Performance Related Energy Exchange in Haptic Human-Human Interaction in a Shared Virtual Object Manipulation Task

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Abstract

In order to enable intuitive physical interaction with autonomous robots as well as in collaborative multi-user virtual reality and teleoperation systems a deep understanding of human-human haptic interaction is required. In this paper the effect of haptic interaction in single and dyadic conditions is investigated. Furthermore, an energy-based framework suitable for the analysis of the underlying processes is introduced. A pursuit tracking task experiment is performed where a virtual object is manipulated, jointly by two humans and alone. The performance in terms of the root-mean-square tracking error is improved in dyadic compared to individual conditions, even though the virtual object mass is reduced to one half in the latter. Our results indicate that the interacting partners benefit from role distributions which can be associated with different energy flows.

1 Introduction

As robots become gradually part of our daily life, ways have to be found to enable intuitive physical human-robot interaction. This is relevant whether the robot is an autonomous assistant, is used to extend the human work space as in teleoperation, or is a virtual partner. Interaction is defined as the bidirectional causal exchange of signals between a human and a robot. Haptic interaction is based on the exchange of force and velocity signals between the partners, i.e. involves the human haptic perception and motor system at the same time. Whenever human and robot interact in a haptic way, the partners are connected either limb-to-limb (e.g. holding hands) or indirectly via a physical link (e.g. an object).

Due to this close physical coupling, the partners are able to adapt their behavior continuously to each other which makes causality analysis challenging. This explains why a pure replay of recorded human signals is not successful as shown in [8]. Hence, it is desirable to find a model of haptic interaction which can be implemented on a robot to enable it to adapt to the human behavior and receive and send the most relevant haptic signals. So far only little is known about the characteristics of haptic human-human interaction (HHI) and haptic interaction models [14], [6].

Known studies on haptic interaction describe behavior changes in partner trials compared to individual trials by performance measures. Performance is increased when interacting with a partner [1], [5]. These performance differences motivate research on individual behavior in interaction in contrast to single task behavior. However, those performance measures provide no detailed description on the interaction itself but only on its effects.

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In literature, there are various attempts to explain this effect, e.g.:

- Social facilitation: People tend to try harder to achieve a task just because there is another person in the room watching them [11].

- Human biomechanical system: When in haptic interaction participants might constantly push and pull against each other such that their muscles are in a prestressed state. This might allow faster reaction of their motor system and result in a higher accuracy [10].

- Lower individual required forces: Manipulating a certain object in a desired way, the necessary overall force remains the same, independent if one or two people act on it. In case of an interacting couple each partner has to apply less force than a single person to achieve the same performance and, hence, the task is physically easier to execute and performance is increased. That this explanation is not true Reed [9] showed for his task by introducing a condition where the inertia of the object was halved.

- Roles or strategies: Individuals within a dyad focus on specific aspects of the task, which results in a smaller amount of required actions [4]. In [9] such strategies are identified. They distinguish between specialized and non-specialized couples in a pointing task. In the specialized case one partner is accelerating and, at the same time, the other one decelerating a common object. In the non-specialized case both partners act in the same way.

Except for Reed's discrete role definitions [7], no measures could be found to actually describe the underlying processes of haptic interaction. Therefore, a framework to describe the individual behavior within an interacting dyad is missing.

In this paper we introduce a theoretic framework based on energy flows as a way to approach this topic. Haptic interaction is determined by the exchange of velocity and force signals. Therefore, the energy flow, which considers the applied forces *as well as* the velocity, is an appropriate measure to describe the behavior in such tasks. Additionally, models based on energy flows have been introduced in telemanipulation for system analysis and control design, e.g. Port-Hamiltonian systems [12]. No previous work applies such energy-based models to describe the behavior of haptic human-human interaction in a joint object manipulation task. There, the link between behavioral studies and system-theoretic applications is missing. This paper is supposed to help to establish such a link.

As already mentioned, few studies compare single person performances and dyadic performances to gain insight into haptic interaction [1], [5]. Those studies use pointing or cyclical movement tasks to study haptic interaction. Haptic tasks involve motion trajectories and the related forces. If two partners carry out the task collaboratively, they have to find a common trajectory for the object or the interaction point of their hands. Haptic interaction allows them to negotiate on their common trajectory. Because the planned trajectories in haptic interaction tasks (e.g. dancing, one partner assisting the other with carrying a bulky object) are not directly measureable, we abstract them to a virtual tracking task scenario and, thus, are able to study the negotiation in an experimental design. To our best knowledge pursuit tracking tasks involving a virtual object as a cursor, have not been used to study the fundamentals of shared object manipulation. This setup allows to investigate single trials as well as dyadic haptic interaction trials.

Interaction can be the basis of either collaboration or competition. Here, we focus on collaboration which involves the negotiation of intentions, consisting of common goals, strategies and action plans [13]. "Interaction entails only acting on someone or something else, collaboration is inherently "with" others; working (labore) jointly with (co)." [2]. We distinguish between lower level collaboration and higher level collaboration in dependence of the amount of information concerning action plans and goals communicated exchanged between partners. Because haptic interaction/collaboration is not yet a well studied subject, we will keep the intentions constant and thus study a lower level of collaboration where the trajectory is given and does not have to be negotiated. In this case some collaboration is still of advantage: the two partners should find an optimal strategy to combine their inputs (forces/positions) to the common scenario.

The goal of this study is to present experimentally gained information on performance in shared object manipulation by comparing single persons and rigidly coupled dyads. A tracking task scenario is introduced as simplified interactive task. The energy flow framework is applied to the behavioral data.

The paper is structured as follows: After introducing our research questions in section 2 the experimental design is described followed by a detailed description of the included measurements in sections 3 and 4. We present results on performance and energy flows in section 5 and end with a conclusion.

2 Hypothesis & Research Question

In order to obtain the specifications of a HHI model we analyze a) the effects of HHI as well as b) aspects of its underlying processes.

In literature different human behavior for single and haptic interaction conditions is reported [1], [5]. Based on a performance measure, we analyze the behavior of an interacting couple in comparison to a single person performing the same pursuit tracking task. We expect tracking performance to be better in partner condition than in single condition.

With respect to [9] we raise the question whether increased task performance in the partner condition p) (also called interaction or dyadic trials throughout the remainder of this paper) is due to reduced, necessary individual forces. Therefore, we differentiate between two single conditions, one where the required forces are the same as in the dyadic condition (af) and one where they are halved (ah). More details on how this is achieved follow in section 3.

If reduced, necessary individual forces are no explanation for an expected increased performance in dyadic trials, we can assume that a different advantage is taken of interaction. To describe this advantage an energy flow framework is introduced in section 4.2. We strive to explain the experimentally gained data on human interaction behavior in shared object manipulation on the basis of energy exchange between partners.

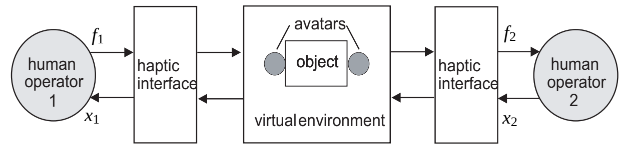

Figure 1: Interaction with virtual environment via haptic interfaces in case of the dyadic condition

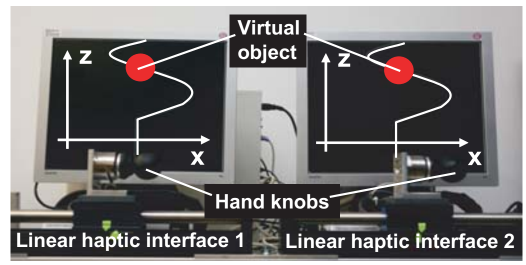

Figure 2: Experimental setup consisting of two linear haptic interfaces (linked by the virtual mass) and two screens with the graphical representation of the tracking path

3 Experiment

The following section will introduce details on the task, the experimental setup and the experimental description including participants, design and procedure. In this experiment participants had to perform a pursuit tracking task either on their own or in interaction with a partner. In the latter case the two partners were linked by a virtual object (see Fig. 1) and thus exchanged haptic signals.

3.1 Experimental Setup

The graphical representation of the path was implemented in C++. The path was visualized as a white line on a screen and participants were asked to follow this path as accurately as possible with a red ball representing a virtual mass as the path was scrolling down the screen with a constant velocity of $\dot{z} = -15$ mm/s. The overall path length was kept constant consisting of repeated components such as triangles, curves, straight lines and jumps (see Fig. 2). The order of the path components was randomized between trials to prevent learning effects. One trial took $t_{final} = 161$ s. The horizontal position of the red ball renders the position of either one haptic interface or both haptic interfaces depending on the condition. As shown in Fig. 2 the two 1 DOF linear haptic interfaces (designed at our lab) are each equipped with force sensors (Burster, model 8524), wooden hand knobs and linear actuators (Copley Controls Corp., Thrusttube module, motor type 2504). These haptic interfaces are characterized by their high rigidity and force capability.

The control of the linear haptic interfaces is implemented in Matlab/Simulink and executed on the Linux Real-Time Application Interface (RTAI). The graphical representation of the path runs on another computer and communication is realized by a UDP connection in a local area network.

The control is designed to model the mechanical properties of the virtual object. In Fig. 1 the model of the virtual object is introduced and the relevant forces and positions are defined. The motion of the virtual object is in 1 DOF and its dynamics is modelled according to Newton's law

$$\begin{aligned} f_{sum}(t) &= f_1(t) + f_2(t) = \\ &= m\ddot{x}_{vo}(t) + b\dot{x}_{vo}(t) + kx_{vo}(t) \end{aligned} \tag{1}$$

where f_{sum} is the sum of the forces applied by the participant/s, m, b and k are the virtual mass, damping and stiffness, respectively and

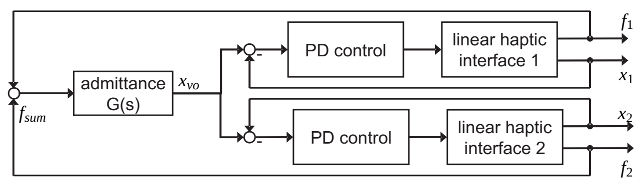

Figure 3: Position-based admittance control of the linear haptic interfaces in the dyadic condition

$\ddot{x}_{vo}$, $\dot{x}_{vo}$, and x_{vo} are the desired acceleration, velocity and position of the virtual object and, hence, of the linear haptic interfaces. In this experiment b and k are set to zero and only a virtual mass m is implemented. Hence, the transfer function in the Laplace domain of the virtual model simplifies to

$$G(s) = \frac{X_{vo}(s)}{F_{sum}(s)} = \frac{1}{ms^2} \quad (2)$$

and is implemented in the “admittance” block in Fig. 3.

A low level PD controller is used to control the actual positions of the haptic interfaces $x_1(t)$ and $x_2(t)$ to the position of the virtual object $x_{vo}(t)$. It compensates for external forces and friction. Taking into account the high-gain position control it can be assumed that $x_{vo}(t) = x_1(t) = x_2(t)$ and the transfer function of the overall system consisting of the virtual model and the haptic interfaces can be written as

$$G(s) = \frac{X_1(s)}{F_{sum}(s)} = \frac{X_2(s)}{F_{sum}(s)} = \frac{1}{ms^2}. \quad (3)$$

This setup allows not only the measurement of the resulting force $f_{sum} = f_1 + f_2$ but also of the individual forces f_1 and f_2 applied by the participants. This is an important aspect for the experimental data analysis.

When participants performed the tracking task on their own, they are seated in front of one of the haptic interfaces. This means $f_2 = 0$ for the single conditions.

3.2 Description of Design, Procedure and Participants

In the presented experiment 24 participants took part. Mean age was 27 years (std. deviation: 2.7 years). The participants were assigned to six groups of four people, each including two males and two females. Otherwise the assignment to groups was random. This round robin design [3] involved that each partner interacted with the other three members of the group. The chosen design resulted in 6 dyadic data sets per group.

With respect to the research question we compare three within-subject conditions:
1) condition ”with partner” (*p*)
2) condition ”alone with full mass” (*af*) and
3) condition ”alone with half mass” (*ah*),
where the full mass was chosen to be 20 kg.

For each participant two single trials (*af* and *ah*) and three haptic interaction trials with different partners (*p*, e.g. A with B, C and D) were recorded (repeated measurement). Within the round robin design, we balanced the order of conditions to control for sequence effects. To standardize the test situation further we undertook the following arrangements: participants not taking part in the on-going trial had to wait outside the laboratory; a wall was placed between the two participants so they did not gain visual information about their partners’ movements; participants used their right hand to perform the task (all of the participants were right-handed); participants were not allowed to speak to each other during the experiment; white noise was played on the headphones worn by participants, so the noise of the moving haptic interface would not distract; the position (left or right seat) was randomized with the order of experimental condition and participants; the order of the experimental conditions was randomized.

In addition to a general instruction at the beginning of the experiment, the participants had a test-curve at the beginning of each trail. This curve was not part of the analysis. Participants were informed beforehand about the upcoming condition.

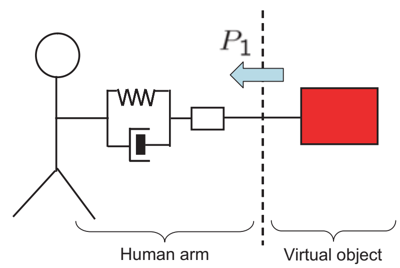

Figure 4: Mechanical model of single human operator interacting with the virtual object

4 Measures

After introducing the performance measure, we give details on the energy-flow framework.

4.1 Performance Measure

In order to analyze the performance in the three different conditions, we evaluate the root-mean-square error between the virtual object position and the reference path.

$$RMS_x = \sqrt{\frac{\sum_{i=1}^{N}(x_{ref,i} - x_{vo,i})^2}{N}} \quad (4)$$

where N is the the number of samples per trial.

4.2 Energy Flow

We would like to gain a deeper understanding of the underlying processes of haptic interaction to be able to derive an interaction model. As we consider haptic human-human interaction to be connected to energy exchange between the human operators we evaluate the energy flow (i.e. the power) between the different involved subsystems (human arm/s, virtual object) in our experiment.

A simple mechanical model is used to define and explain the energy flow between the subsystems. Although there is no haptic human-human interaction in the single conditions and we do not evaluate the energy flow in these conditions, we present the mechanical model to introduce the basic principle and assumptions made in this simple scenario. Next, we introduce the more complex case of the partner condition.

In the **single** conditions (*ah*, *af*) two subsystems are defined: the human arm and the virtual object (see Fig. 4). The human arm is described by a mass-spring-damper model that is connected rigidly to the virtual object. Based on this mechanical model the energy flow between the subsystems is

$$P_1(t) = f_1(t)\dot{x}_{vo}(t) \qquad \forall t \in [0; t_{final}] \quad (5)$$

with f_1 the force applied by the human operator on the haptic interface and $\dot{x}_{vo}$ the velocity of the virtual object. The direction of the force and velocity vectors is defined in such a way that energy injected by the human to the virtual object has a negative sign and energy absorbed by the human from the virtual object a positive one.

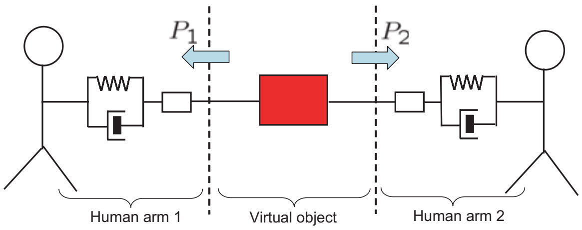

Figure 5: Mechanical model of interacting couple

In this model we neglect friction and assume the virtual object to be ideally rigid, because of the high-gain position control. For this reason and because of energy conservation *all* the energy injected/absorbed by the human arm to/from the virtual object results in a change of its kinetic energy dE_{kin}/dt (acceleration/deceleration):

$$\frac{dE_{kin}(t)}{dt} + P_1(t) = 0 \qquad \forall t \in [0; t_{final}] \tag{6}$$

with

$$\frac{dE_{kin}(t)}{dt} = m\ddot{x}_{vo}(t)\dot{x}_{vo}(t) \qquad \forall t \in [0; t_{final}] \tag{7}$$

Furthermore, as neither of the participants touches the knobs in the beginning and at the end of the trials and the virtual mass is not moving in these time instants, i.e. $\dot{x}_{vo}(t=0) = \dot{x}_{vo}(t=t_{final}) = 0$ m/s, the kinetic energy $E_{kin}(t=0) = E_{kin}(t=t_{final}) = 0$ J in the system can be considered to be zero in these moments. Thus, according to energy conservation laws, energy once injected by the participant, has to be absorbed by her/him in a later instant. Hence, the mean energy flow between the operator and the virtual object is 0 J/s over the whole trial

$$\overline{P}_1 = \int_0^{t_{final}} P_1(t)dt = 0 \text{ J/s}. \tag{8}$$

In the **partner** condition (p) the situation is more complex. As depicted in Fig. 5, here, three subsystems are defined: human arm 1, virtual object and human arm 2 with the respective energy flows

$$P_1(t) = f_1(t)\dot{x}_{vo}(t) \qquad \forall t \in [0; t_{final}] \tag{9}$$

and

$$P_2(t) = f_2(t)\dot{x}_{vo}(t) \qquad \forall t \in [0; t_{final}]. \tag{10}$$

This represents a classical 2-port architecture where an energy flow occurs between the virtual object and each of the human arms. Again, for reasons of energy conservation, energy injected in every time instance by one partner is either converted to kinetic energy of the object or absorbed by the other partner and vice versa

$$P_1(t) + P_2(t) + \frac{E_{kin}(t)}{dt} = 0 \qquad \forall t \in [0; t_{final}] \tag{11}$$

where $dE_{kin}(t)/dt$ is defined in accordance with the single condition (7).

It is assumed that the virtual object is not moving in the beginning and the end of the trial $E_{kin}(t=0) = E_{kin}(t=t_{final}) = 0$ J. Hence, because of energy conservation laws, energy once injected by *either* of the interaction partners has to be also absorbed by *either* of them. Hence, the mean energy flow of the two interacting partners is zero

$$\overline{P_1(t) + P_2(t)} = 0. \tag{12}$$

However, this does not imply that the mean energy flows $\overline{P}_1$, $\overline{P}_2$ are zero, because from equation (12) it follows

$$\overline{P}_1 = -\overline{P}_2. \tag{13}$$

In order to interpret this equation, two cases have to be distinguished:
CASE 1: $\overline{P}_1 = -\overline{P}_2 \neq 0$
In this case two conclusions are drawn. First, *on average* one partner is injecting more energy to the virtual object than absorbing from it ($\overline{P} < 0$). Second, with respect to the overall trial, the exessive energy that is injected by one of the partners has to be absorbed by the other one, e.g. $\overline{P}_1 < 0 \Rightarrow \overline{P}_2 > 0$. Hence, on average there is an energy flow from one partner to the other via the virtual object.
CASE 2: $\overline{P}_1 = -\overline{P}_2 = 0$
Here, the partners inject on average the same energy to the virtual object as they absorb from it. However, if we consider every time instance and not the mean value, it is still possible that energy injected by one partner is absorbed by the other one.

We consider one other remark worth mentioning, where we consider the energy flow in every time instance.
An energy flow from one partner to the other occurs if and only if one of the interaction partners is injecting energy to the system while the other one is absorbing it, i.e.

$$sgn(P_1(t)) \neq sgn(P_2(t)) \Leftrightarrow \begin{array}{l}\text{energy flow from one partner to}\\ \text{the other via the object.}\end{array} \tag{14}$$

In this case, in every time instance the energy flow between the interaction partners via the virtual object equals the smaller one of the energy flows $P_1(t)$ or $P_2(t)$.
Otherwise, i.e. if $sgn(P_1(t)) = sgn(P_2(t))$ or if either of $P_1(t)$ and $P_2(t)$ is zero, there is no energy flow between the interaction partners. The partners' energy flows contribute only to the kinetic energy of the virtual object.

In summary, we state the following four important points that are crucial for the analysis of the energy flows:
1) We assume that the virtual object is not moving in the beginning and the end of the trial $E_{kin}(t=0) = E_{kin}(t=t_{final}) = 0\ J$.
2) Because of 1) and energy conservation, energy injected to the system representing the virtual object in one time instance has to be released by it in a later instance.
3) The energy injected by one of the partners in one time instance must not be absorbed necessarily by the same person in a later instance. **An indirect energy flow from one partner to the other can take place via the object.**
4) In every time instance, each of the interaction partners can **either** inject energy to the virtual object ($P(t) < 0$) **or** absorb energy from it ($P(t) > 0$).

Finally, the mass-spring-damper model of the human arm helps to interpret how the energy is injected/absorbed by the human operator. However, it is important to note that a) this simple model of the human arm does not describe the complex processes in the human arm completely and b) we cannot determine the different energies of the human arm explicitly. Hence, we cannot distinguish if there is an energy flow between the two partners and the virtual object at the human-object interfaces because they pull/push against each other (potential energy) or because one partner is generating energy in his/her muscles while the other one is dissipating in the muscle's viscosity (dissipative energy). What we can conclude is that an energy flow from/to the virtual object to/from the human arm results in an in-/decrease of either potential energy or dissipative energy.

As we assume HHI to be connected to an energy exchange between the collaborating partners the mean energy flows between the three subsystems $\overline{P}_1$ and $\overline{P}_2$ are analyzed for the partner condition.

5 Results & Discussion

The following results are based on analyses taking into account the *mean* performance RMS_x and *mean* energy flow measures. First,

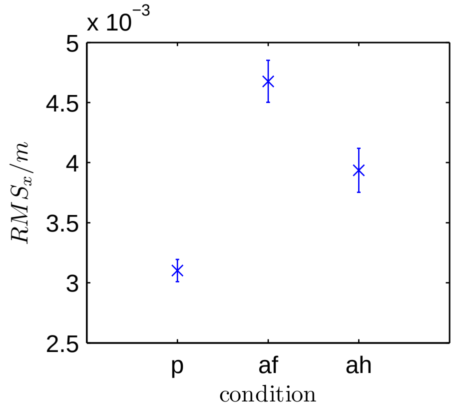

Figure 6: Performance analysis by RMS_x (Mean and standard error)

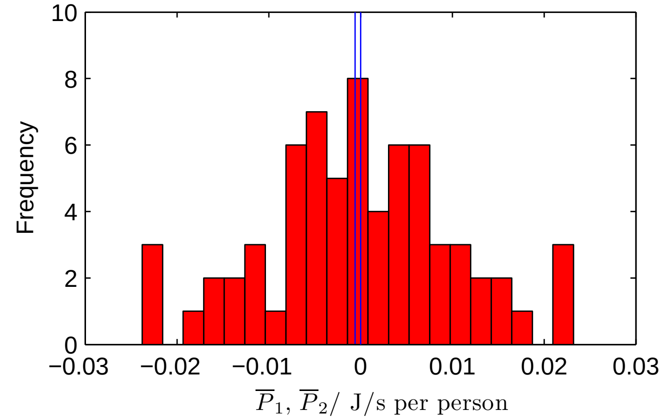

Figure 7: Histogram of $\overline{P}_1$ and $\overline{P}_2$ in *p* condition and the reference interval (blue lines)

we analyse if tracking performance is different in partner and single trials, focusing on the effect of different masses in the single conditions. Next, the energy flows are evaluated in order to gain an insight in the underlying processes of HHI.

5.1 Performance

As mentioned in the previous section, participants performed the task in three different conditions, two of them on their own (*af*, *ah*) and one in haptic interaction with a partner (*p*).

There is one statistical challenge. Due to the chosen round robin design, our measurement data sets are not independent variables, because one person interacted in several dyads. For this reason, most of the classic statistical methods are not applicable. To circumvent this problem, we chose a subset of 12 independent data sets by analyzing only two dyads from each group (both mixed-gender).

Performance is increased for the partner condition (mean: 3.10 mm, standard error: 0.09 mm) compared to both single conditions, as depicted in Fig. 6. In single conditions participants performed with lower RMS_x when they had to move only half the weight (mean: 3.94 mm, standard error: 0.18 mm) of the virtual mass compared to the full mass (mean: 4.68 mm, standard error: 0.18 mm). A repeated measurement ANOVA showed significant influence of the factor "tracking condition" on the performance measure ($F(2,22) = 30,729$; $p < 0.000$; partial $\eta^2 = 0.736$). Bonferroni adjusted pairwise comparisons revealed significant differences ($p < 0.05$) between all three levels (*p*, *af*, *ah*) of the factor.

While it is not surprising that participants showed higher performance in terms of RMS_x when dealing with lower virtual mass in the single tracking conditions, they performed even better, when they interacted with a partner. Our hypothesis that the RMS_x is lower in interaction trials can be confirmed. Performance in the dyadic trials is even better than in the half mass trials. Thus, performance difference in single and dyadic tasks has to be due to interaction instead of the reduction of necessary individual forces as considered in our research questions. There, we attempt to describe this interaction by energy flows.

5.2 Energy Flow between Interacting Partners

Our goal of the energy-flow analysis is to determine which of the two cases introduced in the previous section is true for our experiment. Before approaching this, we have to check if our assumption of a lossless system can be verified and equations (8) and (13) are satisfied (units are J/s):

$\overline{P}_1 + \overline{P}_2$ (*p* condition): mean = -1.62e-4; std. deviation = 1.07e-4

$\overline{P}_1$ (*af* condition): mean = -5.14e-5; std. deviation = 5.16e-5

$\overline{P}_1$ (*ah* condition): mean = -1.72e-5; std. deviation = 1.85e-5

We note that the equations (8) and (13) are not satisfied anymore, but consider the differences of the mean values from 0 to be caused by measurement errors and uncompensated friction. Thus, we think of our system to be lossless in good approximation.

This causes problems to distinguish between CASE 1 and CASE 2: If $\overline{P}_1$ and $\overline{P}_2$ are unequal to 0 (as considered in CASE 1), we cannot seperate anymore if this is caused by the above mentioned measurement errors (disturbances) or if CASE 1 is actually true. It is problematic to falsify CASE 2.

To approach this, we have to gain knowledge if it is more probable that a value of the individual energy flows $\overline{P}_1$ and $\overline{P}_2$ in the partner condition is explained by the disturbance distribution (described here by the above listed mean values and standard deviations) or that the value belongs to a different population. Not only because it is theoretically appealing that the sources of disturbances are identical in the two single conditions, but also because the mean values do not differ significantly (paired-sample: t(10) = -1.938, p(two-tailed) = 0.081, one pair excluded from analysis because the energy value in *af*-condition was more than two standard errors away from the mean), we treat the two single conditions as one sample to compare it with the individual energy flows in the partner condition. Due to the non-independency of our measurement data and the non-Gaussian distribution we are unaware of any statistical procedure which allows to test for this. Therefore, we decided for the following procedure. We determined the overall minimum and maximum value $\min_d$, $\max_d$ of the disturbance distribution and define $[\min_d \ \max_d] = [-0.6 \text{ mJ/s} \ \ 0.005 \text{ mJ/s}]$ to be the reference interval. If a value of $\overline{P}_1$ or $\overline{P}_2$ in the partner condition lies within this interval, we assume its deviation from 0 to be explained by measurement errors and CASE 2 is given. If the value is outside the interval, we interpret this as indication for CASE 1. To illustrate this, the histogram of $\overline{P_1}$ and $\overline{P_2}$ in the partner condition and the chosen reference interval are presented in Fig. 7. Because 97% of the $\overline{P}_1$ and $\overline{P}_2$ in the partner condition are outside the reference interval, we conclude that CASE 1 is an appropriate description of our data.

This means, over the whole trial, in each couple one of the partners is injecting more energy to the virtual object than he/she is absorbing while the other partner is absorbing more energy than he/she is injecting. On average, there is an energy flow from one partner to the other over the virtual object. However, as introduced in section 4 it is not possible to distinguish if the energy flow between the virtual object and the human arms is measured because the interacting partners push/pull against each other to feel each other or because one partner is generating energy while the other one is dissipating energy what could be interpreted as a role allocation.

Finally, the data is spread over a large intervall which indicates that haptic interaction is not the same for each couple. We assume that this variation is caused by different behavioral characteristics of the interacting partners.

6 Conclusion

To evaluate the effect of haptic interaction on human behavior in a joint pursuit tracking task, we analysed performance in single as well as partner trials. Results are based on three different conditions: with a partner, alone with the same mass as in the interaction trials and with half of the mass. In accordance to [9], [1], we can confirm our hypothesis that performance is increased in the "partner" condition. Thus, we can generalize the performance related results of pointing tasks and cyclic motions to joint pursuit tracking tasks. Because interaction in the "partner" condition was even better than in the "alone-half-mass" condition, it is concluded that the improved task performance in dyadic trials is not only a result of force reduction for the individual but different explanations have to be considered, which were presented in the introduction.

One of these explanations is the existence of different roles of the haptic interacting partners. Based on a mechanical model energy flows are introduced to approach the challenge of defining different interaction behavior. Furthermore, this framework provides the theoretical background for an energy-based model, like e.g. a Port-Hamiltonian system.

An evaluation of the mean energy flows between the interacting partners $\overline{P}_1$ and $\overline{P}_2$ revealed, on average, there is an assymmetric energy flow between the partners via the virtual object. This is shown by the fact, that in each trial of the "partner" condition there is one partner who is on average injecting energy, while the other one is absorbing energy. The cause of energy flow between the virtual object and the human arms is either the interaction partners pushing/pulling against each other or one partner generating energy while the other partner is dissipating energy. The latter case would be a role allocation where one partner could be modeled *on average* as a source and the other one as a sink. This would be of special interest for the energy-based model we would like to derive.

Furthermore, the energy flows are not constant for all interacting couples but are spread over a large interval. This indicates that haptic interaction varies between different couples. We explain this to be caused by the individual behavior characteristics of the partners. A model of haptic interaction has to comprise these different types of interaction couples. However, time series analysis is required to allow further benefit from the energy-flow framework in haptic interaction.

In future, other explanations for the benefit of interaction in shared object manipulation contrasting individual performance have to be addressed. Out of the explanations offered in literature and listed in section 1, this paper addressed two. Further studies may investigate the social facilitation factor. We plan to focus on the influence of the human biomechanical system by experimentally manipulating aspects which affect this system.

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References

[1] S. Gentry, E. Feron, and R. Murray-Smith. Human-human haptic collaboration in cyclical fitts' tasks. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2-6 August 2005, Cambridge, MA, USA.*, pages 3402–3407, 2005.

[2] B. J. Grosz. Collaborative systems. *American Association for Artificial Intelligences National Conference on Artificial Intelligence*, 2(17):67–85, 1996.

[3] D. A. Kenny. The design and analysis of social-interaction research. *Annu. Rev. Psychol.*, 47:59–86, 1996.

[4] G. Knoblich and J. S. Jordan. Action coordination in groups and individuals: Learning anticipatory control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29:1006–1016, 2003.

[5] K. Reed, M. Peshkin, J. E. Colgate, and J. Patton. Initial studies in human-robot-human interaction: Fitts' law for two people. In *International Conference of Robotics and Automation*, 2004.

[6] K. Reed, M. Peshkin, M. J. Hartmann, M. Grabowecky, J. Patton, and P. M. Vishton. Haptically linked dyads. Are two motor-control systems better than one? *Psychological science*, 17(5):365–366, 2006.

[7] K. B. Reed. *Understanding the haptic interactions of working together*. PhD thesis, Northwestern University, 2007.

[8] K. B. Reed, J. Patton, and M. Peshkin. Replicating human-human physical interaction. In *IEEE International Conference on Robotics and Automation*, volume FrB4.1, 2007.

[9] K. B. Reed, M. Peshkin, M. J. Hartmann, J. E. Colgate, and J. Patton. Kinesthetic interaction. In *IEEE International Conference on Robotics and Automation (ICRA), New Orleans, April 2004*, 2005.

[10] D. J. Reinkensmeyer, P. S. Lum, and S. L. Lehman. Human control of a simple two-hand grasp. *Biological Cybernetics*, 67:553–564, 1992.

[11] B. H. Schmitt, T. Gilovich, N. Goore, and L. Joseph. Mere presence and social facilitation: One more time. *Journal of Experimental Social Psychology*, 22:242–248, 1986.

[12] C. Secchi, S. Stramigioli, and C. Fantuzzi. *Control of Interactive Robotic Interfaces: A Port-Hamiltonian Approach (Springer Tracts in Advanced Robotics)*. Springer-Verlag New York, Inc., Secaucus, NJ, USA, 2007.

[13] M. Tomasello, M. Carpenter, J. Call, T. Behne, and H. Moll. Understanding and sharing intentions: The origins of cultural cognition. *Behavioral and Brain Sciences*, 28:675–735, 2005.

[14] Z. Wang, J. Yuan, and M. Buss. Modelling of human haptic skill: A framework and preliminary results. In *17th IFAC World Congress, July 6-11, 2008, Seoul, Korea*, 2008.