2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

The Influence of Human-Robot Interaction Order During Fast Lifting Tasks for Different Levels of Weight Compensation

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***Abstract*- When human operators employ robotic lifting aids, haptic feedback about the lifted object is important. In an experimental study we manipulated two factors that influence haptic feedback to the operator: the percentage of compensated weight, and the way the lifted object is held: robocentric (the human hand lifting the robot that holds the object) or anthropocentric (the robot lifting the human who holds the object). We hypothesize that directly holding the object (anthropocentric approach) will improve the realized trajectories when rapidly lifting partly compensated weights. Subjects (n=10) performed a fast semi-repetitive lifting task, lifting a 4kg object to a designated target in either an anthropocentric or robocentric lifting scenario, at different levels (50% - 75% - 95%) of weight compensation. The anthropocentric approach yielded significantly smaller mean over- or under- shoot compared to robocentric lifting, especially for the first trials. The difference increased for higher levels of compensation. We conclude that for fast lifting, the anthropocentric approach better helps subjects to estimate the required forces to move the weight to the target, especially for unexpected movements at high levels of compensation.**

I. INTRODUCTION

Physical human-robot interaction (pHRI) creates a scenario where the robot and human jointly perform a task, for example to train in virtual environments[1]–[3] or to perform super-human feats of strength and endurance[4], [5]. The force provided by the robot inherently alters the force interaction with the environment as felt by the human[6]–[9]. A traditional approach for these systems is to attempt to provide a clear, transparent, and uniform scaling between the user and the environment they are interacting with[10]. In the case of exoskeletons for strength augmentation, or in the case of scaled interaction in telemanipulation[11], carefully designed control systems are used to alter the apparent size or mass of the object the user is interacting with, within the abilities of the robotic system. In other words, this approach seeks to convincingly emulate the behaviour of an interaction with a real object, albeit one of a differing size or mass. It requires the system to be able to accurately translate the intentions of the operator to the actions of the robotic system. As the complexity of the task increases, and the required control strategies become opaque to the designer, it may place a higher cognitive burden on the operator, as the operator has to increasingly understand not only the task, but also how the robot will react to a given input.

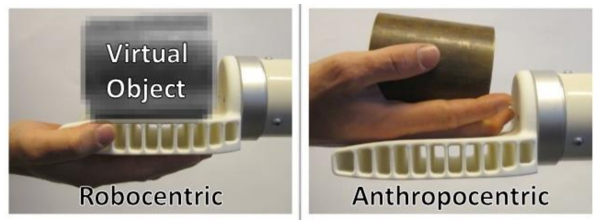

Figure 1. Two experimental conditions: robocentric scenario (left) and anthropocentric scenario. In both cases, the robot is programmed to act as a constant bias force. In anthropocentric interaction, this bias force is applied to the subject's hand, which directly holds the object. In robocentric interaction, the robot holds the object (here modeled as a virtual mass), with the bias force applied to this (virtual) object, and only the residual weight applied to the subject.

It is well-known that humans are able to quickly adapt and learn how to interact with novel dynamics[12]–[14], so the issues described above may be most relevant for unexpected movements. Humans learn to improve the internal model required for smooth goal-directed movements[15], [16] by using the haptic and visual feedback they receive during movements[17] (as well as after the movement occurred, to optimize subsequent movements).When realistic feedback is altered, it may deteriorate initial movements, requiring adaptation or learning, For example, humans significantly underestimate the mass of an object when interacting with it in a weightless environment[13], [18], i.e. when haptic feedback about the weight does not correspond to the inertia anymore. For lifting aids, such a distortion in haptic feedback may also occur when the lifted object rests on the robot, and the human holds this robot (robocentric approach, see left panel of **Fig. 1**), a popular interacting scheme in many experimental lifting aids and exoskeletons[5], [19]. The human operator will not feel the weight of the object, since this is (partly) compensated by the robot. An alternative approach to allow interaction between the

This research is part of the H-Haptics programme, supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs.

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lifted object and the robot, is the anthropocentric approach (right panel of **Fig. 1**). Here, the operator directly feels the weight of the object on his/her hand, as well as the support by the robot. This may be more intuitive for some situations. For example, it might be especially beneficial for fast, untrained movements.

In a first experimental study we aim to investigate differences between these two approaches for fast goal-directed lifting, at different levels of compensation. We hypothesize that subjects in an anthropocentric interaction will have reduced over- or under- shoot during fast goal directed reaching tasks, compared to subjects in a robocentric interaction scheme.

II. MATERIALS AND METHODS

Subjects:

A total of ten subjects, aged 20-40 years, nine males and one female were recruited from the Technical University Delft population to participate in this study. This study was approved by the Technical University Delft Ethics Committee, and informed consent was obtained for all subjects

Experimental setup:

A HapticMASTER system[20] from MOOG FCS was used to measure the force, position, velocity, and accelerations during this experiment. The haptic environment was fully constructed within the standard HapticMASTER API. The HapticMASTER is an admittance controlled robotic device, and was programmed to act as a constant bias force, scaled to compensation level, either acting on the real object in anthropocentric condition, or on the virtual object in the robocentric condition. An illustration of the anthropocentric and robocentric interaction scenarios is shown in **Fig. 1.** A custom end effector that can act as a support for the hand in anthropocentric interaction, or as the interaction surface in robocentric interaction is also shown in **Fig. 1.** All data was logged via the internal data logging function of the HapticMASTER, and was recorded at 2048 Hz. Data processing and visualization were accomplished with Matlab r2013b, The Mathworks.

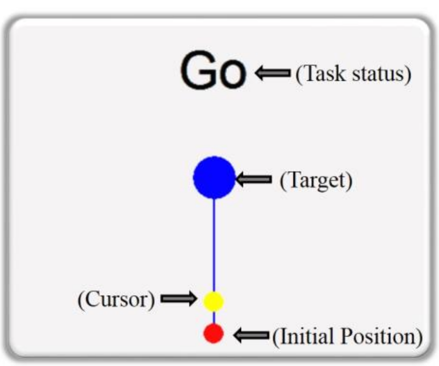

Figure 2. Visual display to subject during the movement portion of the task. The initial position and target distance are chosen from a pre-defined set of combinations. The target size is varied in proportion to the distance from the initial position to the target, such that the ratio remains constant. Object labels have been superimposed for clarity of explanation.

An object, either an eight cm diameter brass cylinder weighing four kg in the anthropocentric condition or a simulated four kg object in the robocentric condition was used for all subjects. During anthropocentric interaction subjects are instructed to allow the cylinder to rest in their hand, and allowed to stabilize the object with their thumbs, while resting the dorsal side of the hand in a concave (d=8 cm) divot on the upper surface of the end effector. During robocentric interaction, subjects hold the end effector from below. There is a convex locating feature (d=8 cm) which projects from the bottom of the interface to allow for consistent hand placement. Subjects are allowed to stabilize the end effector with their thumb.

Subjects are presented with a projected visual display which shows a cursor object, a starting point, and a target. This projection is calibrated to the physical HapticMASTER such that the target cursor appears to project directly from the endpoint manipulator of the HapticMASTER, and moves at a 1:1 scale with the end effector to eliminate perception errors due to visual scaling. This visual display can be seen in **Fig. 2.**

Protocol:

Ten subjects were randomly assigned to an order of interaction scenario, giving five subjects per scenario.

Each subject experienced one order of interaction (robocentric vs anthropocentric) and experienced five different levels of gravity compensation. The levels of compensation and order of presentation were the same for all subjects. The order and level of compensation are presented in **table 1**. The initial ordering of level of compensation was chosen randomly.

Subjects are instructed that their task is to move the cursor from a starting position which can vary in vertical position, to a target which is displayed on a projection screen. The starting height and the travel distance are varied between three different values, giving a total of nine unique trajectories. Starting heights vary from -5 cm, 0, +5 cm. Trajectory lengths vary from 10.0 cm, 13.5cm and 17.0 cm. Each combination of which was encountered three times per

Block I (27 trials)	Block II (27 trials)	Block III (27 trials)	Block IV (27 trials)	Block V (27 trials)
25%	10%	95%	75%	50%

Table 1. Level of weight compensation, as presented to each subject. Blocks are presented sequentially, I-V, with a short period of rest between each. Each subject performs a total of 135 trials.

weight compensation level, giving a total of 27 trials per compensation level. The size of the target was varied in proportion to the length of the travel distance, such as to produce a constant ratio between the two. This constant ratio was used to satisfy the Shannon formulation of Fitts's law[21], such that the mean time to complete the task should always be the same. This approach allows for more ready comparison between trajectories of different length, as time to complete remains consistent. The presentation order of each start position and trajectory combination were chosen randomly. This random presentation order was used for all trial blocks, for all subjects.

Subjects are verbally told the mass of the object that they are interacting with – they are additionally presented with a brass cylinder with an equivalent mass to prevent visual estimation errors. They are allowed to hold the brass cylinder before beginning. This is done for both interaction conditions. The subjects are informed that the object will be subjected to a weight compensation field which reduces the weight of the object, but are not informed as to the magnitude of the weight compensation force before they encounter it for the first time. Subjects are allowed to stop the experiment at any time, and are asked between blocks if they wish to take a short break.

Subjects are instructed that their goal is to 'Move the cursor from the starting position to the target as quickly and carefully as possible'. After subjects 1-4 performed the experiment, it was noticed that satisficing behavior was occurring with some subjects, where they would adopt a slower initial trajectory that would allow them to use visual feedback in the task, leading to a drop in task-completion time. This behavior was adopted, even though faster trial times could be achieved with an accurate feed forward control. A 'last trial' timer display was added for subjects 5-10 to encourage them to focus on completing their task quickly, before the visual feedback loop could exert itself. An illustration of what the subject sees is presented in **Fig. 2.**

Trials were initiated automatically, with an on-screen countdown of 'ready' 'set' 'go' being presented. Subjects were instructed to remain within the start marker until the 'go' instruction was displayed. Each trial was counted successful once the cursor was brought within the target circle for a period of 500ms. Subjects were visually cued via changing the color of the target cursor when they were inside of the target area. Total time to complete the experiment is approximately 60 minutes per subject.

Independent two-sample Kolmogorov-Smirnov tests were performed between each of the interaction orders for each compensation level.

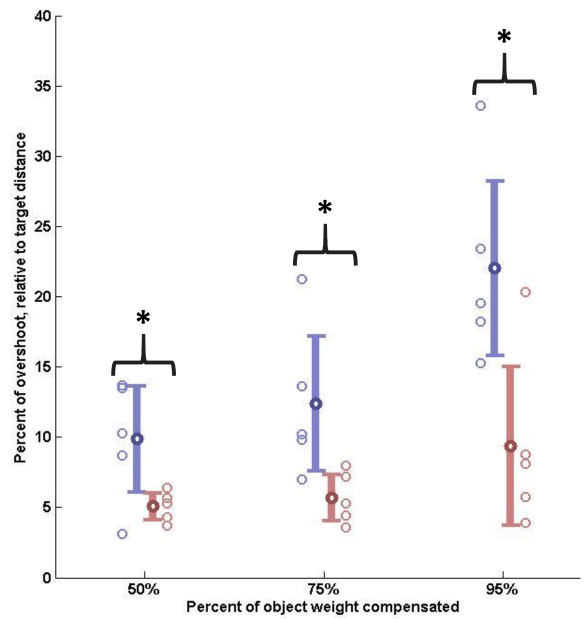

Figure 4. Percentage of overshoot for robocentric (blue) and anthropocentric lifting (red), averaged over all trials. Means of peak overshoot for each subject shown with 'o'. Total population mean for each condition, with 95% confidence interval are show adjacent to each set of means. Each level of compensation shows significance between interaction orders, via independent two-sample Kolmogorov-Smirnov tests, with $c(\propto)$ better than 1.36 (*)

III. RESULTS

During the course of the experiment, it was noted that the HapticMASTER had difficulty maintaining consistent contact with the operator in the case of the very low levels of compensation during the anthropocentric trials. This produced erratic and eccentric movement strategies during the low levels of compensation – 10% and 25% - during the anthropocentric lifting scenario. Typically, the human operator would slightly out-accelerate the haptic master, which would then collide with the operator when they began to slow down. This produced a shock, and it was noted that subjects either slowed down their motions, or undershot the target, with the expectation that the HapticMASTER would bump them into the target. The trials completed with low levels of weight compensation are therefore excluded from these results. The decision to discard the data from the trials performed under 10% and 25% compensation is based purely on the HapticMASTER's inability to provide the necessary levels of compensation for the anthropocentric lifting scenario, leading to erratic interaction with the setup.

The vertical endpoint position trajectories from representative subjects, from each of the interaction scenarios are shown in **Fig. 3**. The large variation in trials can be seen quite clearly in the resulting plots. **Fig. 3** shows the resulting mean, standard deviations, and first trial plots for the same representative subjects. In this figure, it is quite clear that both the initial trial and the subsequent mean trials experience a significantly greater initial overshoot in the robocentric interaction scenario.

The mean overshoot, for all subjects, for all scenarios is shown in **Fig. 4.** Additionally, the 95% confidence intervals are shown. Via independent K-S testing, the anthropocentric lifting scenario was found to have a significantly ($c(\propto)$ better than 1.36) lower overshoot for all the tested compensation levels. The mean settling time for all subjects was also investigated, and no statistical significance in settling time was found between the robocentric and anthropocentric lifting scenarios, for any level of compensation.

IV. DISCUSSION

We found a strong difference between the robocentric and anthropocentric scenario, in terms of realized trajectories during fast goal-directed movements. In general the robocentric trials showed an overshoot that the anthropocentric trials did not show. This effect was largest for the first trials, and was especially strong for the highest compensation level (95%). However, the fact that the overshoot difference was also found for all three compensation levels, shows that even repeated training did not eliminate the performance difference between the two tested conditions. The anthropocentric approach allowed subjects to feel the weight of the object on the hand, and see it as well. Apparently this helped subjects to more quickly obtain a correct estimate of the required force profile needed to accelerate the supported object to its endpoint position. These results suggest that subjects were able to integrate the weight estimate (from the object resting on their hand, and the robot supporting it) into their existing internal model,

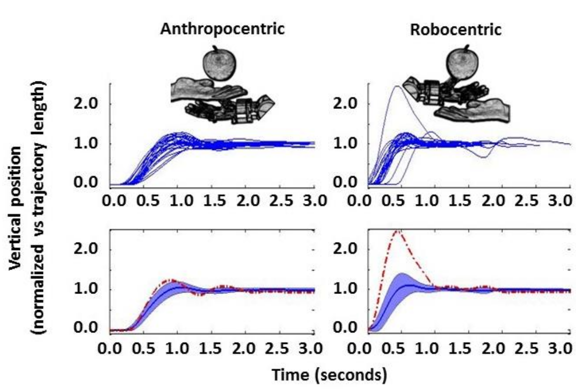

Figure 3. Trajectory plots from two representative subjects. Compensation level is 95%. Right shows robocentric lifting, left anthropocentric lifting. Traces show vertical position, normalized by the vertical trajectory length. Bottom traces display the mean trajectory (dark blue line), first trial trajectory (dashed red line) and standard deviation (light blue area).

and generate significantly more optimal trajectories. Note that the difference between the two approaches might be exaggerated by the lack of visual information in the robocentric case (when only a virtual mass could be used). We attempted to address this lack of visual feedback by providing a real object for the subjects to see and feel before the trial began, by allowing this object to remain in view, and by projecting the visual task on a screen in both cases.

We employed a fast movement task to emphasize feed-forward control and limit the contributions of feedback during the movement. Subjects were able to improve their performance over time: therefore the difference between robocentric and anthropocentric was particularly strong for the first trial, and then steadily diminished. Indeed, the steady state performance is reached after six trials and is very similar between the two approaches. This is particularly interesting when comparing the work of Happee[14] to that of McIntyre et al[13]. Happee found that humans rapidly adapt their goal-directed reaching behavior to sudden changes in the inertia they are moving in a 1DOF horizontal movement task, while McIntyre finds that mass estimation remains while lifting inaccurate for some time during sustained simulated microgravity. These two findings appear to be inconsistent. Happee[14] found a long-latency EMG response after the change in virtual mass, which he hypothesized to represent the effect of an update in the internal model that concerning the new object mass. The quickly updating internal model that Happee hypothesizes requires a well-trained model which can be updated rapidly, which may not have been present in the simulated microgravity experiments of McIntyre. Further experimentation would be necessary to investigate this further, as well as how this would relate to lifting aids.

Comfort, utility and satisfaction were not explicitly studied in this experiment, but several subjects in the anthropocentric interaction portion of the experiment reported discomfort, from their hand being placed between the hard end effector and the solid four kg mass. No subjects reported discomfort in the robocentric case. This raises the issue that with anthropocentric interaction, operators are subjected to higher interaction forces, without the benefit of any contact force reduction, with the further compression of the operator between the supportive robot and the load. This implies that for the anthropocentric case extra care is necessary in designing a comfortable physical interface between the lifting robot and the hand; and that for very large force the approach may be undesirable, or even unachievable. This effect may be less relevant when the object is not rigid (e.g. lifting a patient).

Limitations

There are several inherent limitations to this work. The device used in the experimental system, the MOOG HapticMASTER, is limited, in that it is only able to safely produce forces up to 100N. This limitation significantly reduces the upper limit on the simulated and tested object mass, which in turn limits our ability to investigate large objects, where the influence of differing mass and weight perceptions might be more easily determined, and where robotic assistive systems are typically designed to be used. Additionally, the equipment is only able to *simulate* an object in the robocentric lifting scenario, rather than interacting directly with a real object. This may make the experiment such that we may be detecting the difference between the simulation and reality, rather than the differences between interaction orders. This confounding issue is planned to be addressed in future work, by employing a physical lifting aid.

We argue that while these equipment limitations limit the value of these results, the equipment is in fact a realistic representation of what may be achieved with current robotic systems. Therefore, similar limitations to that of the HapticMASTER will be present, in greater or lesser degree in any hardware system which is realized.

There are additional experimental aspects which could be changed to produce a more powerful experiment. Use of a repeated measures study would allow for a more robust statistical analysis. K-S tests were used to examine significance between the loading scenarios for each of the compensation levels, due to the fact that the mean distribution was non-normal.

V. CONCLUSION

For the experimental conditions studied, an anthropocentric order of interaction yielded benefits over a robocentric order, during fast goal-directed movements while lifting a weight that was partly supported by an assistive robot. The difference between the two approaches was present where the weight compensation exceeds 50%, and was more pronounced for higher levels of compensation. The difference was mainly in reduced overshoot, an effect that was strongest during the first trial, and which diminished with learning during subsequent trials. We hypothesize that the benefit of the anthropocentric approach for these tasks is due to the subject's benefiting from directly sensing the static and dynamic forces of their hand between the object and the lifting robot.

Anthropocentric interaction is an easily realized implementation to improve the weight estimation for the purposes of the human in determining feed-forward muscle activation. Other, equally useful methods to introduce this information to the operator, such as by enhanced visual scaling, artificial damping, enhanced inertias, or other methods. The apparent intuitive usefulness of anthropocentric interaction should not be discounted, however.

The significantly better performance metrics in the anthropocentric interaction scheme, even at the highest compensation levels or during the first encounter with a particular compensation level implies that the operators have a more complete internal model of the combined system. We encourage designers of pHRI systems to investigate for which cases an anthropocentric interaction scheme might produce a reduced learning curve and more performance robustness during unexpected or untrained movements.

Acknowledgements

The authors would like to recognize A. Oort for his machining assistance, A. Schouten for the use of his laboratory space and equipment, and C.M. Kappers for providing the motivations for this research. This research was performed in collaboration with Hankamp Gears, Siza, and InteSpring.

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