45) = 2.19, $p > 0.01$ and $F (1, 45) = 0.63$, $p > 0.01$, respectively. However, the statistical test result for upward/downward direction shows significant difference between its sub-direction, $F (1, 45) = 35.53$, $p < 0.01$. Leftward and rightward direction task smoothness was similar because the task was not associated with a large change in gravitational force[74]. In forward/backward direction, forward was mentioned to be more awkward than backward direction[74]. They reported that subject 2 had to support more weight when he extended his hand during the task. However, we realized that in forward/backward task, the effect of hand extension should be cancelled out by both subjects (in Forward task, subject 1 extended, subject 2 flexed; in Backward task, subject 1 flexed and subject 2 extended). Thus, the similarity of task smoothness should exist between the sub-direction. The difference in results with the previous researcher[74] may exist due to the used of the jerk value rather than the error value as cooperative motion smoothness indicator. In upward/downward, the downward task was associated with more awkward task. Subjects informed that they have to be more careful during the downward task, since they felt lighter when moved the object from start to target position. Analysis on average velocity indicated that lower average velocity was observed during downward compare to upward task.

The difference between End and Center case was tested for each task direction, e.g. leftward/rightward End case was compared with leftward/rightward Center case; the same procedure was carried out for upward/downward and forward/backward cooperative task. A significant difference was found between the End and Center cases for the cooperative task in leftward/rightward, $F (1, 45) = 69.62$, $p < 0.01$, and upward/downward direction, $F (1, 45) = 114.57$, $p < 0.01$. This means that the Center case generated a smoother cooperative motion. However, the same effect was not observed for the cooperative task in the forward/backward direction, $F (1, 45) = 1.30$, $p > 0.01$. In the Center case of leftward/rightward and upward/downward cooperative task, both subjects looked at and shared almost the same area of the experimental object. Thus, both subjects managed to visualize and share the same information of the object's motion and moved the same part of the object in the same axis and plane towards target position (see Fig. 19(a)). Eventually, it produced more frequent, smoother and natural cooperative motion.

In contrast, during the End case of leftward/rightward and upward/downward cooperative task, both subjects looked at the end part of the 2D image. Thus, it was similar for them to look at the experimental object's end part that was closed to their hands. Since the image has two ends, therefore, both subjects were not looking at the same area while moving and matching the experimental object to the target position. Thus, both subjects did not visualize and share the same information about the object's motion and they moved the object in a separate axis and plane towards target position (see Fig. 19(b)). In human-robot cooperation, therefore, it is suggested that both subjects should visualize and share the same information of the object`s motion to generate a smooth cooperative motion.

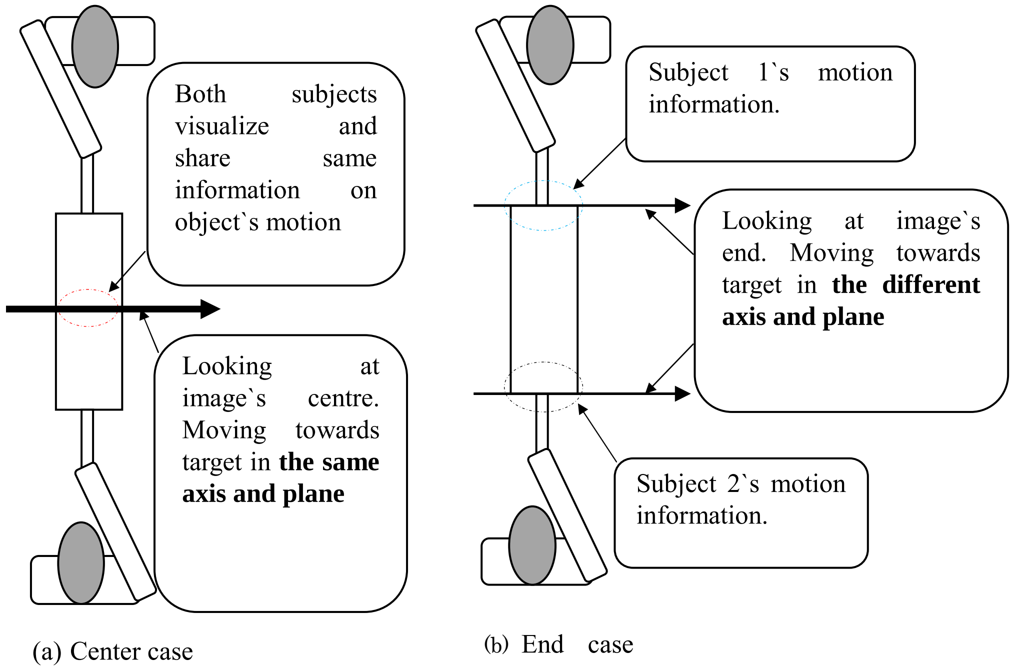


Fig. 19 The difference in visualizing and sharing the information between Center and End case in leftward/rightward and upward/downward cooperative task. Arrows indicates the direction of the cooperative motion. In Center case, both subjects share the same information and the arrow is thicker (to show sharing of information). In End case, they move the image based on the separate object`s motion information.

Figure 20 and 21 show different characteristics between the Center and End cases of the cooperative task in leftward/rightward direction, respectively. The example was taken from the same group of subjects, with the same distance and direction. In Fig. 20 (Center case), the position profiles of both subjects were almost similar from the beginning towards the target position. They also managed to reach the target position at the same time, as shown in Fig. 20 (b). In contrast, in Fig. 21 (End case), they did not look at the same part of the image; the position profile of both subjects started to be apart when time approached between 0.5 and 1 s. Eventually, the cooperative motion became awkward. Moreover, they did not reach the target position at the same time, as shown in Fig. 21(b) (see velocity profile, subject 1 reached zero velocity faster than subject 2). The phenomena shown in figure 20 and 21 were also observed in upward/downward direction. However, in forward/backward direction task, regardless of End or Center, both subjects managed to reach the target at the same time.

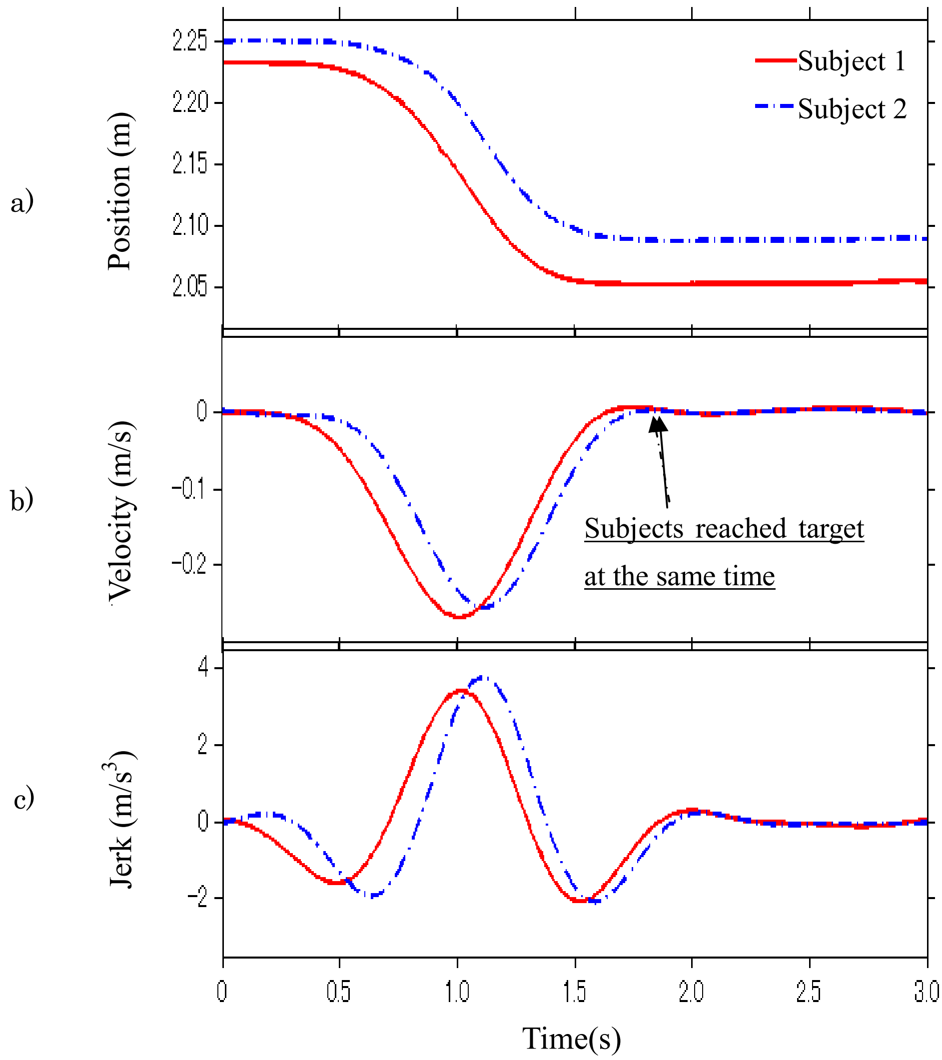


Fig. 20 Trajectories of cooperative task for Center case in leftward/rightward direction. From top: a). Actual position in the direction of cooperative motion. b). Actual velocity profile. c). Actual jerk profile.

a)

b)

c)

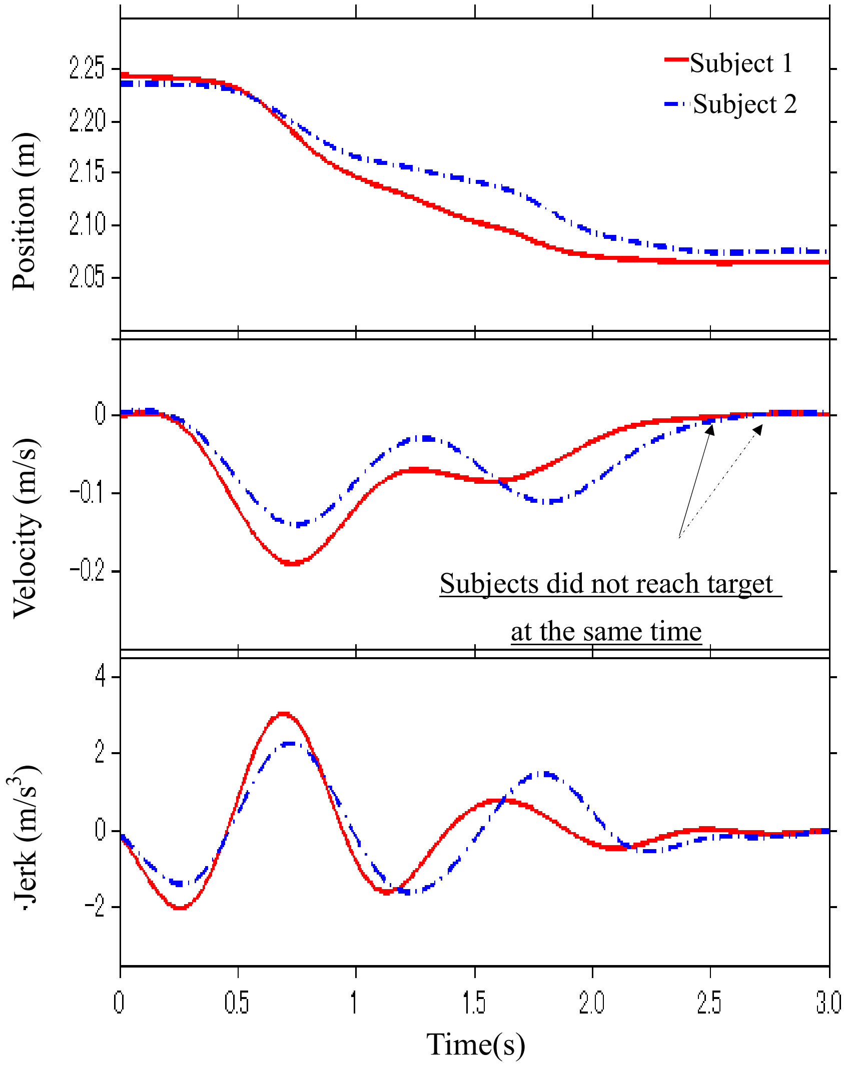


Fig. 21 Trajectories of cooperative task for End case in leftward/rightward direction. From top: a). Actual position in the direction of cooperative motion. b). Actual velocity profile. c). Actual jerk profile.

The cooperative task in forward/backward direction was reported to being more influenced from the force interaction (implicit information) between subject 1 and subject 2 [68, 84-88]. Relative to the cooperative task in leftward/rightward and upward/downward direction, the smoothness of the task in forward/backward in mode 1 is almost similar to mode 4, as shown in Fig. 17(e) and 17(f). In mode 1, subject 2 was not provided with any task information, he/she depends on force information to estimate a task`s initiation and termination. Thus, our experimental results also indicated that in forward/backward cooperative task**;** force interaction was more influential on the cooperative motion smoothness. Therefore, in forward/backward direction, regardless of looking at End or Center, the force interaction between subjects generates similar cooperative motion smoothness.

Another thought for the similarity between End and Center case in forward/backward direction was due to the information that they shared during the cooperative task. In Center case, they shared the same information of the object and moved in the same axis and plane (see Fig. 22(a)) as in leftward/rightward and upward/downward Center case. However, for the End case, although they did not visualize the same part of the object, they still shared the same object`s motion since they moved the object in the same axis and plane towards the target position (see Fig. 22(b)). Perhaps, this also another factor that had induced the similarity between End and Center cases for the cooperative task in forward/backward direction.

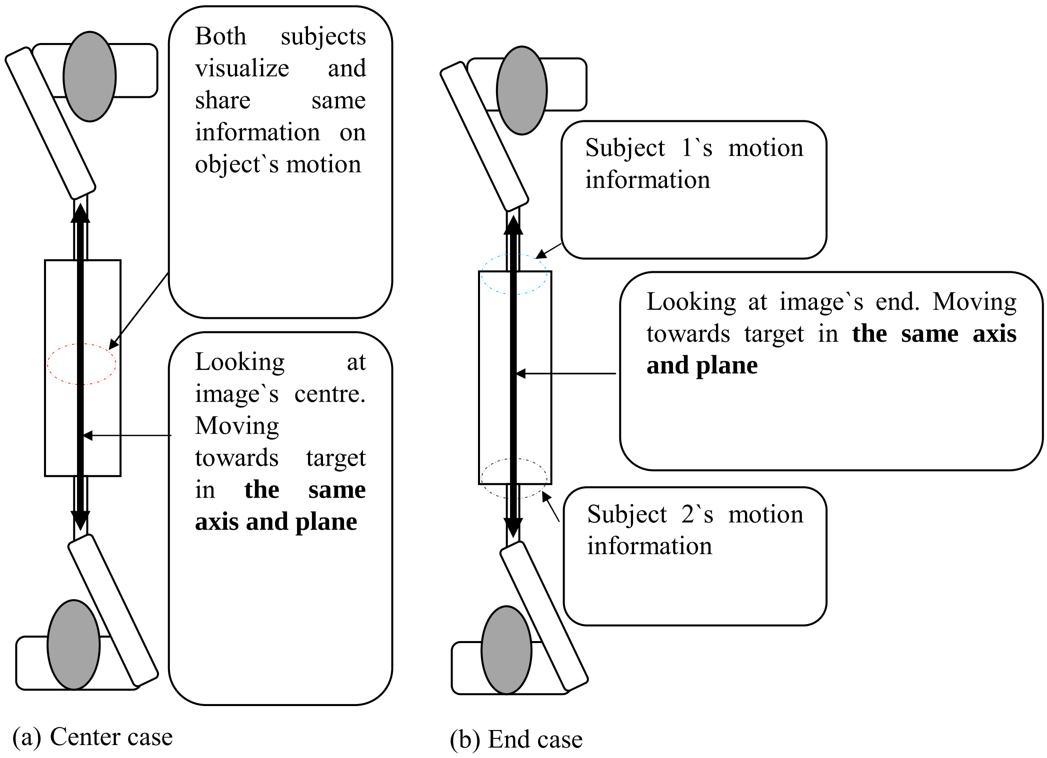


Fig. 22 Visualizing and sharing the same information for Center and End case in forward/backward direction cooperative task. Arrows indicates the direction of the cooperative motion.

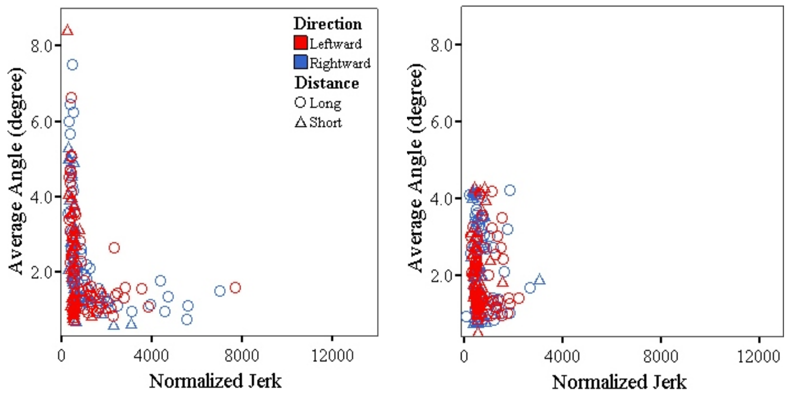
2.5.3 Error value, *ERv* or Normalized Jerk as motion smoothness indicator.

The results obtained from Figure 17(a), (c), (e) were compared to the results obtained by previous researcher (previous research only focus on End case cooperative motion) [74]. In previous research, Mode 1 was highest; however Mode 2, 3 and 4 showed similar cooperative motion smoothness (similar *ERv* values) for upward directions. Although in Mode 2 and 3, both information i.e. the signal to start and the location to stop the cooperative motion was not possessed by both subjects, they showed similar cooperative motion smoothness as in Mode 4. This was contradicted to the findings that only Mode 4 could generate smooth cooperative motion in all directions. In rightward direction also the difference of error value between Mode 1, 2 and 3 was not much. Yet, in forward and backward directions, the reduction of error value from Mode 1 towards 4 showed different trends. In these directions, the force interactions were more reported to have more influence in generating smooth cooperative motion.

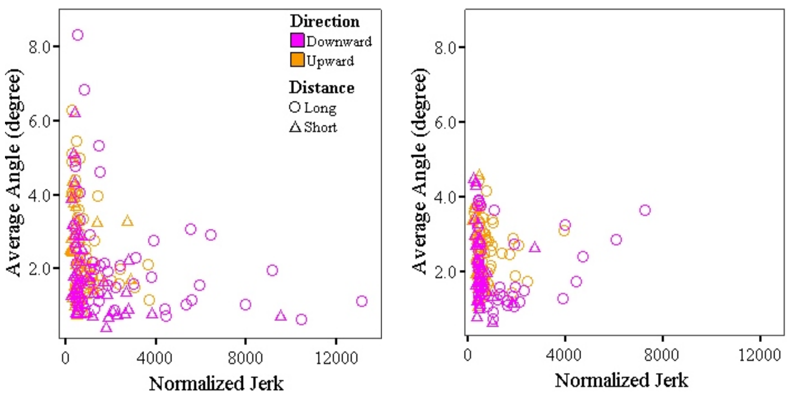
However, in this research, it was clear that there was a decrease in Normalized Jerk value from Mode 1 towards Mode 4. Yet, the difference between modes could be clearly understood. Thus, it could be conclude that the utilizing normalized jerk was better as cooperative motion smoothness indicator than the error value.

2.5.4 Object rotational motion in End and Center case

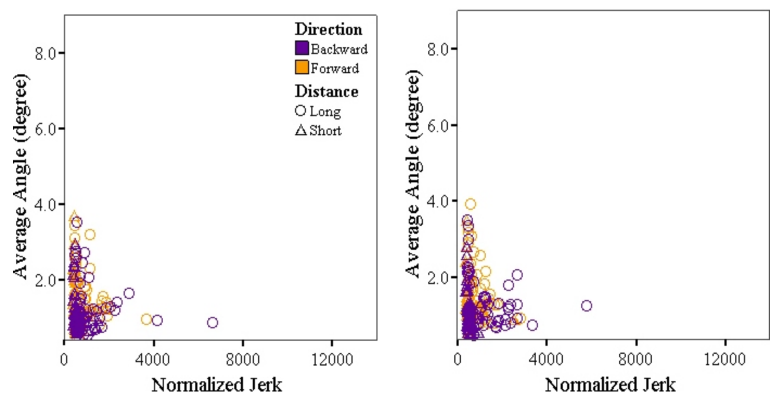
Figure 23 shows the relationship between object rotational motion (average angle) and cooperative task smoothness. The object`s angle was calculated on the plane parallel to the cooperative task direction (e.g. leftward/rightward task was executed parallel to horizontal plane, thus the angle was calculated on based on horizontal plane). We hypothesized that less object rotation was generated during smooth cooperative motion. Thus, the results presented were obtained from mode 4 where more frequent and smooth cooperative task was generated. The result shows that smooth tasks (Normalized jerk value is less than 600) in End case were associated with a range of 0 to 8 degree angular change during the task. On the other hand, the smooth cooperative tasks in Center case were associated with lower range of angular change, i.e. 0 to 5 degrees. Thus, we could infer that smooth tasks in Center case were associated with less object rotation compare to the smooth task in End case. The result is true for leftward/rightward and upward/downward direction. However, in forward backward direction, almost similar range of angular change was observed either in End or Center case. The effect of End or Center was not significant on the object rotation in smooth cooperative task executed in forward/backward direction.



(a) Leftward/rightward (End) (b) Leftward/rightward (Center)



(c) Upward/downward (End) (d) Upward/downward (Center)



(e) Forward/backward (End) (f) Forward/backward (Center)

Fig. 23 Object rotational motion over cooperative task smoothness in each task direction for End (Left column) and Center (Right column).

2.6 Summary

We have investigated the characteristics for generating a smooth cooperative object transfers in human-human system with regards to the information exchanges occurs between subjects. The analysis revealed that two critical information i.e. signal to start and location to stop had induced frequent smoother cooperative task regardless of which part of the object was being perceived during the task. The result is in agreement with the previous researches [67-71, 74]. Comparing either End or Center case, the result shows that the Center case (both subjects perceived at same area on the object) generated more frequent, smoother and natural cooperative motion. Moreover, the Center case shows less objects rotation during smooth cooperative task. The result is true for the cooperative task executed in leftward/rightward and upward/downward direction; however, it is not for the cooperative task executed in forward/backward direction. In forward/backward direction, the cooperative task smoothness did not show any significant difference between the End and Center case. Also, in both End and Center cases of forward and backward direction, a similar range of object rotation during smooth task was observed. A force interaction between subjects was more influential on the cooperative task smoothness than visual effect in forward/backward direction.

It was understood from the previous and current research that in mode 4, subject 2 did not follow subject 1 motion from the beginning, however, he/she generated smooth trajectory towards the target position based on his/her own hand's rhythm (feed-forward manner). In implementing mode 4 in human-robot system, the robot is not required to follow the human subject to generate a smooth cooperative task (similar to the phenomenon in human-human system). Once received instruction to initiate the task, the robot could move towards the target with its own rhythm. In other words, the human motion is not required to be feedback to the robot to generate a smooth cooperative task. Thus, the robot will be adapted with a smooth trajectory of one of human subject (subject 2) which was obtained from mode 4 of human-human cooperative system. The smooth trajectory was similar to the trajectory generated using the Minimum Jerk Model. Thus, the trajectory of the robot will be based on the trajectory of the Minimum Jerk Model. In using the Minimum Jerk Model to generate a smooth trajectory for the robot mimicking the trajectory of human (human-human system), the relationship between movement time and travel distance of human subject was required. Since the Center case generated more frequent smoother motion than the End case, the relationship of the two parameters was investigated using the Center case of the cooperative task. The next chapter investigated the relationship between the two parameters.

CHAPTER 3

A RELATIONSHIP BETWEEN TRAVELED DISTANCE AND MOVEMENT TIME

3.1 Introduction

In chapter 2, we have investigated the effect of perceiving different or same part of the object on the cooperative task smoothness. It was understood that perceiving at the same part of the object (Center case) with both information (start signal and stop location) were made available to both subjects had generated more frequent smoother cooperative motion in human-human system. Thus the objective of this chapter is to discuss the relationship between movement time and traveled distance in Center case with both information were made available to both subjects. The reason for investigating the relationship between the two parameters could be explained using the Minimum Jerk Model equation. Equation (4) of the Minimum Jerk Model could be solved by using Euler-Poisson method [26]. Solving Eq. (4) by using the following boundary equation,

$$x(0) = x_i,\ x(t_f) = x_f;\ \dot{x}(0) = 0,\ \dot{x}(t_f) = 0\ ;\ddot{x}(0) = 0,\ \ddot{x}(t_f) = 0 \tag{9}$$

one dimensional minimum jerk trajectory equation was obtained,

$$x(t) = x_i + (x_f - x_i)\left(10\left(\frac{t}{t_f}\right)^3 - 15\left(\frac{t}{t_f}\right)^4 + 6\left(\frac{t}{t_f}\right)^5\right) \tag{10}$$

where x_i is the initial hand position at $t = 0$, x_f is the final hand position at $t = t_f$. $\dot{x}$ and $\ddot{x}$ are the instantaneous velocity and acceleration of the hand, respectively. The t_f also indicates the movement time from initial to final position. The (x_f - x_i) component indicates the distance traveled during the cooperative motion. Differentiating Eq. (10), we could obtain a minimum jerk velocity equation,

$$\dot{x}(t) = (x_f - x_i)\left(30\left(\frac{t}{t_f}\right)^2 - 60\left(\frac{t}{t_f}\right)^3 + 30\left(\frac{t}{t_f}\right)^4\right) \quad (11)$$

In Eq. (11), understanding the relationship between movement time and traveled distance will enable the equation to be applied in robot for generating a smooth manipulator motion.

3.2 Experimental Equipment

The experimental equipment consisted of a position measurement system (Optotrack Certus 3020 camera and Personal Computer), two LCD monitors, two height-adjustable chairs and an experimental object as shown in Fig. 24. The experimental object has the same dimension and configuration as in Fig. 8. When both subjects moved the experimental objects in any directions, the 3D camera in the position measurement system detected signals from the diode marker and sent it to the main computer. The computer processed the signal (position data) and converted it to a two dimensional (2D) rectangular image mimicking the experimental object translational and rotational motion in real time. The image was displayed on the LCD monitors in front of both subjects (see Fig. 25) and its size was 10 mm (W) x 100 mm (L). In leftward/rightward task, the 2D image represented 180 mm x 460 mm surface area of the real object. In upward/downward and forward/backward task, the 2D image represented 60 mm x 460 mm surface area of the real object. The start and four targets position were presented as two parallel lines and if its centerline coincides with rectangular image's centerline, it provides 3 mm gaps to tolerate the image positioning. The targets were positioned in four types of distances (50, 100, 150 and 200 mm) in each direction. Position data (X, Y and Z coordinates with origin at the center of the 3D camera) from each marker was recorded into the computer at every 10 ms of sampling interval. Each data was low-pass filtered by using a second order dual-pass Butterworth filter with a cut-off frequency of 5 Hz.

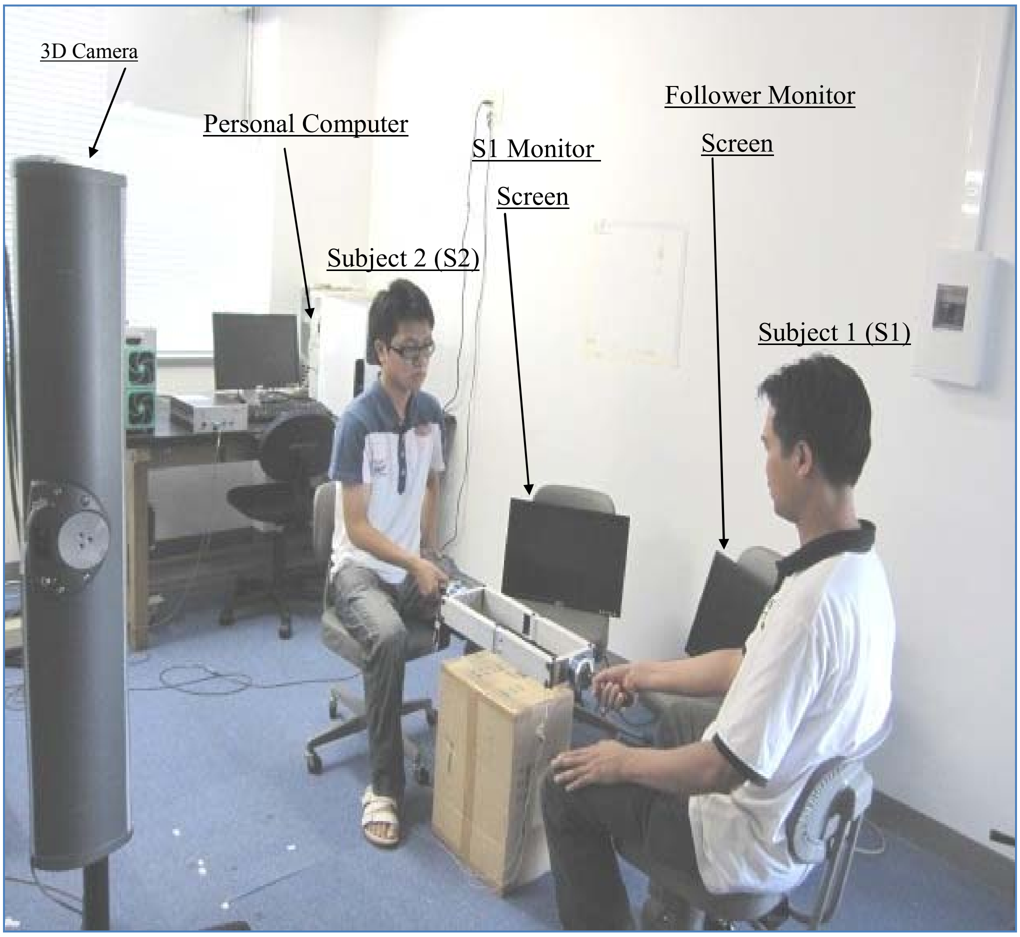


Fig. 24 Experimental equipment

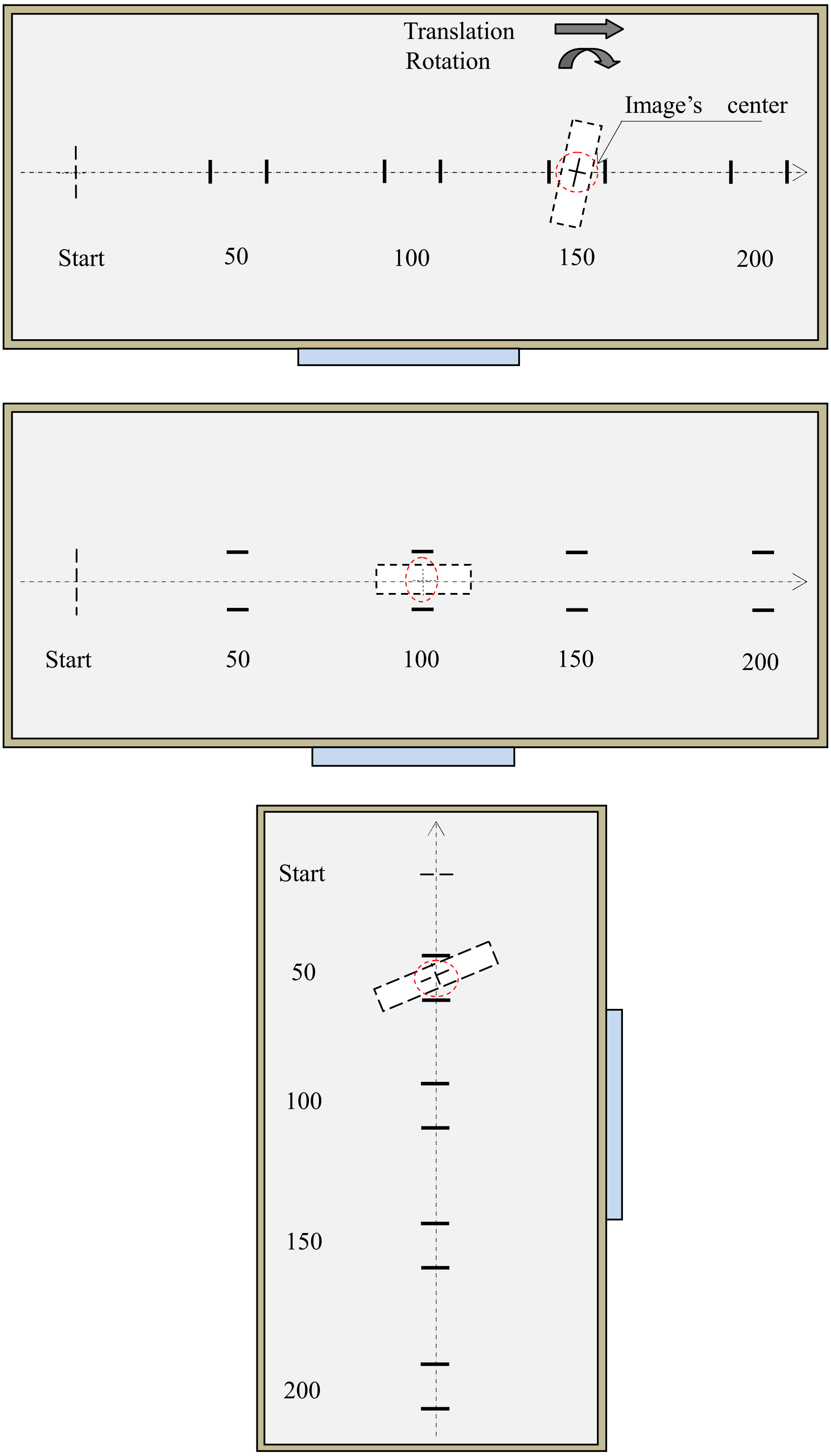


Fig. 25 Image appears on the screen in front of both subjects. Top (leftward/rightward), middle (forward/backward) and bottom (upward/downward)

3.3 Experimental Method

3.3.1Subjects

Six right-handed male students had been selected as experimental subjects which aged between 20 to 40 years old, physically and mentally healthy. Subjects did not report any sensory, neurological, muscular, cutaneous or impaired related problems. All of them had no experiences in executing the current experiment. All subjects were provided with informed consents and instructions on the experiment. In executing the cooperative object transfer, mode 4 of information understanding was used where both subjects understand the two critical information. Five groups of subjects were formed for the cooperative motion experiment.

3.3.2 Procedure

During the experiment, one subject known as host, worked at the computer (start up the software, recording, etc) and other two subjects known as subject 1 and subject 2 worked at the experimental object area. Both subjects sat on their respective chair facing each other as shown in Fig. 24. The distance between the chairs was fixed for each group and it was decided so that all subjects could move smoothly from the start position to the farthest target on the screen in all cooperative task major directions i.e. leftward/rightward, upward/downward and forward/backward. The major directions were defined relative to subject 1.

Before executing the task, Host started up the software and a 2D image resembling the experimental object appeared on the screen in front of both subjects. Host instructed both subjects to hold the experimental object with their right hand and matched the center of the 2D image on the start position. The start position on the screen was similar to the middle point located between both subjects. Mimicking the real cooperative task, subject 1 decided and informed the target position to subject 2. A verbal signal was given to subject 2 by subject 1 to indicate cooperative task onset. Once started, subject 1 cooperated with subject 2 in bringing the experimental object from the start to the target position together. At the vicinity of the target position, both subjects perceived at the center of the 2D image and matched it to the target. The 3D camera recorded their cooperative motion and position data was saved in the computer. Once reached the target, both subjects returned the experimental object to the start position. Both subjects rested for about 15 seconds before executing the next experiment.

Although the hand movement towards target consisted of two motion phases, the transfer phase from start to target position and precise positioning phase of object at target area, the article only discussed on the transfer phase. Thus, the targets were merely provided as a guideline to terminate the cooperative task. Both subjects were allowed to terminate the task as they approached near to the target area (only data with half of the image reached the target was considered). The subjects were required to practice by moving the object for several times before proceeding with the experiments. The practice was very important in order for subjects to adjust to the changes of the experimental conditions and familiarized with each other’s motion. Furthermore, it resembled a trained motion (as it was done daily) performed by the industrial workers. The experiments were conducted with 10 repetitions for each direction and distance. Only smooth motions were selected in each distance and direction. The selection was based on the calculated minimum jerk value, where value less than 500 (normalized jerk) was considered as a smooth cooperative motion. Statistical analyses were performed using the Statistical Packages for the Social Sciences (SPSS). Differences between the levels of each variable were detected using ANOVA. A significant level for all statistical tests was set at $p < 0.01$.

3.4Results & Discussion

3.4.1 Movement time and traveled distance-linear relationship

The scatter plots of cooperative movement time, t_f (s) versus traveled distance, D (m) for the cooperative task in three major directions i.e. leftward/rightward, upward/downward and forward/backward are shown in Fig. 26, 27 and 28. Group name was indicated at the top of each plot. The symbol in each plot was classified based on subjects and sub-directions (referring to each direction in major direction, e.g. leftward in leftward/rightward direction cooperative task). In any plot, the movement time was positively correlated to the traveled distance where all significant values were less than 0.01 (all ps < 0.01). The results indicated that an increased in the target distance will result in a linear increment of the time to perform a smooth cooperative task. The result is in agreement with other researchers although angle was used as parameters in some of the researches [89, 90].

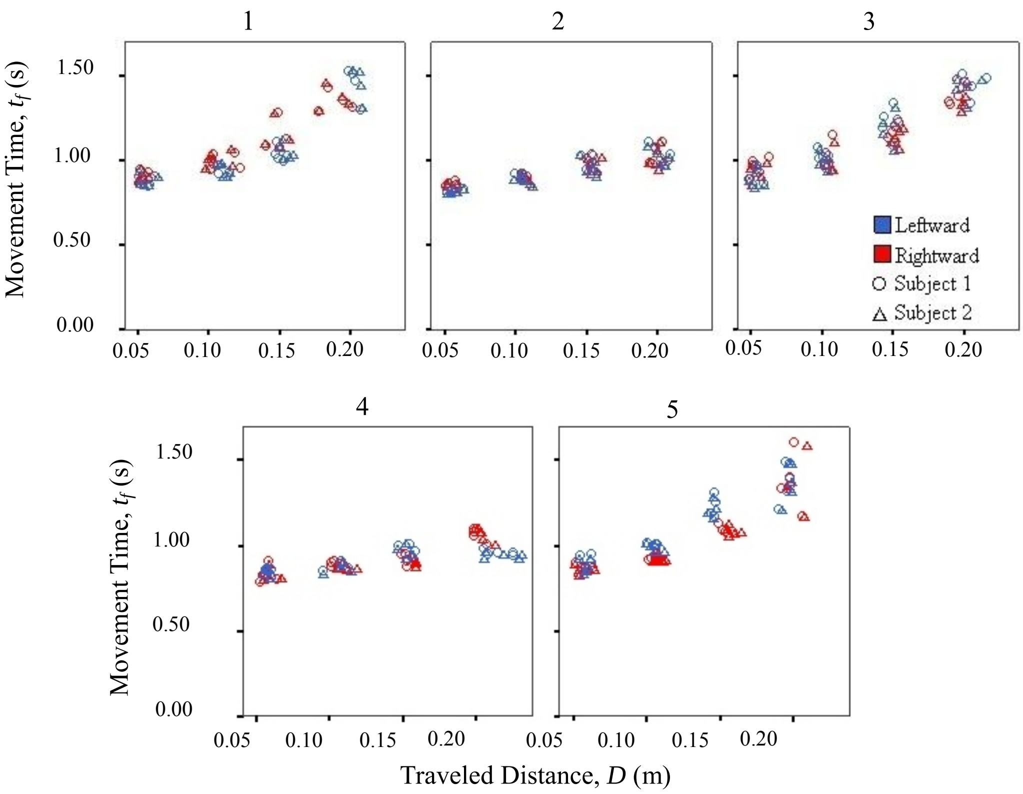


Fig. 26 Relationship between movement time, t_f (s) and traveled distance, D (m) of leftward/rightward cooperative task

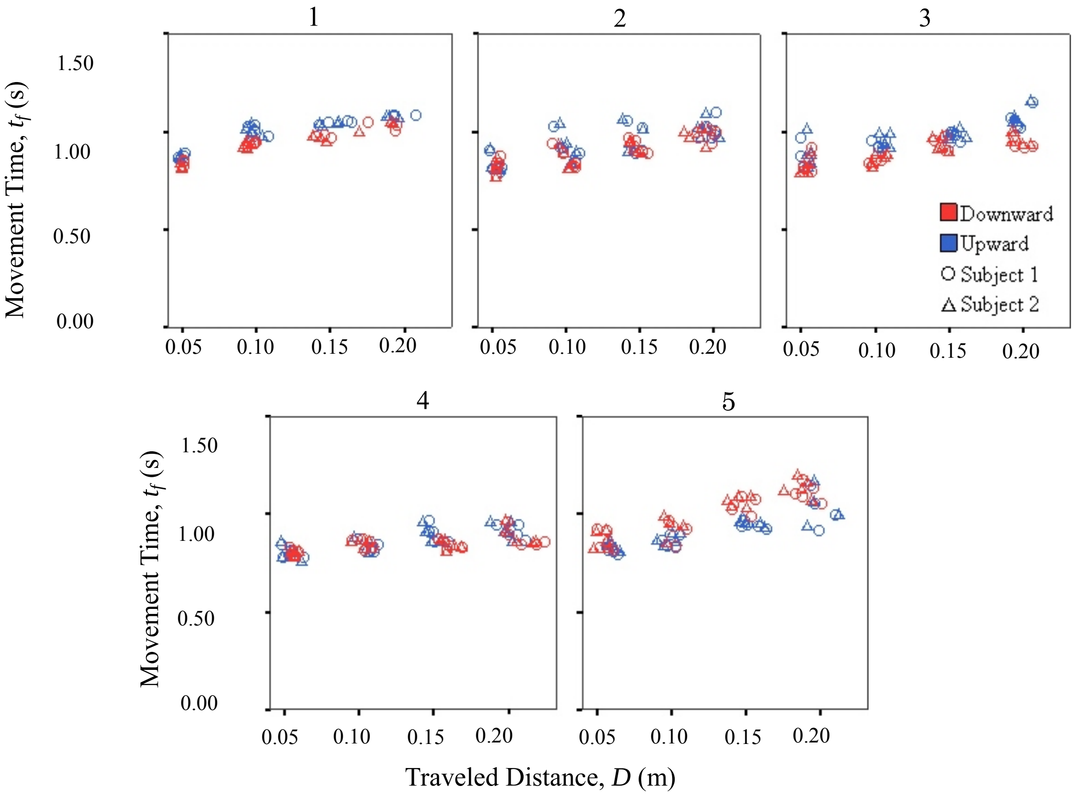


Fig. 27 Relationship between movement time, t_f (s) and traveled distance, D (m) of upward/downward cooperative task

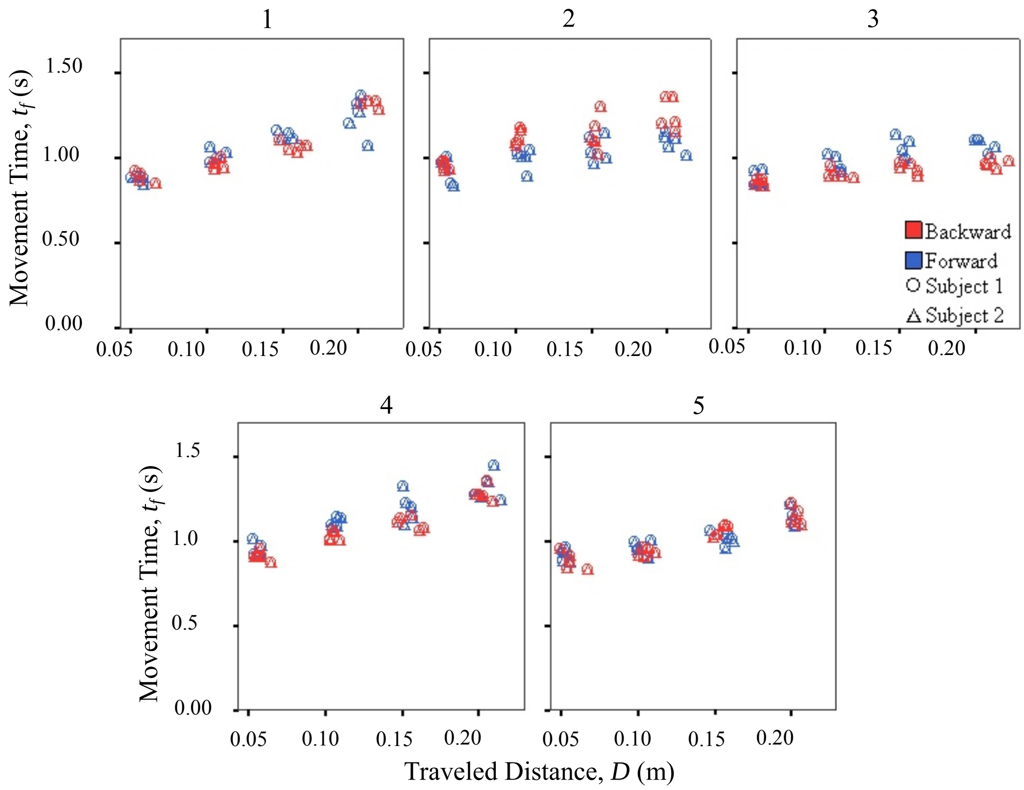


Fig. 28 Relationship between movement time, t_f(s) and traveled distance, D (m) of forward/backward cooperative task.

All positive correlation coefficients are shown in Table 3. Although a linear relationship was obtained, variations of the traveled distance were observed in the plots. The variation arose because subjects were not asked to terminate the cooperative task precisely, however, they could terminate as they approached near to the target area (half of the image is within the target area). Thus, the variations of traveled distance were due to the part of the experimental procedures.

Table 3. Correlation coefficients of cooperative movement time and distance. All *p*s < 0.01.

Group	Pearson correlation coefficient, *r*		
	Leftward/Rightward	Upward/Downward	Forward/Backward
1	0.878	0.100	0.919
2	0.880	0.758	0.677
3	0.928	0.736	0.686
4	0.795	0.662	0.909
5	0.900	0.804	0.880

3.4.2 Representing movement time and traveled distance relationship using linear regression

In previous section, the relationship between cooperative movement time and traveled distance was found to be linear. Thus, the following equation represents the general equation for the relationship between cooperative task movement time, t_f(s) and traveled distance, D (m),

$$t_f = t_0 + mD \qquad (12)$$

where m is the gradient of the line and t_0 is the starting time. This equation is true for the cooperative task with a distance equal and more than 50 mm as conducted in this experiment. Figure 29, 30 and 31 show the scatter plot of the movement time and traveled distance classified based on group and direction. In each plot, the regression line and its corresponding equations for both subjects were indicated. Subject 1 and subject 2 equation is located at the top and bottom of each plot, respectively.

The value of t_0 indicated that the initial cooperative movement time was faster or slower. However, as the distance increases, it was difficult to identify which group generated faster or slower cooperative motion than the other groups for a similar cooperative task sub-direction. The same phenomena were also observed in between cooperative task sub-directions. Moreover, the difference of movement time between upward and downward [91]; and also between leftward, rightward, upward and downward direction [90] of a single human hand motion was reported as non-significant. In their research, the experiments were executed with single hand motion and comfortable motion was not considered. In this research, a small different of movement time between sub-direction could be significant because the interaction between humans was involved during cooperative task execution.

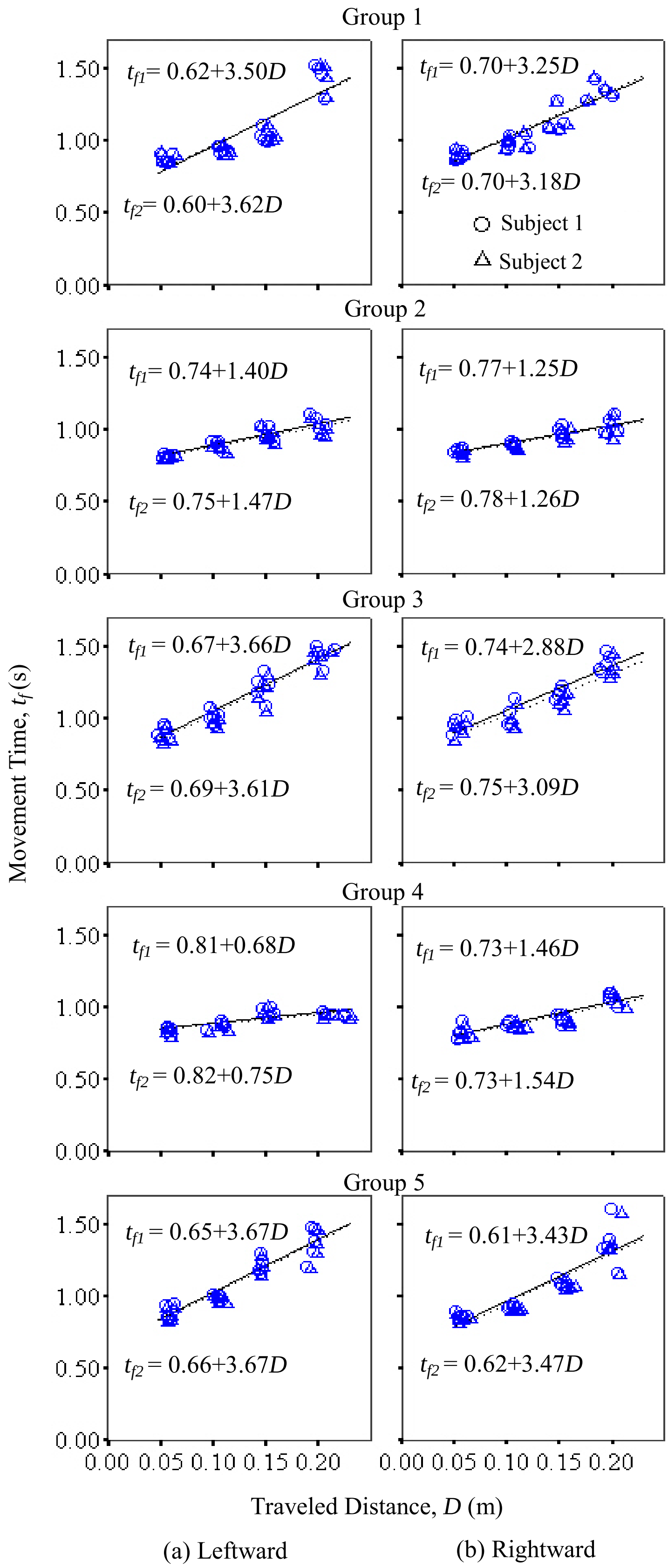


Fig. 29 The relationship between movement time and traveled distance in leftward/rightward direction

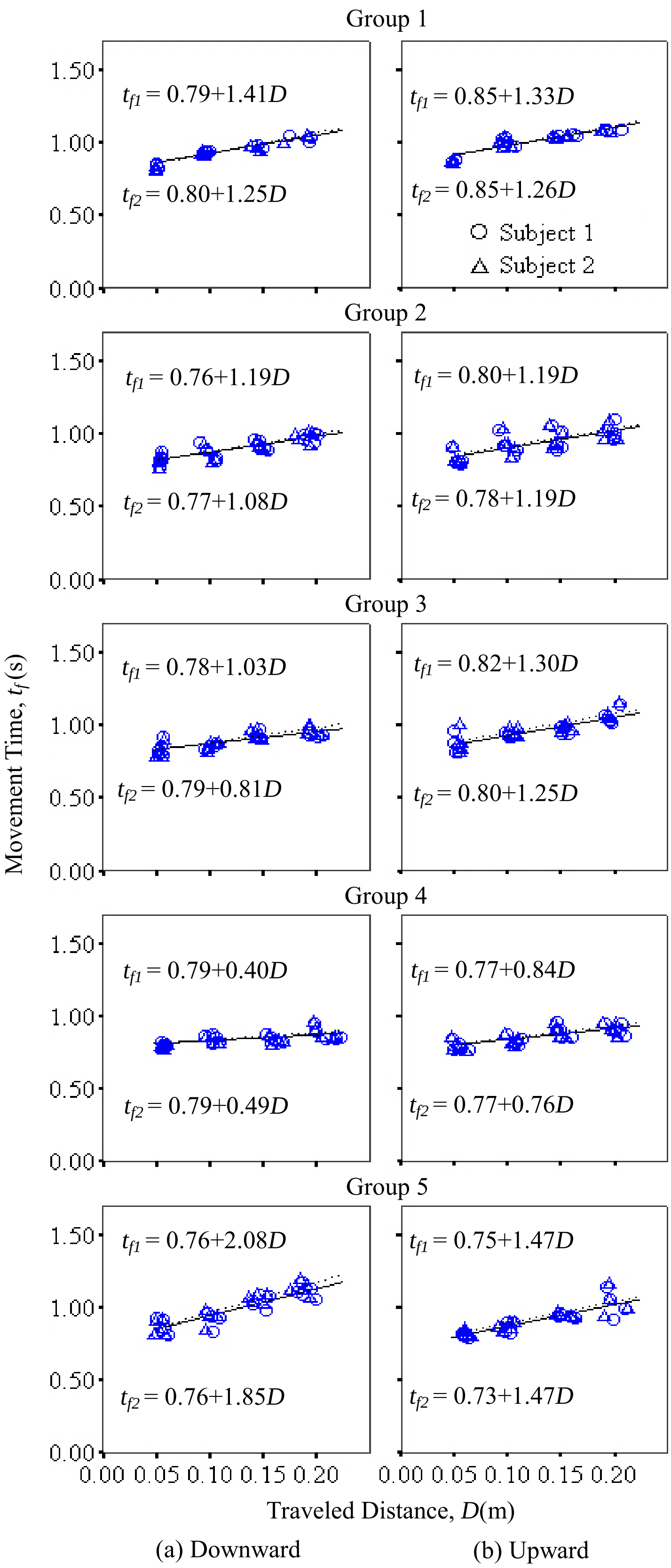


Fig. 30 The relationship between movement time and traveled distance in upward/downward direction.

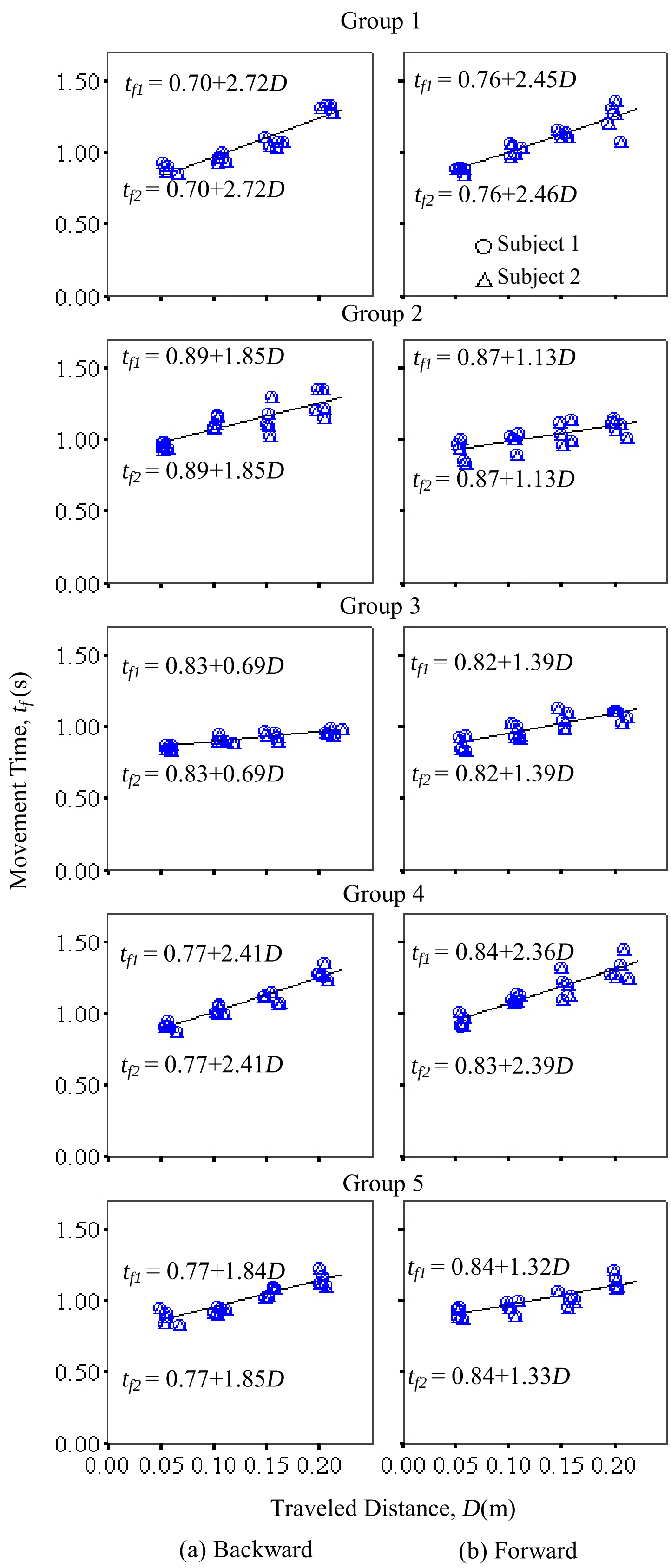


Fig. 31 The relationship between movement time and traveled distance in forward/backward direction.

Inconsistencies of t_f and m parameters of Equation (12) of each subject were found in each group and direction of the cooperative task. The inconsistencies were obvious especially in leftward/rightward and upward/downward direction compared to forward/backward direction. The cooperative tasks in leftward/rightward and upward/backward were prone towards two dimensional motions although subjects were asked to move the object in one dimensional motion[92, 93]. However, the movement in forward/backward direction was easily executed in one dimensional motion. Thus, the difference of t_f and m between subjects in forward/backward directions was small.

With the inconsistencies of the t_f and m value, it is difficult to utilize Eq. (12) in human-robot cooperative system i.e. each subject will have different t_f and m value in each direction to generate smooth cooperative motion with robot. In other words, the numbers of equation to be programmed to robot will increase proportionally with the number of subject.

As an alternative to this problem, a single representative equation for all human subjects in each cooperative task direction could be used. This means that any human subject could use the single equation to generate smooth cooperative motion with robot. Moreover, in some real applications, the numbers of human subject were unknown, and it could not be pre-programmed before the cooperative task e.g. when robot we required to work in an environment with many people. Thus, we preferred to use single equation in each cooperative task direction to represent all subjects' motions.

In obtaining a single equation in each cooperative task direction, the data of all human subjects in each cooperative task direction were compiled together as shown in Fig. 32. It was obvious from Fig. 32 that the movement time were distributed over certain range in each distance for all cooperative task directions. In formulating a single equation for each direction, the most preferable movement time in each distance should be determined. Finally, we could proposed a single linear equation in each direction (this equation represent the relationship between movement time and traveled distance in each direction) by using the least square method for all preferred movement time in each distance and direction.

In identifying the most preferable movement time, an average movement time of each cooperative task distance was determined. In addition to the average movement time, some other movement times were also determined for each subject involved in the experiments. The first two were the maximum and minimum movement times which were obtained from the maximum and minimum value of the movement time in each distance and sub-direction of human-human cooperative task. Another two movement times known as Midmax and Midmin were calculated so that the values were in the middle of the maximum and average movement time, and the minimum and average movement time, respectively. All these movement times were determined within the range of data obtained from human-human cooperative motion in this experiment.

Some movement times which were not in the range of human-human motion data obtained from this experiment were identified for each subject. These movement times were set as the upper and lower limit in each distance and direction of the cooperative task. Figure 33 shows the example of determining the movement times in leftward direction cooperative task. Table 4 and 5 show the movement time values to be tested in each human-robot cooperative task sub-direction. In each test, a questionnaire with an appropriate evaluation method should be provided to identify the most suitable movement time that generates the most comfortable cooperative task between human and robot.

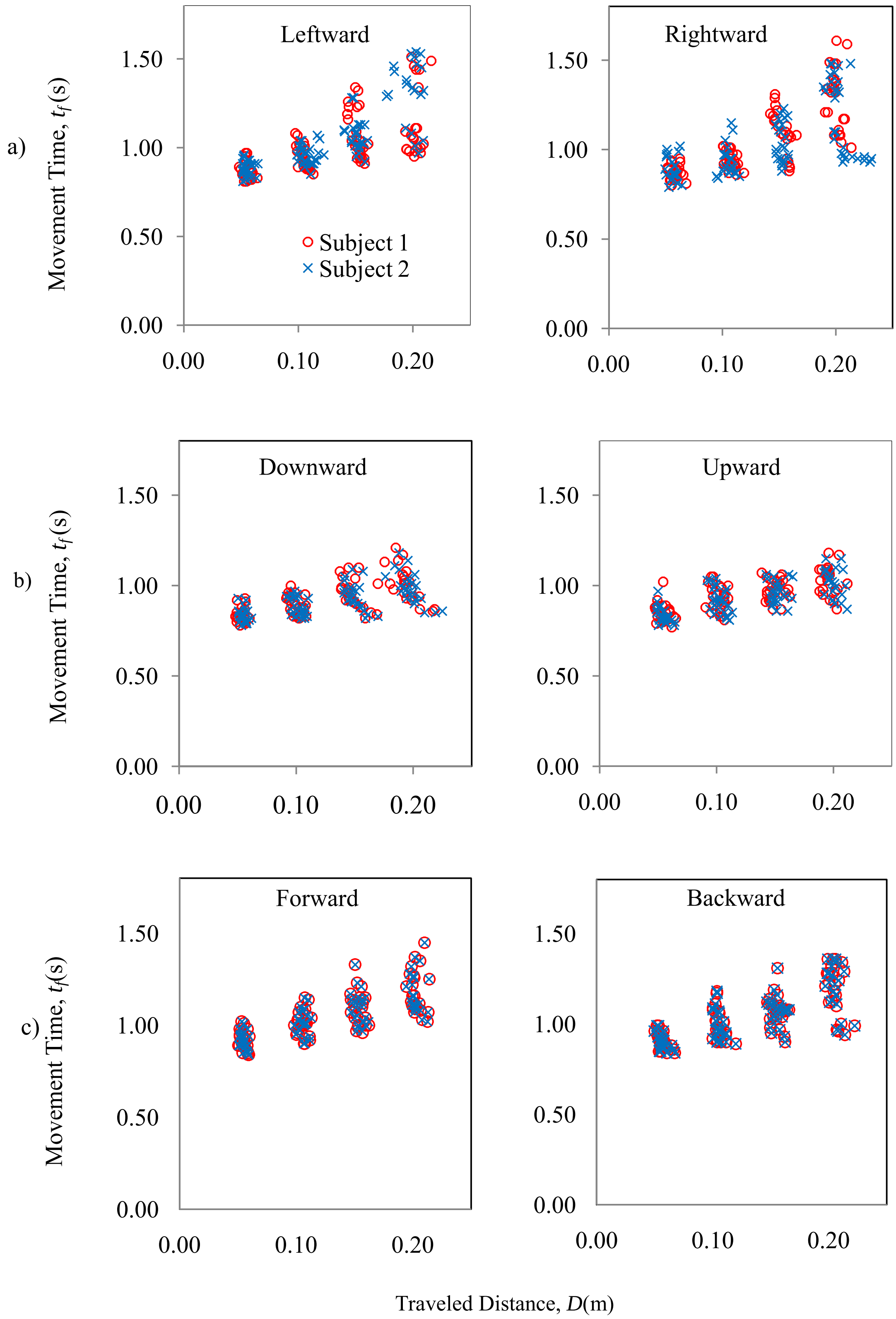


Fig. 32 Relationship between movement time and traveled distance of all subjects in each cooperative task direction.

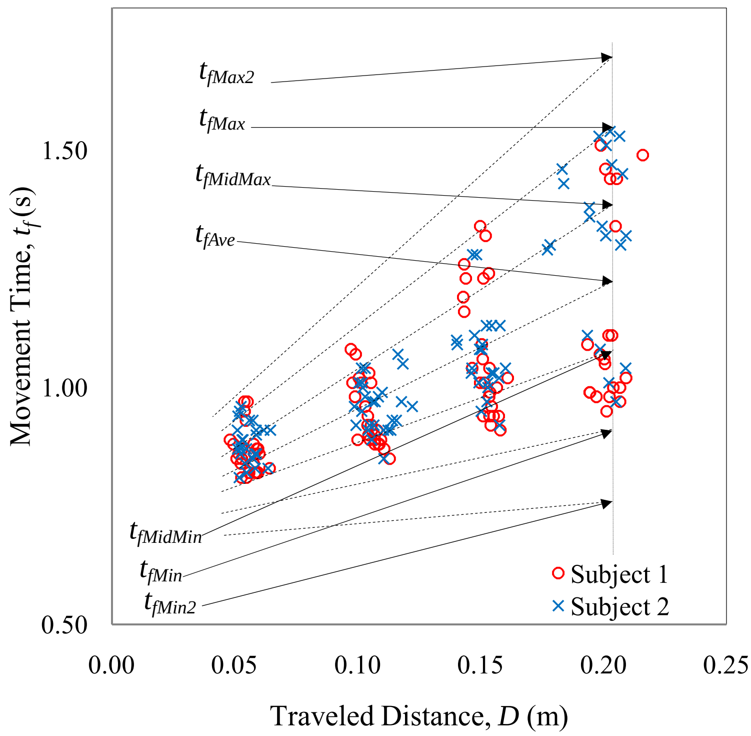


Fig. 33 Maximum, Midmax, Average, Midmin, and Minimum movement time were at 200mm distance in leftward direction. These movement times were within the range of the data obtained from human-human cooperative motion cooperative task. Maximum2 and Minimum2 were not in the range of human-human motion data from this experiment.

Table 4. Movement time of each distance in leftward, rightward and upward direction.

Direction	Movement Time (s)	50mm	100mm	150mm	200mm
Leftward	t_{fmax2}	1.010	1.241	1.471	1.702
	t_{fmax}	0.954	1.149	1.343	1.538
	$t_{fmidmax}$	0.898	1.057	1.215	1.374
	t_{fave}	0.843	0.965	1.088	1.210
	$t_{fmidmin}$	0.825	0.906	0.987	1.068
	t_{fmin}	0.807	0.846	0.886	0.926
	t_{fmin2}	0.789	0.787	0.785	0.784
Rightward	t_{fmax2}	1.079	1.347	1.614	1.882
	t_{fmax}	1.003	1.221	1.440	1.658
	$t_{fmidmax}$	0.926	1.096	1.265	1.434
	t_{fave}	0.850	0.970	1.090	1.210
	$t_{fmidmin}$	0.822	0.916	1.010	1.104
	t_{fmin}	0.795	0.862	0.930	0.998
	t_{fmin2}	0.767	0.808	0.850	0.891
Upward	t_{max2}	1.024	1.082	1.139	1.196
	t_{max}	0.965	1.023	1.080	1.137
	t_{midmax}	0.906	0.964	1.021	1.079
	t_{ave}	0.848	0.905	0.963	1.020
	t_{midmin}	0.813	0.855	0.898	0.941
	$Fmin$	0.778	0.806	0.833	0.861
	t_{min2}	0.743	0.756	0.769	0.782

Table 5. Movement time of each distance in downward, forward and backward direction.

Direction	Movement Time (s)	50mm	100mm	150mm	200mm
Downward	t_{fmax2}	0.965	1.077	1.189	1.301
	t_{fmax}	0.923	1.013	1.104	1.194
	$t_{fmidmax}$	0.880	0.950	1.019	1.088
	t_{fave}	0.838	0.886	0.934	0.982
	$t_{fmidmin}$	0.808	0.843	0.877	0.912
	t_{fmin}	0.778	0.799	0.820	0.842
	t_{fmin2}	0.748	0.756	0.764	0.771
Forward	t_{fmax2}	1.056	1.218	1.380	1.543
	t_{fmax}	1.009	1.146	1.283	1.420
	$t_{fmidmax}$	0.963	1.074	1.185	1.297
	t_{fave}	0.916	1.002	1.088	1.174
	$t_{fmidmin}$	0.876	0.948	1.020	1.092
	t_{fmin}	0.835	0.894	0.952	1.011
	t_{fmin2}	0.795	0.840	0.884	0.929
Backward	t_{fmax2}	1.025	1.162	1.300	1.437
	t_{fmax}	0.980	1.102	1.224	1.345
	$t_{fmidmax}$	0.935	1.041	1.148	1.254
	t_{fave}	0.891	0.981	1.072	1.162
	$t_{fmidmin}$	0.864	0.925	0.987	1.048
	t_{fmin}	0.837	0.870	0.902	0.935
	t_{fmin2}	0.811	0.814	0.818	0.821
	t_{fmin3}	0.784	0.759	0.733	0.708

3.5 Summary

A relationship between movement time and traveled distance during cooperative task of carrying a rigid object involving two humans was investigated. The relationship was required to be used with Minimum Jerk Model which was calculated based on one of the subject motion's data. The analysis revealed that the movement time and traveled distance were found to be positively correlated, where an increase in the traveled distance resulted in the increase of the movement time. Subsequently, the relationship between movement time and traveled distance was represented using the regression line with starting time, t_0 and gradient, m as parameters. This mean that the value of movement time for each cooperative task distance could be determine based on the value of t_0 and m.

The relationship between movement time and traveled distance of human subject was planned to be used in robotic program to enable implementation of human cooperative behavior in human-robot cooperative system .However, in each group of each cooperative task sub-direction, each human subject shows different value of t_0 and m. This mean that each subject should use different relationship (different value of t_0 and m) when generating smooth cooperative motion with robot. Thus, many different relationships should be determined and used when the numbers of subject increase. Instead of this, we proposed to used a single representative relationship in each cooperative task sub-direction and distance.

In finding a representative relationship, the movement times of all human subjects were combined for each cooperative task sub-direction. Then, it was found that in each sub-direction, the movement times of all human subjects were distributed over certain range of each cooperative task distance. Subsequently, in each sub-direction of combined data, an average regression line was identified to represent the average relationship of movement time and traveled distance. Then, an average movement time in each cooperative task distance and sub-direction was calculated. Additional to this average movement time, another six movement times were identified from each distance and sub-direction of human-human cooperative task experimental data. In the next phase of experiment, these movement times were utilized with minimum jerk model and tested with subject 1 from this experiment. Finally, in each sub-direction and distance, the most suitable movement time will be selected and used to formulate a representative relationship between movement time and traveled distance. The representative relationship will be used to generate smooth cooperative motion in human-robot system.

CHAPTER 4

IMPLEMENTING HUMAN-HUMAN COOPERATIVE BEHAVIOR IN HUMAN-ROBOT COOPERATIVE SYSTEM

4.0 Introduction

In previous chapters, we have investigated the characteristics for generating smooth motion in human-human cooperative system. In this chapter, two main objectives were set as follows,

1. Verifying the human-human cooperative behavior obtained in previous chapters using human-robot cooperative system.
2. In chapter 3, the movement time of all subjects were found to be distributed over certain range at each cooperative motion distance and sub-direction. Selecting the most preferred movement time for all human subjects facilitate the implementation of human-robot cooperative system. Thus, the most preferred movement time of all human subjects were determined based on comfortable motion characteristics i.e. the motion's speed which based on the preset movement time was not too fast, not too slow, less vibration and suitable for human-robot cooperation.

In achieving the second objective, the Thurston case V [94-98] method of pair wise comparison was utilized to evaluate the most preferred movement time. This method gives subjective scale of stimuli presented to the subject [99]. The method assumed that each time a stimuli is represented to subject; the stimuli could then be represented by a point along a one dimensional psychological scale. The location of the point is determined by an unknown discriminal process by which the organism identifies, distinguishes, discriminates or reacts to the stimuli. However, because of certain nature of human's perceptual state, the same stimulus does not excite the same discriminal process. It is assumed that repeated occurrence of a stimulus produce a distribution called a discriminal dispersion of such processes along the psychological scale. These random events will create a normal distribution around a mean. The mean is associated with the scale value of the stimulus, and the standard deviation is interpreted as the unit of measurement along the internal scale[100]. The method was chosen because the underlying measurement model is intuitively appealing and the numerical procedure involves in the experiment is simple. Each subject in the group is presented with every one of the $n(n-1)/2$ possible pairs of n numbers of movement times [98].

In chapter 3 (human-human cooperative system), both subjects have the two critical information prior to the cooperative task execution and thus, they were defined as Leaders. In the experiment, Subject 2 had gained the information through verbal means by subject 1. In this chapter (human-robot cooperative system), both agents were also defined as Leaders and thus both have the critical information. However, the robot was not equipped with speech recognition or image processing system or force sensors to receive information from human. The information were given to the robot through program by a third person involved in experiment and known as Host. Obviously, there is a difference in the method of gaining the information between human-human and human-robot system. However, the difference in the method of gaining the information between the two systems was not importance because the definition of Leader was only based on having or not having the critical information.

4.1 Experimental Equipment

Fig. 34 illustrates the human-robot cooperative system. The system consisted of a 7-degree-of-freedom manipulator (Mitsubishi PA10), angular velocity controller and a personal computer. The computer has an Intel Pentium processor (800MHz) to control the manipulator motion with a sampling rate at 2ms. Figure 35 shows the concept of the block diagram to control the manipulator movement. The desired position, X_d and velocity, V_d were computed based on the Minimum Jerk Model equation. The movement time, t_f and traveled distance, $x_f - x_i$ were taken from table 4 and 5.

The experimental object has the same dimension and configuration as in human-human cooperative system. The object was attached to the manipulator using a THK rod end (NOS 8T) as shown in Fig. 36. The rod end has an allowable rotation angle more than the angle obtained in human-human cooperative system (object rotation angle during cooperative task in human-human system is less than 8 degrees).

The human Leader required the visual information of experimental object and also the stop location of the cooperative task. Thus, a 3D motion capture system was provided in the experiment to give such information to the Leader. The experimental object has same dimensions and configuration as in Fig. 9. When the object was moved in any direction, the 3D camera in the position measurement system detected signals from the diode marker and sent it to the main computer. The computer processed the signal (position data) and converted it to a two dimensional (2D) rectangular image mimicking the experimental object translational and rotational motion in real time. The image was displayed on the LCD monitors in front of Leader and its size is 10 mm (W) x 100 mm (L). The start and four targets position were presented as two parallel lines and if its centerline coincides with rectangular image's centerline, it provides 3mm gaps to tolerate the image positioning. The targets were positioned in four types of distances in each direction. The distances were set at 50, 100, 150 and 200 mm as shown in Fig. 26. Position data (X, Y and Z coordinates with origin at the center of the 3D camera) from each marker was recorded into the computer at every 10 ms of sampling interval. Each data was low-pass filtered by using a second order dual-pass Butterworth filter with a cut-off frequency of 5 Hz. The signal (position data) will be used for evaluating the cooperative task smoothness offline.

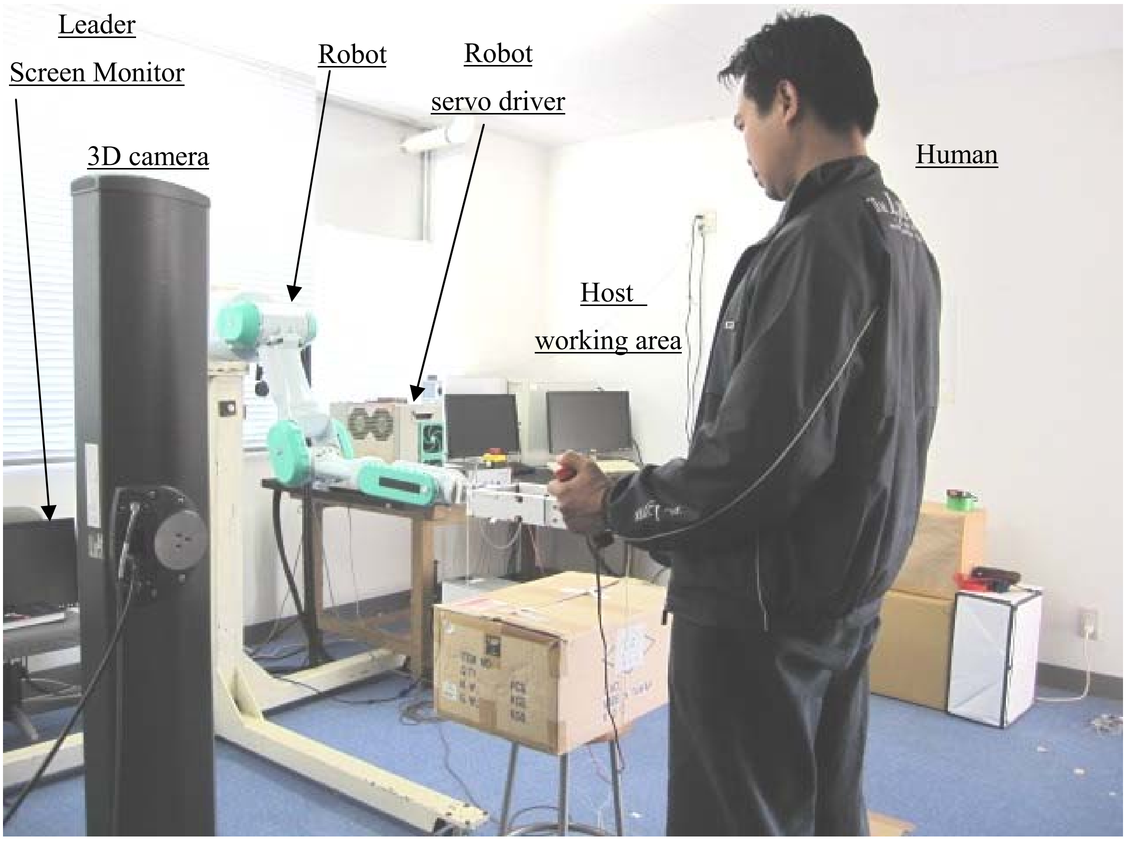
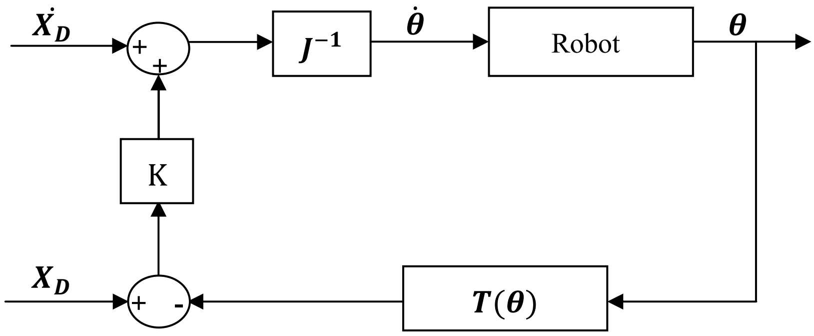


Fig. 34 Experimental Equipment



End effector desired position, $X_D = [x_d, y_d, z_d]^T$

End effector desired velocity, $\dot{X}_D = [\dot{x}_d, \dot{y}_d, \dot{z}_d]^T$

Jacobian, $J(\theta)$

Transformation Matrix, $T(\theta)$

Joint angle, $\theta = (\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7)$

Fig 35. Block diagram of the control system of the Mitsubishi PA10 robot system. Velocity control with position feedback mode was used for the system.

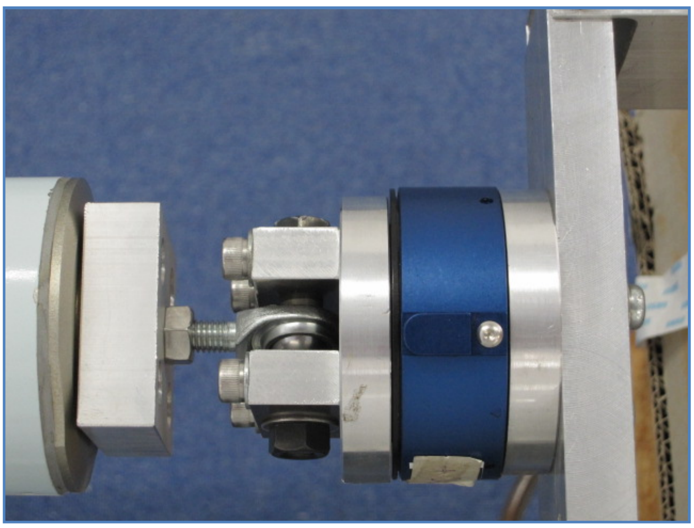


Fig. 36 Rod end joining the experimental object and robot manipulator

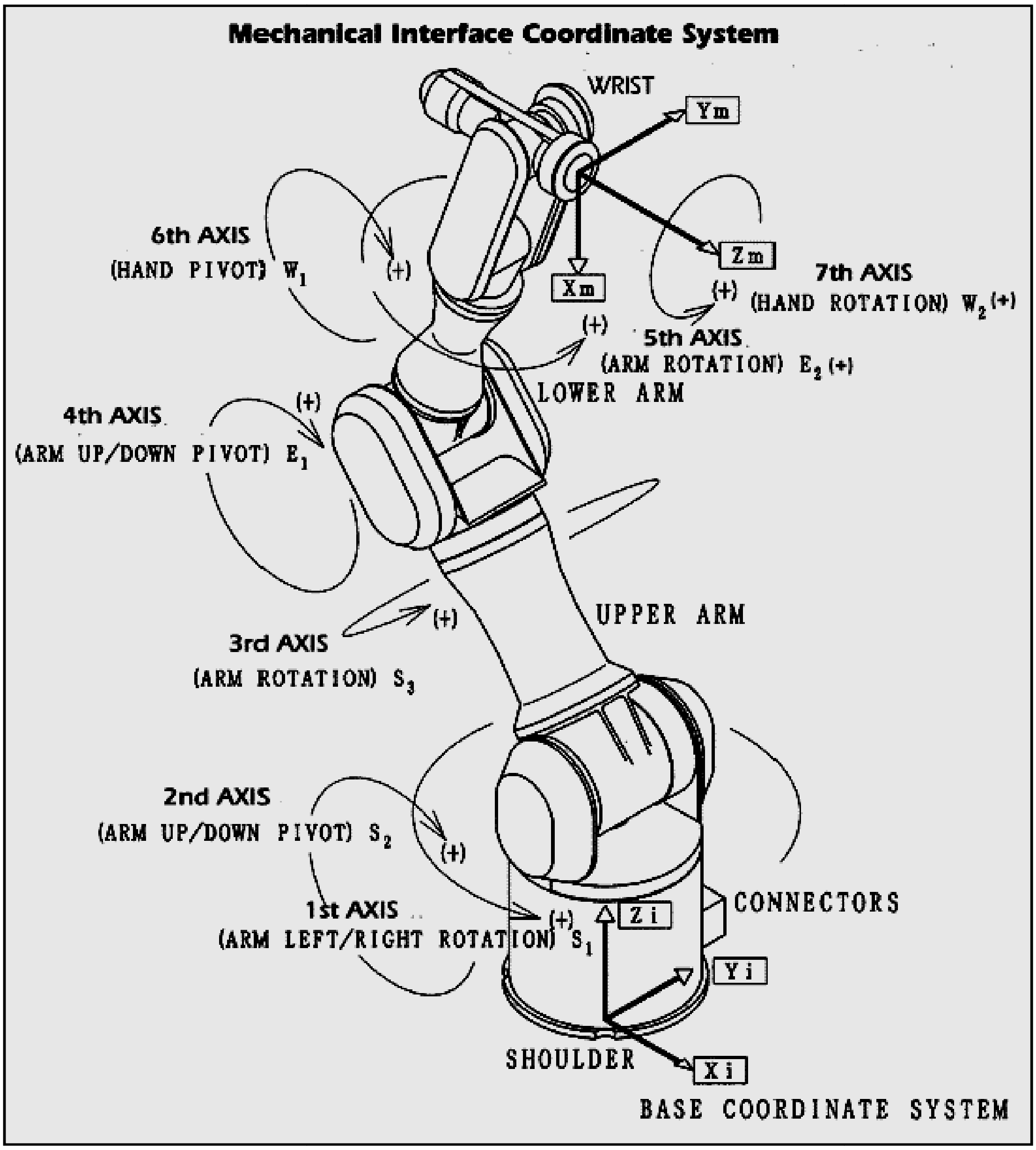


Fig 37. Axis Designation for Mitsubishi PA10 7 degree of freedom.

4.2 Experimental Method

4.2.1 Subjects

Five right-handed male students had been selected as experimental subjects which aged between 20 to 40 years old, physically and mentally healthy. Subjects did not report any sensory, neurological, muscular, cutaneous or impaired related problems. The subjects in this experiment are the same subject as in human-human cooperative system. All of them had experienced in executing the experiment of carrying an object in human-human cooperative system but not with human-robot system. All subjects were provided with informed consents and instructions on the experiment. Five groups of dyads were formed.

4.2.2 Procedure

The procedure of the experiment was carried out to help the human Leader select the most suitable movement time that generated smooth and comfortable cooperative motion. The Thurston's method of pair-wise comparison was used to evaluate the results and the experimental procedure reflected the evaluation method. The experiment with 200mm in leftward direction was taken as an example to explain the experimental procedures. At 200mm distance, 7 numbers of movement times were used as parameters for finding the best movement time with smooth and comfortable cooperative motion, see table 4. Based on Thurston's method case V, 21 (7*(7-1)/2) numbers of pair-wise comparison was conducted for 200 mm distance. The pairs were shown in table 6. The table consists of *i* rows and *j* columns. The 0 and 1 scale were used as the rule for pair-wise comparison [101]. The movement time in the row, t_{fi} were compared with the movement time in the column, t_{fj}. In the diagonal of the table (i=j), no value was necessary because movement time was compared with itself. When individual believes t_{fj}

was better than t_{fi}, then he certainly belief that the t_{fi} is worst than t_{fj}. Thus, the section above diagonal is reciprocal of the section below diagonal. When t_{fi} is compared with t_{fj} and human preferred t_{fi} to t_{fj}, 1 is inserted, if t_{fj} is preferred t_{fi}, then 0 is inserted.

Table 6. Pair-wise comparison at 200mm target location.

	t_{fMax2}	t_{fMax}	$t_{fMaxMid}$	t_{fAve}	$t_{fMinMid}$	t_{fMin}	t_{fMin2}
t_{fMax2}	-	1st	2nd	3rd	4th	5th	6th
t_{fMax}		-	7th	8th	9th	10th	11th
$t_{fMidMax}$			-	12th	13th	14th	15th
t_{fAve}				-	16th	17th	18th
$t_{fMidMin}$					-	19th	20th
t_{fMin}						-	21th
t_{fMin2}							

In executing the experiment, one subject known as Host, worked at the computer area (start up the software, recording, etc), and human worked with robot at the experimental object area. The human stood while facing the robot and the human's right shoulder was in line with the robot's midline. Before executing the task, Host attached one's end of the experimental object to the robot and instructed the human to hold the other's end of the object with their right hand. Host started the motion capture system and the 2D image's center resembling the center of the real experimental object appeared on the screen in front of Human. The 2D image's center was matched to the start target location and human perceived at the image's center to match it to the next target location.

In human-human system, one human subject gave verbal instruction to another human subject to initiate the cooperative task. However, in this research, the robot was not equipped with a system to identify the task initiation signal generated by human. The initiation signal was important to generate simultaneous cooperative task onset between human and robot. In human-robot system the following procedures were taken to ensure simultaneous cooperative task onset between human and robot and also to compare the speed between two movement times set to the robot.

Host set the robot with the first movement time. Then, Host gave signal to the controller to initiate the robotic motion. The manipulator's motion was delayed for 6 seconds after receiving the initiation signal from Host. Host counted the initiation time loudly to inform human subject on the task onset. After 6 seconds, human moved and the robot cooperated with him in bringing the experimental object from the start to the target position together. Once human realized that he was near to the target location, he perceived the 2D image's center and matched it to the target location. Human memorized the first motion's speed.

Then, Host gave signal to return the human-robot cooperative system to the start position. He set the robot with the second movement time. The same procedures as in first motion were executed and human compared the second and the first motion's speed. Human informed the preferred motion and Host recorded it in table 6. Human was required to practice by moving the object with the robot for several times before proceeding with the experiments. Each human has 5 movement times to be tested with the robot for each cooperative task direction and distance. However, after some preliminary test, we found that the different in the speed based on the set movement time at 50mm distance could not be distinguished by human subject. They reported that the distance was too short to understand the difference between the two cooperative motions. Thus, the cooperative motions based on the 50mm target distance were excluded from the research. Furthermore, the cooperative movement times for 100mm and 150mm were reduced to give a suitable experimental total time to human subject. The final movement times to be used in the experiment were shown in table 7 and 8. Table 9 and 10 show the velocity associated with each cooperative task movement time.

The smoothness of each cooperative motion was evaluated offline where the normalized jerk value less than 500 was used as a guideline. In our previous research normalized jerk value less than 600 was defined as smooth[102]. However, in this experiment, the normalized jerk value less than 500 was found to be better to indicate smooth cooperative motion. Statistical analyses were performed using the Statistical Packages for the Social Sciences (SPSS). Differences between the levels of each variable were detected using ANOVA. A significant level for all statistical tests was set at $p < 0.01$.

Table 7 Movement time in leftward, rightward, upward direction of human-robot system.

Direction	Movement Time (s)	100mm	150mm	200mm
Leftward	t_{fmax2}	1.241	1.471	1.702
	t_{fmax}	1.149	1.343	1.538
	$t_{fmidmax}$	-	1.215	1.374
	t_{fave}	0.965	1.088	1.210
	$t_{fmidmin}$	-	-	1.068
	t_{fmin}	0.846	0.886	0.926
	t_{fmin2}	0.787	0.785	0.784
Rightward	t_{fmax2}	1.347	1.614	1.882
	t_{fmax}	1.221	1.440	1.658
	$t_{fmidmax}$	-	1.265	1.434
	t_{fave}	0.970	1.090	1.210
	$t_{fmidmin}$	-	-	1.104
	t_{fmin}	0.862	0.930	0.998
	t_{fmin2}	0.808	0.850	0.891
Upward	t_{fmax2}	1.082	1.139	1.196
	t_{fmax}	1.023	1.080	1.137
	$t_{fmidmax}$	-	1.021	1.079
	t_{fave}	0.905	0.963	1.020
	$t_{fmidmin}$	-	-	0.941
	t_{fmin}	0.806	0.833	0.861
	t_{fmin2}	0.756	0.769	0.782

Table 8 Movement time in downward, forward, backward direction of human-robot system.

Direction	Movement Time (s)	100mm	150mm	200mm
Downward	t_{fmax2}	1.077	1.189	1.301
	t_{fmax}	1.013	1.104	1.194
	$t_{fmidmax}$	-	1.019	1.088
	t_{fave}	0.886	0.934	0.982
	$t_{fmidmin}$	-	-	0.912
	t_{fmin}	0.799	0.820	0.842
	t_{fmin2}	0.756	0.764	0.771
Forward	t_{fmax2}	1.218	1.380	1.543
	t_{fmax}	1.146	1.283	1.420
	$t_{fmidmax}$	-	1.185	1.297
	t_{fave}	1.002	1.088	1.174
	$t_{fmidmin}$	-	-	1.092
	t_{fmin}	0.894	0.952	1.011
	t_{fmin2}	0.840	0.884	0.929
Backward	t_{fmax2}	1.162	1.300	1.437
	t_{fmax}	1.102	1.224	1.345
	$t_{fmidmax}$	-	1.148	1.254
	t_{fave}	0.981	1.072	1.162
	$t_{fmidmin}$	-	-	1.048
	t_{fmin}	0.870	0.902	0.935
	t_{fmin2}	0.814	0.818	0.821
	t_{fmin3}	0.759	0.733	0.708

Table 9 Average velocity based on each movement time in leftward, rightward, upward direction of human-robot system.

Direction	Velocity(m/s)	100mm	150mm	200mm
Leftward	V_{tfmax2}	0.081	0.102	0.118
	V_{tfmax}	0.087	0.112	0.130
	$V_{tfmidmax}$	-	0.123	0.146
	V_{tfave}	0.104	0.138	0.165
	$V_{tfmidmin}$	-	-	0.187
	V_{tfmin}	0.118	0.169	0.216
	V_{tfmin2}	0.127	0.191	0.255
Rightward	V_{tfmax2}	0.074	0.093	0.106
	V_{tfmax}	0.082	0.104	0.121
	$V_{tfmidmax}$	-	0.119	0.139
	V_{tfave}	0.103	0.138	0.165
	$V_{tfmidmin}$	-	-	0.181
	V_{tfmin}	0.116	0.161	0.200
	V_{tfmin2}	0.124	0.176	0.224
Upward	V_{tfmax2}	0.092	0.132	0.167
	V_{tfmax}	0.098	0.139	0.176
	$V_{tfmidmax}$	-	0.147	0.185
	V_{tfave}	0.110	0.156	0.196
	$V_{tfmidmin}$	-	-	0.213
	V_{tfmin}	0.124	0.180	0.232
	V_{tfmin2}	0.132	0.195	0.256

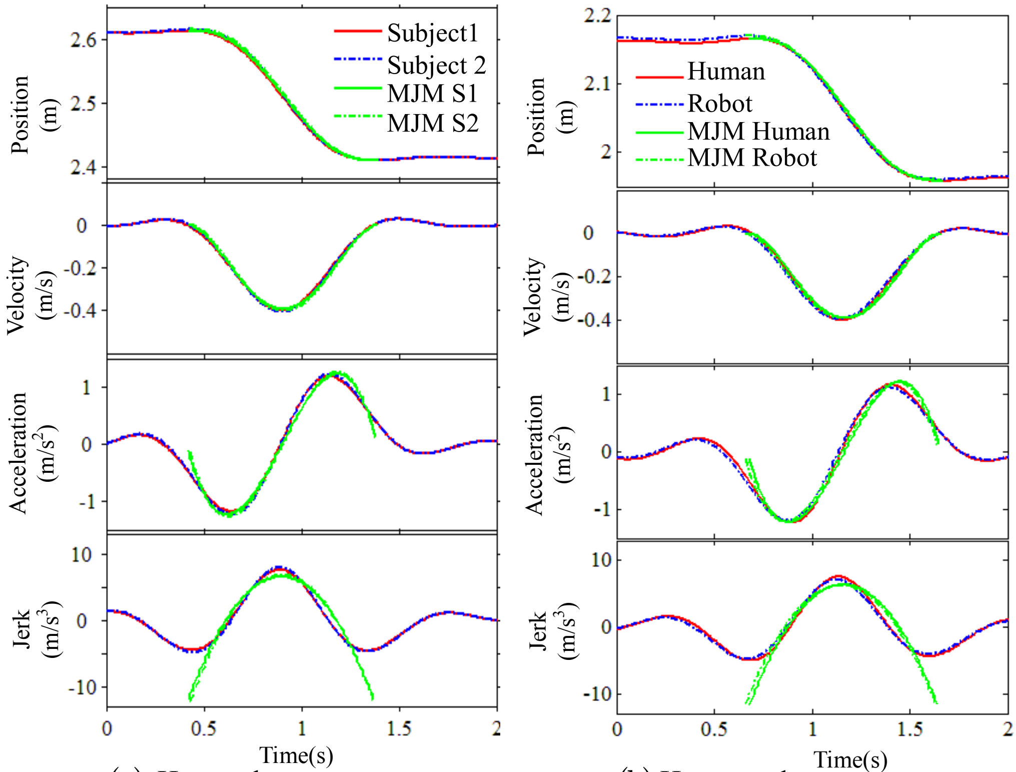
Table 10 Average velocity based on each movement time in downward, forward and backward direction of human-robot system.

Direction	Velocity(m/s)	100mm	150mm	200mm
Downward	V_{tfmax2}	0.093	0.126	0.154
	V_{tfmax}	0.099	0.136	0.167
	$V_{tfmidmax}$	-	0.147	0.184
	V_{tfave}	0.113	0.161	0.204
	$V_{tfmidmin}$	-	-	0.219
	V_{tfmin}	0.125	0.183	0.238
	V_{tfmin2}	0.132	0.196	0.259
Forward	V_{tfmax2}	0.082	0.109	0.130
	V_{tfmax}	0.087	0.117	0.141
	$V_{tfmidmax}$	-	0.127	0.154
	V_{tfave}	0.100	0.138	0.170
	$V_{tfmidmin}$	-	-	0.183
	V_{tfmin}	0.112	0.158	0.198
	V_{tfmin2}	0.119	0.170	0.215
Backward	V_{tfmax2}	0.086	0.115	0.139
	V_{tfmax}	0.091	0.123	0.149
	$V_{tfmidmax}$	-	0.131	0.160
	V_{tfave}	0.102	0.140	0.172
	$V_{tfmidmin}$	-	-	0.191
	V_{tfmin}	0.115	0.166	0.214
	V_{tfmin2}	0.123	0.183	0.244
	V_{tfmin3}	0.132	0.205	0.283

4.3 Results & Discussion

4.3.1 Verifying cooperative motion smoothness in human-robot system.

Figure 38(a) and 38(b) show the kinematics profiles of smooth human-human and human-robot cooperative motion, respectively. Both figures were obtained from the same dyad in leftward direction and 100mm distance cooperative task. In Fig. 38(a) (human-human system), the kinematics profiles of dyad in human-human system were overlapping indicated a good cooperative motion. In Fig. 38(b) (human-robot system), the kinematics profiles of the dyad were slightly separated from each other. However, as mentioned in Shahriman et. al [74], the cooperative motion with slight difference in kinematics profile was considered smooth. Furthermore, we verified the cooperative motion smoothness in human-robot system quantitatively using the normalized jerk value (normalized jerk value < 500 is considered smooth, please refer procedural section 4.2.2). Figure 39 shows the normalized jerk value obtained in this experiment for all cooperative task sub-directions. Obviously, smooth cooperative motion was generated in all directions of human-robot cooperative system.



(a) Human-human system (b) Human-robot system

Fig.38 Kinematics profiles in human-human and human-robot system

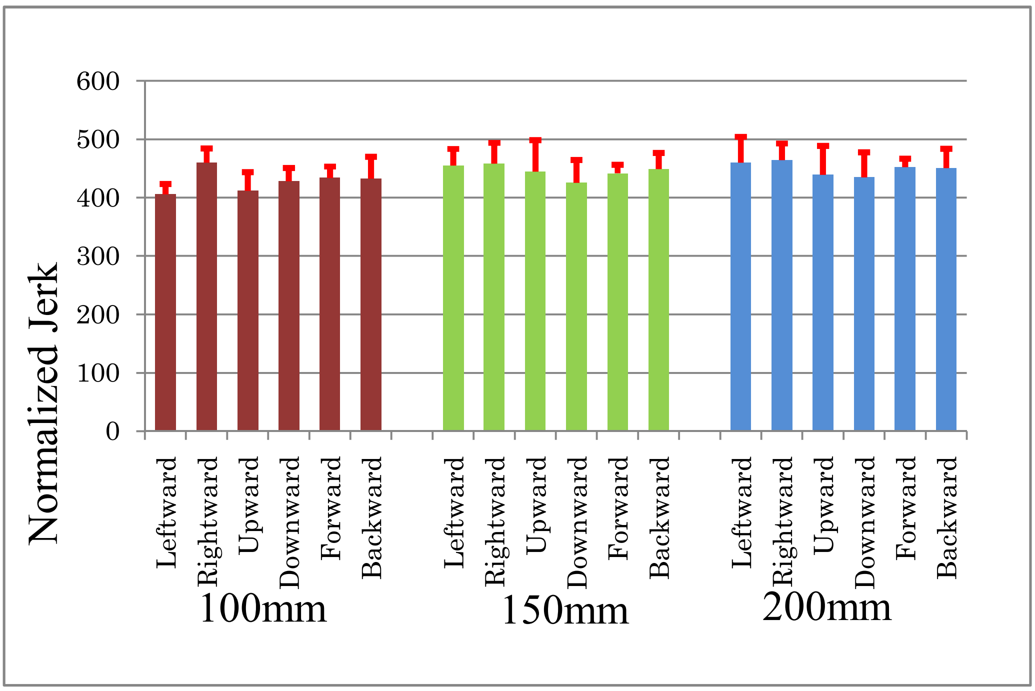


Fig. 39 Normalized jerk value of human-robot cooperative motion in all direction and distance were less than 500. These indicated a good cooperative motion.

4.3.2 Selection of Preferred Movement Time

As mentioned in procedural section, subjects were asked to select one of the two movement times given to them. The movement time they preferred was given mark as 1, and the rejected movement time was given mark as 0. Finally, the frequency of selected movement time of all subjects in each cooperative task direction and distance were tabulated. Table 11 shows the frequency of selected movement time in leftward direction. Then, each element in frequency matrix was divided with numbers of participant involved in the experiment (number of participants are 5). The result was shown in percentage matrix as in table 12. Then, each value in table 12 was converted to Z score (return the value of Z based on the standard normal cumulative distribution). The result was shown in table 13. Finally, the average Z score of each movement time (each row) was calculated. The highest value gives the most preferred movement time in each direction and distance. Table 11-28 show the frequency, percentage and Z score in each cooperative task direction.

The results of the preferred movement time in each distance and direction were shown in table 29 and plotted in Fig. 40 - 45. Obviously, in all cooperative task directions, the preferred movement times were in the range of the data obtained from human-human cooperative motion. A linear equation representing the relationship between movement time and traveled distance were shown in each Fig 40 - 45. The equation was calculated using least square method based on the preferred movement time in each cooperative task direction and distance. Those equations will be used with the minimum jerk model to generate smooth cooperative motion in human-robot system.

In leftward, rightward, upward and forward direction, a single movement time was preferred in each cooperative task distance. However, in downward and backward direction, 100mm and 150mm respectively, more than one movement time were preferred. It was understood that individual differences for the preferred movement time in these two cases were large compare to other cases. The individual difference has generated two preferred movement times in these two cases.

In these cases, the preferred movement time was determined so that the final linear equation (a straight line representing the equation) which included the 50mm distance were in the range of the data obtained from human-human cooperative motion. Therefore, for downward and backward direction, t_{fmax} and $t_{fmidmax}$ were chosen respectively.

Table 11 Frequency of selected movement time in leftward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0	1	0	1	3	3
Max	5	-	3	4	2	3	5
MidMax	4	2	-	3	4	2	5
Ave	5	1	2	-	3	3	5
Midmin	4	3	1	2	-	3	5
Min	2	2	3	2	2	-	5
Min2	2	0	0	0	0	0	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	1	0	0	3	4
Max	4	-	3	3	5	5
MidMax	5	2	-	4	4	5
Ave	5	2	1	-	4	5
Min	2	0	1	1	-	5
Min2	1	0	0	0	0	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	2	2	2	2
Max	3	-	3	3	3
Ave	3	2	-	3	5
Min	3	2	2	-	5
Min2	3	2	0	0	-

Table 12 Percentage of selected movement time in leftward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.01	0.2	0.01	0.2	0.6	0.6
Max	0.99	-	0.6	0.8	0.4	0.6	0.99
MidMax	0.8	0.4	-	0.6	0.8	0.4	0.99
Ave	0.99	0.2	0.4	-	0.6	0.6	0.99
Midmin	0.8	0.6	0.2	0.4	-	0.6	0.99
Min	0.4	0.4	0.6	0.4	0.4	-	0.99
Min2	0.4	0.01	0.01	0.01	0.01	0.01	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.2	0.01	0.01	0.6	0.8
Max	0.8	-	0.6	0.6	0.99	0.99
MidMax	0.99	0.4	-	0.8	0.8	0.99
Ave	0.99	0.4	0.2	-	0.8	0.99
Min	0.4	0.01	0.2	0.2	-	0.99
Min2	0.2	0.01	0.01	0.01	0.01	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	0.4	0.4	0.4	0.4
Max	0.6	-	0.6	0.6	0.6
Ave	0.6	0.4	-	0.6	0.99
Min	0.6	0.4	0.4	-	0.99
MIn2	0.6	0.4	0.01	0.01	-

Table 13　Z scores of leftward direction cooperative task.

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	-2.326	-0.842	-2.326	-0.842	0.253	0.253	-0.972
Max	2.326	-	0.253	0.842	-0.253	0.253	2.326	**0.958**
MidMax	0.842	-0.253	-	0.253	0.842	-0.253	2.326	0.626
Ave	2.326	-0.842	-0.253	-	0.253	0.253	2.326	0.677
Midmin	0.842	0.253	-0.842	-0.253	-	0.253	2.326	0.430
Min	-0.253	-0.253	0.253	-0.253	-0.253	-	2.326	0.261
Min2	-0.253	-2.326	-2.326	-2.326	-2.326	-2.326	-	-1.981

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	-0.842	-2.326	-2.326	0.253	0.842	-0.880
Max	0.842	-	0.253	0.253	2.326	2.326	1.200
MidMax	2.326	-0.253	-	0.842	0.842	2.326	**1.217**
Ave	2.326	-0.253	-0.842	-	0.842	2.326	0.880
Min	-0.253	-2.326	-0.842	-0.842	-	2.326	-0.387
Min2	-0.842	-2.326	-2.326	-2.326	-2.326	-	-2.029

100mm						
	Max2	Max	Ave	Min	Min2	Average
Max2	-	-0.253	-0.253	-0.253	-0.253	-0.253
Max	0.253	-	0.253	0.253	0.253	0.253
Ave	0.253	-0.253	-	0.253	2.326	**0.645**
Min	0.253	-0.253	-0.253	-	2.326	0.518
Min2	0.253	-0.253	-2.326	-2.326	-	-1.163

Table 14 Frequency of selected movement time in rightward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0	0	0	0	1	3
Max	5	-	2	1	3	2	5
MidMax	5	3	-	2	3	4	5
Ave	5	4	3	-	3	4	5
Midmin	5	2	2	2	-	3	5
Min	4	3	1	1	2	-	5
Min2	2	0	0	0	0	0	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Min2	-	0	0	0	1	3
Max	5	-	1	2	3	4
MidMax	5	4	-	3	4	5
Ave	5	3	2	-	5	5
Min	4	2	1	0	-	3
Min2	2	1	0	0	2	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	3	1	1	2
Max	2	-	2	2	3
Ave	4	3	-	4	3
Min	4	3	1	-	1
Min2	3	2	2	4	-

Table 15　Percentage of selected movement time in rightward direction cooperative task

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.01	0.01	0.01	0.01	0.2	0.6
Max	0.99	-	0.4	0.2	0.6	0.4	0.99
MidMax	0.99	0.6	-	0.4	0.6	0.8	0.99
Ave	0.99	0.8	0.6	-	0.6	0.8	0.99
Midmin	0.99	0.4	0.4	0.4	-	0.6	0.99
Min	0.8	0.6	0.2	0.2	0.4	-	0.99
Min2	0.4	0.01	0.01	0.01	0.01	0.01	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.01	0.01	0.01	0.2	0.6
Max	0.99	-	0.2	0.4	0.6	0.8
MidMax	0.99	0.8	-	0.6	0.8	0.99
Ave	0.99	0.6	0.4	-	0.99	0.99
Min	0.8	0.4	0.2	0.01	-	0.6
Min2	0.4	0.2	0.01	0.01	0.4	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	0.6	0.2	0.2	0.4
Max	0.4	-	0.4	0.4	0.6
Ave	0.8	0.6	-	0.8	0.6
Min	0.8	0.6	0.2	-	0.2
Min2	0.6	0.4	0.4	0.8	-

Table 16　Z Score in rightward direction cooperative task.

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	-2.326	-2.326	-2.326	-2.326	-0.842	0.253	-1.649
Max	2.326	-	-0.253	-0.842	0.253	-0.253	2.326	0.593
MidMax	2.326	0.253	-	-0.253	0.253	0.842	2.326	0.958
Ave	2.326	0.842	0.253	-	0.253	0.842	2.326	**1.140**
Midmin	2.326	-0.253	-0.253	-0.253	-	0.253	2.326	0.691
Min	0.842	0.253	-0.842	-0.842	-0.253	-	2.326	0.247
Min2	-0.253	-2.326	-2.326	-2.326	-2.326	-2.326	-	-1.981

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	-2.326	-2.326	-2.326	-0.842	0.253	-1.513
Max	2.326	-	-0.842	-0.253	0.253	0.842	0.465
MidMax	2.326	0.842	-	0.253	0.842	2.326	1.318
Ave	2.326	0.253	-0.253	-	2.326	2.326	**1.396**
Min	0.842	-0.253	-0.842	-2.326	-	0.253	-0.465
Min2	-0.253	-0.842	-2.326	-2.326	-0.253	-	-1.200

100mm						
	Max2	Max	Ave	Min	Min2	Average
Max2	-	0.253	-0.842	-0.842	-0.253	-0.421
Max	-0.253	-	-0.253	-0.253	0.253	-0.127
Ave	0.842	0.253	-	0.842	0.253	**0.547**
Min	0.842	0.253	-0.842	-	-0.842	-0.147
Min2	0.253	-0.253	-0.253	0.842	-	0.147

Table 17 Frequency of selected movement time in upward direction cooperative task

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	2	1	1	2	3	4
Max	3	-	3	3	5	4	5
MidMax	4	2	-	2	3	5	5
Ave	4	2	3	-	3	4	5
Midmin	3	0	2	2	-	4	5
Min	2	1	0	1	1	-	5
Min2	1	0	0	0	0	0	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	1	1	0	2	4
Max	4	-	3	2	3	4
MidMax	4	2	-	2	5	4
Ave	5	3	3	-	5	5
Min	3	2	0	0	-	5
Min2	1	1	1	0	0	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	3	2	1	1
Max	2	-	3	3	4
Ave	3	2	-	4	4
Min	4	2	1	-	4
Min2	4	1	1	1	-

Table 18 Percentage of selected movement time in upward direction cooperative task

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.4	0.2	0.2	0.4	0.6	0.8
Max	0.6	-	0.6	0.6	0.99	0.8	0.99
MidMax	0.8	0.4	-	0.4	0.6	0.99	0.99
Ave	0.8	0.4	0.6	-	0.6	0.8	0.99
Midmin	0.6	0.01	0.4	0.4	-	0.8	0.99
Min	0.4	0.2	0.01	0.2	0.2	-	0.99
Min2	0.2	0.01	0.01	0.01	0.01	0.01	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.2	0.2	0.01	0.4	0.8
Max	0.8	-	0.6	0.4	0.6	0.8
MidMax	0.8	0.4	-	0.4	0.99	0.8
Ave	0.99	0.6	0.6	-	0.99	0.99
Min	0.6	0.4	0.01	0.01	-	0.99
Min2	0.2	0.2	0.2	0.01	0.01	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	0.6	0.4	0.2	0.2
Max	0.4	-	0.6	0.6	0.8
Ave	0.6	0.4	-	0.8	0.8
Min	0.8	0.4	0.2	-	0.8
Min2	0.8	0.2	0.2	0.2	-

Table 19　Z score for upward direction cooperative task

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	-0.253	-0.842	-0.842	-0.253	0.253	0.842	-0.182
Max	0.253	-	0.253	0.253	2.326	0.842	2.326	**1.042**
MidMax	0.842	-0.253	-	-0.253	0.253	2.326	2.326	0.873
Ave	0.842	-0.253	0.253	-	0.253	0.842	2.326	0.710
Midmin	0.253	-2.326	-0.253	-0.253	-	0.842	2.326	0.098
Min	-0.253	-0.842	-2.326	-0.842	-0.842	-	2.326	-0.463
Min2	-0.842	-2.326	-2.326	-2.326	-2.326	-2.326	-	-2.079

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	-0.842	-0.842	-2.326	-0.253	0.842	-0.684
Max	0.842	-	0.253	-0.253	0.253	0.842	0.387
MidMax	0.842	-0.253	-	-0.253	2.326	0.842	0.701
Ave	2.326	0.253	0.253	-	2.326	2.326	**1.497**
Min	0.253	-0.253	-2.326	-2.326	-	2.326	-0.465
Min2	-0.842	-0.842	-0.842	-2.326	-2.326	-	-1.436

100mm						
	Max2	Max	Ave	Min	Min2	Average
Max2	-	0.253	-0.253	-0.842	-0.842	-0.421
Max	-0.253	-	0.253	0.253	0.842	0.274
Ave	0.253	-0.253	-	0.842	0.842	**0.421**
Min	0.842	-0.253	-0.842	-	0.842	0.147
Min2	0.842	-0.842	-0.842	-0.842	-	-0.421

Table 20　Frequency of selected movement time in downward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	3	3	2	3	3	5
Max	2	-	5	4	4	5	5
MidMax	2	0	-	3	3	5	5
Ave	3	1	2	-	1	5	5
Midmin	2	1	2	4	-	3	5
Min	2	0	0	0	2	-	5
Min2	0	0	0	0	0	0	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Min2	-	3	1	1	3	5
Max	2	-	5	3	4	5
MidMax	4	0	-	2	4	5
Ave	4	2	3	-	4	5
Min	2	1	1	1	-	5
Min2	0	0	0	0	0	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	1	0	2	2
Max	4	-	4	3	2
Ave	5	1	-	1	4
Min	3	2	4	-	4
Min2	3	3	1	1	-

Table 21 Percentage of selected movement time in downward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.6	0.6	0.4	0.6	0.6	0.99
Max	0.4	-	0.99	0.8	0.8	0.99	0.99
MidMax	0.4	0.01	-	0.6	0.6	0.99	0.99
Ave	0.6	0.2	0.4	-	0.2	0.99	0.99
Midmin	0.4	0.2	0.4	0.8	-	0.6	0.99
Min	0.4	0.01	0.01	0.01	0.4	-	0.99
Min2	0.01	0.01	0.01	0.01	0.01	0.01	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.6	0.2	0.2	0.6	0.99
Max	0.4	-	0.99	0.6	0.8	0.99
MidMax	0.8	0.01	-	0.4	0.8	0.99
Ave	0.8	0.4	0.6	-	0.8	0.99
Min	0.4	0.2	0.2	0.2	-	0.99
Min2	0.01	0.01	0.01	0.01	0.01	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	0.2	0.01	0.4	0.4
Max	0.8	-	0.8	0.6	0.4
Ave	0.99	0.2	-	0.2	0.8
Min	0.6	0.4	0.8	-	0.8
Min2	0.6	0.6	0.2	0.2	-

Table 22　Z score in downward direction cooperative task.

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	0.253	0.253	-0.253	0.253	0.253	2.326	0.514
Max	-0.253	-	2.326	0.842	0.842	2.326	2.326	**1.401**
MidMax	-0.253	-2.326	-	0.253	0.253	2.326	2.326	0.430
Ave	0.253	-0.842	-0.253	-	-0.842	2.326	2.326	0.495
Midmin	-0.253	-0.842	-0.253	0.842	-	0.253	2.326	0.346
Min	-0.253	-2.326	-2.326	-2.326	-0.253	-	2.326	-0.860
Min2	-2.326	-2.326	-2.326	-2.326	-2.326	-2.326	-	-2.326

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	0.253	-0.842	-0.842	0.253	2.326	0.230
Max	-0.253	-	2.326	0.253	0.842	2.326	**1.099**
MidMax	0.842	-2.326	-	-0.253	0.842	2.326	0.286
Ave	0.842	-0.253	0.253	-	0.842	2.326	0.802
Min	-0.253	-0.842	-0.842	-0.842	-	2.326	-0.090
Min2	-2.326	-2.326	-2.326	-2.326	-2.326	-	-2.326

100mm						
	Max2	Max	Ave	Min	Min2	Average
Max2	-	-0.842	-2.326	-0.253	-0.253	-0.919
Max	0.842	-	0.842	0.253	-0.253	**0.421**
Ave	2.326	-0.842	-	-0.842	0.842	0.371
Min	0.253	-0.253	0.842	-	0.842	**0.421**
Min2	0.253	0.253	-0.842	-0.842	-	-0.294

Table 23　Frequency of selected movement time in forward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	1	0	0	2	2	3
Max	4	-	1	2	4	2	4
MidMax	5	4	-	2	2	3	5
Ave	5	3	3	-	1	4	5
Midmin	3	1	3	4	-	4	5
Min	3	3	2	1	1	-	5
Min2	2	1	0	0	0	0	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0	1	0	1	3
Max	5	-	2	3	3	5
MidMax	4	3	-	3	3	5
Ave	5	2	2	-	5	5
Min	4	2	2	0	-	4
Min2	2	0	0	0	1	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	2	0	1	1
Max	3	-	5	4	2
Ave	5	0	-	4	4
Min	4	1	1	-	4
Min2	4	3	1	1	-

Table 24　Percentage of selected movement time in forward direction cooperative task

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.2	0.01	0.01	0.4	0.4	0.6
Max	0.8	-	0.2	0.4	0.8	0.4	0.8
MidMax	0.99	0.8	-	0.4	0.4	0.6	0.99
Ave	0.99	0.6	0.6	-	0.2	0.8	0.99
Midmin	0.6	0.2	0.6	0.8	-	0.8	0.99
Min	0.6	0.6	0.4	0.2	0.2	-	0.99
Min2	0.4	0.2	0.01	0.01	0.01	0.01	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.01	0.2	0.01	0.2	0.6
Max	0.99	-	0.4	0.6	0.6	0.99
MidMax	0.8	0.6	-	0.6	0.6	0.99
Ave	0.99	0.4	0.4	-	0.99	0.99
Min	0.8	0.4	0.4	0.01	-	0.8
Min2	0.4	0.01	0.01	0.01	0.2	-

100mm					
	Max2	Max	Ave	Min	Min2
Max2	-	0.4	0.01	0.2	0.2
Max	0.6	-	0.99	0.8	0.4
Ave	0.99	0.01	-	0.8	0.8
Min	0.8	0.2	0.2	-	0.8
Min2	0.8	0.6	0.2	0.2	-

Table 25 Z score of forward direction cooperative task.

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	-0.842	-2.326	-2.326	-0.253	-0.253	0.253	-0.958
Max	0.842	-	-0.842	-0.253	0.842	-0.253	0.842	0.196
MidMax	2.326	0.842	-	-0.253	-0.253	0.253	2.326	**0.873**
Ave	2.326	0.253	0.253	-	-0.842	0.842	2.326	0.860
Midmin	0.253	-0.842	0.253	0.842	-	0.842	2.326	0.612
Min	0.253	0.253	-0.253	-0.842	-0.842	-	2.326	0.149
Min2	-0.253	-0.842	-2.326	-2.326	-2.326	-2.326	-	-1.733

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	-2.326	-0.842	-2.326	-0.842	0.253	-1.217
Max	2.326	-	-0.253	0.253	1.000	2.326	1.131
MidMax	0.842	0.253	-	0.253	0.253	2.326	0.786
Ave	2.326	-0.253	-0.253	-	2.326	2.326	**1.294**
Min	0.842	0.000	-0.253	-2.326	-	0.842	-0.179
Min2	-0.253	-2.326	-2.326	-2.326	-0.842	-	-1.615

100mm						
	Max2	Max	Ave	Min	Min2	Average
Max2	-	-0.253	-2.326	-0.842	-0.842	-1.066
Max	0.253	-	2.326	0.842	-0.253	**0.792**
Ave	2.326	-2.326	-	0.842	0.842	0.421
Min	0.842	-0.842	-0.842	-	0.842	0.000
Min2	0.842	0.253	-0.842	-0.842	-	-0.147

Table 26　Frequency of selected movement time in backward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	1	2	1	1	2	4
Max	4	-	3	2	3	3	5
MidMax	3	2	-	2	3	4	5
Ave	4	3	3	-	3	3	5
Midmin	4	2	2	2	-	3	5
Min	3	2	1	2	2	-	2
Min2	1	0	0	0	0	3	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Min2	-	2	1	2	2	5
Max	3	-	3	1	4	5
MidMax	4	2	-	3	3	5
Ave	3	4	2	-	3	5
Min	3	1	2	2	-	4
Min2	0	0	0	0	1	-

100mm						
	Max2	Max	Ave	Min	Min2	Min3
Max2	-	1	1	1	1	3
Max	4	-	2	2	2	3
Ave	4	3	-	4	2	3
Min	4	3	1	-	4	5
Min2	4	3	3	1	-	5
Min3	2	2	2	0	0	-

Table 27 Percentage of selected movement time for backward direction cooperative task.

200mm							
	Max2	Max	MidMax	Ave	Midmin	Min	Min2
Max2	-	0.2	0.4	0.2	0.2	0.4	0.8
Max	0.8	-	0.6	0.4	0.6	0.6	0.99
MidMax	0.6	0.4	-	0.4	0.6	0.8	0.99
Ave	0.8	0.6	0.6	-	0.6	0.6	0.99
Midmin	0.8	0.4	0.4	0.4	-	0.6	0.99
Min	0.6	0.4	0.2	0.4	0.4	-	0.4
Min2	0.2	0.01	0.01	0.01	0.01	0.6	-

150mm						
	Max2	Max	MidMax	Ave	Min	Min2
Max2	-	0.4	0.2	0.4	0.4	0.99
Max	0.6	-	0.6	0.2	0.8	0.99
MidMax	0.8	0.4	-	0.6	0.6	0.99
Ave	0.6	0.8	0.4	-	0.6	0.99
Min	0.6	0.2	0.4	0.4	-	0.8
Min2	0.01	0.01	0.01	0.01	0.2	-

100m						
	Max2	Max	Ave	Min	Min2	Min3
Max2	-	0.2	0.2	0.2	0.2	0.6
Max	0.8	-	0.4	0.4	0.4	0.6
Ave	0.8	0.6	-	0.8	0.4	0.6
Min	0.8	0.6	0.2	-	0.8	0.99
Min2	0.8	0.6	0.6	0.2	-	0.99
Min3	0.4	0.4	0.4	0.01	0.01	-

Table 28　Z scores for backward direction cooperative task.

200mm								
	Max2	Max	MidMax	Ave	Midmin	Min	Min2	Average
Max2	-	-0.842	-0.253	-0.842	-0.842	-0.253	0.842	-0.365
Max	0.842	-	0.253	-0.253	0.253	0.253	2.326	0.612
MidMax	0.253	-0.253	-	-0.253	0.253	0.842	2.326	0.528
Ave	0.842	0.253	0.253	-	0.253	0.253	2.326	**0.697**
Midmin	0.842	-0.253	-0.253	-0.253	-	0.253	2.326	0.444
Min	0.253	-0.253	-0.842	-0.253	-0.253	-	-0.253	-0.267
Min2	-0.842	-2.326	-2.326	-2.326	-2.326	0.253	-	-1.649

150mm							
	Max2	Max	MidMax	Ave	Min	Min2	Average
Max2	-	-0.253	-0.842	-0.253	-0.253	2.326	0.145
Max	0.253	-	0.253	-0.842	0.842	2.326	0.567
MidMax	0.842	-0.253	-	0.253	0.253	2.326	**0.684**
Ave	0.253	0.842	-0.253	-	0.253	2.326	**0.684**
Min	0.253	-0.842	-0.253	-0.253	-	0.842	-0.051
Min2	-2.326	-2.326	-2.326	-2.326	-0.842	-	-2.029

100mm							
	Max2	Max	Ave	Min	Min2	Min3	Average
Max2	-	-0.842	-0.842	-0.842	-0.842	0.253	-0.623
Max	0.842	-	-0.253	-0.253	-0.253	0.253	0.067
Ave	0.842	0.253	-	0.842	-0.253	0.253	0.387
Min	0.842	0.253	-0.842	-	0.842	2.326	**0.684**
Min2	0.842	0.253	0.253	-0.842	-	2.326	0.567
Min3	-0.253	-0.253	-0.253	-2.326	-2.326	-	-1.083

Table 29 Preferred movement time in second for each cooperative task distance and direction. The value in bracket indicated the average velocity (m/s) associated with each movement time and distance.

Direction	**100mm**	**150mm**	**200mm**
Leftward	t_{fave},0.965 (0.104)	$t_{fmidmax}$,1.215 (0.123)	t_{fmax},1.538 (0.130)
Rightward	t_{fave},0.970 (0.103)	t_{fave},1.090 (0.137)	t_{fave},1.210 (0.165)
Upward	t_{fave},0.905 (0.110)	t_{fave},0.963 (0.156)	t_{fmax},1.137 (0.176)
Downward	$t_{fmax/min}$,1.013/0.799 (0.099/0.125)	t_{fmax},1.104 (0.136)	t_{fmax},1.194 (0.168)
Forward	t_{fmax},1.146 (0.087)	t_{fave},1.088 (0.138)	$t_{fmidmax}$,1.297 (0.154)
Backward	t_{fmin},0.870 (0.115)	$t_{fmidmax/ave}$,1.148/1.072 (0.131/0.140)	t_{fave},1.162 (0.172)

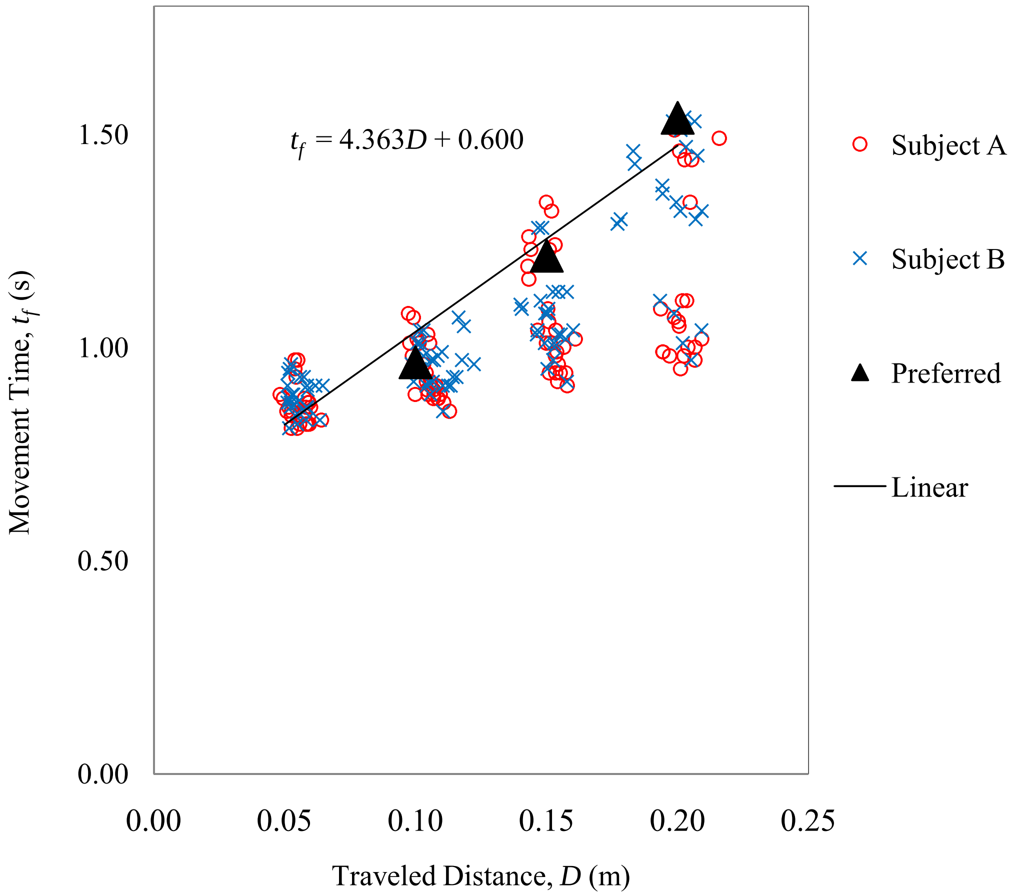


Fig. 40 Preferred movement time for each distance in leftward direction cooperative task. A relationship between movement time and traveled distance was shown using linear equation in the graph.

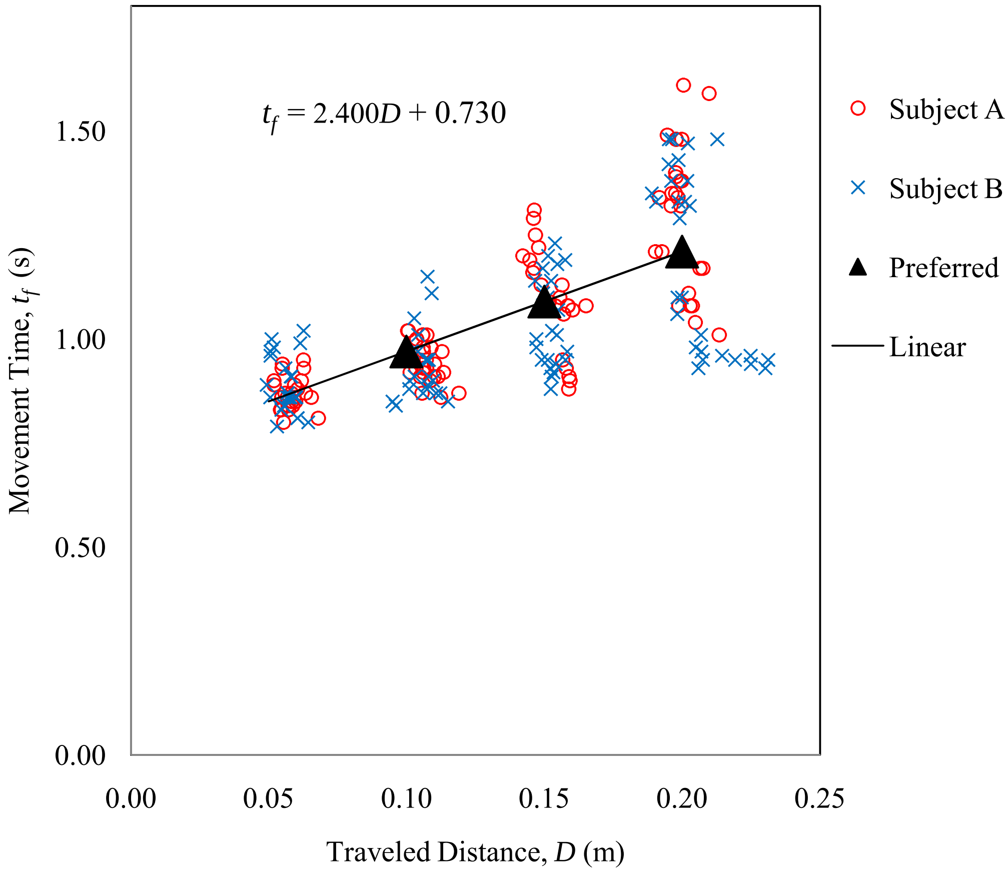


Fig. 41 Preferred movement time for each distance in rightward direction cooperative task.

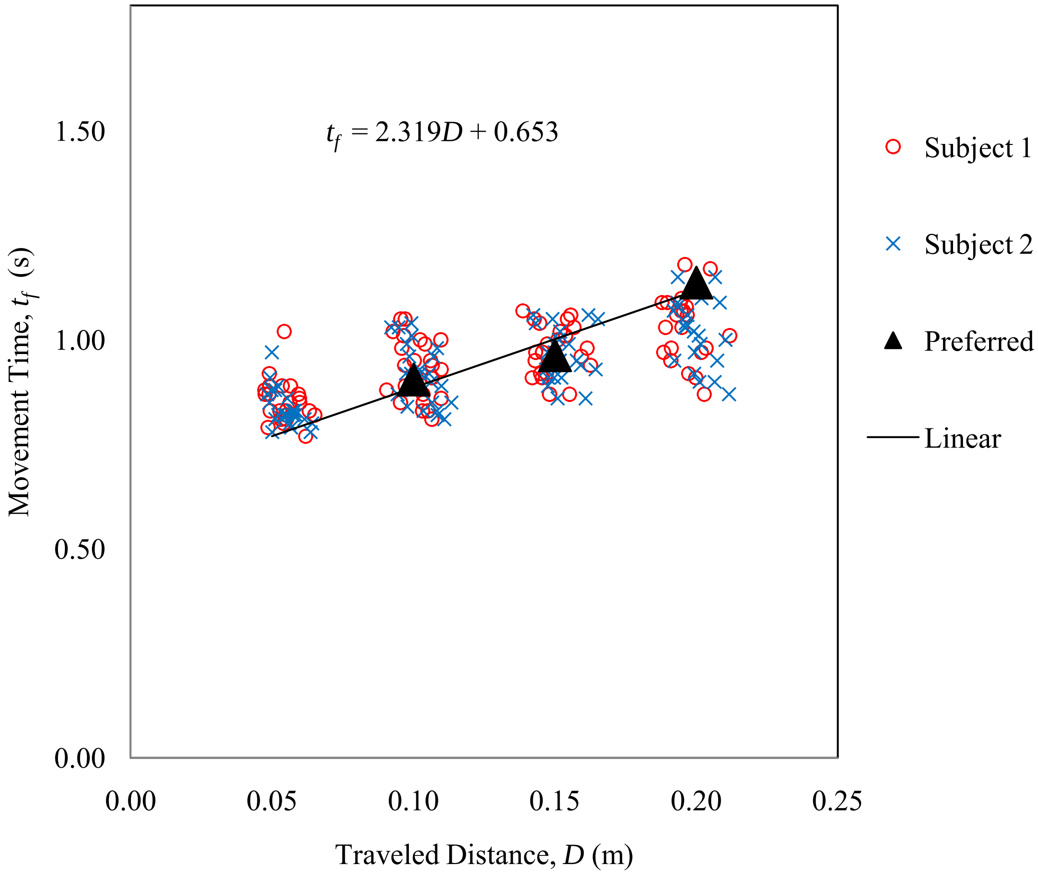


Fig. 42 Preferred movement time for each distance in upward direction cooperative task.

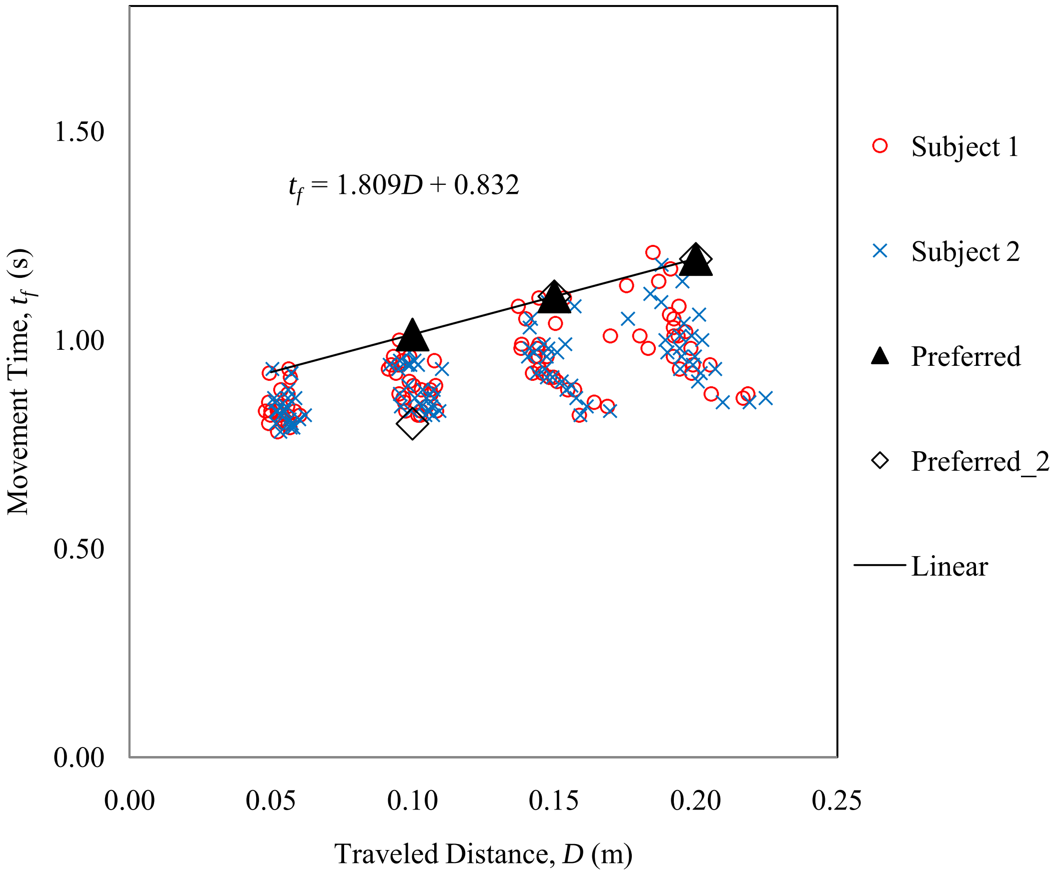


Fig. 43 Preferred movement time for each distance in downward direction cooperative task.

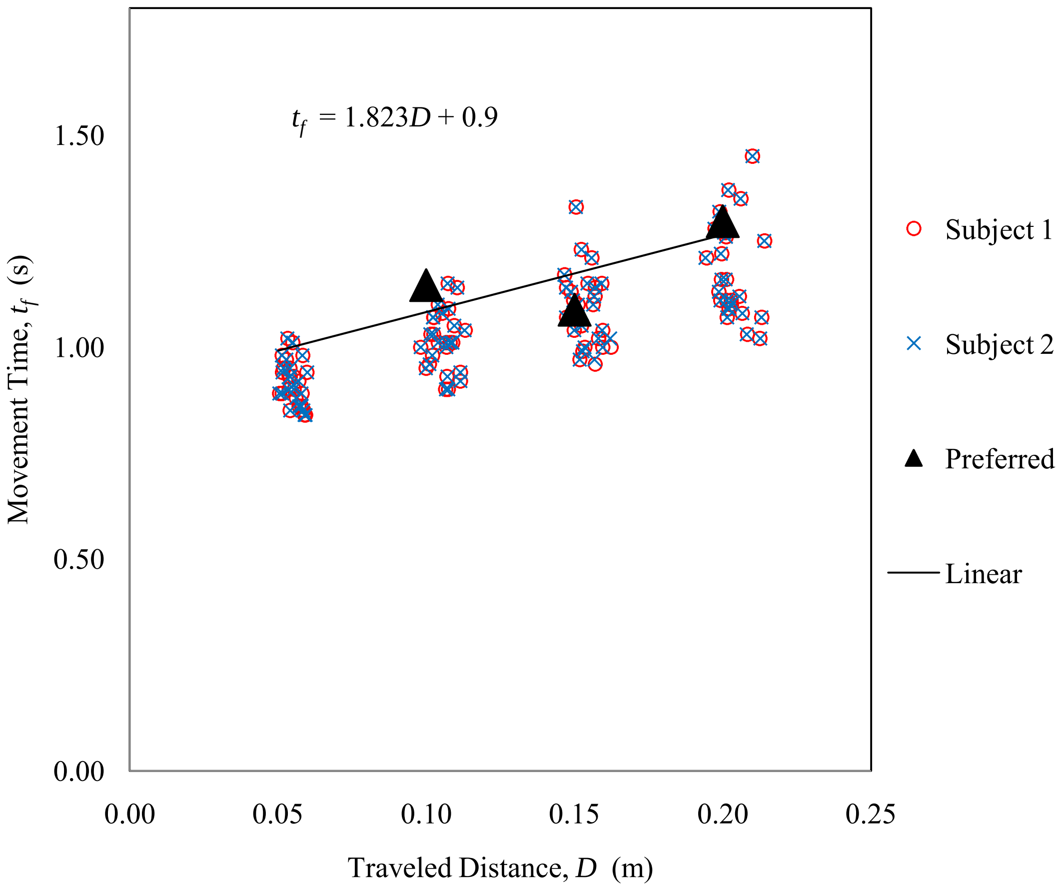


Fig. 44 Preferred movement time for each distance in forward direction cooperative task.

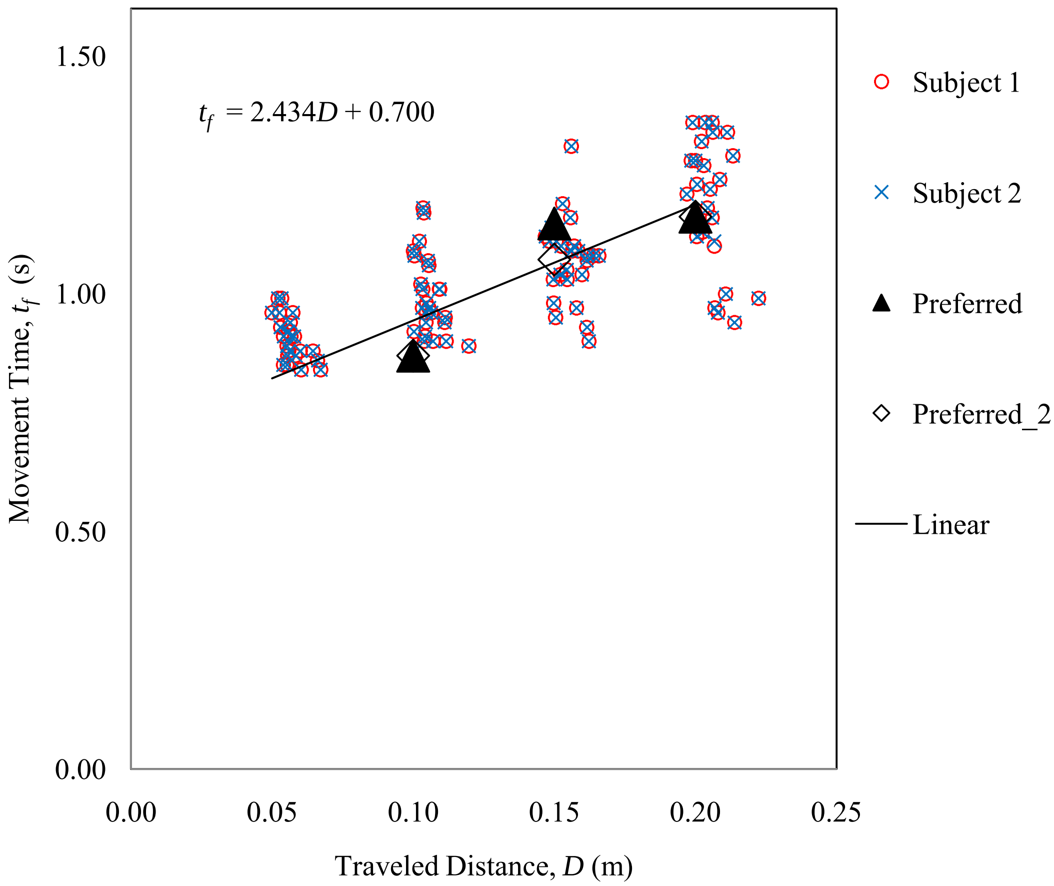


Fig. 45 Preferred movement time for each distance in backward direction cooperative task.

4.4 Summary

In this chapter, the cooperative characteristic obtained from human-human cooperative system was verified with human-robot cooperative system. The results show that smooth cooperative motion could be achieved in human-robot system when dyad possessed information on signal to initiate and location to stop the task. Also, the best movement time that suitable for all human subjects to work cooperatively and comfortably with robot in each distance was determined. Finally, equations were formulated based on the least square method in each cooperative task direction. The equation will be used with the minimum jerk model and programmed into the robot to generate a smooth cooperative motion at any distance between 50 and 200mm in human-robot system.

CHAPTER 5

CONCLUSIONS

5.0 Discussion

The research was aimed to generate a smooth cooperative rigid object transfer by human's hand and a robot's manipulator mimicking the same motion smoothness as performed by two humans. Thus, prior to the development of such system, we have investigated the characteristics for generating a smooth cooperative motion in human-human system. The cooperative motion smoothness was evaluated using normalized jerk which was originated from the Minimum Jerk Model equation.

We have compared the effect of perceiving different (End case) or same part (Center case) of the object in transfer on the cooperative motion smoothness and object rotational motion in human-human cooperative system. Also, the effect of possessing and not possessing two important information i.e. a signal to start and a location to stop the cooperative task on the cooperative motion smoothness was re-evaluated using the normalized jerk value.

The results showed that when both information were available, both subjects (subject 1 and 2) have generated smoother cooperative motion compared to when information were not available and was partially available. This was true for both End and Center case of leftward/rightward and upward/downward cooperative task. However, in forward/backward direction, the cooperative task smoothness was almost similar either in the case of both subjects possessed both information or did not possess them completely.

In either End or Center case, the results showed that perceiving at the center of the object generated smoother cooperative motion. The reason for such phenomenon was explained in section 2.4.2. Moreover, in Center case which had generated smoother cooperative motion was associated with less object rotational motion. Thus, the Center case was preferred to be used for generating smooth cooperative motion in human-robot system.

In human-robot cooperative system, the minimum jerk model was programmed in the robot to generate a smooth cooperative motion. In utilizing the minimum jerk model in human-robot system, the relationship between movement time and traveled distance in human-human cooperative system was investigated. The investigation was done using the Center case i.e. both subjects were asked to look at the center part of the image during the cooperative task. The movement time for each distance and direction of the cooperative task was obtained.

Subsequently, the movement time of subject 2 (human-human cooperative system) was programmed into the robot (human-robot cooperative system). Then, the robot performed the cooperative motion tests with the human subject (subject 1 from human-human cooperative system). The tests have two objectives; the first objective was to verify the generation of smooth cooperative motion in human-robot system using the smooth cooperative motion characteristics obtained from human-human system. The second objective was to identify the most preferred movement time for any human subject to work cooperatively with robot. In each test, human subject decided the best movement time for each distance and direction of the cooperative motion based on comfortableness criterion i.e. the cooperative motion was not too slow, not too fast, less vibration and suitable for human-robot cooperation.

The results showed that implementing human cooperative behavior based on human-human cooperative system generated a smooth cooperative motion in human-robot cooperative system. The results were verified quantitatively using the normalized jerk value (< 500 was set for indicating smooth cooperative motion) for all cooperative task sub-directions. The preferred movement time was obtained for each cooperative task direction and distance. Then, a single representative equation was formulated in each cooperative task direction. The equation was calculated based on the least square method using the preferred movement time in each distance. The equation will be used with the minimum jerk model to generate a smooth cooperative motion between 50 to 200mm distances in human-robot cooperative system.

5.1 Future Directions

The research had investigated some fundamental issues of human cooperative behavior for generating smooth cooperative motion. Finally, the characteristics were verified using the human-robot cooperative system. In human-human cooperative system, consideration on different weight of the experimental object、 aged of subjects, number of participant and wider range of cooperative task distances should be included. In human-robot system, current experiment did not include system (audio and visual) for robot to identify starting signal and target location. It is recommended that such system is included and tested to mimics the real human-human cooperative task.

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