Chapter 7
Cooperative Physical Human-Human and Human-Robot Interaction

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Abstract This chapter examines the physical interaction between two humans and between a human and a robot simulating a human in the absence of all other modes of interaction, such as visual and verbal. Generally, when asked, people prefer to work alone on tasks requiring accuracy. However, as demonstrated by the research in this chapter, when individuals are placed in teams requiring physical cooperation, their performance is frequently better than their individual performance despite perceptions that the other person was an impediment. Although dyads are able to perform certain actions significantly faster than individuals, dyads also exert large opposition forces. These opposition forces do not contribute to completing the task, but are the sole means of haptic communication between the dyads. Solely using this haptic communication channel, dyads were able to temporally divide the task based on task phase. This chapter provides further details on how two people haptically cooperate on physical tasks.

7.1 Introduction

There are many ways to classify human-human interaction. Two people can interact by speaking, changing facial expressions or body posture, shaking hands or hugging, and written word. Some types of human-human interactions have been studied extensively, such as interactions at a distance. Simply by sight alone, two people will naturally and subconsciously synchronize their actions, such as swinging a leg [1], and are able to consciously synchronize a swinging pendulum [2, 3]. One explanation for this ability is that mirror neurons in the brain can develop a representation of actions performed by another individual [4, 5]. In another study, Sebanz et al. [6] show that two participants working in close proximity to each other on different tasks can influence each other.

Although there are significant interactions that occur at a distance, the research discussed in this chapter focuses on how groups of individual agents *physically* work together. The physical interaction between two people directly connected has

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only recently been studied with significant rigor even though groups of people have been working together throughout history, for example during tug-a-war and when a giver knows when a receiver has control of a drinking glass and can let go [7]. In a review of joint action, Sebanz et al. [8] suggest that understanding how groups of people interact will likely further our understanding of how the brain works in isolation and state that "the ability to coordinate our actions with those of others is crucial for our success as individuals and as a species." However, complications can arise in physical communication since a person perceives self generated forces and received forces differently [9]; each person may believe the other person is more commanding than they really are.

In one of the first studies on human-human interaction, Wegner and Zeaman [10] discussed some control tasks that occur between multiple individuals in everyday life, such as the see-saw, the two-handled saw, and balancing on a tandem bicycle. Shaw et al. [11] also discussed couples teaching physical activities, such as swinging a golf club and dancing. Other common activities requiring cooperative control are moving and placing large objects, exchanging objects like a glass of water without spilling, and symmetrically positioning a bed linen on a mattress. In these examples, the two people develop a cooperative partnership in which they must divide control and compromise according to the task at hand. Knoblich and Jordon [12] suggest that group coordination may be beneficial since each person in the group has fewer actions to deal with.

Devices that mediate the interaction between two people, such as teleoperators and compliant structures, often inhibit physical communication. When two people are working together, it is important that each member feels the force from the other person or object. Many haptic devices cannot reproduce the forces perfectly, which makes interaction through the devices particularly difficult. Force reproduction can become a significant problem when working over great distances, such as in teleoperation. Teleoperation research tends to look at issues related to accurately recreating forces, such as time lag, and less on how the two remote agents interact. The work discussed in this chapter focuses on the cooperation between two or more agents with essentially no time delay and a high fidelity interaction. The goal of many of these works is to understand the fundamental interactions for later inclusion into other robotically mediated interactions.

Before looking at human interaction further, it is interesting to look at a species that is also highly adept at physical cooperation. Some of the effects seen in groups of humans interacting can be seen in groups of ants, specifically in the Asiatic Ant (*Pheidologeton diversus*). In a paper outlining how ants transport food in groups, Moffet [13] wrote: "Group transport (the carrying or dragging of a burden by two or more individuals) is better developed in ants than in any other animal group." The most notable finding from his study is that each ant working in a group carries more weight per ant than an ant carrying an object alone. One ant alone can carry five times its body weight. Yet, in one example, 100 ants worked together to carry a worm that weighed 5000 times the body weight of an ant; each ant carried 50 times its own body weight. Moffet found that the ants can carry exponentially more weight with increasing ants until about 11 ants are working together. Moffet speculated that the space around the perimeter of an object limits the effectiveness of ants that can actually work together, thus group effectiveness grew slower for groups larger than 11 ants.

Moffet also found that transport velocity was fairly constant for groups of 2–10 ants, which were twice as fast as individual ants. Groups of 11 or more slowed down to less than half the speed of smaller groups. His efficiency metric of velocity $\times$ object weight showed that the ants were increasingly efficient as more ants worked together up to groups of 11 ants, at which point effectiveness increased at a slower rate.

Not all ant species use cooperative group transport. In other ant species, if a second worker ant grabs an object, the first ant's progress is halted until the second worker releases the object. These species tend to break the food down into smaller pieces and carry them individually, which could be thought of as the most rudimentary form of group cooperation. It is only some species of ants that have developed this ability to cooperatively carry large work loads.

Although ants cooperating to carry large loads is not directly related to studying how humans interact or how a robot can cooperate with a human, there have been several studies that used ants and other insects as inspiration for developing swarms of smaller robots to work together [14, 15]. These bio-inspired robotic studies have had some success and are likely to benefit from a further understanding of group dynamics.

The body of literature presented in this chapter aims to bring together the recent studies on the cooperative motion of groups of humans as well as groups of human-robot teams. The chapter starts with the performance of groups compared to individuals in Sect. 7.2, then the interaction forces between the two individuals are discussed in Sect. 7.3, and finally, several methods of implementing human-robot interaction based on how two humans interact are discussed in Sect. 7.4.

7.2 Group Performance

It is often accepted that people prefer to work alone on tasks that require accuracy, finding a partner to be an impediment. However, in one of the first studies on cooperative motion, Wegner and Zeaman [10] found that dyads could follow a path significantly better than individuals, and quads significantly better than both dyads and individuals. To compare groups to individuals working alone, they used a "pursuit rotor" task in which a participant tried to follow a path marked on the top of a rotating turntable. However, they were unable to determine a satisfying explanation, possibly since they did not measure the forces exerted by the participants. This section will first focus on the nature of group performance, how perception affects group performance, and a discussion about how Fitts' Law applies to multiple physically interacting humans; the interaction forces will then be described in Sect. 7.3.

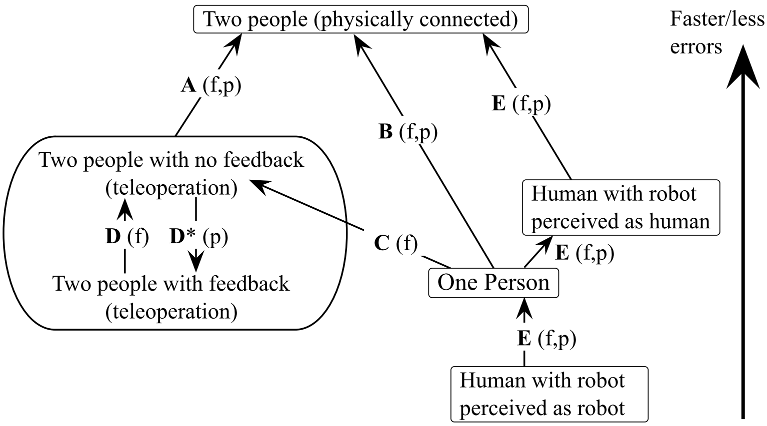

Fig. 7.1 Summary of several experiments that compare the speed and error rate of several algorithms for mediating human-robot-human interactions. Each of these used a second order inertial system, except for D*, which used a zero-order system. An ‘f’ indicates that the other member’s force was displayed while a ‘p’ indicates position was displayed (**A**—Summers et al. [16] and Field et al. [17]; **B**—Reed et al. [18, 19]; **C**—Glynn et al. [20]; **D**—Glynn et al. [21]; **E**—Reed et al. [22, 23])

7.2.1 Human-Human Group Performance

A number of recent studies have examined the performance of different group compositions and the effect that the interface between the members has on the performance. Figure 7.1 summarizes many of these results and the remainder of this section will expand on each of the studies referenced in the caption.

Glynn and Henning [20] examined several methods of combining the forces from two members of a dyad. They showed that using the average of the commands without haptic interaction resulted in faster and more accurate task execution than one person alone. In their maze following study, the average of the force applied by each partner to a joystick controlled the acceleration of an inertial mass. The participants were not physically interacting as there was only visual feedback and no force feedback. The force applied to the virtual mass was the average of the desired path of each operator who cooperated without haptic interaction. Glynn and Henning found that teams completed the maze 14.5 seconds faster than individuals, an increase of 8%. Collisions were reduced from 484 for individuals to 334 for teams. It makes sense that the collisions are less since any faulty motion would be diluted by the other member’s action. Statistically, the chance of both participants producing the same collision-producing motion would be less than that of one person acting alone. The improved performance may also be explained by a diluting effect. Since the action of each participant is diluted, the effect may not be as noticeable, and thus, both participants may attempt to push harder than they would alone. This could result in each participant applying more force and, thus, completing the task faster. Since there was no haptic interaction between the participants, this effect would not likely have been noticed.

A related study by Summers et al. [16] examined similar methods to mediate the input commands from two people using the two flight sticks in an airplane cockpit. Just like Glynn and Henning's study, they found a significant performance benefit when using coupled interaction compared to the uncoupled Fly-By-Wire method. The uncoupled Fly-By-Wire is essentially averaging the inputs from each flight stick and the coupled interaction is similar to the mechanical method where both sticks have the same motions. Even though performance is better for two people with an average of their commands, it does not necessarily mean that pilots, or other shared control tasks, should use this control mechanism as this could have detrimental effects; imagine one pilot pulling up and the other pushing down to avoid a collision—the average would be straight ahead. The forces, which will be discussed in the next section, are an important part of mediating a physical interaction.

In an extension to the maze studies, Glynn et al. [21] also used force feedback, so the participants were haptically interacting. The interaction was simulated using a spring between the two manipulandums. They compared the interactions with and without force feedback using position and force control. The added feedback when using position control improved performance. During force control, the performance time was unchanged. With two people interacting physically, they are able to communicate both on position and force, thus there should be no detrimental interaction like there is in the force control experiment.

In a series of experiments using a 1 DOF crank with two handles, Reed et al. [18] examined the completion times of dyads performing a target acquisition task with a rigid connection; the forces and motions were directly conveyed to each individual. To allow comparison of dyads and individuals, the experiment consisted of one or two participants completing the task of moving a crank into a series of targets. During the experiment, many of the participants reported the typical opinion of difficulty when working with a partner; few reported cooperation. This perception of poor cooperation likely stems from the increased force exerted by each member of the dyad. In fact, each dyad member applied forces 2.1 times larger than when working individually. Most of this increased force was applied in opposition to the other member.

Despite the increased forces and lack of perceived cooperation, dyads completed the task faster than individuals [18]. The completion time for dyads decreased by an average of 54.5 ms compared to the average completion time of the two constituent individuals working alone. The average completion time for individuals was 680 ms. Increased force associated with the dyad condition might result from a faster participant pulling along a slower one. However, dyads averaged 24.8 ms faster than the faster of the constituent individuals working alone. Only two of 30 participants were faster than their respective dyad. The dyads established the faster performance quickly, generally within 20 seconds after the dyad started working together. The rotational inertia of the crank was doubled in the dyad case, so the faster performance cannot be caused by sharing the load between the dyad members.

7.2.2 Perception Affects Performance

The performance of individuals in a group setting is often correlated with the perceived environment around them, such as who is watching or what they are interacting with. To examine the effects of the perception of one's partner, Reed et al. [18, 19] extended their original crank study by recreating a partner using the forces found during their previous human-human experiments. In order to prevent the variations in forces and completion times among participants from affecting the results, the robotic partner was based on a recorded version of the individual's forces during individual trials. Since the performance was based on each individual, any differences can be attributed to the interaction of the simulated partner and not because the robotic partner was faster or slower than the participant. The participants were expected to work with the robotic partner in a similar way as they did with a human partner. The interaction forces are further described in Sect. 7.3.1.

In this experiment, each participant performed the crank task both individually and with the robotic partner. Half the participants did not have a human on the other side of the table, so they clearly knew they were working with some non-human agent. The other half of the participants had a human across the table and assumed they were working with a human. A curtain prevented the participants from knowing what the other person was actually doing. The human "confederate" was actually working with the experimenter and did not actually participate to move the crank; the robot did. Ten of the eleven participants with a confederate present stated that they thought a person was working with them and were surprised to discover at the end of the experiment that they worked with a robot and had not worked with the other person. Thus, the participants working in the presence of a confederate consciously believed they were working with a human partner. This indicates that such a robotic partner was able to cognitively pass a haptic version of the Turing test [24–26].

When a confederate was present, the human working with the simulated partner was on average 5.8 ms (1%) faster than the same participant working alone. The human-human teams were 48.8 ms (7%) faster than the human-robot team with a confederate present. When the confederate was not present, the participant working with the robot was 24.8 ms (3.5%) slower than working alone. When the participants were aware that they were working with a non-human agent, the participants performed worse than when they were working alone. When the participants thought they were working with a human, their performance did not change relative to their individual performance. This implies that the perceived origin of forces in physical collaboration affects how a person will interact with a partner.

One hypothesis for why dyads are faster is social facilitation [23]. Social facilitation research has a long history [27, 28] with many studies showing that simply having a person in a room observing a participant will lead to better performance on a given task. This is typically explained by the mere presence of others elevating drive levels. Mere presence tends to improve performance on simple, or well mastered, tasks and inhibits the performance on complex, or poorly mastered, tasks [29]. Social facilitation may have accounted for some of the performance increase. However, the participants knew the experimenter was always watching, so, in both versions of the test, there was someone visually present, which is the sole requisite for improved performance as stated by social facilitation. Wegner and Zeaman [10], when studying groups and singles on a pursuit rotor task, suggested social facilitation as an explanation of the increased performance of groups, but stated that it could not account for all of their observed effects. Also, during the cooperative crank studies, the participants could only feel the other member of the dyad and they could not see each other due to a curtain hanging between them. Social facilitation has only been demonstrated through visual interaction, not physical interaction. The only aspect of the task that is changing is whether they are holding the handle or not. It is possible this physical change could elicit the same effect, but in all other versions of social facilitation described in the literature, the two participants are physically disconnected from each other. They are predominantly communicating through vision, which is the basis of most of the social facilitation literature.

This performance increase is likely due to the motor control systems of both people working cooperatively and not for the reasons explained in the social facilitation literature. The improved performance suggests that social facilitation could also be caused by a similar "haptic presence" effect, but this needs further evaluation in future studies. Even if haptic presence had a similar effect to social facilitation, it would not be able to fully explain all of the improved performance for dyads on the cooperative crank tasks. Dyads improved by 54.5 ms, whereas the difference of performance increase between the human-robot and human-robot-confederate groups was only 24.8 ms, half the difference time.

7.2.3 Groups Obey Fitts' Law

Fitts' law [30] is an empirical relation observing that the time it takes a person to reach a target is related to the distance to the target, D, and the size of the target, S. The distance and target size vary linearly with the index of difficulty ID, which is defined as the logarithm of $\frac{D}{S}$, or $t = a + b * \log_2(\frac{D}{S})$, where a and b are constants specific to the task. In other words, for a given target size, it takes longer to move a large distance than a small distance and, for a given distance, it takes longer to move into a small target than into a large target.

Fitts' law has proven to be remarkably robust since it was first described in 1954. It has been used to describe and analyze tasks of varying complexity and in multiple degrees of freedom, for instance: path tracking [33]; 3D computer games [34]; scrolling time on a computer [35]; GUI design [36]; cursor movement along a line to a target line segment; cursor movement in a plane to a target disk, stringing beads, placing a can on a shelf, putting a peg into a hole, and many others [31]. The coefficients of Fitts' law vary depending on the task (and from person to person), but the linearity in $\log(\frac{D}{S})$ is observed throughout a wide range of the index of difficulty measure, and over a wide variety of tasks, which makes it well suited to analyzing how two people cooperate on a physical task. Fitts' law has recently been tested for multiple people interacting.

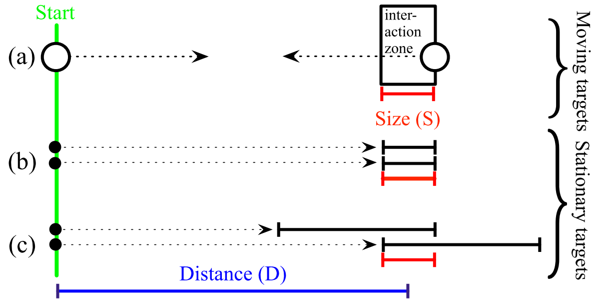

Fig. 7.2 The variations of Fitts' Law for two people. (**a**) The target is the other person's hand, so the target is moving toward as each member of the team attempt to reach the target. This type of experiment was performed in [7, 31]. (**b**) The target is stationary and the two members work together to reach the same target [32]. (**c**) The two individuals have different, but overlapping, targets, so they must physically work together to reach the target [32]

Sallnäs and Zhai [7] used Fitts' Law to study how two individuals handoff an object in a haptic simulation. Two people sat in-front of a computer with a manipulandum to control the position of their virtual hand. The size of the interaction zone varied according to Fitts' law. They measured the time it takes for one person to hand off a virtual object to another person within certain spatial targets (see Fig. 7.2a). Sallnäs and Zhai found that Fitts' law is valid for a two person handoff task. They performed experiments with and without force feedback in the manipulanda. They found that performance time did not change significantly with different amounts of force feedback, but the error rate (number of dropped objects) was significantly lower with haptic feedback. The two people in this study only felt the sensations the haptic device can simulate since they were not physically connected.

The experiment performed by Sallnäs and Zhai's consisted of participants exchanging an object within certain spatial limits. In everyday life, these spatial limits do not exist. In this case, the target would be moving, not stationary, as shown in Fig. 7.2a. Mottet et al. [31] performed a Fitts' law study with moving targets. The setup consisted of two manipulanda and two displays of LEDs each showing the position of their target and the position of their own manipulandum. Each person's target was the other person's manipulandum. As each person moved towards the target, the target also moved closer to them. Mottet et al. showed that this type of dual motion task also obeys Fitts' law, meaning that for small targets, it takes longer to reach each other than it does for larger targets.

When two individuals are physically cooperating on the same task, their performance time also obeys Fitts' law [32], but does not when they must compromise. In this experiment, two individuals were cooperatively moving a crank into targets. Two types of targets displayed to the users were tested, as shown in Fig. 7.2b and c. In one case, the targets shown to each member were the same; the second case showed different, but overlapping, targets to each member. In the same target case, Fitts' law was obeyed. In the different overlapping target case, the performance did not obey Fitts' law regardless of whether the individual target size or the overlapping target size was used. The deviation from Fitts' law is likely caused by the necessary compromise since the only solution required each member to be on the edge of the target, not in the center as they were when the targets were the same size.

7.3 Force Interactions

The forces that each member of a group feels during an interaction allows them to determine many aspects about the object and the person. For example, one can quickly get a distinct impression from the firmness of a handshake and people rarely drop objects when exchanging them because they know when the other person has control of the object. Prior to studying the interaction forces, several researchers were unable to adequately explain the effects felt when cooperating on a task. Wegner and Zeaman [10] reported that some of the participants completing a "pursuit rotor" task mentioned that the mechanism felt more mechanically stable in group conditions. The participants in this study manually controlled a stylus via a handle in two dimensions. The stylus had multiple handles so that individuals or teams of two and four could be tested in the same way. The investigators tried to increase the stability through mechanical means, but their attempts only decreased the path tracking ability. Many of their attempts to understand the interactions were unsuccessful since they did not measure the forces applied by each of the individuals. This section will look specifically at several recent studies of the forces involved between members of a group when completing various tasks.

Shergill et al. [37] examined the forces exchanged between two people without motion. In this experiment, two participants each put their finger in a lever attached to a force transducer. Each participant was told to push with the same force they felt, but the participants were unaware of the instructions given to the other participant. Alternately, as instructed, each participant applied the force. Shergill et al. found that in every case, the forces escalated from trial to trial. They explained that the participants are reporting the true perception of the force and the increasing force is due to neural processing.

In a second set of experiments, Shergill et al. asked the participants to recreate a force applied on one finger with a finger from the other hand. The participants consistently generated a force larger than the original. Shergill et al. suggest that externally generated forces are perceived as stronger than internally generated forces. This result implies that each person in a group will always feel that he/she is contributing less to the overall task than the other member, even though that is not and cannot be the case. When working cooperatively with a partner on a task, each participant may want to contribute equally, which could lead to an escalation in performance.

In some applications, forces can relay vital information. If the perception of forces is reduced, as suggested by Shergill el al.'s study [37], or the transfer of forces is hindered, communication can be significantly diminished. Fly-By-Wire (FBW), a design for airplane control, eliminates the direct mechanical connection (and thus some of the forces) between the pilot and the plane's control surfaces and also between the two pilots. Depending on the configuration and design of the FBW system, the flight sticks allow little or no haptic interaction between pilots. Summers et al. [16] conducted a series of experiments on pilots using a Flight Simulator at NASA Ames Research Center. They examined four different cases, ranked by the pilots in order from most preferred to least preferred: coupled, uncoupled with a disconnect switch, uncoupled with priority logic (essentially the largest input wins), and uncoupled (average of inputs). The pilots significantly preferred the coupled (haptic) FBW more than the uncoupled (non-haptic) FBW.

In a study among 157 commercial aircraft pilots, Field and Harris [17] found that communication was lost when using FBW. This loss of communication is likely to decrease the pilots' awareness of current situations. Many pilots in the study stated that it is important and useful to be able to feel the forces and motions of the other pilot and that they wanted to feel what the autopilot was doing so they could determine if the plane was flying correctly. In a direct mechanical connection, the pilots can feel what the other person is doing as well as a response from the plane itself. Shergill et al. [37] explained how an individual can separate their forces from an external force, but the pilots are unable to separate the forces in a flight stick into those from the other pilot and those from the force feedback of the plane.

Glynn et al. [21] performed experiments where participants had to jointly track an object. The haptic display had force feedback that modeled the interaction as a spring, so the two participants could feel the motions and forces of the other person. The force feedback displayed to each person was programmed as either "social force-feedback" where each dyad member could sense the position of the other dyad member via force feedback and "system force-feedback" where both dyad members could sense the simulated mass. They compared these two conditions and the same two conditions with a 0.25 second lag and a no force feedback condition. The lag increased both time taken and collisions. Without force feedback, the participants caused less damage and were able to stay closer to the center of the path. Glynn et al.'s only explanation for the larger path deviation was that the feedback interacts with the dynamics of the second order system in complex ways. Just like the pilots in Field and Harris's study, it is possible that each member has difficulty separating the force feedback of the device from the other member's forces. The force feedback is possibly more beneficial during position control since the position does not overlap with the force. With two people interacting physically, they are able to communicate both on position and force, thus there should be no detrimental interaction like there is in the force control experiment.

Another cooperative feedback mode was discussed and compared to two cooperative feedback modes similar to those in Glynn et al.'s, shown in Fig. 7.3. In this experiment, the interaction between the two humans and a slave robot were mediated by three control laws designed for mediating different aspects of the redundant control afforded by multiple human users [38]. The third mode, called Dual Force Feedback, allows both users to feel the same force that is proportional to the difference between the average position of the two master robots and the position of the slave robot. This has the advantage that both participants feel the exact same force. However, it has the disadvantage that it is nearly impossible to distinguish whether you are fighting with your partner or if the slave robot is restricted. This mode was

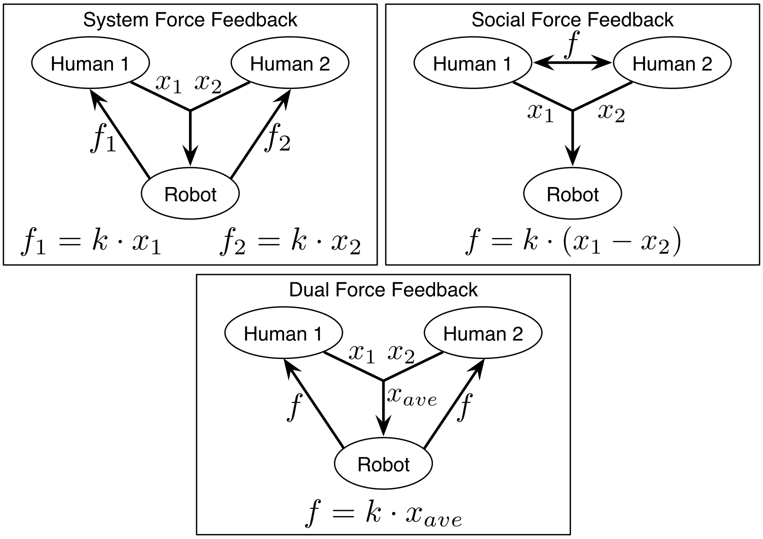

Fig. 7.3 Figure showing the three interaction modes used in [21, 38]. Each mode mediates the redundancy between the two users to enable different types of interaction

found to cause more fighting between the two participants, but also allows identical forces to be felt by each user, which would be beneficial during teaching/learning tasks.

Although couples dancing has been mentioned as an example of a physical interaction, it had not been studied until Gentry [39, 40] examined how this interaction works between dancers. She describes dancing as a finite state machine where dancers move between a limited number of poses and interact through force and motion. Dancers coordinate their actions through various elements, some internal to the dancers and some external. The rhythm, or beat, of the music is an external event that synchronizes the motion of each dancer's movements and is the strongest element coordinating their actions. The poses are a predetermined position of the bodies of the dancers. Some dances, such as the Waltz, have only one pose, whereas Lindy Hop has multiple. The leader moves from position to position while indicating what to do next. The transitions are coordinated based on previous knowledge of a small set of moves. In another study using haptic recordings of couples dancing, a male dancing partner was synthesized [41]. An adaptation law allowed the step size of the robot to change to accommodate the female partner.

The physical connection in dancing is maintained though the follower's right hand holding onto the leader's left hand. This physical connection allows the leader to send messages to the follower as well as for both partners to exchange energy. A good follower will keep her hand in the same position relative to her body, which allows the leader to communicate. Most of the communication is based on haptic cues even though the dancers can see each other. Gentry performed experiments on experienced couples dancing blindfolded and found that they were capable of performing quite well with only haptic communication.

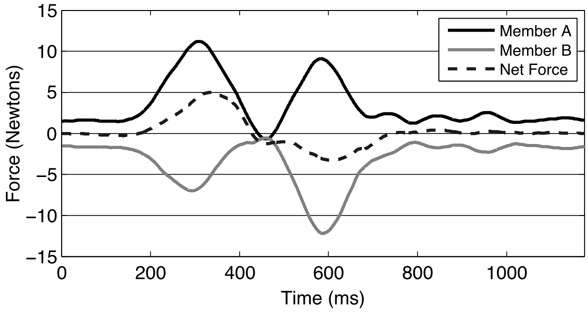

Fig. 7.4 The dyad specializes, which is where each member only pushes in one direction. Each member contributes to certain aspects of the task: member A accelerates while member B decelerates. The forces sum to a force profile similar to an individual performing the task. Figure used with permission from [23] (© 2007 IEEE)

7.3.1 Specialization

When a single person becomes part of a dyad, many new solutions to completing the task develop due to redundant limb motion [42, 43]. There is no longer a one-to-one correspondence between dynamics and kinematics. For example, in a dyadic task, one member of the dyad can choose not to contribute at all, to only help with the acceleration phase, or only to use elbow extensor muscles. Knoblich and Jordon [12] suggest that when groups work together, they might perform better because each person has fewer actions to deal with. In essence, they hypothesize that the members can get out of each other's way and only deal with a few actions.

In a series of experiments to further understand how two humans resolve the redundancy problem occurring during cooperative motion, Reed et al. [44] showed that two people naturally specialize their forces. They analyzed the forces from each individual on a one DOF target acquisition task. They transformed the forces exerted by each individual into a "net force" and a "difference force". The net force is the sum of the members' forces, which is the task relevant force that accelerates the crank. The difference force has no physical effect on crank acceleration and is a measure of the disagreement between the two members. A similar measure that excludes forces with different magnitudes in the same direction has also been used to quantify the interaction forces [45].

Figure 7.4 shows the net, difference, and each member's force for a single trial by a dyad exhibiting the typical specialization pattern. The dyad completed this task at approximately 600 ms. Even though the constituent members of a dyad produced very different force profiles, the net force for dyads produced a trajectory similar to the minimum jerk trajectory that individuals performing alone typically produce on reaching tasks [46]. The members of a dyad divide the task to achieve the same motion as an individual. As shown in Fig. 7.4, member A pushes toward the target during the beginning of the trial to accelerate the crank while member B either passively or actively resists the acceleration. Member B then pulls away from the target during the later part of the trial to decelerate the crank while member A continues applying a force toward the target. During the entire trial, member A primarily contributes to accelerating the crank and member B primarily contributes to decelerating the crank. This acceleration/deceleration specialization pattern is clearly revealed by inspecting the difference force, which remains always the same sign. Only the characteristic shape of the difference force matters—it could be mirrored around the x-axis if the participants were standing on opposite sides of the crank.

A metric for measuring specialization within a dyad is based on the contribution from each participant for each phase of the task. A highly specialized dyad would consist of one member contributing to most of the force during the acceleration phase and the other member primarily contributing to the deceleration phase. To find the contribution from each dyad member, the forces applied to each handle over the acceleration and deceleration phases were integrated and divided by the integrated net force for that phase. The result provides four fractional contributions of each member of the dyad during the acceleration and deceleration phases. The contributions during each phase from both members of the dyad necessarily sum to one. A negative contribution indicates that the member was applying a force opposite to typical motion of that phase, for example accelerating during a deceleration phase, or decelerating during an acceleration phase, even if the force was only due to passive inertia. A contribution greater than one indicates that this member had to apply a large force to compensate for the negative contribution of the other dyad member. As a comparison, specialization could also occur in another way where one member always pushes right and the other always pushes left, which would be expected for a left-handed member paired with a right-handed partner. In Reed et al.'s study [22], eleven of the fifteen dyads show significantly more acceleration/deceleration specialization than left/right specialization.

The dyads in the crank task learned to specialize their applied forces temporally to generate a net force similar to how a single person would complete the task, but faster. The participants divided the task solely through a haptic communication channel as no other communication was allowed. Similarly, Feygin et al. [47] found participants could learn the temporal aspects of tasks better using haptic guidance than they could using visual guidance. One hypothesized way specialization could be implemented in the human control system is to precue an action [48] so that when some other event happens they perform a certain prepared action [19]. With two people cooperating on a task, the accelerator could focus on the start of the task and the deceleration specialist could wait for some cue, such as reaching a particular location and/or velocity and would then begin to decelerate the crank.

A person individually performing a target acquisition task would be expected to use the triphasic burst pattern where an agonist muscle burst initiates the movement and an antagonist muscle burst is initiated to brake the movement and a second agonist burst is initiated to maintain the limb at the final position [49–51]. These bursts represent careful planning based on prior knowledge, rather than feedback received during the task [52, 53]. These patterns have been shown to represent optimal movements that accomplish the task within limiting physiological constraints such as the muscles activation rates [53, 54] and the limited torque [55] and force [56] generating capacity in different areas of the workspace. The specialization of roles has also been shown to be beneficial from an energy flow analysis [57]. Consequently, the rate at which muscles can turn on and off becomes a less limiting factor if one person can be ramping up while the other is ramping down, which is presumably what specialization enables the two members to accomplish.

In another study examining specialization on a 1 DoF crank system with two people, the radial force, which is the force directed toward the center of the crank that does not contribute to any acceleration or deceleration, was also studied [58–60]. They found that the radial forces were larger than the tangential forces in many instances. One of their conclusions was that the radial force stabilizes the interaction around a certain set point, much like the restoring effect that gravity has on a pendulum, but where the individual's radial force serves as the restoring force.

An individual performing a bimanual task exhibits a similar specialization strategy. Reinkensmeyer et al. [61] show that an individual holding a pencil between two fingers on different hands will use one hand to accelerate and the other hand to decelerate the object, which might be taken as a bimanual model for this observed two person acceleration/deceleration specialization. For a single individual the inward force from both hands allows the pencil to accelerate and decelerate while being tightly held and not dropped. The tight neural coupling between both arms allows an individual to effectively coordinate the actions of each arm [62–64]. However, in dyadic tasks there is no neural coupling between the individuals, so the developed strategy must have occurred through the haptic communication channel instead since the participants could only communicate physically.

7.3.2 Perturbation Rejection

Individuals are able to adapt to perturbations from the environment, either from unexpected deviations in a trajectory or from an external source. One method of overcoming external forces is to co-contract both the agonist and antagonist muscles on the same joint, which increases the stiffness in individuals [65, 66]. Co-contraction is a common strategy when individually interacting with unstable force fields [67, 68]. If a person is interacting with an ungrounded object individually, any force applied to the object will cause that object to accelerate. When working with a partner, each member can apply a force even though the object is not accelerating, as long as the sum of the forces are equal and opposite.

At the end of each trial on the crank interaction tasks discussed in Sect. 7.3.1, the two members bring the crank to rest as they wait for the next target to appear. During this time, the dyad members exert an average of 4 Newtons of force in opposition to one another [23]. This force may help dyads to resist perturbations by increasing the stiffness of the dyad in the same way that muscle co-contraction increases arm stiffness in an individual. In dyads, the force applied in opposition to each member could serve this same purpose. Since this type of interaction is a type of co-contraction within a dyad, it has been called "dyadic-contraction" [23]. Dyadic-contraction is a strategy similar to those used in parallel robotics and in human bimanual control [69, 70].

The dyadic-contraction force was examined by looking at individuals and by looking at dyads [22]. In the individual case, an external force of 0, 5, and 10 Newtons was applied to the participant as they performed a target acquisition task. At the end of each trial, a motor applied a 100 ms perturbation force and the change in position due to the perturbation was used as a measure of the perturbation effect. The three force levels showed a significantly different response with the largest displacement at the lowest force and the smallest displacement at the largest force [22]. This shows that an externally applied force can act in a similar fashion as co-contraction to help stiffen a person's arm.

The location of the arm when the perturbation was applied also had a significant effect on the response. Part of this effect was due to the arm reaching across the table so the inertia ellipse changed [71, 72]. The other effect was due to the direction of the perturbing force. On the participant's dominant side (i.e., same side as the hand holding the crank), the displacements were larger when the perturbation pushed away from the center of the crank.

Unlike the performance metrics, dyads actually performed this perturbation task worse than they did as individuals [22]. A similar pattern of perturbation rejection was found in same-handed dyads as in individuals, but the dyads had larger displacements. In many of the previous experiments, handedness did not make a difference, but because the inertia ellipses were different for left and right handed individual, it did make a difference here. When the dyad members consisted of one left-handed and one-right handed member, the overall perturbation rejection characteristics were better than the average of all locations of the same-handed dyads, but not quite as good as the best of the same-handed dyads. When the dyads had slightly different roles, the ability to reject a perturbation improved and was similar to the average of an individual. Figure 7.5 shows the results of the dyadic crank perturbation study.

Another hypothesis is that dyadic-contraction could also serve as a simple message between partners that they are working with a partner [22]. Without applying any force, there is no way to know what is happening or who is on the other side of the curtain. By applying a small force, each person feels a resistance that helps them to determine what is opposite them. In order to explore a surface, a person may try to maintain an optimum force [73, 74]. In order to learn about their partner, each member may be trying to keep the optimum force.

The question of what measures are correlated to other measures often arises when looking at how two humans interact. In [75], many of these correlations are examined; specifically the reaction times of the individuals, which dyad member started first, how much specialization was present, the performance of the dyad, and the amount of the dyadic-contraction force. All but two of these correlations had an R^2 value of 0.1 or less, so they do not indicate much of a relationship. It would be reasonable if the member with the faster reaction time on the individual trials would be the member that would be the acceleration specialist. However, the individual with a faster reaction time only had a correlation of $R^2 = 0.25$ with being the accelerator. The highest correlation was the dyadic-contraction force compared to the dyad member that started the motion, which had an $R^2 = 0.73$. This is likely because the participant that is already pushing toward the target due to dyadic-contraction tends

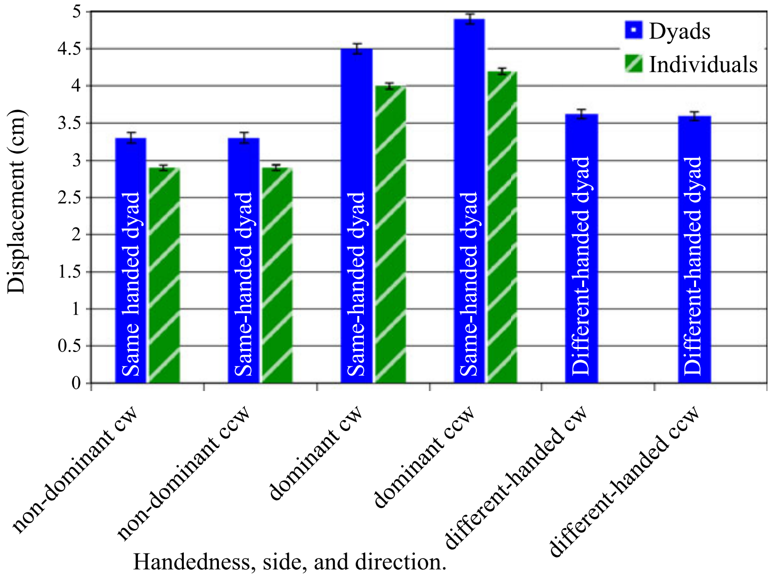

Fig. 7.5 The individuals and same-handed dyads exhibit the same pattern, but the dyads had a larger response to the perturbation. The same-handed dyads did not have improved performance by cooperating like they did for specialization. However, the different-handed dyads exhibited a consistently good cooperative effort as they appear to use the best of each member's ability for each perturbation type. Error bars represent 95% confidence intervals. Figure used with permission from [22] (© 2007 IEEE)

to push in the direction of the new target. This likely relates to the different ramp up/down characteristics of muscles [76].

7.4 Human-Robot Cooperation

One of the goals of studying human-human interaction is to further our understanding of how humans fundamentally work with another agent. Several groups have attempted this feat to varying levels of success.

Since two participants can perform a strategy similar to a single person performing a bimanual task, would a simulated partner that displays an acceleration/deceleration specialized trajectory be enough to elicit the same response? Reed et al. [22] examined this question using a simulated partner in a test similar to the Turing Test [24]. Alan Turing originally proposed a test for evaluating a computer's ability to produce human like conversation via text, but it has since been used more broadly for other human like attributes. The robotic partner used in this experiment is a motor that generates a force at the end of the crank and is composed of two parts: a force based on a recording of the individual trials and a simulated inertia. The first part mimics the motions of a partner (Sect. 7.3.1) who has taken on the role of accelerating the crank by modifying the participant's own force trajectory that was recorded and averaged during the individual trials. A recorded version of the individual's forces was used so that variations in forces and completion times among participants would not affect the results.

The participants working with a robotic partner were provided with the forces similar to those found in the dyadic interactions. Each participant was assumed to take on the role of a deceleration specialized partner, so they would be completely responsible for all the force during deceleration, whereas the participant was free to choose their force during the acceleration phase. The robotic partner could have been programmed to take on the role of deceleration specialist, but every individual has the ability to complete either role, so it should not have made a difference. Since the acceleration role was easier to program, the robotic partner took on this role and applied enough force to accelerate both the crank and the participant's arm. However, the participants did not develop the specialized roles as expected, even though they consciously believed they were working with a human partner as discussed in Sect. 7.2.2. In terms of a Turing test, the results were split between consciously believing (i.e., passing) and physically acting different (i.e., failing). The human's forces did not show a very noticeable change even though the participants consciously believed the robotic partner was human [22].

With a participant's own amplified force applied as a feedforward force, the participants were given an easy way to specialize. There was no motor force during deceleration, so the participant was required to apply all the force, whereas they could choose their force during the acceleration phase. Comparing the applied force from a participant working alone to a participant working with a motor shows that they did not significantly change their feedforward force during the acceleration phase. They tended to accelerate similarly and actually applied slightly more peak force, but switched to deceleration earlier than they did when working alone. It seems that the participants were pushing with a preprogrammed feedforward force similar to their previous trials alone, but began to correct it and slowed down the crank earlier.

When working individually, each participant can accurately predict the result of their action. A human partner is less predictable, so the result of a cooperative action is slightly uncertain. Sebanz et al. [6] show that people can develop a representation of the actions of a person nearby when working on a complementary action. Presumably, humans have the same ability for haptic interactions, which would enable two people working together to depend on their partner's actions to complete the complementary action of specialization. It is expected that a person would also learn to depend on the robotic partner to complete the complementary action of specialization, but this was not the case. Scheidt et al. [9] show that people can adapt to unpredictable forces within one trial and, since the robotic partner's forces are more predictable than a human's forces, it is surprising that the participants did not learn to work with a predictable robotic partner in the same way as they did when working with an unpredictable human partner.

Lifting and moving a large or awkward object cannot be done individually, so people either get help from another person or, in some cases, a robot. Takubo et al. [77] demonstrate a robotic assistance system to empower a single human to work with a single robot to handle unwieldy objects. Their control strategy consists of a dominant human who leads while the robot emulates a virtual non-holonomic constraint. Initially, they kept the device in the horizontal plane allowing only 2-D motion. They experimentally validated the usability of this method by showing that participants could transport an object to an arbitrary location and orientation with only a small amount of learning by using "skills similar to using a wheelbarrow."

Takubo et al. [77] also extended the method to 3-D space. Interacting with the robot in 3-D space requires a substantial amount of planning in order to place it in an arbitrary location. In order to move the object directly down, the participant must first lower his end of the object and pull the object down along the declined angle to get the robot end at the correct height. At this point, the participant must raise his end and push the object back to the original horizontal location. This same strategy must be completed for each desired direction of motion. Although this control was inspired by human cooperation behavior, they are not trying to simulate the human interaction. Two humans cooperating can perform the task with one person attempting to act as a non-holonomic constraint, but this is not the most natural strategy. There are other cooperative strategies available. Two people can jointly maneuver an object to a desired location in a much more direct path, but this has the complicating factor that both people must know the goal destination. Learning to implement other strategies for how two humans cooperation haptically could help in creating more intuitive communication between a robot and a human.

Rahman et al. [78, 79] studied humans physically interacting using a one DoF placement task. They characterized the humans as either being a master or a follower. A master controlled the position of the object. The follower tracked the motion of the master with impedance control. The impedance model of the follower robot, discussed by Rahman et al. [80], changed the stiffness and damping throughout the motion. The impedance was high in the beginning and was essentially zero after 0.4 seconds. They determined the impedance mode by analyzing the resistance an arm will apply when it is led through a given path. By using the follower characteristics of a human response found in their studies, Rahman et al. [81] implemented the same response in a robot. Their aim was to make the robot imitate the response of a human when interacting with another human. Throughout this series of experiments, they do not discuss physical communication between the two humans and they do not take into account how the completion strategy changes from working alone to working with a partner.

Another study examined how a robot could act like a human who lacks knowledge of the end goal. Corteville et al. [82] gave an example of a blindfolded person who attempts to help a partner complete a task. They discussed how the blindfolded helper would wait for a trigger that indicates when the motion has begun before assisting. Throughout the task, the helper does not know where the leader is going, but the helper will begin to guess based upon the motions of the leader. Using an estimate of the motion, the helper will join in on the motion. Corteville et al. programed a robotic assistant based upon the motion estimation of a blindfolded human helper. The robotic assistant assumes that the path will follow a minimum jerk trajectory. An admittance controller provides assistance once an estimate of the operator's path is obtained. Based on the input from the participant, the controller will provide a scaled force along the predicted path that will aid in reaching the target. This design has the potential to directly take human control and apply it to a robotic controller. However, the robot motion is not adaptable to unknown targets in its current form. They assume that the start and end points are known to the controller, which are necessary for calculating the robotic trajectory. They mention that a first step of building versatile robots consists of "building up experience with simple tasks."

Another cooperative feedback mode (see [83] and Chap. 13 of this book) uses the concept of a negotiated interface point (NIP), which connects to the virtual object through a spring and damper. The NIP is similarly controlled using two haptic interface points, one of which is connected to the user and the other is connected to a controlled user. The role of the controller was set to switch between equal control, role blending, or user dominant, depending on the input from the user. The experiments were based on a target acquisition task and were conducted in two-dimensional space. Their results indicate that the model is more personal and more human-like.

7.5 Conclusions and Future Directions

This chapter provides an overview of how two humans interact and how this interaction can be extended for use in human-robot interaction. Generally, two people are faster on cooperative tasks compared to individually, but it comes at the price of much more energy exerted. Some of this energy is exerted against the partner as can be seen in specialization, where the two members of the dyad take on different temporal aspects of the task and in dyadic-contraction, where two individuals continue to push against each other even after the mutually held object is inside the target. Although co-contraction in individuals assists in the ability to reject perturbations, the similar dyadic-contraction effect does not provide the same benefit in dyads. When interacting with another agent, the perception of where the interaction force originates is also a factor in determining the response. Externally applied forces are viewed differently than self-generated forces and forces applied by a known non-human agent are perceived differently than the same forces applied by what appears to be a human agent.

There is still much to understand regarding how two humans interact and how best to implement human-robot interaction. Many of the current technologies will enable researchers to probe deeper into the minds and perceptions of physical group interaction using analysis techniques, such as fMRI, and interfaces such as brain-computer interfaces (BCI). These technologies will possibly reveal how people think about interacting with other people as opposed to many of the current methods that observe the result of the interactions. Understanding how one internally exploits the interaction with a partner will likely reveal improved methods for human-robot interaction.

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