Human Preferences in Industrial Human-Robot Interactions

Markus Huber[1], Claus Lenz[2], Markus Rickert[2], Alois Knoll[2], Thomas Brandt[3], Stefan Glasauer[1]
[1]Center for Sensorimotor Research, Department of Neurology, Ludwig-Maximilians-Universität München
[2]Robotics and Embedded Systems Lab, Department of Computer Science, Technische Universität München
[3]Department of Neurology, Ludwig-Maximilians-Universität München

***Abstract*— Joint-action is one of the key research areas in robotics and especially important in physical human-robot interaction. The two main criteria for robots, which should be integrated in everyday life, are safety and efficiency. Therefore, it is of particular interest to understand how humans work together in order to transfer the resulting facts from these studies to direct human-robot interaction. In this work, we investigate a simple case of physical human-robot interaction, i.e. the handing over of small objects from a robot to the human. Experiments, in which six cubes were handed over from the robot to the human, were performend with two different robot systems, a robot arm in a humanoid set-up and a typical industrial set-up. Two different velocity profiles were integrated in the robot systems, a trapezoidal velocity profile in joint coordinates and a human inspired minimum jerk profile in cartesian coordinates. In both set-ups the use of the minimum jerk profile lead to shorter reaction times of the humans for the interaction. The humanoid setup showed with both profiles shorter reaction times than the industrial setup. It was also investigated in the experiments, whether the human body position adopts during the experiments to an optimal position for the hand-over. During the experiments the body spatial position stayed largely invariant, which indicates, that the subjects were not frightened and felt comfortable with the given hand over position. The result of our experiments along with the given comparison to natural human-human behaviour provides a solid basis for more efficiency of collaboration of humans and assistive robot systems.**

I. INTRODUCTION

The field of physical interaction of humans and robots is developing rapidly as robots become more capable of coping with challenges in natural environments of human beings. Industrial assembly tasks, house care and housing support hope to gain enormous advantages by developing robot systems that assist, help, and cooperate directly with humans. However such robot systems can only be integrated successfully in human environments if they meet high demands regarding safety and efficiency aspects. So it is reasonable to look at humans which are experts in safe and efficient cooperation. Investigating high-level joint action strategies between humans might enable a transfer of those strategies to competitive robot systems [1].

At the moment, human-robot collaboration is mainly based on a master-slave level with a human worker tele-operating the robot or programming it off-line allowing the robot to execute only static tasks. To ensure safety, the workspaces of humans and robots are strictly separated in time or in space in industrial production processes. This workspace splitting does not take advantage of the potential for humans and robots to work together as a team, where each member has the possibility to actively assume control and contribute towards solving a given task based on their capabilities. Such a mixed-initiative system supports a spectrum of control levels, allowing the human and robot to support each other in different ways, as needs and capabilities change throughout a task [2]. With the subsequent flexibility and adaptability of a human-robot collaboration team, production scenarios in permanently changing environments as well as the manufacturing of highly customized products become possible. One step towards the goal of an efficient collaboration between humans and robots, is the exploration of the basic aspects of physical interaction, where e.g. the handing over of objects plays an essential role. In our studies, we focus on repetitive handing over tasks between humans. So far, single arm and hand movements as well as grasping has been investigated well [3] along with a developement of various mathematically models to describe them [4] , but studies of the research field of physical joint action [5], [6] and [7] are rar.

In this paper, we present results about the unconscious adaption of various parameters in a hand over task between a human and an industrial robot. For the experiments the robot plattform of *JAHIR* [8] was used, consisting of an industrial robot connected to a conveyer belt and equipped with diverse sensors.

Even though the subjects know the overall task, i.e. the passing over of a fixed number of objects in a common workspace, concrete parameters are not specified. Parameters including the timing of motions and the evaluation of the hand-over position have to be negotiated by the subjects during the experiment. It is expected that these parameters become smoother and more accurate during the repetitions to achieve a maximum in comfort and efficiency.

II. EXPERIMENTAL SET-UPS

The experiments performed in this work aim to investigate the unconscious adaption of various parameters in a hand over task between a human and an industrial robot. The results are compared with similar experiments done in a human-human and a human-humanoid hand-over task. All experimental set-ups are described shortly in the following Sections.

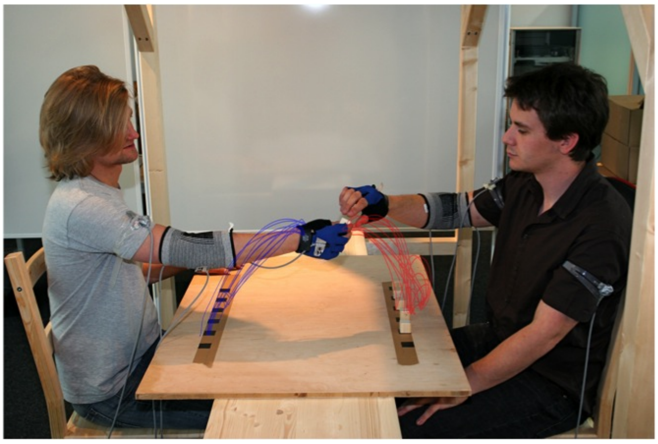

Fig. 1. Set-up for the Human-Human hand over experiments

A. Human-Human Set-up

The human-human hand-over experiment is based on the set-up described in [9]. Two test subjects sit opposite to each other on a table with a width of 0.75 m. The movements of the human subjects are measured during a hand-over task using the magnet-field based motion tracking system *Polhemus Liberty* with four markers per human to estimate the position of the back of each hand and of each shoulders. Six wooden cubes were handed over from one subject (*giving subject*) to its counterpart (*taking subject*). The size of the cubes was chosen to $0.03 \times 0.03 \times 0.03$ m, because this requires the more accurate precision grip.

The cubes were placed in one row on pre-defined marks on the table. The same marks at the other side of the table served as target postitions to place the cubes after each hand-over. The distance between the two rows of marks was 0.55 m. The setup is in depicted in Figure 1.

16 pairs of subjects (all students and university personal with body heights of 1.60 to 1.90 m) participated in the experiments. The giving subject was triggered with a sound presented through headphones to initialize the handing over of a new cube. Only a few instructions were given to the subjects before the experimental run:

- The person with the cubes will hand over the cubes, one after the other.
- The other person should place them on the marks in front of him.
- While the giving person is waiting for the start signal both subjects should place their hands on the table beside the marks.

The results of the human-human experiments serve as reference values to the following experiments with the robot systems.

B. Human-Robot Set-ups

In the experiments with the robotic systems, two motion profiles were tested consecutively on all participating subjects of each set-up: the hand trajectory of the robot was determined either as minimum-jerk trajectory [10] in spatial coordinates or as trapezoidal velocity profile in joint coordinates. The order of the profiles was balanced between the subjects minding human adaption capabilities.

1) Minimum Jerk Trajectory: The minimum jerk trajectory leads to the objective function c(r) (1), where $\mathbf{r}$ is the grippers positions-vector and t_e is the duration of the movement.

$$c(\mathbf{r}) = \frac{1}{2}\int_0^{t_e} \left| \frac{d^3\mathbf{r}}{dt^3} \right|^2 dt \tag{1}$$

Minimizing this objective function leads to a fifth-order polynomial. Given initial/end position, velocity and acceleration for the trajectory, we can specify the polynomial coefficients. The derivation of this equation results in the velocity profile (2), where $\mathbf{r}_0$ and $\mathbf{r}_e$ denote the initial and end-positions of the gripper, with the desired duration t_e.

$$\dot{\mathbf{r}}(t) = (\mathbf{r}_0 - \mathbf{r}_e)\left(60\frac{t^3}{t_e^4} - 30\frac{t^4}{t_e^5} - 30\frac{t^2}{t_e^3}\right) \tag{2}$$

The corresponding trajectories in Cartesian space for all 6 cube positions are plotted in the right diagram of Figure 2. Interpolation was performed in Cartesian space of the robot, resulting in straight lines.

2) Trapezoidal Velocity Profile: The second set of trajectories was calculated based on a trapezoidal velocity profile in joint coordinates $\dot{\theta}(t)$, with a constant acceleration $\ddot{\theta}_a$ and deceleration $\ddot{\theta}_d$ phase (4). t_a is the acceleration, t_d the deceleration time. Because of the joint coordinates, the trajectories are not straight like in the minimum jerk profile (upper part of Fig. 2). The recorded velocity profile does not show a trapezoidal shape because of the transition from joint coordinates to Cartesian coordinates (middle diagram of Figure 2).

$$\dot{\theta}(t) = \begin{cases} \ddot{\theta}_a t + \dot{\theta}_0, & 0 \le t < t_a \\ \ddot{\theta}_a t_a + \dot{\theta}_0, & t_a \le t < t_d \\ \ddot{\theta}_a t_a + \ddot{\theta}_d(t - t_d) + \dot{\theta}_0, & t_d \le t < t_e \end{cases} \tag{3}$$

$$\ddot{\theta}(t) = \begin{cases} \ddot{\theta}_a, & 0 \le t < t_a \\ 0, & t_a \le t < t_d \\ \ddot{\theta}_d, & t_d \le t < t_e \end{cases} \tag{4}$$

Instead of calculating the trajectory off-line for each movement, an on-line calculation after each update step of the robot controller is possible. In the present experiment however, we only included a joint-space interpolation for the trajectory, resulting in curves in the Cartesian space.

The parameters for the velocity profiles were adapted in order for the robot to take about 1.2 s for each point to point trajectory. This movement duration was taken from the trajectories recorded in the human-human experiments [9]. The maximum velocities of the robot were calculated from the duration parameter. After the experiment, the subjects were asked questions about how human-like the movements were and how secure they felt. Each question had to be scored from 1 (not at all) to 5 (very much).

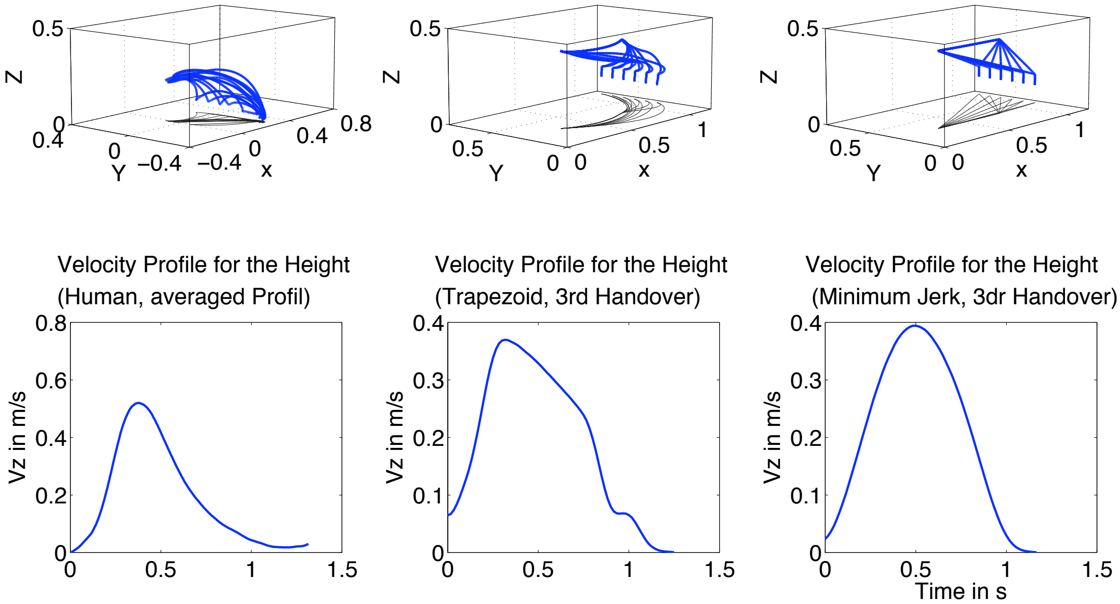

Fig. 2. Resulting trajectories of the robot gripper. from left to right: A typical human giving subjec trajectorie, the trapezoid velocity profile and the minimum jerk profile

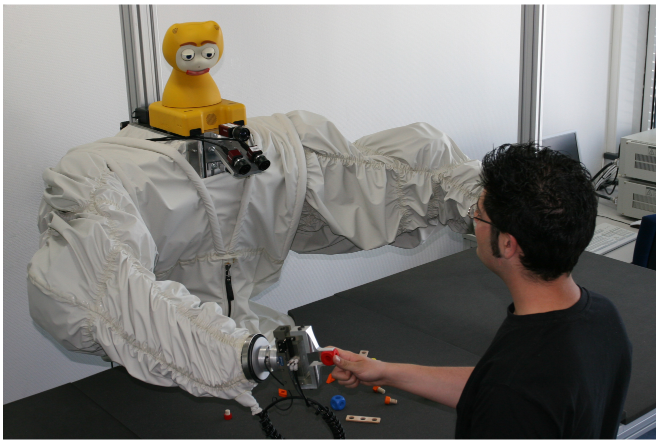

Fig. 3. Set-up for the Human-Humanoid hand over experiments

3) Human-Humanoid Set-up: The humanoid robot system JAST – described in detail in [11] – was used for hand-over experiments from a human-like robot system to a human. Figure 3 shows the JAST robot system in such a hand-over situation. A detailed describtion of the experimental set-up and the results with this system are published in [9] to which we kindly refer.

4) Human-Industrial Robot Set-up: Like in the predeceeding human-humanoid set-up, the giving subject was replaced by a robot system [8]. Opposite to the set-up of Section II-B.3 an industrial robot mounted in an industrial like position with a connection to a conveyer belt was used. A picture of the robot system is shown in Figure 4.

The six cubes for the hand over were placed on carriers transported on the conveyer belt. The robot system picks up the cubes from this carrier and hands them over to the subject. The subjects were instructed as in the experiments before to put each cube on marked positions on the shared working desk in front of them after receiving it from the robot. A force torque sensor mounted on the tool center point of the robot was used to determine if the human has grasped the cube. As soon as the force torque sensor measured a force on the gripper the cube was released. After the hand over, the robot moves to a resting position in mid-air, so that the human has free access to the workspace. The robot waits in this position for the next time-triggered hand over.

The waiting times are between zero and four seconds between two hand overs, so that the human is not able to adapt to a periodical behaviour of the robot. The times were adjusted to fit the previous experiments to be able to compare the results. The hand over position the robot moves to stays fixed throughout the experimental runs.

To track the back of the hand and the centre of the chest of the subjects, a marker based infrared tracking system was used[1]. Unlike to the set-up described in [8] robot and working desk were rotated, so that the robot was placed on the left side of the table as depicted in Figure 4. This was done, because one of the two motion profiles (minimum jerk

[1] `http://www.ar-tracking.com`

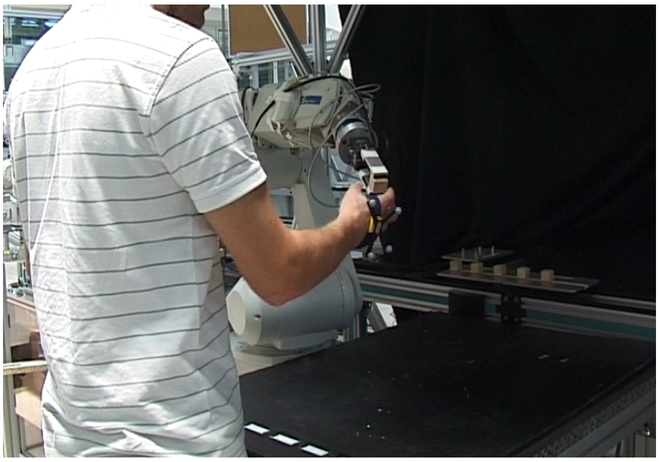

Fig. 4. Set-up for the Human-Industrial Robot hand over experiments

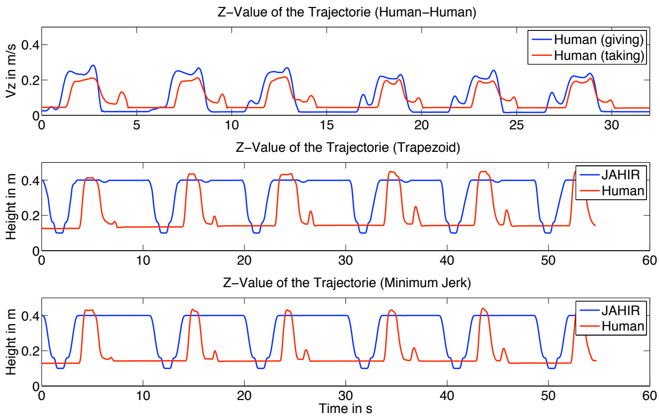

Fig. 5. Typical trajectories for the height of the Hands / gripper over the table during the time. Top: trajectories for two humans handing over the six cubes. Middle: trajectories for the *JAHIR* robot system handing over the cubes with the trapezoid prfile. Bottom: trajectories for the *JAHIR* robot system handing over the cubes with the min. jerk profile

[10]) generates a straight line in cartesian space from the initial cube-position to handing over point of the gripper (see Figure 2, upper left), therefore it was not possible for the robot to reach the conveyer belt with this profile in the initial setting.

III. Results

In this work, we compare the timing characteristics of humans with a robot, that is not human like at all, but widely used in industrial environments. We are also interested in how humans interpret different velocity profiles in a non human-like robot system and the question of finding an optimal handing over position in industrial settings.

Figure 5 shows three trajectories – i.e. the height of the hands and gripper over the table during time – for two humans handing over the cubes and the *JAHIR* robot system using the two different velocity profiles. Every hand-over can be sequenced in three time sections, defined in detail in [9]:

1) *reaction-time*
2) *manipulation-time*
3) *post-handover-time*

Table I contains the mean time duration for the new human-human and human-industrial robot experiments as well as the previous published results for experiment with the humanoid robot system JAST using the same velocity profiles [9]. In contrast to the human-human experiment in [9] the giving subject was triggered by a headphone to start the handing over, leading to shorter reaction times in average than in the previous experiment. As expected, the reaction times are with 0.22 s$\pm$0.02 (mean$\pm$SEM) the smallest for human-human hand-overs.

The experiments performed with humanoid robot system JAST showed reaction times of 0.50 s$\pm$0.06 s for the trapezoid profile and 0.39 s$\pm$0.04 s for the minimum jerk profile [9]. Statistical analysis revealed that reaction times in the minimum jerk condition were significantly shorter [F(1,7)=9.74;p=0.017] than in the trapezoidal condition. So the human inspired profile shows advantages in efficiency and comfort in the handing over, however the reaction time is still larger than the reaction times between humans.

The question arises if the the same velocity profiles still show different timings, if the robot system has a typical industrial arrangement. The last column in table I shows the averaged times for the different profiles in the *JAHIR* set-up. Here also the minimum jerk profile shows better results in the reaction time. The reaction times are 0.86$\pm$0.03 s for the trapezoid and 0.69$\pm$0.03 s for the minimum jerk profile (F(1, 14)=12.108;p=0.0037). Any effects in other time sequences as well as an adoption during the repetition could not be observed. The reaction times however, are higher than the reaction times in the humanoid robot set-up thus in average at least three times larger than the human-human reaction time. Therefore, a human like set-up for the robot is likely to increase efficiency for assistant-robot systems. Figure 6 gives a closer look to the reaction times in the human-human experiment and the experiments with the industrial robot system *JAHIR*. Figure 7 shows all time sequences for each handing over trial for the human-human experiment as well as the experiments with the industrial robot system.

The middle of the chest of the subjects was measured during the experiments to estimate the most comfortable position for the fixed hand-over position and if the subjects are surprised during the first hand-overs due the high absolute velocities (max. 1.74 m/s for the trapezoid profile, max. 1.67 m/s for the minimum jerk profile) of the robot gripper moving directly towards the subject.

The subjects kept the same distance to the table during the experiment for both tested profiles of the robot. The mean distance to the handing over point was 0.39 m for both profiles. The standard deviation of the mean body-position for the subjects herby is 0.05 m for the trapezoid profile, respectively 0.04 m for the minimum jerk profile (see left of Figure 8). The results reveal that there was no discomfort even for the first movement of the robot towards the subjects.

Calculations of the mean of the standard deviation of the subjects (see right of Figure 8) show that the subjects perform insignificant little body-movements during the experiment

Profile	Reaction Time	Manipulation Time	Post Handover Time	Overall Time
		Human-Human		
	0.22	1.28	0.15	1.65
		Human-Humanoid		
Trapezoid	0.50	(1.82)	(0.67)	(2.96)
Min Jerk	0.39	1.49	(0.78)	(2.68)
		Human-Industrial Robot		
Trapezoid	0.86	1.34	0.70	2.90
Min Jerk	0.69	1.42	0.64	2.75

TABLE I

AVERAGE DURATION OF THE TIME SECTIONS DURING A HANDOVER FOR THE MINIMUM JERK AND THE TRAPEZOID VELOCITY PROFILE IN SECONDS. DUE MECHANICAL ISSUES DURING THE HUMAN-HUMANOID EXPERIMENT THE VALUES IN BRACKETS ARE NOT RELIABLE.

Fig. 6. Reaction time for all six trials (red: reaction time for the human-human handover, blue: reaction time for the JAHIR robot system using the trapezoid profile, green: reaction time for the JAHIR robot system using the minimum jerk profile). Error bars indicate standard deviation, the straight lines indicates the mean over all trials.

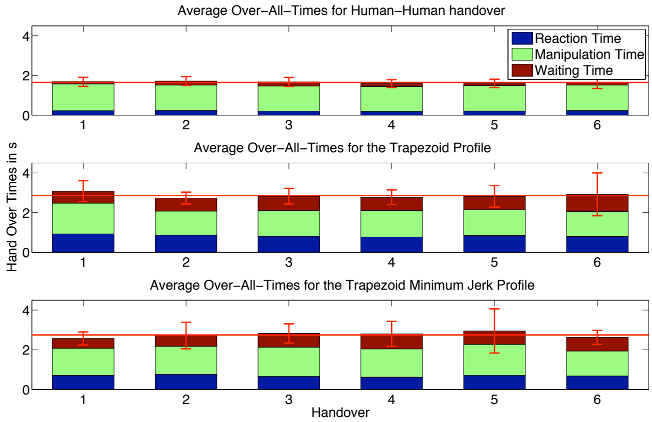

Fig. 7. Overall hand-over duration for all six trials together with the respective time sections (blue: reaction time, green: manipulation time, red: post-handover-time). Error bars indicate std of overall duration, the straight lines indicates the mean over all trials. Top: Overall duration for the human-human experiment. Middle: Overall duration for the handing over with the JAHIR robot system using the trapezoid velocity profile. Bottom: Overall duration for the handing over with the JAHIR robot system using the minimum jerk velocity profile.

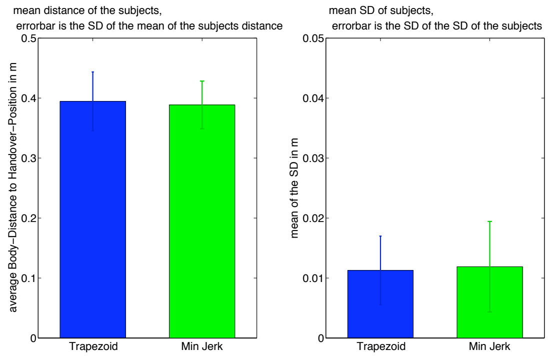

Fig. 8. Distance (x-component) of the handing over position to the body position. SD: standard deviation

towards the robot (0.01 m for both profiles). This indicates that with the chosen hand-over position we met the region of comfort for the subjects. Further more, it leads to the interpretation that as soon as the hand-over position is in a region of comfort, humans do not need to further optimise their body position.

After the experiments the subject had to fill a short questionnaire. In the former questionnaire, after the experiments on the humanoid robot system JAST, the subjects did not report any differences in the profiles in term of human-like motion, however the subjective safety was significantly higher in the minimum jerk profile [9]. The evaluation of the answers in the industrial setting show that there are neither preferences in terms of how human-like the robot movements were nor in a subjective feeling of security (statistics are shown in Figure 9. Despite of the high maximum velocities of the robot system the questionnaire indicated a relatively high feeling of subjective safeties in both profiles (averaged 4.1 scores out of 5 for the trapezoid profile, 4.3 scored out of 5 for the minimum jerk profile).

IV. DISCUSSION

In this paper a comparison of two different robot systems in terms of their efficiency in working together with humans was done. In detail, a humanoid robot system (JAST [11]) and a industrial robot system (*JAHIR* [8]) was compared in their acceptance by humans. The robot systems had to hand over six cubes with different velocity profiles. In both robot set-ups a trapezoidal velocity profile in joint coordinates and a more human inspired, minimum jerk velocity profile in cartesian coordinates was used to perform this task. It was shown that in both set-ups the minimum jerk profile leads to faster reaction times and is better accepted by humans. Significant differences in the reaction times were detected comparing the two robot system set-ups: The humanoid set-up leads to shorter reaction times (0.50/0.39 s for trapezoid/min. jerk profile) than the industrial set-up (0.84/ 0.69 s for trapezoid/min. jerk profile). A human inspired velocity profile added with a human like arrangement showed the

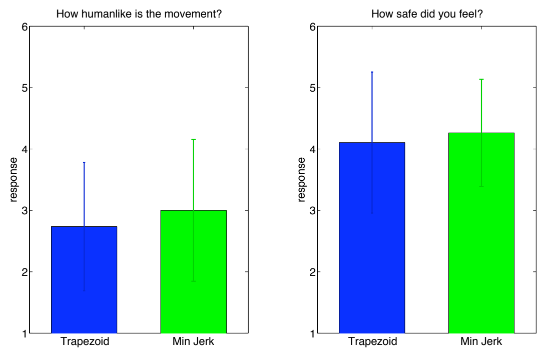

Fig. 9. Interview of the subjects after the experiments: the subjects had to answer (from 1 to 5) how human-like they thought the robot movement was and how safe they felt during the experiment.

best performance in a human-robot cooperative workflow. Generalizing the minimum jerk profile in three cartesian coordinates does not fit human trajectories, there are even problems to describe planar human interaction trajectories [7]. Thus, matching also the trajectories, e.g. by implementing a minimum variance model [12] may lead to even better acceptance.

The over all time for handing over items was despite to enormous technical disadvantages of the robot system compared to humans, such as a gripper instead of a human hand, surprisingly efficient for both profiles.

In the present work with the *JAHIR* robot system, additionally the body position of the subjects was tracked. The position of the subjects during the experiments did not vary much, as well as the mean position for all subjects itself. This indicates that the subjective feeling of safety is very high even with high maximal velocities of the gripper (up to 1.74 m/s for the trapezoid profile and 1.67 m/s for the minimum jerk profile). A questionnaire after the experiment also proofed this result. This is in contrast to other reports, where humans had to choose a comfortable maximum speed by themself for a planar handing over machine. Here a maximum velocity of 0.225 m/s was reported to be the most comfortable [13]. The subjects did not make differences between robot movements and human movements in terms of the maximal velocities which lied in the human-human experiment at a maximum of 1.3 m/s.

Due to the arbitrary position for the subject in front of the table and the small pauses during the handover it would have been possible to adapt the position to the most comfortable handing over position, but no adaption was found. This leads to the assumption that the fix implemented handing over point was in a region of comfort and therefore no adaptation was needed. The average body distance to the gripper was about 0.39 m, in human-human experiments the average body distance for the taking subject to the handover position has been measured with 0.55 m. Therefore, we assume a relatively wide comfortable area of the handing over position for the taking subjects, without the need for correcting the body position.

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