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A Handle Robot for Providing Bodily Support to Elderly Persons

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Abstract— **Age-related loss of mobility and an increased risk of falling remain major obstacles for older adults to live independently. Many elderly people lack the coordination and strength necessary to perform activities of daily living, such as getting out of bed or stepping into a bathtub. A traditional solution is to install grab bars around the home. For assisting in bathtub transitions, grab bars are fixed to a bathroom wall. However, they are often too far to reach and stably support the user; the installation locations of grab bars are constrained by the room layout and are often suboptimal. In this paper, we present a mobile robot that provides an older adult with a handlebar located anywhere in space - "Handle Anywhere". The robot consists of an omnidirectional mobile base attached to a repositionable handlebar. We further develop a methodology to optimally place the handle to provide the maximum support for the elderly user while performing common postural changes. A cost function with a trade-off between mechanical advantage and manipulability of the user's arm was optimized in terms of the location of the handlebar relative to the user. The methodology requires only a sagittal plane video of the elderly user performing the postural change, and thus is rapid, scalable, and uniquely customizable to each user. A proof-of-concept prototype was built, and the optimization algorithm for handle location was validated experimentally.**

I. Introduction

As the COVID-19 pandemic rages on, over 800,000 adults aged 65 or older have died of COVID in the U.S. alone [1]. The pandemic has severely impacted all in-person eldercare services, including assisted living facilities, visiting nurses, and home care; many people have lost care services and community interactions. Furthermore, elders and their families are increasingly favoring aging in place options rather than nursing homes. The current work was motivated by the need for delivering high-quality eldercare services regardless of living location in a manner that is pandemic resilient.

Roughly 25 million Americans rely on help from caretakers and use assistive devices such as canes, walkers, raised toilets or shower seats to perform essential daily activities [2]. Falls represent a major risk, especially for isolated seniors, as the vast majority of falls occur when an elderly person is alone [3]. Thirty percent of people over the age of 65 fall each year, with falls listed as a contributing factor to 40% of nursing home admissions [4]. In a hospital study, almost 80% of patients who fell were unassisted, and 84.7% of total falls happened in the patient's room [3]. Lost balance was the prevailing reason given by patients, and the most common activities at the time of a fall were ambulation, getting out of bed, and sitting down or standing up – all activities requiring significant changes in body posture, often with physical assistance from a person or a device [4].

TABLE I. Comparison of Assistive Home Devices for the Elderly

Device	Uses	Limitations
Transfer sling	Supports transfers to/from a bed, wheelchair, car, etc.	Requires a human to operate
Patient lift (Hoyer lift)	Supports transfers in and out of a bed and/or bath.	Expensive; narrowly tailored for specific tasks
Walk-in shower	Allows an elderly person to safely enter a shower	Expensive; requires home renovation
Grab bar	Provides support for various activities	Placement constrained by room layout; only provides support in vicinity of bar

Existing elderly assistive devices are effective for specific use cases, but their applications are often limited, as shown in Table 1. Some devices, such as transfer slings, require another person to set up and deploy, and are thus of limited use outside of institutional care settings. In addition, most are tailored for only a specific task or set of tasks. A patient lift - also known as a Hoyer lift - can be used by seniors to get in and out of bed [5], but offers no help with toileting, ambulating, or navigation. Barrier-free home improvement provides elderly people with some supports such as widening doorways, installing stair lifts and replacing bathtubs with walk-in showers [6]. While these environmental modifications can improve access, they are targeted to specific areas and activities, are generally very costly, and require a lot of time to install. The disturbance to daily life during installation can be a formidable challenge to many seniors.

Among the most widely used household balance and transfer aids, grab bars are often prescribed to seniors to assist with mobility [7]. Grab bars are handlebars attached to walls and hard surfaces in critical locations – near bathtubs, on the sides of toilets, and adjacent to doorways – that elderly people can grab for bodily support. In one study, 87% of seniors who had installed grab bars reported using them for assistance on a regular basis [7]. Besides providing assistance with various tasks, they have also been shown to reduce the incidence of falls in certain scenarios [8]. However, the placement of grab bars is a major challenge, since they must be rigidly attached to a nearby surface, are constrained by the room layout, and are not adaptable from individual to individual. This sometimes leads to inappropriate bar locations for diverse activities, which may increase fall risk. Furthermore, since the bars are fixed, they must be installed in every high-risk area, which is often

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costly. Once the user is finished using a grab bar for assistance, it provides no further support for other activities. A moveable tension pole has been proposed as a means to assist with both walking and standing [9], though this device requires a continuous flat ceiling and cannot travel through doorways.

The necessity for physical support, both to reduce falls and to improve quality of life, highlights the need for a comprehensive assistance system that can be deployed to help elderly persons navigate the home environment. The goal of the current work is to extend the functionality of the widely-used grab bars such that they can be available anywhere within the environment (e.g. home or nursing home) and adaptable to the individual's needs and location. We propose to use a mobile robot with a repositionable handlebar that can provide a point of support for various activities requiring postural change, including bathing, sit/stand transfers, and toileting. The support is both physical (through offloading body weight onto the handle) and cognitive, as previous research has shown that providing contact cues at the fingertip can reduce postural sway by 50-60% [10]. By placing the handlebar effectively based on the user's body pose, we hope to emulate the assistance given by a human caretaker, thereby potentially decreasing the need for human physical assistance. Unlike a human caretaker, the robot can provide every elderly person with personalized assistance 24/7, which is especially important given that 58.5% of falls occur at night [3]. To overcome the challenge of providing safe care with a fully autonomous system, we place a human in the loop to remotely monitor and control the robot's movements when necessary. This has the added benefit of making the support system pandemic resilient, allowing a caregiver to access older adults without being physically present.

Our target population for this device consists of elderly people who retain sufficient muscular strength to safely support themselves at a constant posture, but have difficulty performing activities that require postural changes. Currently, mobility assistance devices are prescribed depending on both the user's movement ability and their home environment [11], either through the use of a simple patient questionnaire to assess functional independence (such as the Barthel index) or via quantitative measures of motor performance. Guidelines from the U.S. Centers for Medicare and Medicaid Services regarding the frequency of weight-bearing [12] indicate that our device would be most suitable for patients who benefit from a standard or offset cane (minimal to intermittent weight-bearing). This encompasses up to 16.4% of the elderly population, or 5.8 million people [13].

Compared to existing eldercare robots [14], our system is unique in that it specifically emulates the functionality of a grab bar. Most existing eldercare robots are narrowly tailored towards supporting a predefined postural change (e.g. sit-to-stand) [15] or dynamic movement (e.g. walking) [16]. We hope to overcome these limitations in functionality by focusing on static bracing for common activities of daily life, which has the advantage of being both relatively safe (as the robot does not perturb the human) and widely flexible, encompassing every activity where the user is within reach of the handlebar.

In the following, we describe the design concept of a remotely controllable robotic support system, Handle Anywhere, along with a methodology for determining how to best place the handlebar. The handle placement methodology is tested experimentally using the robotic system, and its efficacy is evaluated based on quantitative metrics (e.g. force exerted on the handlebar) and qualitative feedback from the user. Furthermore, the remote operation of the system is demonstrated with a professional caregiver accessing the robot from a hospital.

II. Robot Design and Implementation

Our general idea is to extend the concept of grab bars such that they can be positioned anywhere in the home. We developed a list of functional requirements for the design and physical dimensions of the robotic system based on the characteristics of our target population, which consists of elderly people who require support and mobility assistance. These requirements reflect the interrelated goals of utility, feasibility, and technological acceptance, and can be separated into stipulations for the physical construction of the robot (first three bullet points) and its control and operation (final two bullet points).

- Provides both haptic and body-weight support via a handlebar
- Handlebar can be positioned arbitrarily, to assist with different activities of daily living
- Can navigate the standard home environment
- Human-in-the-loop: for safety, robot must be controlled by a caretaker if necessary
- Capable of remote teleoperation, so a caretaker is not required to be physically present

To further determine design specifications, we consider typical use scenarios and environment conditions, as shown in Fig. 1. The robot must be able to maneuver thorough a confined space such as a bathroom or a bedroom. If the elderly person is in bed and desires to sit up, we would like to be able to place the handlebar based on his or her current body position (Fig. 1, top left). The handle should also be able to assist the user during ambulation sequences; for example, by helping the user stand up in a bathtub (green-colored pose, Fig. 1, top right) and then step over the bathtub lip (normal-colored pose). In addition, the system should provide the caretaker with the ability to execute a sequence of steps for a complex motion, such as getting out of bed. Such an action requires repositioning the handlebar to offer lie-to-sit support, sit-to-stand support, and assistance navigating the room.

These functional requirements were realized through our implementation of the robotic system, which consists of a 6-

In the bedroom: lie-to sit and sit-to-stand transitions   Entering or exiting a bathtub

Figure 1. Example robot usage scenarios.

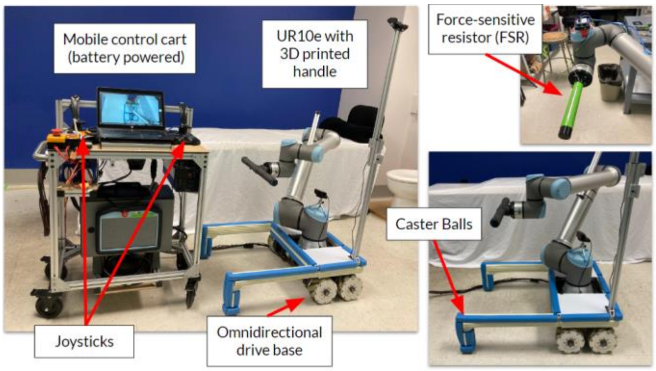


Figure 2. Handle anywhere robot system.

TABLE II. DESIGN CONSIDERATIONS FOR THE ROBOT DIMENSIONS

Dimension	Value	Rationale
Drive base width	66 cm	Most common home doorways are ≥ 71 cm (28”) wide [17]
Drive base length	84 cm	Allows for a 48 cm U-shaped drive base for elderly person to stand/walk in
Handle length	46 cm	Sufficient for a two-handed grip
Handle diameter	3.8 cm	Ergonomics studies suggest an optimal range of 3.56-4.06 cm [18]
Handle reach from robot	44 cm	Limited to this value to prevent the robot from tipping

DOF Universal Robotics UR10e arm mounted on a custom-made omnidirectional vehicle with four Mecanum wheels (Fig. 2). The flat, U-shaped base was designed to fit underneath common bed and table configurations, and provides a space for the elderly person to stand in. At the end of the robot arm, we attached a T-shaped handlebar instrumented with a 6-DOF force/torque sensor and embedded grip sensors. The use of a UR10e allowed the handle to be placed in any arbitrary position and orientation. Both the vehicle and the handlebar were padded with thick foam to reduce the chance of injury; in the case of the handle, this also served to increase grip friction and prevent the user’s hands from slipping. The dimensions of the drive base and handle, presented in Table 2, were chosen based on empirical ergonomics research and typical home layout constraints. In addition, the UR10e control box and all power equipment were mounted on a battery powered mobile cart to make the robot more compact and maneuverable.

To satisfy the requirements for versatility and human-in-the-loop control, as well as for remote teleoperation, we adopted a semiautonomous control scheme where the robot movement was overseen and controlled by a human operator with various tools (Fig. 3), in a form of human supervisory control [19]. This scheme allows a caretaker to monitor/assist a patient’s movements remotely via an internet link to the robot. The robot has the capability of moving autonomously, so that the handlebar and/or drive base can be positioned automatically, but the robot’s movements can be overridden at any time by the remote human operator. We envision this teleoperation paradigm as a step towards pandemic-resilient eldercare, since our system enables a caregiver to physically support elderly users without having to be present in person.

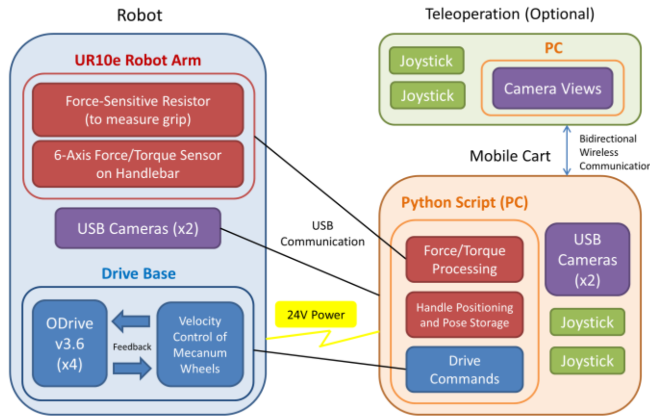


Figure 3. Block diagram of the robotic system. The UR10e interfaced with the Python script using URScript’s interpreter mode. All actuators were controlled using a proportional-derivative (PD) control scheme.

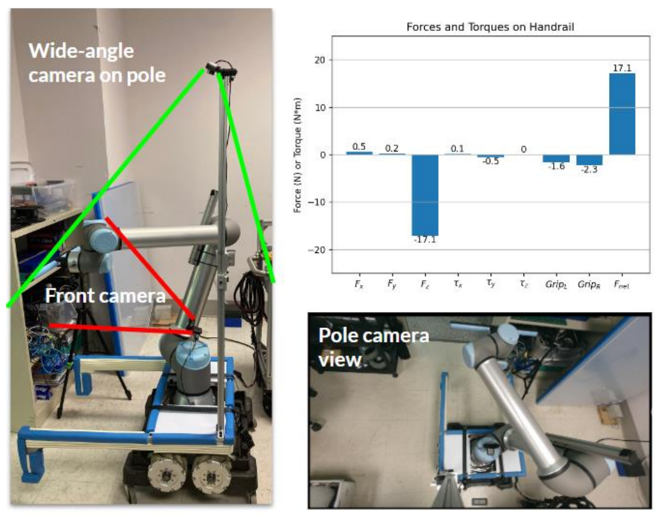


Figure 4. Caretakers’ view during teleoperation.

Four camera views (two from the robot, two from the cart) along with a graph of the 6-axis force and torque data, grip strength on the left and right of the handle, and net applied force (Fig. 4) were transmitted to a remote computer using Parsec. The cameras were mounted to provide a front view of the patient as well as a wide-angle view of the robot and its surroundings. Joysticks were used for human control of the robot. The operator could change the handlebar’s height, distance from the center of the robot arm, and rotation relative to the mobile base. The actuators were controlled by PD position or velocity control, with a safety stop to prevent injury to the user. Since the mobile base allowed for holonomic movement, each degree of freedom was mapped to a 3-axis joystick (the 3rd axis being the rotation of the joystick). In addition, the robot had the capability to switch to “freedrive” mode, whereby the handlebar could be manually positioned by an in-person caretaker. This allowed for the user’s preferred handlebar placements to be saved and retrieved from memory.

A live bidirectional audio and visual link enabled the caretaker to communicate with the user and receive consent for each movement. Depending on the user’s feedback, the caretaker could modify the handle position to better support the patient. Continuous force and grip monitoring would alert the operator when the user grabbed or released the handle, and if the net weight on the handlebar exceeded the payload of the UR10e, the movement of the robot would cease and the system would enter a protective stop.

While the robot hardware allowed for the handlebar to be used to apply a force on the user (e.g. pulling them up from a chair), we constrained the handlebar to be completely stationary while the user grabbed onto it. From our experience, elderly adults tend to be afraid of assistive devices that might move when they are not expecting it, as they fear such a movement might cause a fall or a slip. Since our target users are expected to shift a significant amount of their body weight onto the handlebar, we believe that a stationary handle will be perceived as safer and more trustworthy, especially since elderly adults are already familiar with grab bars. Therefore, to increase adoption of the robot system and to eliminate any possibility of the robot triggering a fall, we decided to rigidly fix the handlebar in place while it actively supported the user.

The robot system was tested remotely with a physical therapist at Spaulding Rehabilitation Hospital, and was confirmed to work as a proof-of-concept of remote eldercare. The physical therapist was able to successfully teleoperate the robot and position the handlebar to assist with toileting and bathing. Future work involves eliminating the mobile cart, which was a necessity to house the control box of the UR10e, so that the robot can be truly untethered as originally intended.

III. Optimization of Handle Location

This section develops a generalized mathematical model to find an optimal location of the handlebar relative to the user's position. The model is subsequently implemented on the Handle Anywhere robot to maximize the utility provided by the handlebar, and to assist the teleoperator with positioning the handlebar for the elderly user.

A. Analysis

We assume that the body movement is quasi-static, ignoring inertial forces acting on the body. This is a reasonable assumption, considering that movements of older adults are relatively slow. For modeling purposes, we also assume that the process is lossless in that all the joint torques generated at the user's arm are transmitted with no internal loss.

Consider a Center of Mass (CoM) of the entire body. When a user performs a body motion, such as getting up from a chair, the body will move at both a linear and angular velocity at the CoM, which are collectively denoted as $\dot{p}_{CoM} \in \mathcal{R}^6$. Let $W_{CoM} \in \mathcal{R}^6$ be a wrench (force and moment) generated at the CoM by the arms holding the handlebar, as shown in Fig. 5. To evaluate the effectiveness of the wrench W_{CoM}, consider the power transmitted to the body moving in the direction of $\dot{p}_{CoM}$:

$$P = {W_{CoM}}^T \dot{p}_{CoM} \tag{1}$$

If the wrench acting at the CoM is not aligned with $\dot{p}_{CoM}$, there must be a component of W_{CoM} perpendicular to $\dot{p}_{CoM}$. This component $W_\perp$ does not contribute to the power for moving the body in the direction of $\dot{p}_{CoM}$. Given that the

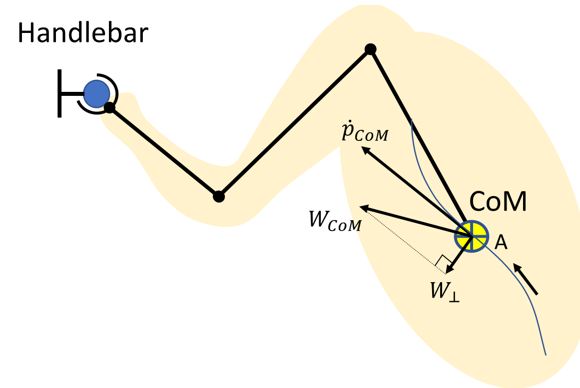


Figure. 5. Force and torque wrench w_{CoM} and velocity $\dot{p}_{CoM}$ generated by the arms on the body's center of mass (CoM).

strength of the arms is limited, the most effective W_{CoM} is the one aligned with $\dot{p}_{CoM}$. Therefore, we aim to generate a W_{CoM} such that

$$W_{CoM} \;//\; \dot{p}_{CoM} \tag{2}$$

This can be achieved by selecting joint torques τ such that $\tau = J^T(c \cdot \dot{p}_{CoM})$, where c is an arbitrary scaling constant. Thus, only the ratio of the torques $\tau_1 : \tau_2 : \ldots : \tau_n$ is important for our analysis.

The human arm can be modeled as a kinematic chain consisting of an n degree-of-freedom serial linkage with joint displacements $q \in \mathcal{R}^n$, and joint torques $\tau \in \mathcal{R}^n$. While real human arms have complex musculoskeletal properties, we simplify them to n joint torques, which are aggregate muscle forces reflected to the individual joints. The CoM linear and angular velocity $\dot{p}_{CoM}$ is related to the joint velocities $\dot{q}$ by the Jacobian matrix J: $\dot{p}_{CoM} = J\dot{q}$, which also relates the joint torques to the wrench W_{CoM} as

$$\tau = J^T W_{CoM} \tag{3}$$

For the user to effectively support their body weight without exerting a large muscle effort, it is desirable to generate a large W_{CoM} magnitude using small joint torques. In other words, we want to maximize the mechanical advantage defined by

$$MA = \frac{|W_{CoM}|}{|\tau|} \tag{4}$$

As the arm linkage approaches a singular configuration, this mechanical advantage rapidly increases. However, the body must be moved at the desired linear and angular velocity $\dot{p}_{CoM}$. Treating the arm structure as a multi-input, multi-output transmission mechanism, a spatial "gear ratio" or a type of manipulability [20] can be defined:

$$GR = \frac{|\dot{p}_{CoM}|}{|\dot{q}|} \tag{5}$$

In this system, there is an inherent tradeoff between mechanical advantage and gear ratio. We desire to position the handlebar to maximize the mechanical advantage while applying a penalty for reduced gear ratio, since with a lower gear ratio, the patient will have difficulty in following their desired body trajectory. We therefore consider an index L that is the product of mechanical advantage and gear ratio:

$$L = MA \times GR = \frac{|W_{CoM}|}{|\tau|} \cdot \frac{|\dot{p}_{CoM}|}{|\dot{q}|} \tag{6}$$

From the alignment condition (2), the inner product of W_{CoM} and $\dot{p}_{CoM}$ is reduced to

$$W_{CoM}{}^T \dot{p}_{CoM} = |W_{CoM}||\dot{p}_{CoM}| \tag{7}$$

due to the loss-less assumption,

$$W_{CoM}{}^T \dot{p}_{CoM} = \tau^T \dot{q} = |\tau| \cdot |\dot{q}| \cos(\phi) \tag{8}$$

where ϕ is the angle between vectors τ and $\dot{q}$ in joint space. Substituting (7) and (8) into (6) yields

$$L = \frac{\tau^T \dot{q}}{|\tau| \cdot |\dot{q}|} = \cos(\phi) \tag{9}$$

Note that since the joint torques τ are related to W_{CoM} via the Jacobian matrix J, which varies depending on the joint angles q, the index L varies depending on the joint angles. Namely, it changes depending on the location of the handlebar relative to the shoulder and the center of mass. Our goal is therefore to find an optimal handlebar location that maximizes the index L with regard to the joint angles q.

$$q^o = \arg\max_q L(q) \tag{10}$$

The optimal handlebar location does not depend on the magnitude of force and moment, but on the angle between vectors τ and $\dot{q}$ in the joint space. When L is maximized, there should be an optimal balance of mechanical advantage and manipulability (gear ratio) for the handlebar user.

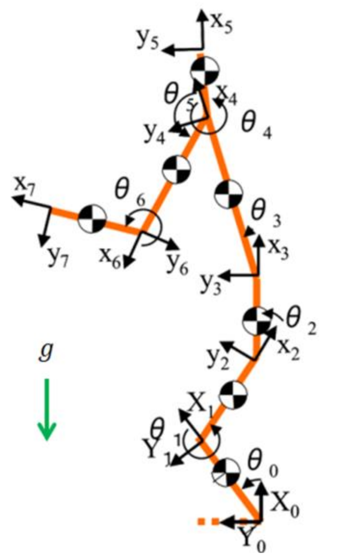
B. Implementation

We made the following assumptions to simplify the analysis and computation required for implementing the model on the Handle Anywhere robot, such that the various parameters necessary for the optimization problem (CoM, $\dot{p}_{CoM}$, etc.) can be rapidly estimated from a single video of the person performing the action. This enables the robot to generate a customized handlebar placement for each individual user, across a wide range of activities.

- For many activities of daily living, body movement is largely confined to the sagittal plane, so we represented the user's body and the handlebar location in this plane (Fig. 6).
- The optimal handlebar location was determined at a single point along a trajectory of body movement: point A shown in Fig. 5. Body posture varies continuously in any movement scenario, and therefore the optimal handlebar location changes depending on the current body posture. We assumed that there is a particular posture along the trajectory where the user experiences the hardest challenge in moving their body, and we placed the handlebar so that the index L was optimal with respect to that body pose. The handlebar is therefore stationary, but it provides the maximal support when it is most challenging for the user to move their body.
- The moment created by the arms around the CoM was assumed to be zero. Namely, the reaction force from the handlebar was assumed to pass through the CoM.
- The CoM of the body was computed without the arms, so that the CoM does not change based on the handlebar location, assuming that the person grabs the handlebar by only moving their arms. We further enforced this assumption by limiting all possible handlebar locations to be within reach of the arms. Since the arms only encompass 7.5% of the total body mass, little information is lost. The CoM was thus calculated as follows, using the links in Fig. 6:

$$X_{COM} = \frac{1}{M}\sum_{i=0}^{4} m_i x_i$$

$$Y_{COM} = \frac{1}{M}\sum_{i=0}^{4} m_i y_i$$



Link	% of Body Mass
0	7.97%
1	13.54%
2	34.46%
3	25.93%
4	10.65%
5	4.19%
6	3.25%

joint 0 : ankle
joint 1 : knee
joint 2 : greater trochanter
joint 3 : iliac crest
joints 4 and 5 : acromion
joint 6 : elbow
joint 7 : wrist

Figure 6. Model of human body composed of seven linkages, adapted from T. Hatsukari et al. [15].

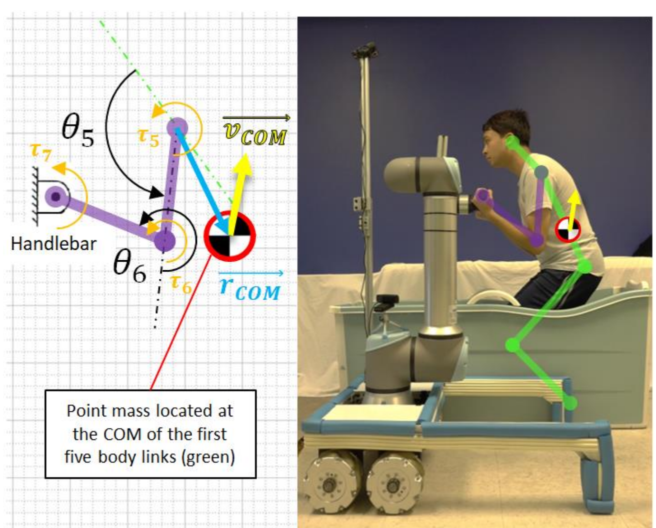


Figure 7. Diagram of the arm serial linkage (left), including the joint torques. The first five links of the body (green, right) are consolidated to a point mass located at the center of mass.

With the arms modeled as a 3-bar linkage, muscle effort is represented via joint torques τ_5, τ_6, and τ_7, acting on θ_5, θ_6, and the end of link 6 (at the origin of frame x_7, y_7), respectively (Fig. 7). We use the joint representation described by Hatsukari et al. [15] with a slight modification: both θ_4 and θ_5 are measured from the coordinate frame x_4, y_4 so that the arm and head angles are relative to the trunk. Each of the links was given a mass based on the physical composition of the corresponding part of the human body, based on standard biological measurements [21], with some links absorbing the mass of multiple body parts (Fig. 6). All masses were normalized so that the sum of the links was the total mass of the body.

Three scenarios (Fig. 8) were selected as representative and diverse examples of activities that elderly people have difficulty performing: sit-to-stand from a bed, squat-to-stand in a bathtub, and sit-to-stand from a toilet [22]. An adult volunteer (23 years old, 60 kg) was filmed in the sagittal plane performing each scenario without any assistance. The experiment was reviewed and approved by the MIT Committee on the Use of Humans as Experimental Subjects (COUHES) under IRB number 2207000712. Afterwards, he identified the body poses that required the maximal muscle exertion, and the body model was manually traced onto his body in a vector graphics program (Fig. 8). The normalized velocity vector of the first five links, $\overrightarrow{v_{CoM}}$, was calculated by analyzing several frames of the recording of the movement. For each scenario, the corresponding optimum handlebar location was determined via numerical analysis. Given a CoM position and velocity, the analysis iterated over all permissible values of the arm joint angles θ_5 and θ_6 and joint torques τ_5, τ_6, and τ_7 to find the combination that yielded the maximum value of the L-index. The arm joint angles were limited to an acceptable region D based on the comfortable range of motion of the arms in each scenario.

$$\begin{pmatrix} \theta_5^o \\ \theta_6^o \end{pmatrix} = argmax\ (\cos\phi), \text{ s.t.} \begin{pmatrix} \theta_5 \\ \theta_6 \end{pmatrix} \in D \qquad (12)$$

With these joint angles, forward kinematics could be used to calculate the corresponding handlebar location relative to the user. For all of the scenarios, our analysis successfully converged to a unique solution for the handlebar placement; these were evaluated in section IV.

IV. Experimental Results

For a representative sit-to-stand scenario, Fig. 9 shows the mechanical advantage (eq. 4), gear ratio (eq. 5), and L index across a region of allowable handlebar locations. The plots show the complex, nonlinear relationship between the arm angles and each metric. It can be seen that arm configurations that maximize only the mechanical advantage or gear ratio are highly inflexible for any dynamic movement, as the handlebar is positioned very close to the user's body. It should be noted that the tradeoff between mechanical advantage and gear ratio/ manipulability is highly dependent on the joint torques. Since the torques are constrained to generate an endpoint force W_{CoM} aligned with $\dot{p}_{CoM}$, the peak L index for motions with a different acceptable handlebar region D and CoM trajectory $\dot{p}_{CoM}$ can be significantly smaller than the peak value of 1 in the scenario presented in Fig. 9.

Figure 8. Human subject at the point of most difficulty (maximal muscle exertion) for three activities of daily living. Also shown is the position (red circle) and normalized velocity (yellow vector) of the center of mass of the first five body links.

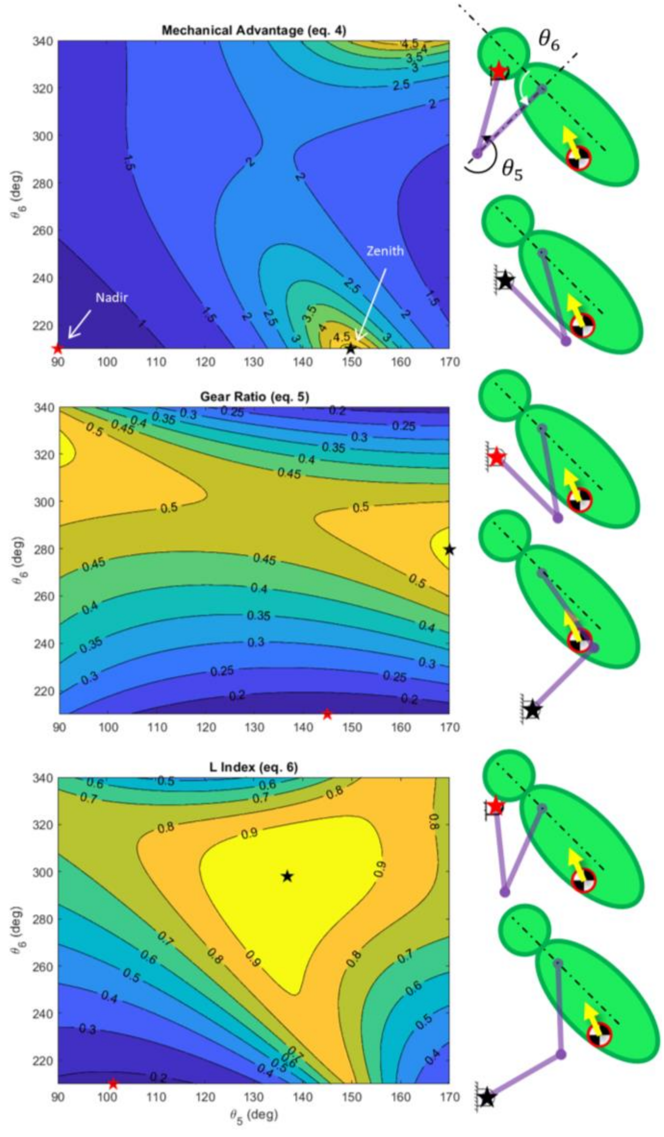


Figure 9. Mechanical advantage, gear ratio, and the L index plotted against an acceptable region D of shoulder (θ_5) and elbow (θ_6) angles, for a representative sit-to-stand scenario. The corresponding arm configurations at the nadir (red star) and zenith (black star) of each metric are shown on the right, visualizing their relationship with the human subject's CoM and instantaneous velocity (yellow arrow) at the point of maximal exertion.

Using the methodology in the previous section, we calculated a pose for the handle in each of the three scenarios. The scenarios were re-enacted with the handle in place, as shown in Fig. 8. In every case, the subject was able to grab the handlebar and complete the body motion naturally, following the same trajectory as without the handlebar. Previous studies by the US military have quantified arm strength in various directions based on the degree of elbow flexion [23]. The data show that push/pull force increases as the arm extends, while up/down force peaks when the arm is bent at 90°. Looking at the CoM velocity vectors in Fig. 10, we notice that in the top two scenarios, the arms assist with lifting the body upwards, and the elbow is positioned closer to a right angle. The bottom scenario mainly involves a forward motion off of the bed, and in this case, the arm is mostly extended. Thus, the handle placements yield arm configurations which optimize strength in the desired directions, in line with the military studies' empirical arm strength data.

Measurements of the force applied on the bar during each motion were also obtained (Fig. 11). Compared to the baseline of no handlebar assistance, these measurements give us an idea of how much body weight the subject offloaded onto the handle. In each scenario, a significant amount of downward force was applied to the handlebar, with the arms supporting a maximum of 20-30% of the total body weight. Since the legs are able to exert roughly 4x more force than the arms [24], this means that the maximal muscle effort was relatively equally distributed between the arms and the legs. The horizontal force represents arm effort towards maintaining the CoM trajectory, e.g. pulling the arms forward to stand up.

For the toilet scenario, we compared our calculated handlebar placement (in front of the user) to the government standard for toilet handrails (on the side). Fig. 12 shows that the test subject applied significantly more force on the side-facing bar as compared to the front-facing bar, with the arms supporting a maximum of 41% of the total body weight. This indicates that the standard toilet grab bar placement leads to highly unequally distributed muscle effort. By contrast, our calculated front-facing handle position led to the arms supporting a maximum of 25% of the body weight, enabling the user to leverage their leg muscles more effectively for the sit-to-stand movement.

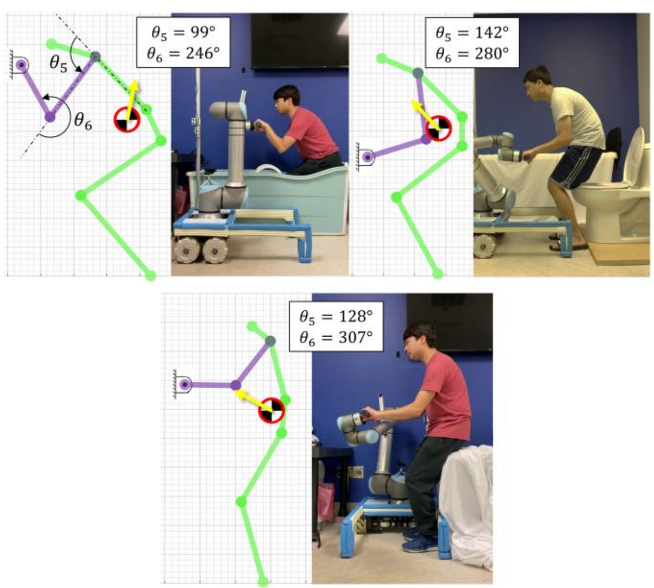


Figure 10. Image of each scenario with the Handle Anywhere robot, including diagrams of the arm angles and center of mass (CoM) velocity.

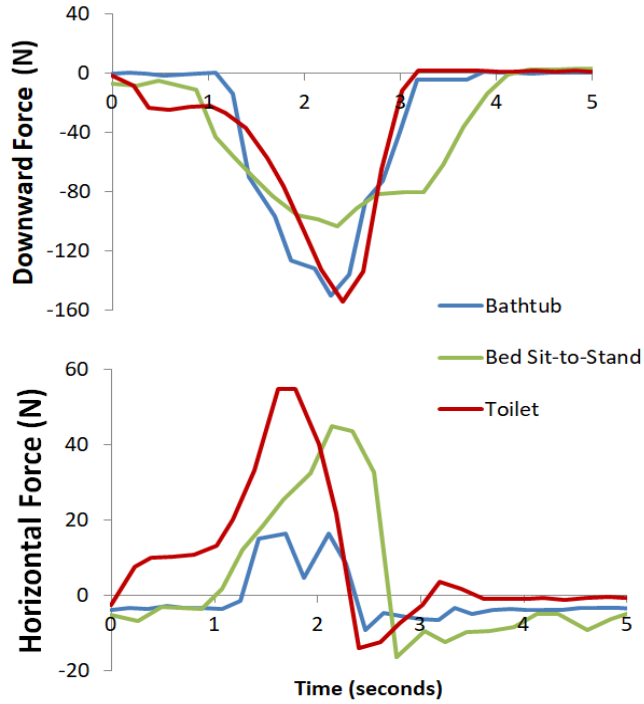


Figure 11. Downward and horizontal (antero-posterior) forces on the handlebar during each scenario.

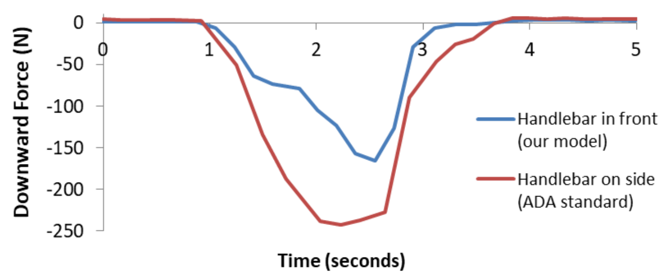


Figure 12. Downward force on the handlebar while standing up from a toilet, when the handle was located on the side (government standard) or in front of the user (L-index optimal handle placement)

Lastly, we asked the test subject to self-report the difficulty of executing each scenario with and without the handlebar (Table 3). This helped to reveal any qualitative differences in muscle exertion or overall patient comfort that were not captured in the force data. In all circumstances, the handlebar lowered the perceived difficulty of performing each task, shifting each scenario to a comparatively easier rating. The difference was most extreme for standing up in a bathtub, likely due to the intense muscle strain necessary to pull the body vertically upwards. Overall, the responses indicate that our system is likely to be readily adopted, especially by users who have difficulty performing some or

TABLE III. SUBJECTIVE DIFFICULTY OF PERFORMING EVERYDAY TASKS. NOTE THAT 1 = EASIEST AND 5 = HARDEST.

Scenario	Difficulty without handlebar	Difficulty with handlebar
Sit-to-stand in a bed	3	2
Standing up in a bathtub	5	2
Sit-to-stand from a toilet	3	1

all of the three scenarios we studied.

V. Conclusion

We designed and constructed a handle robot ("Handle Anywhere") capable of satisfying the identified functional requirements; namely, to provide a repositionable handlebar for a targeted elderly population and facilitate pandemic-resilient remote assistance. To maximize the support provided by the handlebar, we developed a methodology for finding an optimal handlebar location to assist the user at the hardest posture during each body transition. Our model balances the mechanical advantage and generalized gear ratio (related to manipulability) given by the handlebar location. In experimental trials of three activities of daily living, the calculated handlebar locations were successful at offloading a significant portion of body weight and reducing the perceived effort required to perform each activity. We hope to employ our robot to reduce the incidence of falls and assist elderly people during activities requiring postural changes.

The current approved IRB protocol is only for healthy young adults. It is likely that the poses of maximal effort for each activity would be different in elderly persons. However, we believe that this does not impact the validity of our methodology, since we generate a handlebar location based on each individual body pose. Since seniors face a plethora of unique motor disorders, our methodology could be used to generate rapid custom estimates for each user. In future studies, we would like to tackle these questions by repeating the same experiments with seniors. Another limitation to the current work is our representation of muscle contraction as pose-independent joint torques. A musculo-skeletal model will be required to better understand the effect of the handlebar upon individual muscles [25]. Additionally, we aim to investigate methods to safely move the handrail while it is being grabbed, so the robot can actively move or reposition the user, which would greatly increase the utility of the robot in cases where the user has limited muscular strength.

We envision our technology as a step towards pandemic-resilient eldercare devices: assistive tools caregivers can use to maintain a high level of care during periods of physical isolation. A mobile handlebar robot can provide an anchor of support during activities of daily living in a wide variety of environments, supporting both aging-in-place and nursing home care.

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