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# Slaves no longer: review on role assignment for human–robot joint motor action

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**Abstract**

This paper summarizes findings on the growing field of role assignment policies for human–robot motor interaction. This topic has been investigated by researchers in the psychological theory of joint action, in human intention detection, force control, human–human physical interaction, as well as roboticists interested in developing robots with capabilities for efficient motor interaction with humans. Our goal is to promote fruitful interaction between these distinct communities by: (*i*) examining the role assignment policies for human–robot joint motor action in experimental psychology and robotics studies; and (*ii*) informing researchers in human–human interaction on existing work in the robotic field. After an overview of roles assignment in current robotic assistants, this paper examines key results about shared control between a robot and a human performing interactive motor tasks. Research on motor interaction between two humans has inspired recent developments that may extend the use of robots to applications requiring continuous mechanical interaction with humans.

**Keywords**

Motor joint action, physical human–robot interaction (pHRI), human–human interaction, role assignment policies, master–slave, education

## 1. Introduction

Many common tasks, such as sawing, dancing, physical rehabilitation, fighting, mating or carrying a table together (Figure 1), rely on the *motor interaction* of two humans. Here “motor interaction” describes any interaction with the environment, a robot or a human, involving a sensorimotor exchange. We preferred this expression to the commonly used “physical interaction” and “haptic interaction”, because physics is not restricted to mechanics, and haptics focuses on (touch and force) sensing rather than motor action. While we have some knowledge of how humans adapt to passive or active environments (Franklin et al., 2008), how humans control motor interaction with peers is still largely unknown. Understanding how humans collaborate in tasks requiring motor interaction is not only an interesting and challenging new field of research, but may also be crucial in the design of robots interacting with humans (physical human–robot interaction [pHRI]).

Recent years have seen the appearance of “assistive robots”, including assistive devices for manufacturing (Akella et al., 1999; Schraft, Meyer, Parlitz, & Helms, 2005), robotic systems for teleoperation (Hokayem & Spong, 2006), assisted driving systems increasingly included in cars (Gietelink, Ploeg, De Schutter, & Verhaegen, 2006), robotic wheelchairs to increase the mobility of people with physical or cognitive deficits (Zeng, Burdet, & Teo, 2009), workstations with haptic feedback that can be used to train surgeons (Nudehi, Mukherjee, & Ghodoussi, 2005), robotic exoskeletons to increase the user’s force capabilities (Kazerooni, 1990), and rehabilitation robots to increase the amount and intensity of physical therapy after stroke (Kwakkel, Kollen, & Krebs, 2008) .

These applications demand a continuous, or at least a prolonged period of physical interaction between a

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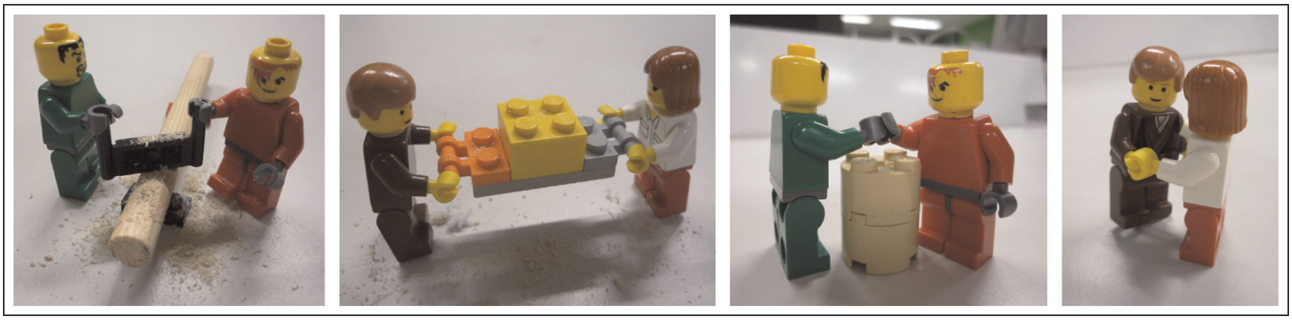

**Figure 1.** Wrestling, sawing, dancing involve specific roles for the two partners.

robot and its human user toward a common goal, during which they use either similar or complementary roles. In some cases these roles are established *a priori*, as a direct consequence of the nature of the task (Jarrassé, Charalambous, & Burdet, 2012). In other situations, the same task allows for a variety of role assignments: For example, two subjects carrying a heavy table could collaborate as equal partners, cooperate as a master–slave dyad (i.e. one subject would provide most of the workforce under the other's partner supervision), or even work as competitors if each wants to bring the table to a different location. In such tasks, it would robots with the capability to negotiate and adapt their own role to the overall goal and the behaviour of their human partner. The capability to understand human motor behaviour and adapt its role in completing a motor task completion is probably the key to developing versatile interactive robots.

Knowing how humans control motor interaction with a partner may aid in the design of efficient human–robot interaction (HRI) strategies. Furthermore, a robot adapting his role and action the same way a human partner do may be more intuitive to a human operator, thus requiring less effort during use. Finally, a robot able to learn from collaboration with a skilled human worker would enable manufacturing companies to move the robot assistant from one workstation to another without extensive reprogramming, in contrast to current industrial robots (Krüger, Lien, & Verl, 2009). In summary, a deeper understanding of the motor interaction between humans or between a robot and a human could widely broaden the scope of robot applications of robots (Santis, Siciliano, & De Luca, 2008).

This paper first provides an overview of simple roles given to robotic assistants based on master–slave control and on the decomposition of tasks into distinct actions. Human–human interaction investigations demonstrating roles of greater complexity are then reviewed. Recent key studies about role assignment policies for improved human–robot joint action are then presented, starting with investigations on human motor joint action, followed by with new approaches to improve pHRI in collaborative actions. Finally, the paper discusses future trends in the field of motor interaction between robots and humans.

## 2. Collaborative actions in pHRI

### 2.1. Existing taxonomies, classifications and roles definitions

The ways through which humans and robots interact with each other have been described in general taxonomies stemming from the field of human–computer interaction (HCI) (Agah & Tanie, 1999; Yanco & Drury, 2002). However, these taxonomies do not specifically address pHRI (Yanco & Drury, 2004).

On the other hand, existing descriptions of the different motor interaction schemes and consequentially difficult to utilize in other applications. For example, Burghart, Yigit, Kerpa, Osswald, and Woern (2002) defined a classification of role distribution schemes between human and robot that is dedicated to the different kinds of joint actions (with or without a tool) performed with humanoid robots. Although interesting, this approach lacks quantitative and exhaustive analysis of interaction parameters along with a rigorous consideration of the observation timescale, which may lead to misinterpretations. For example, considering a small window of time when analyzing the exchanges between subjects can suggest a role repartition that is not representative of the entire task.

As a consequence, studies that have classified possible role distributions are not used practically because of their lack of formal definitions. For instance, Ong, Seet, and Sim (2008) identified five human–robot relationships based mainly on teleoperation theories (Sheridan, 1992): master–slave, supervisor–subordinate, partner–partner, teacher–learner and fully autonomous robot. This framework can be used as a high-level description of the interaction, but not for a detailed analysis, as the relationships between the interacting agents arise from different field/cases (e.g. teleoperation, high-level supervision, learning by demonstration) and would need a quantitative

**Figure 2.** Human–robot joint motor action. Left: KUKA(r) LWR robot used for arc welding (with permission from Mustafa Suphi Erden conducting research at LASA, EPFL). Right: HRP2 robot used by Evrard & Kheddar (2009b). Reproduced with kind permission from the IEEE (Evrard & Kheddar, 2009b)

analysis of role strategies. Many studies have been performed in the field of teleoperation (which addresses the problem of remote physical interaction) on task-specific controllers for haptic assistance and passive/active guidance of the operator (as reviewed by Passenberg, Peer, and Buss (2010)) which are based on simple fixed asymmetric role distributions between human and robot.

The lack of precise terminology on the distribution of roles in motor joint action schemes stems from the complexity of understanding and explaining physical interaction during a task. The multimodal exchange between the partners increases the complexity of the interaction drastically, and an appropriate analysis of this interaction must consider both the energy to physically perform the task and the information used to advise partners about the ongoing action. A taxonomy of roles in motor interactions hat both describe and generate controllers for such interactions has recently been introduced (Jarrassé et al., 2012). This framework, however, awaits to be applied in order to test its utility and describe the specific multimodal exchanges on which transitions are based.

Motor interaction involves potential hazards because of the direct contact and energy exchange. Robotic assistants (Figure 2) are usually designed to produce forces whose magnitude may be as large or even larger than those exerted by humans. Thus, they can cause severe injuries to their human partners. This may explain why HRI has often been treated as a strict asymmetric master–slave relationship, and why much recent work has focused on ensuring safety (De Luca, Albu-Schaeer, Haddadin, & Hirzinger, 2006; Haddadin, Albu-Schaer, De Luca, & Hirzinger, 2008) rather than on increasing the autonomy of robotic partners.

### 2.2. Basic mechanisms: Impedance control and prediction capabilities

Recent works have shown how force and mechanical impedance (the response to an imposed motion perturbation) are adapted in humans (Burdet, Osu, Franklin, Milner, & Kawato, 2001; Franklin, Osu, Burdet, Kawato, & Milner, 2003) in response to specific types of dynamic environments. Similar mechanisms can be implemented in robots (Yang et al., 2011) to ensure stable and efficient performance with minimal effort. Impedance control allows for specification of the dynamic relationship between the position and the exerted force (Hogan, 1985; Kazerooni, Sheridan, & Houpt, 1986).

In robots, impedance control has often been used to deal with environments of unknown or varying mechanical properties (Colgate & Hogan, 1989). Important results were obtained on interaction stability despite force and position signals discretization (Miller, Colgate, & Freeman, 2000; Adams1999, 1999), or in complex tasks such as assembly (Surdilovic, Grassini, & De Bartolomei, 2001). In rehabilitation robots, impedance control is used to implement specific forms of interaction (e.g. active assistance or active resistance) (Marchal-Crespo & Reinkensmeyer, 2009). In all of these cases, the respective “roles” of the robot and the human are established *a priori*. In general, approaches based on impedance control consider an interacting human as a “perturbation”. This limits the supported forms of HRI to situations in which the robot “leads” the movement.

Another approach to improve the motor exchanges between human and robots consists of providing robots with an ability to predict human intention, for example by using gaze tracking (Sakita, Ogawam, Murakami, Kawamura, & Ikeuchi, 2004) or by recognizing characteristic patterns according to human behaviour models (Pentland & Liu, 1999), and reacting or adapting its behaviour accordingly. However, the versatility of human interactive behaviours makes them inherently difficult to predict. Models that consider the different communication channels (language, gesture, conscious and unconscious behaviours, etc.) are thus complex (Sato, Nishida, Ichikawa, Hatamura, & Mizoguchi, 1994) and can only be used for simple interaction scenarios with a small number of possible strategies.

While particular role distributions may emerge from these conventional control strategies for human–robot motor interaction, they do not consider the high-level role assignment issues which are required to deal with the complexity of many collaborative tasks to which a robot could contribute. This will be the main focus for the remainder of this review.

## 2.3. Roles assignment in human–robot motor interaction

*2.3.1. Robotic slaves.* In the area of human–robot motor interaction, the master–slave scheme refers generally to the form of interaction where a human (master) generates commands that the interacting robot (slave) executes. Thus the *master–slave scheme* corresponds to an asymmetric relationship in which only the master makes decisions, and role distribution is not questioned.

An important number of studies have been performed on robotic slaves to assist humans in performing tasks, in particular for lifting and carrying heavy or bulky objects. Various platforms, such as mobile robots with a robotic arm, have been developed (Kosuge & Hirata, 2004), which are equipped with controllers to detect the intentions of the human operator (Maeda, Hara, & Arai, 2001; Yokoyama et al., 2003; Wojtara et al., 2009; Stückler & S Behnke, 2011) or to manage multiple slave robots. The (Kosuge et al., 1994) "leader/follower" concept found in many studies, in which only the follower adapts its movements to synchronize with the leader, is similar to the "master/slave" configuration. For example in the work of Stückler and S Behnke (2011), the robot follows the human guidance during a cooperative table lifting task by tracking the movement of his hands holding the table.

An application of this asymmetric role assignment is common in exoskeletons conceived for the purpose of amplifying the physical capabilities of humans (Kazerooni, 1990; Kazerooni & Guo, 1993). Several such force extender exoskeletons have been developed in recent years, in particular for military applications (Dollar & Herr, 2008; Kazerooni, Racine, & Steger, 2005). Here, the robot is designed to minimize the human master effort, while it is mechanically connected to the human body and transferring power to it.

Robotic slaves also encompass systems to provide forces or trajectory corrections (Khatib, 1999), or to guide movements within a restricted workspace (Peshkin & Colgate, 2001; Zeng et al., 2009). Robotic aids that guide the user's motion along desired directions while preventing motion in undesired directions or regions of the workspace through "virtual fixtures" (Rosenberg, 1993) can be considered slaves because they cannot complete the main task alone and exists only to provide support during action. Such robotic aids are known as *intelligent assistive devices* (IADs). Despite their name, the collaborative robots or *cobots* described by Colgate, Edward, and Peshkin (1996) do not collaborate as an equal partner would, but implement a master–slave behaviour. Cobots track human operator behaviour and react accordingly, for example in the work of Colgate, Peshkin, and Klostermeyer (2003) a load lifting device provides assistance according to the angular movements of the loading cable. Therefore, these assistive devices can be considered slaves.

Finally, robot teach pendants where the human teacher directly moves the robot that records the motion to reproduce it, or imitation learning (Pastor, Kalakrishnan, Chitta, & Theodorou, 2011) (where the robot is moved according to recorded data of human movement), also correspond to a master–slave scheme. Indeed, in these cases, the robot is passively following the human teacher, at least during the learning period.

*2.3.2. Master–slave versus co-activity.* Distinct from the master–slave scheme are *divisible tasks*, where robot and/or human agents interact without needing each to know what the other is doing, and incidentally interact and succeed in the common task through *co-activity*. Separating tasks in independent but complementary subtasks where each agent performs well often is an efficient way to carry out "joint" action: neither sensory exchange nor negotiation is required, enabling simple solutions without inference. Such situations typically arise when the task is decomposed into subtasks carried out by independent controllers. An example is the Acrobot robot assistant for bone surgery (Cobb et al., 2006), which constrains the surgeon's motion to a predefined region, facilitating surgery without requiring knowledge of the surgical task. Similarly, simple assistive devices developed to help manufacturing, e.g. by compensating gravity using springs during tool or parts manipulation (and which are not reacting according to any human worker action), cannot be considered slaves because no information exchange is needed, as the worker and robot complete separate actions.

*2.3.3. Advanced forms of interaction.* While division in independent subtasks may facilitate relatively stereotyped actions, complex tasks would benefit from a more

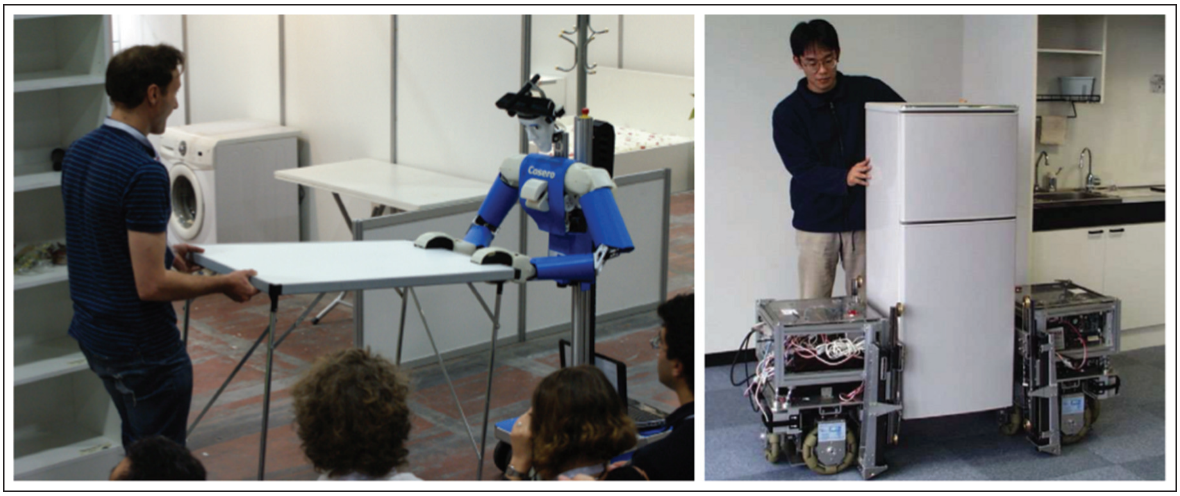

**Figure 3.** Master–slave examples. Left: Cosero. Reproduced with kind permission from the IEEE (Stückler & Behnke, 2011). Right: Dr Helper. Reproduced with kind permission from the IEEE (Kosuge & Hirata, 2004).

**Figure 4.** Arm manipulation of an hemiplegic patient by a physical therapist and an upper-limb robotic exoskeleton, performed at the Raymon Poincaré Hospital, Garches, France. Such tasks require a complex sensorimotor coordination strategy between the physiotherapist and the training patient. Reproduced with kind permission from the IEEE (Crocher, Sahbani, Robertson, Roby-Brami, and Morel, 2012).

sophisticated sharing between the human and robot (Sheridan, 1997). For instance, neuro-rehabilitation (Figure 4), in which robotic devices and their controllers assist patients to develop their movement capabilities (Hogan & Krebs, 2004), requires task sharing beyond pure master–slave roles. For example, successful neuromotor rehabilitation requires a therapist to assist a (e.g. post-stroke) patient in moving the arm while inferring her or his sensorimotor state and tuning motion assistance correspondingly in order to help the patient actively working on improving her or his capabilities. Similarly, the growing field of smart/robotic wheelchairs would benefit from collaborative control strategies and shared control policies letting the user take charge of the overall control of the wheelchair but assisting her or him manoeuvring (Zeng et al., 2009).

## 3. Results from human–human interaction

The presence of multiple actuators and decision centres makes the control of joint motor actions complex. Following pioneering work in the psychology of joint action, research in the field of *human–human interaction* (HHI) has investigated the control of motor interaction between humans. These studies highlighted the potential of collaboration and generated enthusiasm in the HRI field, leading to controllers overriding the rigid schemes and the trick of dividing task into independent subtasks. However, this field is relatively young and has so far led to few real applications.

### 3.1. From HHI to HRI

*3.1.1. Psychological and social aspects of HHI.* Psychological studies have provided some evidence for the benefits of interaction between humans (Sebanz, Knoblich, & Prinz, 2003): the observation and knowledge about the partner’s action affects one’s own actions even when an actual coordination is not required, exhibiting “motor resonance”. Relations between perceptual judgements about the partner’s actions and the current state of one’s own motor system were also identified (Schütz-Bosbach & Prinz, 2007), showing that high-level cognitive processes influence the joint action scenario and the role distribution between partners (through multi-modal exchanges) and affect the interactive performance.

The control of joint actions involves high-level cognitive mechanisms to feel, evaluate and understand the partner's intentions and actions (Sebanz, Bekkering, & Knoblich, 2006). In psychology, the tendency for healthy adults to automatically impute mental states to oneself and others is usually referred as *Theory of Mind* (ToM) (Premack & Woodruff, 1978). ToM provides subjects with an ability to make inferences about others by attributing beliefs, feelings, desires and intentions to oneself and others, and is believed to be essential for social and physical interactions (Sebanz et al., 2003). To perform efficient joint actions, subjects are required to emulate an internal model of the partner or of its influence on the shared task.

Other psychological phenomena considered to be factors of interactive behaviours between humans (Knoblich, Butterfill, & Sebanz, 2010; Obhi & Sebanz, 2011) include *co-representation* mechanisms, such as simulation theory (Gallese & Goldman, 1998) (mental projection in which one subject temporarily adopts the partner's point of view), social facilitation (Zajonc, 1965) (tendency for people to perform tasks in a better way when other people are considering his/her action), and *interpersonal coordination* mechanisms such as mimicry (Chartrand & Bargh, 1999) (unconscious tendency of subject to synchronize and mimic other behaviour or gesture, generally to facilitate acceptation). Related psychological theories are synchrony (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007) (tendency of subjects to synchronize their actions), game theory (Myerson, 1997) (a mathematical approach to model strategic situations in which an individual's success in making choices depends on the choices of others) and the theory of affordance (Gibson, Shaw, & Bransford, 1977) (stating that the world, object or even human partner, is perceived in terms of object possibilities).

*3.1.2. HRI to investigate HHI.* Several studies on joint action were conducted to examine the information transfer for joint action between two humans. The analysis of exchanged signals between subjects and some teleoperated task simulators, suggest that force feedback (Glynn, Fekieta, & Henning, 2001) allows people to perform better in a joint task than when performing alone if haptic and visual feedback are well synchronized. Studies in which two partners manipulated the same virtual object showed that haptic feedback leads to improvements in task performance (Sallnas, 2001; Groten, Feth, & Peer, 2010). Haptic feedback is also crucial for action coordination in more complex tasks such as dancing (Gentry, 2005) as well as for dynamic role division (Pham, Ueha, Hirai, & Miyazaki, 2010). These studies further suggested that even when a haptic communication is established and negotiation phases are observed (Groten et al., 2010), parameters of the role distribution such as the dominance behaviour appear to be more linked to the subjects' nature than to interaction's parameters (Groten et al., 2009).

Reed et al. (2006); Reed and Peshkin (2008) conducted experiments to investigate haptic joint action with continuous physical contact between two partners. The partners were connected by a two-handled crank mounted on a controlled direct-drive motor. This motor could measure and interact with the common circular movement, and the applied force measured at each handle could be used to test interaction strategies. The authors demonstrated that subjects perform point-to-point movements faster when connected than alone (Reed et al., 2006). They also suggested that some dyads (i.e. pairs of partners) adopt specialized roles, where one partner is in charge of the acceleration and the other controls the braking to reach the right position (Reed & Peshkin, 2008), which might explain the benefits from Reed et al. (2006). This pioneering work, however, lacks quantitative evidence of role specialization, and simple modelling implemented on the robot did not succeed in providing the benefits observed with a human partner (Reed, Patton, & Peshkin, 2007). Ueha, Pham, Hirai, and Miyazaki (2009) extended these experiments and accurately defined the human dynamical role division and control by using an additional degree of force measurement (due to the use of external force sensors placed below each handle). These studies have drawn attention to the potential of motor interaction and stimulated further research in this area.

### 3.2. Roles switching: a key to partner's equality?

While the interaction between two agents may be designed as an equalitarian and unconstrained relationship as is believed to be used by humans, typical HHI may correspond more to an asymmetric scheme with multiple switchings between roles. Several studies were thus conducted to try identify and understand the switching processes between strategies for collaboration.

Stefanov, Peer, and Buss (2009) studied interaction during a tracking task and defined a tri-state logic composed of two roles and one "no behaviour" condition based on the signs of the force, velocity and acceleration. A role distribution similar to a leader–follower combination involves a "conductor" who decides what the system should do and expresses this intention via haptic signals (and through energy dissipation), and an "executor" who performs the action as determined by the conductor (thus injecting energy). This approach is interesting as it bypasses the global rigidity of conventional fixed asymmetric relationship, by allowing multiple role switchings (changes of the direction of the asymmetry) during the completion of the task, and by letting the executor participate in the task. It gives an interesting insight about low-level interaction, although the fine temporal resolution and the association of multiple roles to each partner make it difficult to interpret the results. Preliminary work on using such classification in teleoperation has recently been presented by Corredor and Sofrony (2011).

Nevertheless, in light of several considerations from studies on haptic communication, the "role switching" phase could potentially be an episodic and preliminary negotiation phase that would disappear when the task is performed repeatedly by the same partners.

### *3.3. Consideration of mechanical impedance*

While all experiments presented above considered only the kinematics and forces, a recent study (Melendez-Calderon, Komisar, Ganesh, & Burdet, 2011) also investigated how human dyads control impedance, which is important to ensure interaction stability and and robust response to perturbations. This work developed automatic identification of the interaction strategies, and showed that dyads formed of nave subjects that had never met started by a negotiation phase during which roles are switched after which specialization that is specific to a particular dyad and robust to perturbations, occurs (Melendez-Calderon, 2011).

## 4. Control schemes to improve human–robot joint action

### *4.1. Switching and adapting roles*

For a few years, "equalitarian" roles distribution beyond the master–slave scheme have been investigated such as supervisor–subordinate, cooperators, or teacher–learner (Ong et al., 2008; Ikemoto, Amor, Minato, Ishiguro, & Jung, 2009; Pastor et al., 2011). For example, Lawitzky, Mortl, and Hirche (2010) evaluated three different effort sharing policies during transport of a bulky object by a human and a robot: balanced-effort behaviour, maximum, and minimum robot-effort behaviour. Performances obtained with each of these conditions were evaluated, and results showed an improvement (minimization of applied force level and tracking error) through a more proactive robot behaviour which is consistent with previous research on motor interaction.

In addition to these new roles, Evrard and Kheddar (2009a, 2009b) introduced a flexible role distribution enabling each partner to tune between the two distinct extreme behaviours of leader and follower using a homotopy (a weighting function that allows a continuous change between two behaviours), giving rise to an implicit bilateral coupling (Kheddar, 2011). With this approach, each partner can claim or give up leadership in a smooth way. While this attractive framework was recently demonstrated on the object lifting between a human and an HRP2 humanoid robot, it does not determine yet how the redundancy of the two interacting partners is solved, i.e. how it could be used to design interaction control in an application. Using the homotopy framework, an experiment was developed in which the lifting of a table between a human a humanoid was analysed in the state space and identified using Gaussian mixture regression (Evrard, Gribovskaya, Calinon, Billard, & Kheddar, 2009). This probabilistic model was then used by the robot in order to switch between the leader and follower behaviours. The robot was able to adapt its behaviour to human subjects who changed their role during the task, however the results were not very robust, and lacked agreement with human dyads.

In a similar approach to the homotopy, Oguz, Kucukyilmaz, Sezgin, and Basdogan (2010) defined a dynamic role-based effort sharing scheme utilizing a force threshold on a known user force profile to improve interaction quality through role negotiation during a game, in which a ball rolling on a plane must hit several targets. Here, role distribution was restricted to a discrete tri-logic state ("user dominant", "role blending" and "equal control") and led to no statistically significant improvement in task performance metrics including completion time, total path length, deviation of the ball from the ideal path, integral of time, and energy spent. Also, ideas for new online policies have been recently proposed by Passenberg, Groten, Peer, and Buss (2011) where the best assistance that a virtual assistant should exhibit to help a subject minimize error and interaction force during the completion of a 2D maze task is computed.

Based on a formal analysis of HRI during a load transport task, Mortl et al. (2012) defined and evaluated different possibilities for role assignment: two dynamic role exchange mechanisms in which adaptation is based on human force feedback measurement and one generic static role allocation strategy for comparison purposes. The dynamic role allocation strategy parameter is adapted according to the magnitude of the partner's contribution in the redundant direction, defined as the direction where effort sharing between the agents can take place. Role assignment mechanisms were evaluated in a user study on 18 subjects based on both quantitative measures indices (completion time, effort, or amount of disagreement) and qualitative measurement of user experience with a questionnaire. The results showed that a continuous dynamic role assignment policy leads to better performance than a constant role assignment one. However, it seems that

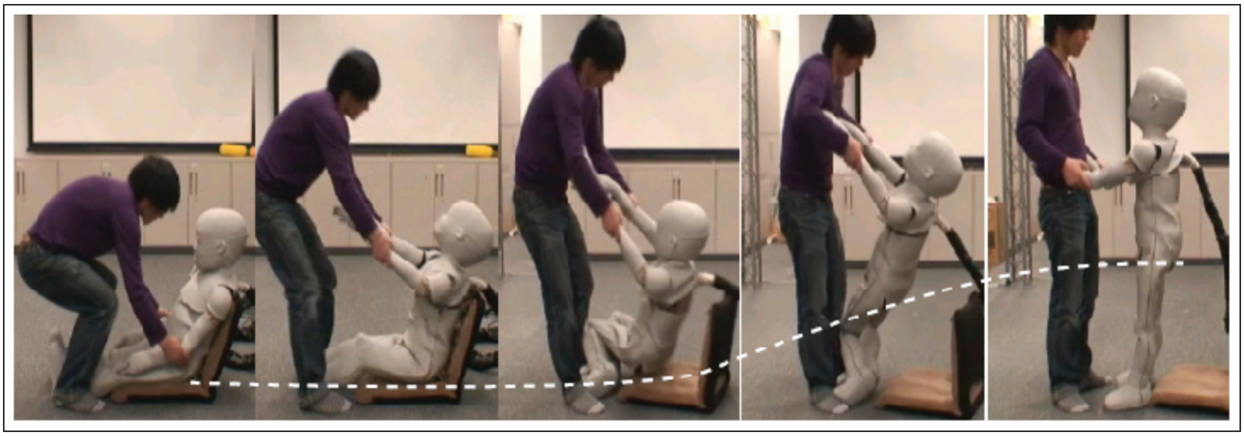

**Figure 5.** Kinaesthetic teaching of a standing-up task. Reproduced with kind permission from the IEEE (Ikemoto et al., 2009).

humans preferred the constant role, where robot behaviour is more predictable and thus easier to consider in their motor action.

Studies on robot adaptive interaction with a human can also be encountered when reproducing human hand-shaking with a robot, an interesting bilateral task. Dedicated robot controllers based on a hidden Markov model approach used to estimate human intentions and adapt robot behaviour (Wang, Peer, & Buss, 2009), or online adaptation to interaction dynamics (Guanghui, Mina J, Deming W, & Hashimoto, 2011) seem to provide realistic experiences.

### 4.2. Education schemes

An important HRI scheme that tends to be increasingly used is *education*, where both the human can teach the robot and conversely some robots may be used to teach a human. For instance, the "learning-by-demonstration" approach where a robot learner is actively performing a task and is corrected by the human teacher through motor interaction (Schaal et al., 1997; Calinon & Billard, 2007; Lee, Ott, Nakamura, & Hirzinger, 2011) is an educational type of interaction, in which a human helps the (humanoid) robot to refine a previously learned movement by kinesthetic teaching.

Similarly, Ikemoto et al. (2009) developed an algorithm dedicated to robot learning through physical interaction with humans. The efficiency of their method was evaluated in an experiment where a human helps a humanoid robot to stand up and to learn temporal aspects of the postural sequence required to stand up (Figure 5). The implementation results in their works showed that improvements are due to a bilateral learning process that takes place in both partners. Even if only the learner's behaviour is described and tuned, these results underline the importance of teacher adaptation to let the subject learn and thus the importance of the bilateral exchange.

On the other hand, a robot may help a human partner to work more precisely, in a more efficient way, with less effort or in a more ergonomic way. For example, in the work of Boy, Burdet, Teo, and Colgate (2007), a passive mobile robotic platform (cobot) mechanically constrains the motion from a human operator encourages them to learn ergonomic paths, and enables them to position heavy objects more precisely and move them with less effort. The results of Boy et al. (2007) show that subjects working with this "learning cobot" adopt a more ergonomic behaviour minimizing the back torsion. We note that in this scheme learning occurs on both sides, as the robot guiding path could be adapted to the changes in the environment or of the human strategy.

Even if the *passive mode* used for the first stage of robotic rehabilitation is similar to a raw master–slave, the *active mode* giving assistance as needed to encourage patient involvement in the task is similar to such education scheme (Lum, 2002). This can be realized by simultaneously relaxing assistance and satisfying performance (Emken & Reinkensmeyer, 2005; Franklin et al., 2008). The robot gradually minimizes its involvement in the task completion to encourage human participation and accelerate motor skill learning (Reinkensmeyer & Patton, 2009).

## 5. Discussion

The area covered by published works on motor interaction between human and robot include the classification of interactive motor behaviours (Yanco & Drury, 2004; Burghart et al., 2002; Ong et al., 2008; Jarrassé et al., 2012), observation and understanding of role distribution in human dyads (Reed et al., 2007; Reed & Peshkin, 2008; Stefanov et al., 2009; Melendez-Calderon et al., 2011), attempts at replicating these interaction kinds with robots (Reed & Peshkin, 2008; Ueha et al., 2009; Lawitzky et al., 2010) and controllers

**Table 1.** Collaborative robots beyond the master–slave scheme.

| Strategy | Task | Existing work |
|---|---|---|
| Divisible task assistant | Load lifting assistance | (Colgate et al., 1996; Peshkin & Colgate, 2001; Colgate et al., 2003) |
| | Motion assistance | (Rosenberg, 1993) |
| Fixed asymmetric roles | Manipulation assistance | (Ueha et al., 2009; Lawitzky et al., 2010) |
| | Kinesthetic teaching | (Pastor et al., 2011; Ikemoto et al., 2009) |
| Switching roles | Load lifting assistance | (Evrard et al., 2009; Evrard & Kheddar, 2009a) |
| | Haptic guidance | (Oguz et al., 2010; Passenberg et al., 2011; Corredor & Sofrony, 2011; Mortl et al., 2012) |
| | Hand-shaking partner | (Wang et al., 2009; Guanghui et al., 2011) |

able to modify the roles during the interaction (Evrard & Kheddar, 2009a; Evrard et al., 2009; Oguz et al., 2010; Passenberg et al., 2011; Corredor & Sofrony, 2011; Mortl et al., 2012). While a large number of papers call for more flexibility than the master–slave scheme, only a few works so far attempted to gain a deep understanding of the physical interaction issues or implement even simple collaborative behaviours.

Table 1 groups studies providing control schemes beyond master–slave. A common goal consists of developing robot assistants capable of *collaborating* with a human partner rather than simply *cooperating* with her or him. In a collaboration, there is no *a priori* role distribution, but a spontaneous role distribution depending on the interaction history and mutual “online” adaptation. In contrast, *cooperation* occurs when different roles are ascribed to the agents prior to the beginning of a task, and this distribution is not questioned until its completion (Dillenbourg, Baker, & Blaye, 1996).

We believe that the following main issues need to be addressed in order to develop robotic systems capable of true collaboration:

- A categorization of role attribution in joint motor action based on multisensory cues should be developed. While research in computational neuroscience commonly analyzes full motion control involving complex coordination and energy consumption, in most studies in human–robot motor interaction the analysis is limited to interaction forces (Groten et al., 2009, 2010).
- There is an increasing number of studies on psychological and social factors affecting joint actions (Sebanz et al., 2006; Chartrand & Bargh, 1999), while most robotic studies have focused on kinematic or force information exchanges, and neglected other cues which are necessary to understand the switching between roles. Preliminary discussions on partner perception such as that of Reed and Peshkin (2008) are worth pursuing. Also, physiological parameters such as heart rate (Damen & Brunia, 1987), gaze patterns (Vertegaal, Slagter, Veer, & Nijholt, 2001), facial expression (Breazeal, Homan, & Lockerd, 2004), may be considered as a mean of inferring a human’s state and thus to select interaction roles.
- Interactive behaviours such as the competition between actors, which are currently under-studied, should be investigated and used. In some cases competition may produce more efficient performance at the dyad’s level than positive collaborations. For example, Passenberg et al. (2011) presented preliminary work on which best strategy the robot should exhibit if the interacting subject agrees or not on the motion to perform.
- Mechanical impedance is a main determinant of interactions, and should thus be considered in human–human and human–robot motor interaction. Modern torque controlled robots and the development of variable impedance actuators (VIAs) (Bicchi, Tonietti, Bavaro, & Piccigallo, 2005) allow implementation of sensitive impedance control strategies. Recent studies introduced human-like concurrent adaptation of trajectory, force and impedance (Franklin et al., 2008; Burdet, Ganesh, Yang, & Albu-Schaeffer, 2010) on the basis of which efficient interaction schemes may be developed.
- As explained above, collaboration may be achieved through switching of asymmetric relations, yielding a symmetric relation overall. Research has so far considered interaction only at the local level, and it is necessary to consider the interactive behaviour at the global level. This requires the development of generic (adaptive) controllers suitable for various tasks. In contrast, existing controllers with adaptive behaviour (Evrard & Kheddar, 2009a; Oguz et al., 2010) are dedicated to a specific task. A few studies (Passenberg et al., 2011; Passenberg, Stefanov, Peer, & Buss, 2011) have started to identify behaviour selection for a robotic assistant.
- Finally, the psychological aspects of the joint action may be a key to a deep understanding of the motor joint action and coordination strategies. Indeed, motor interaction between humans involves both

physical and psychological factors. When a human is collaborating with a partner, s/he tends to analyse the partner's reaction, understand the partner's action, and use this information together with previously learned knowledge to adapt her or his behaviour and strategy. While roboticists focused on the sensorimotor exchanges, psychologists have revealed cognitive processes occurring during collaboration. Pioneering experimental psychologists have begun to build a bridge to robotic studies (Sebanz et al., 2003, 2006), and their research results could be considered for future robot control design. Taking these phenomena into account could both clarify some of the observed phenomena (by limiting the effects of cognition), and provide quantitative results to psychologists enabling them to test and refine their theories.

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