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Sit-to-Stand Assistance with a Balancing Mobile Robot

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***Abstract*— This work presents a method for assisting people in getting out of chairs with a dynamically stable mobile robot. A user study is described in which force profiles and joint trajectories were recorded for a human-human sit-to-stand experiment. These data were used to develop an impedance-based controller designed to allow the ballbot to help people out of chairs. The control strategy is experimentally verified on the ballbot, a balancing mobile robot, exhibiting lean angles of over 15° and applying more than 120 N of assistive force . To our knowledge, this is the first mobile robot to assist people in standing.**

I. INTRODUCTION

Robots should help people out of chairs. Many people need assistance in standing which is both a nuisance and often a danger to the people who offer help. This is especially true for health care professionals. In 2011, hospital workers' injury rate from overexertion was twice that of the average across all industries. Nursing home workers were more than three times more likely to be injured with the greatest risk factor continuing to be the moving and lifting of patients [1]. In this paper, we present a first step toward easing the burden on health care professionals by employing a dynamically balancing robot, the ballbot, to help people get out of chairs.

Assisting people in getting out of chairs, or more formally: sit-to-stand (STS) assistance has had relatively little relevant literature. However, STS as an evaluative and rehabilitative measure has been studied for many years. Kerr et al. studied individuals sitting and standing, observing time of completion and separating the sitting motion into different phases: forward lean, knee extension, vertical displacement, and recovery [2]. This study noted that the elderly were slower in both sitting and standing. Sibella et al. found that obese individuals use less trunk flexion and consistently shift their feet back under the chair causing a lower hip torque but a high knee torque [3]. One study that actually looked at assistive technology in egress from chairs used an ejector seat [4]. It was found to relieve the hip torque demand for elderly people. This study also, however, highlighted that taller chairs are inherently easier to get out of, and may be preferred over an ejector.

Very little research has been conducted with human-scale robots assisting people physically with large forces.

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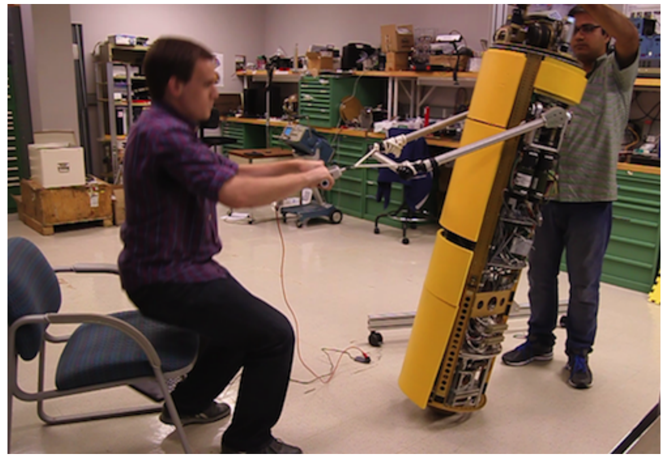


Fig. 1. The ballbot assisting a person out of a chair. The robot is leaning 15°, applying over 120 N of force. An experimenter stands behind the robot for safety

One recent exception is a study of human-robot cooperative manipulation [5]. In this case, it was actually preferable to keep forces between the robot and participant to a minimum, as high forces suggest disagreement. This study did measure forces up to 40 N, however, making it a physical Human-Robot Interaction (pHRI) study of human proportions with an assistive robot. Another robotic study with relevance to the topic of assisting seated individuals is the work [6] of Dautenhahn et al. This study, entitled, "How may I serve you?" investigated how best a robot should approach a seated person in an assistive scenario.

In this robotic assistance study, our experimental platform of choice is the ballbot [7], seen in Fig. 1. It is potentially a very interesting robot for pHRI, due to its inherent physical compliance and similarity in size to an average person. The ballbot will be discussed in more detail in Sec. III-A.

The rest of this paper will be organized as follows: Sec. II describes a human subject trial in which an experimenter assisted subjects out of a chair. Sec. III explains how the data from this subject trial motivated a control strategy for the ballbot. In Sec. IV, the control strategy is verified experimentally, and finally Sec. V and Sec. VI present the conclusions of this work and future directions.

II. HUMAN-HUMAN SIT-TO-STAND

A. *Subject Trial*

In order to gain insight for a robot assisted STS control strategy, a subject trial was conducted to observe how people help other people out of chairs. Fifteen subjects were recruited through online advertising to participate. Nine females and six males participated in the study. All were able bodied, ranging in ages from 18 to 63. The group's average self-reported familiarity with robots on a 1-7 scale was 3.07.

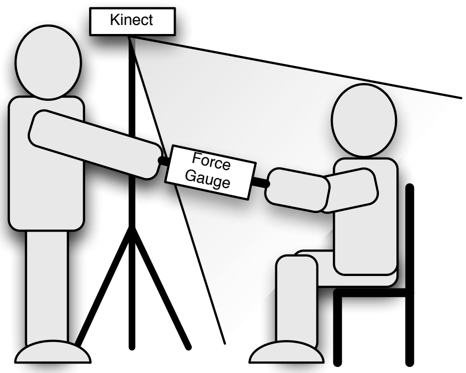


Fig. 2. Participants of the subject trial were assisted in rising out of a chair while their pose was tracked by a Microsoft Kinect. A force gauge measured how much force an experimenter provided in assistance.

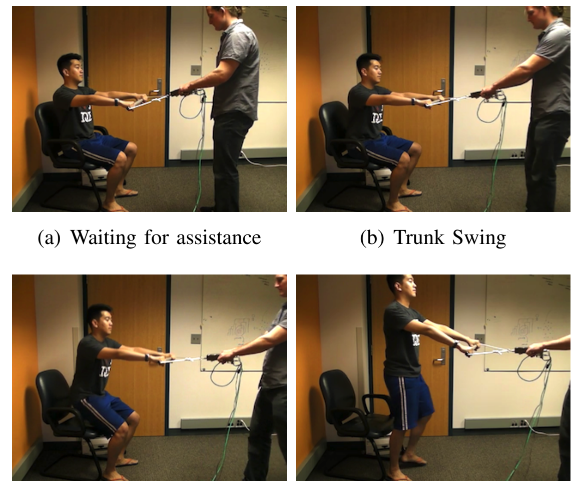
Participants were asked to sit comfortably in a chair. The experimenter, standing, offered the subject a bar attached to a force gauge which the subject could take with both hands. The experimenter then assisted the subject in rising from the chair, by pulling on the other side of the force gauge. During this operation, the subject would be tracked by a Microsoft Kinect running OpenNI [8] skeletal tracking software. A diagram of this experimental setup can be seen in Fig. 2.

Subjects were assisted in rising from four different chairs, four times each. They were free to place their feet wherever they preferred. Subjects were also assisted without the force gauge and given a questionnaire, however, these qualitative components of the study will be used for future work, as discussed in Sec. VI.

A subject can been seen participated in the experiment in Fig. 3. Fig. 3(a) shows the participant holding the bar attached to the force gauge waiting to start getting out of the chair. In Fig. 3(b), the subject begins to swing his trunk and then proceeds to extend his legs in Fig. 3(c). The subject is at a standing equilibrium in Fig. 3(d).

B. Force and Skeletal Data

Data from the subject trial was parsed into joint trajectories and corresponding force curves for each STS experiment. One such experiment's data can be seen in Fig. 4. The skeleton of the subject can be seen on the left with four colors: green, red, cyan, and purple showing the stages of getting out of the chair. The force curve on the right has four colored dots which correlate with the skeleton at each particular time.



(a) Waiting for assistance (b) Trunk Swing

(c) Leg Extension (d) Stable Equilibrium

Fig. 3. A subject is assisted by the experimenter out of the chair using a force gauge while being tracked by a Kinect.

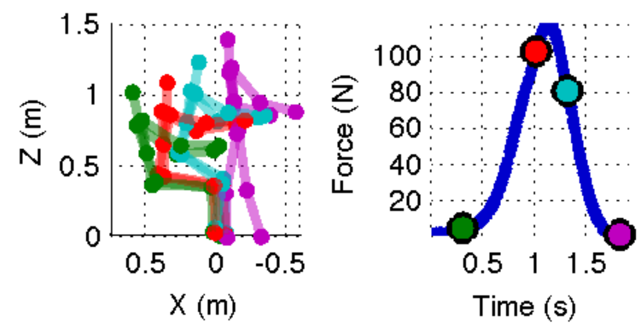


Fig. 4. Side view skeletal tracking data and force data for a single experiment. The color of the skeleton corresponds to the color dot in the force plot.

The joint trajectories were examined in an attempt to find the most consistent set of joints to use as a cue for the STS motion. The shoulder trajectory was found to be the most repeatable and intuitively shows a strong cue as to where in the STS motion a participant is. This follow naturally, as the shoulder trajectory can show both trunk swing and the rise in elevation from leg extension. One particularly consistent subject's data is shown in Fig. 5. The red lines show 11 trajectories of shoulder X and Z position along with the assistive pulling force. The blue lines show the average of all 11 trials, scaled in time to match starts and ends.

III. MODEL AND CONTROL

A. Ballbot

The ballbot is a mobile robot that balances on a single spherical wheel. Dynamically balancing affords the robot inherent compliance, making it a very interesting robot for pHRI [9]. For the purpose of assisting people in STS, a planar model of the system is used, as seen in Fig. 6. A planar model is appropriate as STS is a planar problem, symmetric about

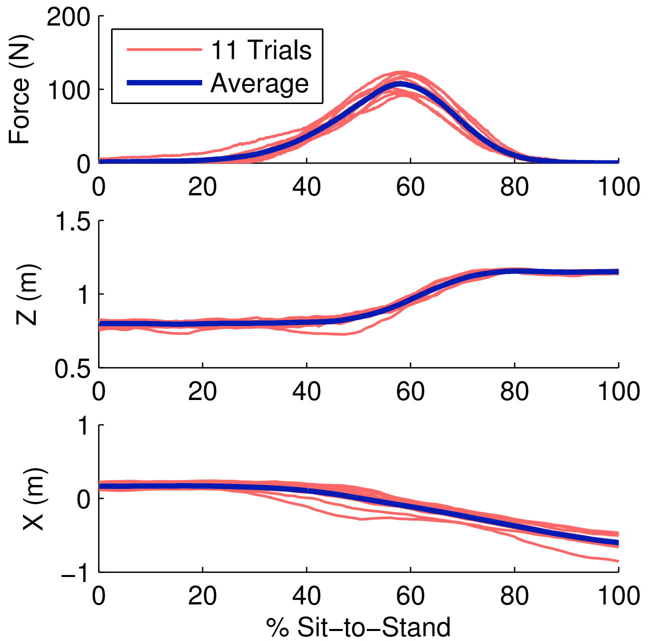


Fig. 5. Shoulder x and z coordinates for a single participant across 11 trials. The force and position for each trial are shown in red with the average shown in blue. The times have been scaled to match the starts and ends of each trial.

the sagittal plane. The ballbot has an independent yaw drive, which is assumed to account for any out of plane deviations.

The ballbot has two 2-degree-of-freedom arms which are used as passive arms and are treated as massless. The mass of the arms is insignificant with respect to the body, and for the purposes of STS, they are assumed to only apply tensile forces tangential to the arm. This means that all the force for assistance comes from leaning. This makes sense geometrically as the ballbot has no elbow joint. This also reduces the complexity of the problem.

Since the ballbot runs an inner-loop attitude controller [10], the problem of creating a desired force becomes one of finding the appropriate lean angle. To find this angle, a quasi-static assumption is enforced. Although STS is a dynamic maneuver, the largest component to the assistive force by far is the lean angle. Also, without this assumption, there is not a one-to-one analytic correspondence. With the quasi-static assumption, simply solving $\sum F_z = 0$ yields

$$F_{exp} = \frac{(M_b + M_w) g l \sin(-\phi)}{r + (d\cos(\phi)\cos(\frac{\pi}{2} - \psi))}. \qquad (1)$$

F_{exp} is the expected tensile force along the arm for a given lean angle, ϕ, and arm angle, ψ. The goal, however, is to find the appropriate lean angle for a force. Solving (1) for ϕ yields

$$\phi_{cmd} = atan2(\frac{rc + \sqrt{b^4 - b^2 r^2 + c^2 b^2}}{b^2 + c^2}, \frac{-r}{b} + \frac{c(rc + \sqrt{b^4 - b^2 r^2 + c^2 b^2})}{b(b^2 + c^2)}) \qquad (2)$$

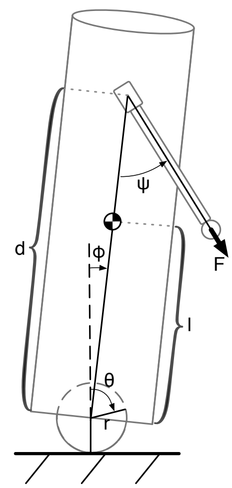


Fig. 6. The planar ballbot model with arms. State variables are lean angle ϕ, ball angle θ, and arm angle ψ. Distance from the center of the ball to the shoulder joint is d. Distance from the center of the ball to the center of mass (COM) is l, and the ball radius is r. F is the assistive force, in line with the arm. Not pictured, the mass of the ball (wheel) is M_w, and mass of the body M_b.

where

$$b = d\cos(\frac{\pi}{2} - \psi), \qquad (3)$$

$$c = \frac{(M_b + M_w) g l}{F_{\text{des}}}. \qquad (4)$$

There are actually two solutions for ϕ, but since F is constrained to be a positive tensile force, this is the only valid solution. (2) give the ability to replay force trajectories with the robot, as will be seen in Sec. IV-A.

B. *Impedance-based Controller*

Replaying force trajectories is not a tractable solution to the STS assistance problem. A human participant could easily miss the opportunity while the robot is pulling. As such, it is beneficial to design a control law that can reproduce the force trajectories from the subject trials, but using a cue that does not depend on time. As previously discussed, the shoulder position is a very repeatable cue to the state of the STS cycle.

A simple impedance controller is chosen which acts simply as a spring-damper system

$$F = k(s_{\text{eq}} - s_{xz}) - b\dot{s}_{xz} \qquad (5)$$

where s_{xz} is the shoulder position in the X-Z plane, s_{eq} is the equilibrium position of the shoulder where no force is applied, and $\dot{s}_{xz}$ is the velocity of the shoulder. Motivation for such a control law comes from active prosthetics [11]. Sup et al. use piecewise impedance functions in different phases of the gait to control a transfemoral prosthetic. These control laws are appealing as they are simple for the user to comprehend and individually stable. For the STS maneuver, two control phases are chosen. This is because of the two natural equilibria at the start and end of the STS. As such, k, b, and s_{eq} in (5) are set by

$$k, b, s_{eq} = \begin{cases} k_1, b_1, s_{eq1} & \text{if } s_z < z_{thresh} \\ k_2, b_2, s_{eq2} & \text{if } s_z > z_{thresh}. \end{cases} \tag{6}$$

To find the optimal k_1,b_1,k_2,b_2, s_{eq1}, and s_{eq2}, the sum squared difference between the average force trajectory from the human subject trials and the output of (5) is minimized:

$$\min \quad \sum_i^n (F_{\text{des}} - F)^2. \tag{7}$$

This is accomplished via an SQP solver in MATLAB. The optimal k's and b's are $k_1 = 392.1$ N/m, $b_1 = 0.0$ Ns/m, $k_2 = 324.3$ N/m, $b_1 = 16.77$ Ns/m. The optimal equilibrium positions are shown in Fig. 7 in black, plotted on top of the average shoulder trajectory. The equilibrium points lines up

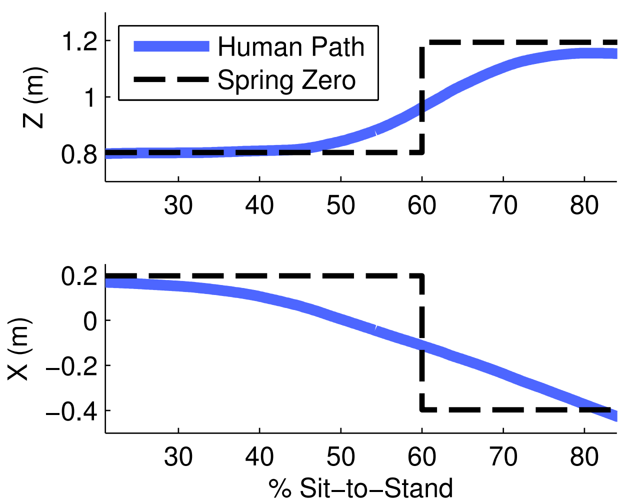


Fig. 7. Shoulder trajectory (blue) in x and z as shown in Fig. 5. The dashed black line shows the equilibrium position of the impedance controllers, optimized to fit the data. Unsurprisingly, the equilibria are very close to the initial and final positions of the subject's shoulder.

very nicely with the start and end of the shoulder trajectory. This is to be expected as there is no assistive force required at the start or end of the STS. The force profile from the optimized values can be seen in Fig. 8. Because the output is discontinuous at the switching point, a low-pass filtered signal is also plotted with a time constant of 50 ms. This is an empirically chosen value to avoid exciting any higher order modes in the system.

Notice that the first phase of the controller which is active during the trunk swing and beginning of leg extension is not actually acting like a "spring." In fact, it behaves as an anti-spring, with s_{eq1} as an unstable equilibrium. This is a necessary behavior as the first half of this assistance must input energy to the system. Furthermore, it must increase in force as the body moves. This is also not a problem as the robot will only apply tensile forces, so it cannot push the participant down into the chair past the s_{eq1}.

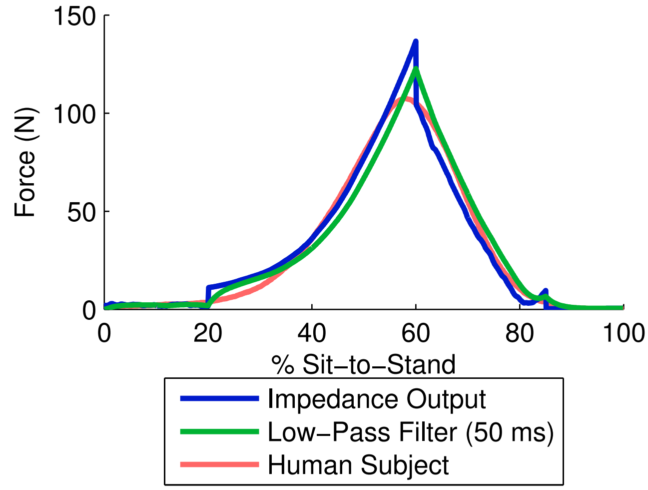


Fig. 8. Average force profile from human subject (orange) shown against the output of the impedance based controller (blue). The output of the controller is discontinous and as such is filtered to ensure smooth operation. A first order low pass filter with 50 ms time constant is shown in green.

IV. EXPERIMENTAL VALIDATION

Three sets of experiments were carried out to assess the validity and feasibility of the proposed STS assistance method. Lean angle trajectories were replayed to assess the ability of the system to track large lean angles. Next, force trajectories were replayed on the system, taking into account arm angle. Lastly, the full controller was tested. An experimenter stood in as the STS participant.

To ensure safety, the robot was tethered with a slack line to an aluminum frame overhead. This ensured that if the ballbot went unstable, it would not fall on any experimenters. The tests were also done with another researcher near the emergency stop on the robot, which disables power to the ball motors and the arms.

The lean angle tracking from the first set of experiments is shown in Fig. 9. The RMS error is $.18°$ with a maximum deviation of $.7°$ at the max lean angle of $12.4°$.

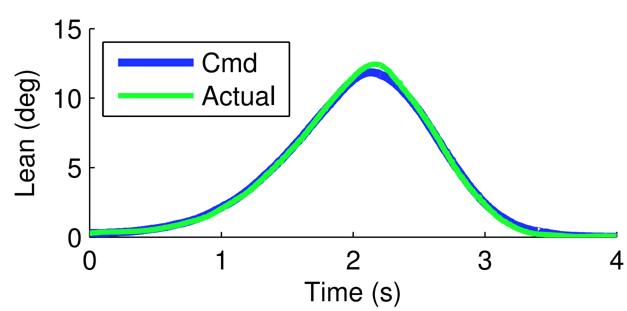
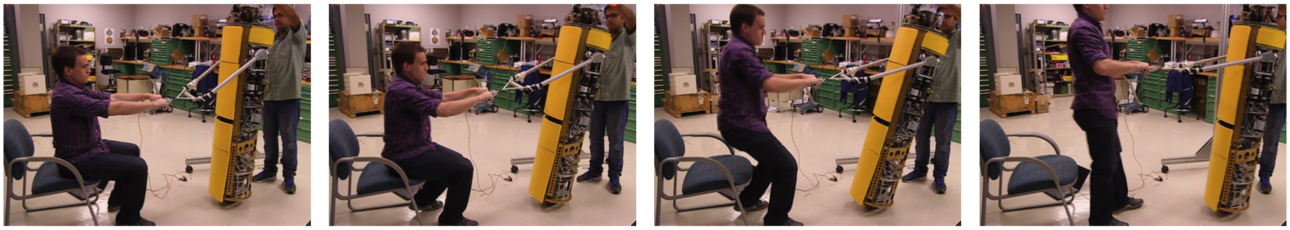


Fig. 9. Desired and actual lean angles from a replayed force trajectory

A. *Force Trajectory Replay*

A replay of the average human subject force trajectory on the ballbot is shown in Fig. 11. This experiment attempted



(a) Preparing to rise (b) Trunk Swing (c) Leg Extension (d) Standing Equilibrium

Fig. 10. The ballbot assisted a person in standing using the impedance based controller. In (c), the robot is applying over 100 N of assistive force. An experimenter stands behind the robot in the event of a failure to press the emergency stop.

to create the same force profile as the average human subject trial, taking into account the arm angle, ψ, dynamically. Note that there is no direct feedback on this force, as there is on lean angle. Still, the tracking is acceptable and stable with the RMS error of 16.2 N, however the maximum deviation was 38.5 N.

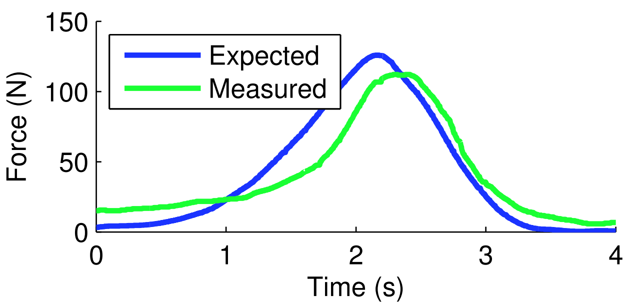


Fig. 11. Desired and actual force from a replayed force trajectory. This takes the arm angle ψ into account from (2)

B. Impedance Controller

To run the impedance-based controller, the shoulder position of the subject must be known to update the control law. To avoid the risk of poor quality live skeletal tracking, it was assumed that the subject's hands were holding the ballbot's arms for the duration of the experiment and that their relative geometry did not change.

The low pass filter shown in Fig. 8 was used to smooth discontinuities. Furthermore, b_2 was empirically lowered to from 16.77 to 5 Ns/m. Lastly a debounce timer of 300 ms was put into the switching law prohibiting the system from switching states more frequently than every 300 ms. This was done to avoid instability caused by nuisance switching at the boundary of the two controller regions.

The result of this experiment is shown in both Fig. 10 and Fig. 12. Fig. 10 shows the participant being assisted by the ballbot throughout the course of an STS.

Fig. 12 shows the force applied to the participant over the course of experiment. Note that the profile is markedly distinct from Fig. 5 because the participant chose to get up more slowly, taking 12 seconds to complete the STS. This shows one of the main advantages of this method. The assistive force is dependent on the position of the participant, which they have control over.

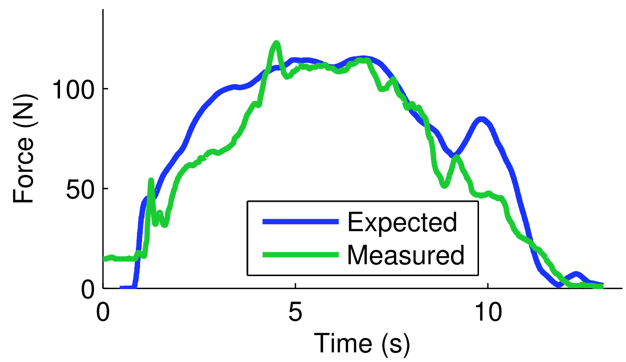


Fig. 12. Desired and actual force using the impedance based controller. These desired and actual forces correspond to the experiment shown in Fig. 10

V. CONCLUSIONS

This work has presented a method for assisting people in getting out of chairs with the ballbot. Using force and joint data gathered through human subject trial, an impedance-based controller was designed and experimentally validated. The feasibility of this control scheme was demonstrated on the ballbot assisting a person with over 120 N of force. This is a step toward robotic technology influencing people's daily lives for the better.

VI. FUTURE WORK

Although the feasibility of this approach has been demonstrated, testing in a user study could determine if this technology could be accepted. The next extension of this work should be adjusting the controller for elderly and non-able-bodied individuals. Also, different cues to switch between control parameters should be explored. This could also be solved with integrated real time robust skeletal tracking. Since only the position of the shoulder axis is necessary for this method, an upper body tracker could be used. Experiments are planned to first use fiducials on a participants chest for initial validation.

It is also desirable to install force sensors on the ballbot's arms and close the force loop. This would enable better force tracking, though may not be as stable as the current method inherently maintains a smooth lean angle command. Having individual force sensors in each arm would also enable yaw compensation. The current method assumes a motion symmetric about the sagittal plane, but some individuals may prefer more force on one side or using one arm to push off an armrest.

Lastly, contingencies must be explored before testing this system outside of a slack-line harness. If the STS participant lets go of the robot while it is executing a large lean angle, it will have to generate a recovery trajectory very quickly [12]. This must all be integrated into the software before larger scale testing is possible.

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