Compliant control of a humanoid robot helping a person stand up from a seated position

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Abstract—Supporting somebody while standing up from a seated position is one of the most frequent tasks envisaged for a humanoid assistant used in order to help somebody with reduced mobility around the house. The safest way to do this for a human carer has been clearly defined in patient handling guides for hospitals where a policy of never lifting the patient is strongly recommended. Based on these guidelines, this paper proposes a stable initial posture for a humanoid robot supporting a person from sitting to standing, as well as a control law to make the robot keep a contact force and follow the motion of the person compliantly. This initial position and compliant control of the robot was implemented and tested on the humanoid HRP-4 interacting with a healthy subject.

I. INTRODUCTION

Extensive research has been undertaken in recent years to study the planning and control of humanoid robots while walking and manipulating objects [1]–[3], the final goal of this kind of research being to make humanoid operation compatible with human environments and the presence of humans. In line with this philosophy, the ROMEO2 project¹ envisages the development of a humanoid who can assist people with reduced mobility in carrying out daily tasks in their household. One of the tasks such a robot will have to carry out is to help the person with reduced mobility stand up. Although a common task for human carers, helping a person stand up is challenging for a humanoid robot because it requires keeping balance while closely and intensely interacting with a human being. Physical human-robot interactions have been previously studied for different scenarios ranging from dancing with a robot to using a robot to perform surgery [4]–[6], however, the scenario of a humanoid robot helping a person stand up safely is, to the best of the authors’ knowledge, a novel idea.

Previous research relevant to the sit-to-stand task presented in this paper include applications where humanoid motion is computed in a scenario where contact on several parts of the robot is required to perform a task that involves moving the whole body of the robot [7], [8]. Control strategies and algorithms for multi-contact planning and whole-body motion have been developed and tested for tasks like walking through obstacles, climbing up stairs and transporting an object between two humanoid robots [9]–[11]. Compared to those tasks, helping somebody stand up, presents the additional challenge of including a human being in the control loop.

This paper reviews the techniques used in hospitals to help patients with reduced mobility stand up in Section II in order to define a safe posture from which the robot can help the person stand up and develop a control algorithm able to support the patient from sitting to standing (Section III). The initial posture of the robot based on the techniques used by human carers and the control algorithm defined for the task are explained and validated in Section III using the humanoid robot HRP-4 (Kawada Industries Inc., Japan) helping a healthy subject stand up from a chair.

II. TECHNIQUES USED BY HUMAN CARERS TO HELP A PERSON FROM SITTING TO STANDING

Helping a person with reduced mobility stand up is a very common task for a human carer. Healthcare providers and institutions have defined clear guidelines for manually handling and moving patients [12]–[14]. These guidelines have the two-fold goal of preventing carers from injuring themselves and preventing carers from injuring patients. The most common injuries suffered by carers from incorrectly handling patients is back injuries [12]. Although a robotic assistant is not going to suffer from back injuries, the strain caused by an unsafe handling technique is likely to destabilise the posture of the robot and put the patient at risk as a result. Therefore, considerations on preventing injuries to human carers are important when defining the task of helping a person from sitting to standing for a humanoid robot. Injuries and issues that patients may experience when incorrectly lifted include: damage on fragile skin, shoulder and neck injuries, an increase of existing breathing difficulties, bruising and cuts [12]. The risk of the robot causing such injuries to the person is to be avoided at all times. In order to do so, the policy of healthcare institutions and providers is to never lift the person manually [14].

A. “No lift” policy

According to patient handling guidelines, patients who cannot take any weight through their legs must not be moved manually and if they cannot raise their bottom off the chair,
then a standing aid or hoist must be used instead of manual support [14], [15]. The reasons given in these guides of good practice to never lift a person manually are [14]: people may weigh too much, people are unpredictable, it is difficult or impossible for nursing staff to get into a safe position to lift, staff are at risk of injury in all manual lifting techniques, most lifts include a risk of injuring the patient, manual lifts are not therapeutic: they do not improve the patients mobility.

The reasons about unpredictability of people and the fact that they might put too much weight on the carer hold even more true for the case of a robot interacting with a person. The impossibility of getting into a safe position to lift states the difficulty of using a human body to safely lift another human body and therefore is also applicable to a humanoid robot. As pointed out earlier, even though a robot cannot get injured, the risk of injuring the carer can be considered equivalent to the risk of making the robot unstable and therefore risking the robot falling on the person. The last of the previous reasons states that, in any case, there is no therapeutical value in lifting a person and therefore it is preferable to use other techniques to help the person stand-up.

Some traditional moves used by carers and nursing staff that involve lifting the patient are are no longer considered good practice and are now considered unsafe or high risk. Two traditional moves used for helping a patient from sitting to standing, now considered unsafe are: the drag lift or any lift that involves the handler placing a hand or an arm under the patient’s axilla (armpit) and the ‘bear hug’. The control system for the task of the robot must therefore explicitly avoid any move of posture that may involve lifting part of the weight of the person and should instead focus on gently pushing the person horizontally to help them transfer their weight from a sitting to a standing position.

B. Deciding on the appropriate patient handling technique

The choice of the handling technique depends on the mobility of the patient and how easily they can perform the actions required to stand up. According to patient handling guides [15], the patient can be classified as:

- **Independent**: if the patient does not require any assistance to stand up; this is the case when the patient is cooperative, able to bear weight fully, consistent and reliable in balance.
- **Supervised**: if the patient requires verbal reminders or equipment to help them stand up.
- **Semi-dependent**: if the person can stand up when minimal to moderate physical assistance is provided. The patient is semi-dependent if able to bear some weight, able to balance somewhat, and able to cooperate somewhat.
- **Dependent**: when the patient requires total assistance to move because they are unable to bear any weight or do it reliably, limited in movement/unwilling to move, unable to move, unpredictable or heavy/obese.

The robot should be able to remind a supervised person to follow all the steps for safe sitting to standing, double-checking with its cameras that the process is followed correctly and ask the person to repeat or correct a move when necessary. The robot should be able to physically assist semi-dependent people that require minimal or moderate assistance without the use of equipment or of a device like a hoist. If the person is dependent or requires the use of a lifting device to stand the use of a robot for assistance is not recommended because of the risk of the person destabilizing the robot and therefore putting themselves at risk.

C. How to correctly help somebody stand up

Before the carer helps the patient stand up, the patient should do the following in order to stand up as independently as possible [14]:

- move their bottom forward in the chair up to the front of the chair,
- place feet on the floor, under their knees, about shoulder-width apart,
- place one foot slightly in front of the other,
- look and lean forward so that their head is over their toes.

When minimal or moderate assistance is required to help the patient stand up, the carer should follow these steps to get into a comfortable and safe initial position for the task [14], [16] (see Fig. 1a):

- Stand on the side of the person, facing the patient side on,
- Place one foot level with the patient’s feet, adopting a wide base of support.
- Bend the knees, keeping the back straight.
- Place the flat of the hand closest to the patient’s back in the small of the patient’s back.
- Place the other hand on the patient’s shoulder.

The robot can also follow these steps to get into the initial posture of the sitting to standing task. To carry out the task, patient handling guidelines then recommend a rocking motion and when the patient is ready, the carer performs a forward body weight transfer maneuver with the upper body forward and shifting weight from the back leg to the front leg (in the direction of the move). The body weight of the carer goes through the patient via their forearm, see Fig. 1b.

![Fig. 1. Human carer assisting a patient from sitting to standing: (a) initial position of the task with both the patient and the carer ready for the task with their arms, legs and feet in the recommended position, the carer pushes the patient up until they reach the (b) final position with both the patient and the carer standing, courtesy from [14].](image-url)
III. DEVELOPMENT OF A COMPLIANT CONTROL TO HELP A PERSON FROM SITTING TO STANDING

Based on the previous patient handling techniques, the sequence of five steps showed in Fig. 2 can be implemented to get the robot in a useful and stable initial posture. In order to decide whether a handling technique with a robotic assistant is appropriate for the person, the mobility of the person needs to be assessed first: if the person is dependent the robot is not considered suitable for the task. Prior to performing the task the environment should be checked, making sure that there is enough space to carry out the task, there are no obstacles in the space required for the task and that the floor is not slippery. Before the robot gets into the initial position of the task, the robot should remind the person to follow the steps explained in Section II-C, that is, to move their bottom forward, place their feet under their knees shoulder-width apart, place one foot in front of the other, place their hands on their knees or the armrests of the chair and lean and look forward. The robot can then get into the initial posture for the sitting to standing task, standing by the side of the person, facing the person side on, and getting his legs, feet, trunk, arms and hands in position.

The initial posture is defined following the patient handling recommendations and biomechanics principles previously reviewed. This initial posture was validated using the humanoid robot HRP-4 as shown in Fig. 3. Thus, for the initial posture of the robot the centre of mass of the robot is lowered down, bending the knees and ankles, and a separation between the feet of the robot is set, with one foot about half a step in front of the other as shown in Fig. 3a. The hands of the robot in Fig. 3a are positioned so that the left hand rests on the lower back of the person and the right hand rests on the shoulder of the person closer to the robot. The position of the person with respect to the robot, sitting on a chair between the hands of the robot is illustrated in Fig. 3b. To validate the initial posture, the robot is commanded to move to the initial position, then lowered down until standing on the floor. The stability of the posture is checked by manually applying a side force on the shoulders and a gentle rocking motion. This initial posture is the first state of the state machine implemented to control the whole sequence of actions for the robot to help a person stand up.

B. State machine to help the person stand up

The algorithm used by the robot to perform the task of helping a person stand up is implemented as a set of actions in a state machine (see Fig. 4). After initialisation (state 1) and getting into the initial posture (state 2), the robot knows that the person is leaning on his hand and is ready to get up by detecting a force applied on the hand higher than a force threshold specified to the controller (transition from state 3 to state 4). From that moment on, the robot supports the upward motion of the person with one hand by applying a force applied to the back of the person and following the motion of the person’s back from sitting to standing (state 4). The robot stops moving when the hands reach their limit position, assuming that at that position the person will be already standing (state 5).

The value of the force that the robot tries to apply for this test only changes with the height of the hand, that is, the higher the hand, the closer to standing the person is assumed...
to be and therefore the less force the robot is required from the robot. Further research into how and depending on what parameters a human carer adapts the supporting force will be required to refine the value of force reference. The robot also supports the front of the person by leaning the other hand on the shoulder of the person and applying a gentle force to support and stabilise the trunk of the person while standing up. The control law to make the interaction between the robot and the person compliant is explained in the next subsection.

**C. Compliant control law for the position of the hands**

The interaction force between the robot and the person during the sit to stand motion can be modelled as:

$$F(t) = F_{\text{robot}}(t) + F_{\text{person}}(t) = m \cdot \frac{d^2r(t)}{dt^2}$$  \hspace{1cm} (1)

Where $F(t)$ is the interaction force, that is, the combination of the force applied by the robot at the contact with the person ($F_{\text{robot}}(t)$) and the force applied by the person ($F_{\text{person}}$). This combination of forces is applied to the mass of the person ($m$), causing an acceleration along the trajectory followed by the mass ($r(t)$). The force applied by the person is unknown and unpredictable. The compliant control law aims at moving the hands of the robot to a position where the interaction force is as close as possible to a force value that is considered sufficient to support the person. This control law is formulated as follows for the three directions of space (see X, Y and Z axes in Fig. 3a):

$$x_{i+1} = x_i$$  \hspace{1cm} (2)

The position along the sagittal plane of the robot ($X$) is kept constant at all times (see Eq. 2) because the sit to stand motion is considered to take place mainly along the frontal plane of the robot (the sagittal plane of the person).

New position reference sent to the controller (horizontal and vertical position in the frontal plane of the robot) for the hands of the robot ($y_{i+1}$ and $z_{i+1}$) is set as a function of the current position ($y_i$ and $z_i$), the current force ($F_{y_i}$ and $F_{z_i}$) sensed by the force sensor mounted at the wrist of the robot and the speed of the hand ($v_{y_i}$ and $v_{z_i}$). The stiffness parameter ($K$) sets the relation between the current position of the hand ($y_i$ and $z_i$) and the interaction force: $F_{y_i}$ and $F_{z_i}$ in Eq. 4 which correspond to $F(t)$ in Eq. 1. The damping parameter ($C$) attenuates the force applied by the robot depending on the velocity of the hand ($v_{y_i}$ and $v_{z_i}$). The value of $F_{\text{ref,xy}}$ in Eq. 3 is the amount of force that is considered sufficient to support the motion of the person. This force reference is used in this task to set the direction of motion for the robot hands: closer to the person if the contact force drops below the reference and further away from the person if the contact force increases above the reference. The magnitude of the force reference is an indication of how much force is sufficient to support the person.

**IV. EXPERIMENTAL VALIDATION OF THE COMPLIANCE CONTROLLER**

The state machine and control law were implemented in the humanoid HRP-4 and validated by making the robot go to the initial posture and follow the motion of a healthy subject while applying a horizontal force on the back and shoulder of the person. To validate the compliant control algorithm developed for this task, the robot was tested pushing the back of a healthy subject and supporting his shoulder in two separate tests as shown in [17]. The first test of the video shows the robot pushing the back of the person and the second test shows the robot applying a force on the shoulder of the person and following the motion of the shoulder. During the validation of compliant control, a constant value of 20N and 10N of force reference were tested for the hand pushing the back and the hand resting on the shoulder. The robot was able to follow the motion for both values of force on both hands. For the hand resting on the shoulder a constant value of 10N was decided to be best as 20N felt too hard a push on the shoulder. For the hand pushing the back of the person, 10N was decided to be an appropriate threshold to set off the compliant control but for pushing the back the force reference was set as a function of the height of the hand of the robot. In this way, when the hand is at its lowest position, that is, the person is still sitting and needs to get out of the chair, a reference force of 30N is set. As the person stands up, the value of force reference is decreased until the person is nearly standing up, when the minimum value of reference force (20N) is set.
The stiffness constant \( (K) \) of the compliant control was set empirically to a value of 100 N/m and the damping constant \( (C) \) was set to a value equal to the square root of the stiffness. Following the motion of the back and shoulder along the vertical \( (Z) \) direction is implemented with the same control as for the horizontal direction \( (Y) \) but setting the force reference to the weight of the hand of the robot, so that the controller looks for a position where the hand of the robot follows the person without applying any vertical force.

Fig. 5 shows several images and the force and position data from the two tests of the hand pushing the back and supporting the shoulder of the person. The top graph in Fig. 5a and b shows the horizontal \( (Y) \) and vertical \( (Z) \) force measured by the force sensor on the hand of the robot as well as the force reference fed to the compliant control algorithm to set the position reference. The bottom graph in Fig. 5a and b shows the horizontal \( (Y) \) and vertical \( (Z) \) position of the hand during the tests.

The top graph in Fig. 5a shows the value of horizontal force on the hand which begins at approximately zero and increases as the person leans back until the threshold of 10N is reached (around \( t = 121s \) in the top figure). From that moment on, the hand of the robot moves towards or away the person as shown in the bottom graph of Fig. 5 depending on whether the sensed force is under or over the reference. The top graph of Fig. 5a also shows the vertical force oscillating around the vertical force reference set to the weight of the hand. In the top graph of Fig. 5b, the reference for the horizontal force is constant \( (10N) \) and the reference for the vertical force is again set to the weight of the hand.

Looking at the force graph in Fig. 5a and b it seems that there is a significant amount of error between the interaction force and the force reference. However, it is important to note that this force reference is not a reference in the traditional sense of a force value that the controller should try to keep at all costs and attenuating oscillations around this reference. When interacting with a human in this task, oscillations around the force reference are due to the autonomous motion of the person as much as to the parameters of the controller (see Eq. 1). The magnitude of the force reference was set empirically, checking how supported the subject felt with each tested value of force. The parameters of the controller (stiffness constant \( K \) and damping constant \( C \) ) were also set empirically, checking that the reaction of the controller to changes in force was fast enough without becoming uncomfortable for the person.

Although the subject felt a firm push on the back from the robot while getting up, there is a concern that the force applied by the robot on the back might need to increase significantly in order to support a subject of a higher weight or reduced mobility. The same applies to the supporting force on the shoulder. The subject felt that the force on the shoulder was slightly too strong, however a different subject might need a strong force on the shoulder in order to keep the back steady. Increasing the force applied by the robot is, however, limited by the hardware and overall control strategy of the robot. The maximum force that can be safely applied on the hand of the robot was experimentally found to be around
V. CONCLUSIONS

This paper proposes a new task for a humanoid designed to help people with reduced mobility: supporting a person while standing up. In the light of its novelty, this paper reviews the techniques currently used by human carers to perform the task and adapts them to define an initial posture and control algorithm for a humanoid robot. From the initial posture of the robot, with knees bent, feet apart and one foot in front of the other, one of the hands pushes the person from the lower back while the other hand supports the shoulder of the person. This initial posture is combined with a compliant control algorithm that calculates where the hand of the robot should move to keep an interaction force sufficient to support the motion of the person.

The task was tested on a humanoid robot interacting with a person making each hand of the robot follow the motion of the person’s back and shoulder separately. The initial position was proved to be stable throughout the experiment. During the experiment, several values of reference interaction force were tested and the parameters of the control law were tuned until obtaining a sufficiently smooth and supportive motion of the hands of the robot.

VI. FUTURE WORK

The next step to fully implement the task of helping a person from sitting to standing in a humanoid robot is to combine the compliant control of both hands which have been tested for this paper separately. Further research is required to isolate the effect the motion of the person and the parameters of the controller have on the oscillations around the force reference. Future work on improving the control strategy will also look into ways of setting the force reference more accurately, considering the circumstances of the person (mobility, weight); this work can look into measuring the actual interaction force that takes place between a human carer performing the task on a patient. More subjects will be used in the future to evaluate the performance of the task.

Currently, the hardware of the robot only allows sensing of the force applied to the whole hand. For this task, the robot should be able to sense the pressure applied along the palm and fingers of his hand. In that way, the position and orientation of the hands can be controlled, distributing the pressure sensed along the surface of the hand, thus making full contact with the back and the shoulder and reducing any physical discomfort that this interaction might cause to the person.

ACKNOWLEDGMENT

The authors would like to thank the Groupe d’Analyse en Ergonomie et de Formation at the Centre Hospitalier Regional Universitaire for their support.

REFERENCES


