16th IEEE International Conference on Robot & Human Interactive Communication
August 26 ~ 29, 2007 / Jeju, Korea

Embodiment and Human-Robot Interaction: A Task-Based Perspective

Joshua Wainer David J. Feil-Seifer Dylan A. Shell Maja J. Matarić
Interaction Laboratory
Center for Robotics and Embedded Systems
Department of Computer Science, University of Southern California
Los Angeles, CA USA 90089-0781
jwainer | dfseifer | shell | mataric @usc.edu

***Abstract*— In this work, we further test the hypothesis that *physical embodiment* has a measurable effect on performance and impression of social interactions. Support for this hypothesis would suggest fundamental differences between virtual agents and robots from a social standpoint and would have significant implications for human-robot interaction.**

We have refined our task-based metrics to give a measurement, not only of the participant's immediate impressions of a coach for a task, but also of the participant's performance in a given task. We measure task performance and participants' impression of a robot's social abilities in a structured task based on the Towers of Hanoi puzzle. Our experiment compares aspects of embodiment by evaluating: (1) the difference between a physical robot and a simulated one; and (2) the effect of physical presence through a co-located robot versus a remote, tele-present robot.

With a participant pool (n=21) of roboticists and non-roboticists, we were able to show that participants felt that an embodied robot was more appealing and perceptive of the world than non-embodied robots. A larger pool of participants (n=32) also demonstrated that the embodied robot was seen as most helpful, watchful, and enjoyable when compared to a remote tele-present robot and a simulated robot.

I. Introduction

Our research agenda is focused on social interaction that will, in the long run, have a positive impact on rehabilitation and recovery. The use of social interaction as a means of achieving task performance is a point of departure from other work on systems in which social behaviors are considered ends in themselves (e.g., entertainment robot [3]).

Considering the possible role robots might play in a rehabilitation setting allows one to leverage existing knowledge in order to structure the system design. For example, the roboticist must prioritize those aspects of the system that address needs of the particular user population and existing models and protocols for particular types of rehabilitation. Our approach has been to create tasks (and suitable environments) which the human user and robot can use as a shared experience for social interactions, but which simultaneously meet the user's recovery needs.

If social robots are to have their place within a range of rehabilitative and assistive technologies, we require a broader understanding of those aspects which make them unique. Perhaps most obvious is physical embodiment. By studying its impact on social interactions we hope to find measurable distinctions (and trade-offs) between robots and other ubiquitous computing systems under development (e.g., virtual companion agents, smart-room, etc.). We describe findings in this paper relating to a participant's impressions of a coach and a user's task performance relative to varying degrees of embodiment of that coach.

This paper describes new experience with a problem domain and methodology outlined in [17]. We compare, for the purposes of this study, a co-located robot, a remote-located robot (to model a perfectly realistic simulation), and a simulated robot. Lessons learned from those pilot trials have resulted in several improvements (see Section IV-C for complete details). The most significant revisions are steps to elevate the primacy of task performance. The results themselves are improved due to: (1) more carefully constructed, direct and local surveys; and (2) a larger pool of participants. We found that participants regarded an embodied robot coach as more watchful, appealing, and helpful than non-embodied equivalents, though we could not make any conclusions about task-based benefits of embodiment or realism.

II. Related Work

In Wainer et al. [17] we highlighted some of the current discussion within the robotics community regarding what exactly constitutes embodiment within a social context, and the question of how this differs from situatedness in such cases. We position the current work as follows. Chrisley and Ziemke [5] define an embodiment range considered by several researchers. These are, in order from least to most constraining:

a. *Physical realization* means that the system is realized in some physical substrate.
b. *Physical embodiment* requires a coherent physical realization to persist over time.
c. *Organismoid embodiment* implies that the physical realization has some (conceivably superficial) characteristics of the bodies of natural organisms.
d. *Organismal embodiment* means that the body be alive, i.e., metabolize, reproduce, etc.

This work can be understood as evaluating a functional ordering of embodiment conditions between physical realization and organismoid embodiment. The purpose of this paper is to

978-1-4244-1635-6/07/$25.00

Fig. 1. The ActivMedia Pioneer 2 DX robot used in the experiments, as seen in the remote robot setting. The motions of the PTZ camera provide feedback that supplements the audio.

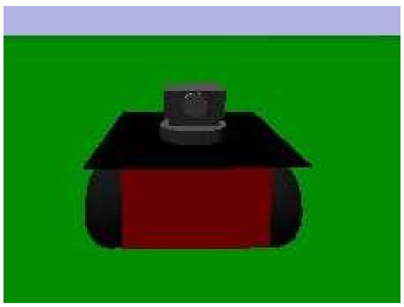


Fig. 2. The standard Gazebo simulation of the above robot.

place three conditions within this range. The physical robot in our experiments has only limited means of expression: prerecorded speech and a PTZ-camera to nod its "head". We characterize our robot as somewhere between physical and organismoid embodiment because, although not as complex as articulate humanoid robots cited (e.g., [2]), it has some anthropomorphic elements (e.g., nodding, camera, and gaze).

Several robotics researchers argue that embodiment requires more than just possessing a physical instantiation. For example, Dautenhahn and Christaller [6] suggest that development of a body image (i.e., an agent's conception of its own body) is necessary for embodied action. Another view is that of Duffy and Joue [7], who describe the requirement of adaptation in moving beyond the status quo, which they term "ON-World," toward systems that are "IN-World," participating within an environment and being actively shaped by it. The former perspective interprets the role of embodiment (i.e., the constraints and complexity that are involved in physical bodily control) as necessary for low-level intelligence. The latter is a viewpoint in which embodiment is considered essential for understanding all levels of cognition, from low-level sensory-motor behavior up to and including abstract thought.

Our contribution is to consider and evaluate embodiment in a social setting: this research asks questions of human participants on the *impression* of other variously embodied agents. The model underlying this work is that differences in impression of embodied agents account for attribution of social properties to such agents. Examples of such properties might include affinity, compassion, etc. The broader goal, as described with regards to the applications in rehabilitation domains, is to exploit such properties, together with social conventions, to achieve positive ends.

In contrast to the preceding philosophical discussions, we believe the distinction should be made on the basis of *functional* differences. There is little empirical work to date that compares robots to other social agents. One example is the work by Bartneck et al. [1] which concluded that robotic embodiment has no more effect on people's emotions than a virtual agent. Our findings suggest that there are several aspects that do differ between a robot and virtual agent. The three conditions explored in this paper (a physical robot body, a physical robot located elsewhere through a video link, and a simulation of a robot) are an attempt to control the many variables in order to isolate the effects of embodiment from realism.

III. Model and Hypotheses

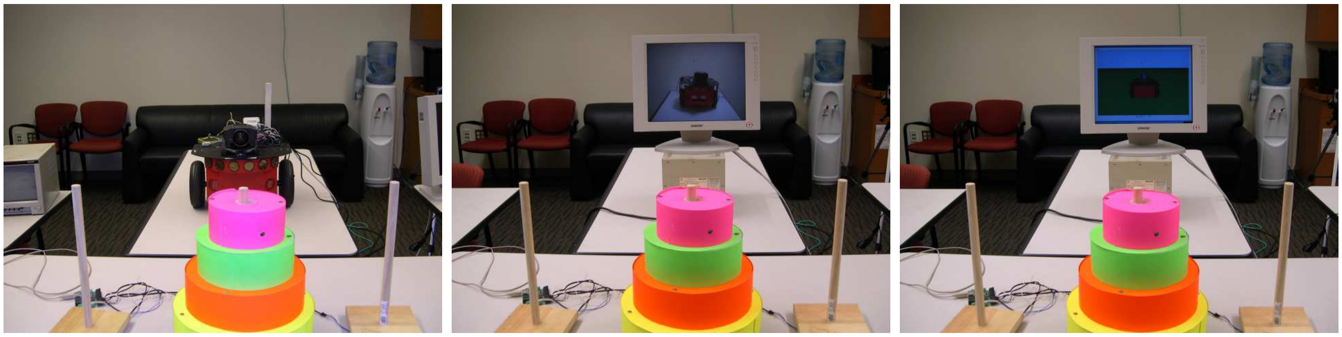
The goal of this experiment was to determine if embodiment and realism have an effect on how a user perceives a robot or computer agent. In this experiment, we used a co-located physical robot as an embodied robot. We used a remote-located physical robot projected on a screen as a perfectly realistic simulation of a robot. Finally, we used a computer-generated simulation as a non-realistic simulation of a robot.

By comparing a physical robot, a remote presence robot, and a non-realistic simulation, we can tease apart the effects of embodiment from the effects of realism. If realism alone explains an effect, than the co-located and remote-located robots will have roughly the same effect, and a greater one than the simulation. If embodiment alone is responsible for an effect, then the co-located robot will have a greater effect than the remote-located robot and the simulation. If embodiment and realism have an effect then the co-located robot will have a greater effect than the remote-located robot, which will have a greater effect than the simulation.

Fogg and Nass [10] suggest that the "rule of reciprocity" that applies to human-human interaction also applies to human-robot interaction. Participants who perceived a conversational agent as helpful also regarded its suggestions as helpful, while those who perceived an agent as unhelpful regarded its suggestions as unhelpful [16]. This perception also led to changes in behavior and reciprocation of behavior when American users dealt with that agent. This data supports the notion that a coach perceived as more helpful would give advice that a user is more likely to follow.

This experiment was designed to determine the effects that embodiment and realism had on a user's perception of a robot or computer agent. Since the attributes of helpfulness and watchfulness may lead to better and more productive interaction between human and robot, those are the attributes that we tested.

Robots offer uniquely controllable experimental conditions which allow social characteristics that have, until now, not



(a) The participant interacts directly with a physical robot.

(b) The participant interacts with a physical robot over a real-time video-conferencing link.

(c) The participant interacts with a simulated robot.

Fig. 3. The three experimental conditions.

been accessible for controlled study. Social robots also raise new research questions. To tease apart the difference between realism and physical situatedness, we formulated the following hypotheses.

We hypothesized that embodiment and realism both have an impact on a user's perception of an agent's watchfulness and helpfulness. We also believed that a co-located physical robot would be seen as more watchful and helpful than a remote-located robot or a simulated robot and that a remote-located robot would be seen as more watchful and helpful than a simulated robot. In addition, we hypothesized that the perception of added helpfulness and watchfulness would translate into a difference in task performance.

The term "co-location" refers to the robot being physically located in the same place as a human interacting with it. By "remote physical robot" we mean to a physical robot in a different physical location but which has sensing relayed to it (over a wireless network) and its actions relayed back to the human through a video conferencing system. The simulated robot replaces the physical robot altogether, rendering the robot to a computer monitor and playing the audio feedback directly for the human.

IV. Method

Drawing on our prior work [9], which showed that even simple robots can be engaging in the post-stroke context, we designed a very simple robot that can act autonomously for the task. We designed the task to have some amount of difficulty as well as requiring interaction with the coach in order to be accomplished. A non-trivial task is necessary in order to provoke a measurable difference in outcomes when assessing performance on the task. This particular task is also relevant to our broader assistive robotics agenda since the physical effort and precision required to play the Towers of Hanoi game are related to a post-stroke rehabilitation setting.

A. Towers of Hanoi Problem Domain

We considered tasks in which the robot could perceive enough of the world to provide feedback autonomously, and we can make the interaction somewhat enjoyable in order to sustain the user's interest and maintain motivation. We designed a task around the classical Towers of Hanoi puzzle [18, pp. 92], in which different-sized rings are individually moved from one peg to another (see Figure 4). In this case, the robot (or simulation thereof) acted as a coach, giving a human user advice and correcting wrong moves. The coach was able to observe the state of the game by tracking the discs on the pegs, and played pre-recorded audio in order to communicate. The coach (details in Section IV-C) provided the participant with a particular stacking goal, such as, "Move the discs to the middle peg." The robot could perceive the puzzle state and give feedback based on an estimate of task progress.

A four-ringed puzzle was sufficiently difficult that the participant would have to interact with the coach frequently in order to verify correctness of moves. The system was sufficiently robust to detect user errors and explain how to put the puzzle back into the last legal state. In addition, this task mirrored goals from the post-stroke domain where the patient would be asked to execute precision movements repeatedly.

B. Experimental Design

The experiment participant and the coach faced each other on either side of the game setup. The coach and the pegs were placed on a table that was 1.2m high. It has been shown that small variations, even up to an isomorphism, can affect the performance of a participant at the puzzle [18], so the same game setup was used in all conditions in order to isolate variations that might have affected playing of the game. Figure 3 shows the differences between the three separate conditions:

(a) The co-located physical robot condition, as a typical model of human-robot interaction. The robot is placed on the table in front of the participant.

(b) The remote presence robot case, in which the audio-video tele-conferencing system provides real-time playback of the robot, despite being situated in a different room.

(c) The simulated robot case. The same screen and audio setup as (b) is used, but without a physical robot; instead a simulated robot world is shown.

The presentation order for the conditions was randomly assigned for each participant. Feedback was provided to the participant through movement on the part of the coach. In all three cases, the coach was a mobile robot with a camera on top. The coach "paced" by moving back and forth, and the camera, which was on a pan-tilt-zoom (PTZ) base, "nodded" and "shook" its figurative head. Ono [13] has shown that head gestures can be simulated with such a configuration. Audio feedback was given through a pre-recorded female voice. In condition (a), the audio was played by speakers on the robot, while in conditions (b) and (c), the audio was played through speakers next to the monitor.

The participant was instructed to follow the coach's instructions for the Tower of Hanoi task and to press a button to end the session when done. We recorded a time-line of all the interaction done on the part of the robot, and all moves made by the participant, and whether those moves were optimal. We also recorded the total amount of time spend on task.

After each trial, the participant was given a questionnaire asking for a ranking of the coach's actions and the perceived competence of the coach. Identical questionnaires were presented for each of the three conditions.

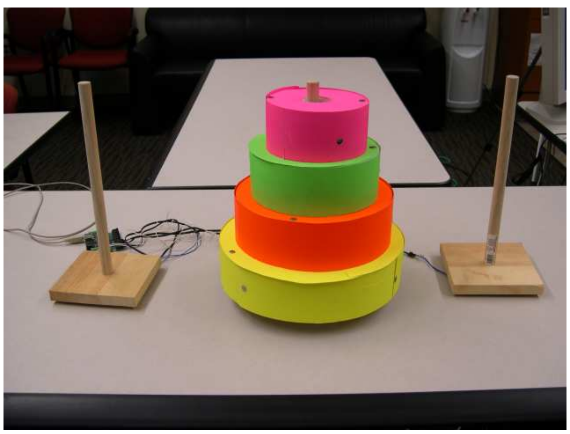


Fig. 4. The classic Towers of Hanoi puzzle with four rings and three pegs as used in the experiments. In our set-up, each of the three rings has a different color and mass. Weight sensors under each peg and a single camera allow the robot to estimate the state of the puzzle.

C. Implementation details

We used an ActivMedia Pioneer 2DX mobile robot with a Sony PTZ camera and speakers for audio output (see Figure 1). Head gestures were simulated using the PTZ camera for the physical robot conditions. Color tracking was done using the ACTS blob-finder [14].

Player [11] was the abstraction layer for programming the equipment used for all three coaches. Player allows the same control software to be used in all three conditions. Since the robot was programmed to be fully autonomous, it exhibited similar behaviors across all three conditions.

The simulated robot was rendered using Gazebo [12] (see Figure 2). The simulator creates a 3-D rendering of its worlds, with simulated dynamics. The simulator contains an approximate physical model of the Pioneer and the PTZ camera used in the physically situated condition of the experiment.

The pegs used for the Tower of Hanoi task were equipped with weight sensors. Though not sensitive enough to determine exactly which weights were on the pegs, the sensors were able to detect when a ring had been removed from a peg or placed on a peg. The rings used for the Tower of Hanoi task were covered in brightly-colored paper. When the weight senors have detected a large enough change on the pegs, the ACTS color blob tracker is used to determine which rings were placed on which pegs. The result was an accurate observation of the state by the camera-blobfinder combination. Player software allowed virtual sensing to be done transparently for experimental conditions (b) and (c) through the use of a driver called *passthrough* that relays sensor readings across the network.

This design also reflects many other improvements from a previous work [17], including:

- *Adding a fourth ring.* The Towers of Hanoi problem is scalable in the sense that adding rings increases both the complexity and length of the game.
- *The coach exhibiting joint-attentive capabilities by nodding at each ring after it was moved.* This helped the users understand when additional moves could be made and added a turn-taking element to the interactions.
- *The coach giving the user specific goals to perform.* This added structure to the task, as it was found that participants did not understand their role in an open-ended, free-form interaction
- *Tracking both the number and the optimality of moves made by the participant.* By making more detailed measurements and tracking richer state-variables, we were able to assess task performance better.
- *Updating surveys.* We designed questions with continuous responses and structured the surveys around questions about the task domain (4 questions) and questions about the participants' perceptions of the moderator (11 questions). These latter questions were designed to assess how strongly the moderator displayed the previously-mentioned desirable traits.
- *Wider range of participants.* Both a larger pool of survey results and a wider range of subject experience.

These improvements were made in order to encourage more frequent and longer-term interactions between the participant and the robot coach. We also intended for these improvements to encourage a higher-resolution task-based measure in order to compare the three experimental conditions.

V. RESULTS

We recruited a series of participants ($n = 21$) in person and over e-mail to participate in this experiment. The gender spread was 17 male - 4 female. The average age was 24.7 years old. Nearly all ($n = 18$) participants were experienced with computers and most ($n = 13$) were experienced with robots.

We asked the participants to rate (on a scale from 1 to 100) the coach as it affected them on a variety of factors: appealing, frustrating, perception of the game, understanding

TABLE I

THE MEAN VALUE OF VARIABLES FOR PHYSICALLY SITUATED, REMOTE PRESENCE, AND SIMULATION (N=21) (***: $p < .01$, **: $p < .05$, * : $p < .1$, NO MARK: NOT SIGNIFICANT)

The coach...	Physically Situated	Remote Presence	Simulation	F(value,df) t (paired)
was appealing to me	65	49.7	45.23	F[5.05,1]**
Physically Situated vs. Remote Presence				t(20)=2.83**
Physically Situated vs. Simulation				t(20)=2.96***
Remote Presence vs. Simulation				t(20)=.81
perceived the game-related items	75.5	59.9	70.2	F[.51,1]
Physically Situated vs. Remote Presence				t(20)=2.98***
Physically Situated vs. Simulation				t(20)=1.00
Remote Presence vs. Simulation				t(20)=-1.43

TABLE II

THE MEAN RANK ORDERING OF ATTRIBUTES FOR PHYSICALLY SITUATED, REMOTE PRESENCE, AND SIMULATION (N=32) (***: $p < .01$, **: $p < .05$, * : $p < .1$, NO MARK: NOT SIGNIFICANT)

Which robot...	Physically Situated	Remote Presence	Simulation	F(value,df) t (paired)
watched the most closely	1.31	2.16	2.28	F[.18,2]
Physically Situated vs. Remote Presence				t(31)=-5.19***
Physically Situated vs. Simulation				t(31)=-3.97**
Realistic Simulation vs. Simulation				t(31)=-.64
helped the most	1.62	2.03	2.28	F[1.12,2]
Physically Situated vs. Remote Presence				t(31)=-2.27**
Physically Situated vs. Simulation				t(31)=-2.78***
Remote Presence vs. Simulation				t(31)=-1.05
I enjoyed the most	1.25	2.21	2.53	F[.01,2]
Physically Situated vs. Remote Presence				t(31)=-7.41***
Physically Situated vs. Simulation				t(31)=-5.80***
Remote Presence vs. Simulation				t(31)=-1.53

of the game, perception of actions, perceptible delay of the coach's actions, coach's understanding how actions affected the game, feedback, helping, teaching, and knowing what it was doing. We then compared the results, by coach type, using an analysis of variance, followed by a t-test. For a full breakdown, see Table I. We learned that participants felt that the embodied robot was more appealing and more perceptive of the game-related items than the non-embodied simulations. None of the other scales yielded significant results.

The coach recorded the participant's performance for each trial. Attributes measured include total time, optimal moves, non-optimal moves, and total moves. We compared those values using analysis of variance. None of the metrics that we used resulted in any significant variations from the mean. For each attribute, differences in value by coach type was dwarfed by differences in value by trial number, although also not significant. Normalizing by trial number had no significant effect on the data. While disappointing, the lack of significance in results can be explained (see Section VII).

We asked all participants to rank order the three coaches based on watchfulness, enjoyability, and helpfulness. We folded in the same survey from a previous study (only differing slightly in execution), for a total pool of $n = 32$, 26 male - 6 female. We performed a dependent-means two-tailed t-test on the rank-order data (see Table II). We found the participants ranked the co-located robot more watchful than the simulated and remote-located robots. We also found that participants ranked the physically situated robot more helpful than the simulated and remote presence robots. The participants ranked the physically situated robot more enjoyable than the simulated and the remote presence robots. We did not find significant results that participants perceived the remote presence robot coach as more helpful, enjoyable, or watchful, than the simulated robot coach.

VI. CONCLUSIONS

The survey data support that a participant's impression of a robot's watchfulness, helpfulness, and enjoyability is significantly affected by embodiment. We cannot conclude that a participant's impression of the robot's watchfulness, helpfulness, or enjoyability was or was not affected significantly by realism.

Additionally, these results support that a physically embodied robot should be more effective in assistive physiotherapy than one that is not. To explain this, it is important to note that helpfulness as defined through social reciprocity [4, 8] as well as the amount of supervision provided by a physiotherapist [15] play significant roles in the effectiveness of rehabilitative physiotherapy. From this, it follows that a physiotherapist who possesses these traits to a greater degree would be a more effective therapist than one that does not. Furthermore Takechi, et al. [16] showed that social reciprocity, as defined by helpfulness, has been observed between humans and software agents. Therefore, because this study also shows that an physically embodied, co-located robot is perceived as being more watchful than its less embodied counterparts, it would be reasonable to infer that there is a positive correlation between the degree of physical embodiment and the predicted effectiveness in assistive physiotherapy.

We cannot make any conclusions based on the task-based data. As was described in Section VII, there are many reasons for this that can be explained by the subject population, task, and time-scale used in the experiment.

However, we can conclude that a physically situated robot will be perceived as more present than either a remote presence or simulation of a robot, but we cannot conclude whether one would be favored over the other.

VII. Discussion and Future Work

A crucial limitation of the study of embodiment in a task-oriented setting is that one must consider interactive roles that can be performed by both a robot and a virtual agent, which immediately reduces the set of conceivable tasks. Specifically, while a robot is the natural candidate for an interactive agent in a task requiring physical contact of any sort, such contact may play a hidden role in social interactions. One would attempt to design contact-free interactions in order to remove the effects of physical contact from task-based social interactions. Although such interactions can be carried out by both robots and virtual agents, they tend to develop into detached "coach" style relationships which are slightly unnatural, socially distant, and possibly asymmetric. In short, an ideal future study would be conducted under natural social conditions, yet would still be able to separate the social effects of the interacting agent from its physical effects.

One of the main limitations of this study from a rehabilitation point of view is that the participants in this experiment had little to no investment in the outcome of the game as they did not expect to earn anything beneficial from their actions. In contrast, the users of a rehabilitation robot are expected to invest considerable time and effort into a task in order to reap highly-valued rewards. As such, it would be beneficial to test the results of this study against one conducted on a population with vested interest in the tasks' outcomes.

Another limitation of this experiment is the short-term nature of the study. Participants spent a maximum of one hour with the coaches, and it was difficult to tease apart the effect of novelty from those of embodiment and realism. Again, adding the robot into an existing long-term therapy regimen may address these concerns, as it would allow testing of the different coach types during the normal course of recovery. However, the short term nature of this study necessitated a repeated measures design.

A methods-related conclusion that we can make is that short-term, repeated-measures studies are suitable for obtaining initial participant impressions, but are not ideal for ascertaining task-oriented metrics. The breakdown of task-based metrics by trial number, while not significant, outweighed any difference by coach type. The trial-based data suggest that the "novelty" factor shown in our results would decrease over time, so a more lengthy study would probably yield cleaner results.

Our continuing work will address the outlined research directions as we continue to reach toward the goals of socially assistive robotics.

Acknowledgments

We thank Emily Mower for lending her voice to the robot, and Evan Drumwright for his help in editing the paper. We thank the Player and Gazebo developers, and particularly Brian Gerkey for his *passthrough* driver. This work was supported by the USC Institute for Creative Technologies, the USC Provost's Center for Interdisciplinary Research, and the Okawa Foundation.

References

[1] C. Bartneck, J. Reichenbach, and A. v. Breemen. In your face, robot! the influence of a character's embodiment on how users perceive its emotional expressions. In *Proceedings of the Design and Emotion 2004 Conference*, Ankara, Turkey, 2004.

[2] C. Breazeal. Infant-like social interactions between a robot and a human caretaker. *Adaptive Behavior.*, 8(1):49–74, 2000.

[3] C. Breazeal, A. Brooks, J. Gray, M. Hancher, J. McBean, D. Stiehl, and J. Strickon. Interactive robot theatre. *Communications of the ACM*, 46(7):76–85, 2003.

[4] R. Campbell, M. Evans, M. Tucker, B. Quilty, P. Dieppe, and J.L. Donovan. Why don't patients do their exercises? understanding non-compliance with physiotherapy in patients with osteoarthritis of the knee. *Journal of Epidemiology and Community Health*, 55:132–138, 2001.

[5] Ronald Chrisley and Tom Ziemke. Embodiment. In *Encyclopedia of Cognitive Science*, pages 1102–1108. Macmillan Publishers, 2002.

[6] K. Dautenhahn and T. Christaller. Remembering, rehearsal and empathy – towards a social and embodied cognitive psychology for artifacts. In *Proceedings of the Tenth Biennial AI and Cognitive Science (AISB'95) Workshop on Reaching for Mind: Foundations of Cognitive Science*, pages 257–282, Sheffield, England, Apr 1996.

[7] B. Duffy and G. Joue. Intelligent robots: The question of embodiment. In *Brain-Machine Workshop*, Ankara, Turkey, Dec 2000.

[8] D.G. Embrey, M.R. Guthrie, O.R. White, and J. Dietz. Clinical decision making by experinced and inexperinced pediatric physical therapists for children with diplegic cerebral palsy. *Physical Therapy*, 76(1):20–33, 1996.

[9] J. Eriksson, M. Matarić, and C Winstein. Hands-off assistive robotics for post-stroke arm rehabilitation. In *International Conference on Rehabilitation Robotics*, pages 21–24, Chicago, IL, USA, Jun 2005.

[10] B.J. Fogg and C. Nass. How users reciprocate to computers: An experiment that demonstrates behavior change. In *CHI Extended Abstracts*, pages 331–332, 1991.

[11] B.P. Gerkey, R.T. Vaughan, and A. Howard. The player/stage project: Tools for multi-robot distributed sensor systems. In *Proceedings of the International Conference on Advanced Robotics*, pages 317–323, Coimbra, Portugal, Jul 2003.

[12] N. Koenig and A. Howard. Design and use paradigms for gazebo, an open-source multi-robot simulator. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2149–2154, Sendai, Japan, Sept 2004.

[13] T. Ono and M. Imai. Embodied communications between humans and robots emerging from entrained gestures. In *Proceedings of the International Symposium on Computational Intelligence in Robotics and Automation*, pages 558–563, Kobe, Japan, July 2003.

[14] P. E. Rybski. *ACTS: Activmedia Color Tracking System Manual*. ActivMedia Robotics, LCC, 44 Concord Street, Peterborough, NH 03458, USA, 2002.

[15] E.M. Sluijs, G.J. Kok, and J. van der Zee. Correlates of exercise compliance in physical therapy. *Physical Therapy*, 73(11):771–782, 1993.

[16] Y. Takeuchi, Y. Katagriri, C. I. Nass, and B. J. Fogg. Social response and cultural dependency in human-computer interaction. In *Proceedings of the CHI 2000 Conference*, Amsterdam, The Netherlands, (submitted) 2000.

[17] J. Wainer, D.J. Feil-Seifer, D.A. Shell, and M.J Matarić. The role of physical embodiment in human-robot interaction. In *IEEE Proceedings of the International Workshop on Robot and Human Interactive Communication*, pages 117–122, Hatfield, United Kingdom, Sept 2006.

[18] J. Zhang and D. A. Norman. Representations in Distributed Cognitive Tasks. *Cognitive Science*, 18(1):87–122, 1994.