

Close-Proximity Vision-Guided Control and Performance Evaluation of a Mobile Robot for Sit-to-Stand Assistance

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Abstract—A safe sit-to-stand (STS) transfer is an essential daily movement, but it can be difficult for older adults with reduced strength, balance, or coordination. Cost-effective STS assistance is therefore important for supporting independence. This paper presents a close-range, single RGB-D-camera solution for estimating pelvis motion and controlling a compact STS-assistive rollator. The robot provides two modes: a predefined fifth-order trajectory-following mode and a vision-adaptive mode that modulates the same nominal motion according to real-time pelvis-robot distance. In a feasibility study with healthy adults ($N=6$ analyzed), both modes reduced lower-limb loading relative to unassisted STS. The predefined mode followed a fixed 3-second trajectory. This trajectory was selected based on our previous SkyWalker implementation and the healthy-adult STS timing literature, and it served as a baseline that provided larger and more consistent support. In contrast, the vision-adaptive mode synchronized the robot timing with the user's real-time pelvis motion, allowing users to stand at their preferred pace and resulting in lower handle loads and smaller compensatory trunk motion. These results suggest that the two modes may serve different assistance needs, with predefined support favoring stronger offloading and vision-adaptive support favoring user-paced interaction.

Index Terms—Rehabilitation robotics, robot control, human-robot interaction, sit-to-stand (STS) assistance, mobility assistance, older adults.

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I. INTRODUCTION

SIT-TO-STAND (STS) transitions are a critical daily activity, yet they present significant challenges for elderly individuals. Age-related declines in muscle strength, balance, and coordination dramatically increase fall risks and compromise independence and quality of life [1]. These challenges are even more pronounced for populations with conditions such as stroke or Parkinson's disease [2], [3]. Consequently, clinical assessments of STS performance are vital for identifying individuals at high risk and enabling targeted interventions to prevent falls [4].

Assistive technologies have emerged as promising solutions to alleviate the physical demand of STS movements and enhance user safety [5], [6]. However, the design of effective interventions hinges on a detailed biomechanical understanding of the movement information that can only be obtained through accurate, real-time monitoring of the user's state. For example, advanced motion capture systems (such as Vicon) can track critical metrics like the trajectory and velocity of the center of gravity [7]. Wearable sensors can be used in indoor and outdoor environments to track features including joint angles and angular velocities, but they require sensors attached to the user and impose setup and comfort burdens [8], [9], [10]. Taken together, the variety of sensing approaches adopted in prior STS studies, including motion capture systems and wearable sensors, reflects how many kinematic and kinetic variables jointly determine a successful STS, and underscores the need for assistive interventions that respond to user-specific conditions rather than imposing a one-size-fits-all profile.

On the other hand, various traditional STS assistance methods have been developed, ranging from human-assisted transfers using passive devices [11] to modern mobility-assistive devices and robotic systems. Some recent innovations include STS robots that provide users with predefined speed and support configurations [5], [12]. For individuals with severe mobility impairments, wearable exoskeletons or prosthetic systems integrated with smart rollators have also been introduced [13], [14]. Two related lines of work are especially relevant here. Bulea and Triolo evaluated a powered vertical-lift walker for STS assistance [15], while Molazadeh et al. proposed cooperative STS assistance using a hybrid exoskeleton and functional electrical

stimulation [16]. Among rollator-style devices, the most common STS support is either static handles/armrests or a prescribed vertical or Cartesian path. Coordinated vertical and anterior-posterior (A-P) hand motion is less common, but it is not unique to this paper. SkyWalker realizes this 2D hand path by translating its lightweight mobile chassis while lifting the lower handles, a design introduced in our prior SkyWalker implementation work to keep the platform compact, comparatively low-cost, and usable in rollator-like indoor and outdoor settings [5]. A comparable hand path can also be produced on a stationary base by directly shaping the handle trajectory; Ackermann et al. recently evaluated several such handle paths and reported favorable objective and subjective results for straighter and S-shaped trajectories [17]. Thus, the contribution of the present work is not the coupled hand path alone, but the close-range, vision-based modulation of that path using real-time pelvis tracking. Nonetheless, several issues remain:

- **Complex and heavy designs:** Many devices rely on multiple body contact points and require therapists or caregivers for proper configuration, limiting the usability outside clinical environments [18].
- **Lack of real-time state monitoring with low number of sensors:** Although various systems have been developed to reliably monitor the user's state during movement while providing personal assistance, many of them require multiple sensor attachments, which limits their practicality for at-home or daily use [19], [20].
- **Predefined Motion Support:** Relying solely on fixed reference motion templates that do not adapt to a user's natural speed, weight, or height. A fixed-motion support can lead to uncomfortable, unnatural interactions and elevated human-robot interaction (HRI) forces [21], [22].

To address the issues mentioned above, our previous works introduced a compact and lightweight STS assistive walker, SkyWalker, designed to support elderly users during walking and STS motions in both indoor and outdoor environments. The robot can generate a predefined S-shaped trajectory to assist the STS motion while providing partial body-weight alleviation [5]. That prior implementation paper provides the detailed mechanical-design rationale for the platform, including the compact form factor and coupled chassis-forward/vertical-lift assistance used here. In addition, we proposed a real-time phase classification method that uses a single low-cost camera to reliably track phase transitions during STS. Yet, for optimal STS assistance, most robotic and mechatronic devices solely rely on predefined support profiles. Examples include standing-up robots that drive the handles or seat along fixed joint-space or Cartesian trajectories [21], semi-wearable pneumatic devices such as SW-SiStA and SW-SiStA2 that impose a prescribed hip-extension torque pattern [23], [24], and multi-functional mobility assist frames that guide the user through parameterized sit-to-stand paths [25], [26]. These systems have been shown to reduce lower-limb joint moments and perceived effort in healthy older adults and

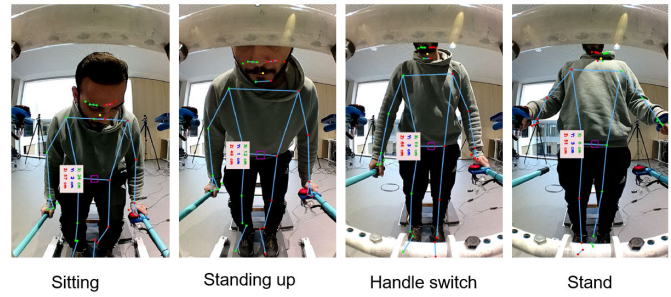


Fig. 1. Phase sequence of SkyWalker-supported STS transition.

patients [21], [25], but the trajectories are typically executed open-loop once triggered. As a result, the robot does not adapt to the user's spontaneous timing, preferred speed, or hesitation, which can lead to uncomfortable misalignment forces at the hands and altered trunk strategies when the robot moves faster or slower than the person [21], [26]. In our own predefined mode, users are instructed to keep their arms vertically aligned with the handles (Fig. 1). When their natural STS speed differs from the programmed profile, they cannot easily slow down or speed up the robot, which reduces comfort and can increase the required handle forces.

Although some groups have started to explore adaptive or intent-based assistance, this line of work is still sparse for STS. Salah et al. proposed an STS training robot that adjusts the arm trajectory based on trunk and shank inertial sensors and a fuzzy controller [27], and Liang and Chen studied mechanically adaptive devices that can tune assistance patterns for different user groups [28]. In locomotor rehabilitation, several cane-type and rollator-type robots regulate their velocity or guidance force according to ground-reaction or handle forces to keep the user in a comfortable region [29], [30]. These examples show the promise of adaptive mobility support, but they typically require multiple wearable sensors or force plates, and none of them use a close-range vision signal such as pelvis motion to regulate STS support on a compact walker.

Biomechanical studies of STS consistently highlight the anterior translation of the pelvis and whole body center of mass during the momentum-transfer phase as a key determinant of successful rising and balance recovery [31], [32], [33]. Forward motion of the pelvis brings the projection of the center of mass toward the feet and is tightly coupled to lower-limb joint moments and trunk flexion strategy [31]. For an STS assistive rollator that applies forces through anterior handles, the relative anterior-posterior (A-P) pelvis-robot distance is therefore a direct, task-relevant proxy for the user's intent and momentum generation: if the pelvis moves forward faster than the robot, the user is catching up and the handles should accelerate, whereas if the robot moves ahead of the pelvis, the controller should slow down to avoid horizontal shear. From a sensing perspective, the pelvis landmark is also the most robust feature of the MediaPipe/BlazePose skeletal model used in this work: it is the root of the kinematic chain and its A-P coordinate is the most stable and accurate of all tracked joints in close-range configurations [34], [35]. In our previous close-proximity evaluation with SkyWalker, we quantitatively compared multiple landmarks against a motion-capture refer-

ence and found that the A-P pelvis trajectory achieved the lowest error across STS trials, whereas distal joints such as knees and ankles were more affected by occlusions and depth noise [36]. These considerations motivated us to design the adaptive controller around the A-P pelvis-robot distance instead of more complex full-body state estimates.

Motivated by these observations, we investigate in this paper a close-range, single-camera adaptive STS controller that operates entirely on board a compact rollator. An RGB-D camera mounted inside the SkyWalker rollator [5], [36] is oriented toward the user's front body and yields the A-P pelvis-robot distance in real time, which is then used to modulate the robot's forward and vertical velocity setpoints along the same nominal path. This design allows us to implement two assistance modes on the same hardware: (i) a predefined fifth-order trajectory that follows a fixed timing profile, and (ii) a vision-adaptive mode that scales the same nominal trajectory in time according to the measured pelvis motion. Implementation is performed entirely on-device using MediaPipe/BlazePose running on an OAK-D camera, enabling low-latency inference without external compute [34], [35], [37].

The predefined mode is included as an open-loop baseline rather than as the novel contribution. It reproduces fixed-timing STS support on the same hardware, allowing the vision-adaptive mode to be evaluated without changing the robot platform.

The main contributions of this paper are summarized as follows:

- 1) We propose and implement an adaptive STS support strategy that modulates the robot's forward and vertical velocity setpoints based on the relative pelvis-robot distance, providing a simple control variable that aligns assistance timing with user-generated momentum while remaining compatible with low-cost, single-camera sensing.
- 2) We conduct a biomechanical experiment with healthy subjects to compare traditional predefined STS support and the proposed adaptive strategy. Using kinetics, kinematics, and temporal metrics, we evaluate how each method reduces lower-limb loading, shapes handle forces, and alters STS movement patterns, and we discuss potential use cases for different user groups.

This paper is organized as follows. Section II introduces the robot hardware and vision system. Section III describes the predefined and vision-adaptive control strategies. Section IV presents the biomechanical experiment and evaluation metrics. Section V discusses the experimental results and key findings. Section VI concludes the paper with limitations and future work.

II. STS ASSISTIVE ROBOT ARCHITECTURE

A. Robot Hardware

The SkyWalker robotic mobility aid provides STS and walking assistance for geriatric users [5]. The device employs a dual-handle design, with static upper handles for support during walking and motorized lower handles for STS aid. Brushless motors actuate the front wheels for locomotion,

while smaller passive casters at the rear enable nimble steering. The vertical lift and the powered front wheels are regulated by low-level velocity PID controllers, while the high-level STS controllers described in Section III generate their velocity setpoints. The lower handles use a two-stage assistance approach. First, they lift users about two-thirds of the way to standing position using a brushless motor for vertical movement, while the powered wheels create forward motion. This dual-handle design serves two key purposes: First, it enables better control of the robotic walker during walking, as longer handles would make precise control more difficult. Second, the design reflects direct input from healthcare professionals, including geriatric specialists and nurses, who recommended partial lift assistance. This approach encourages older adults to complete the final standing motion independently, which helps maintain their muscle strength through regular engagement. The design thus balances immediate mobility assistance with long-term functional independence, incorporating both engineering requirements and clinical recommendations for elderly care.

The STS process, shown in Fig. 1, comprises four distinct phases for the robot and four for the human. To commence the STS sequence, the user places their hands vertically on the lower handles while the robot remains stationary. The robot then initiates the STS motion by simultaneously raising the user with the vertical lift and propelling them forward by driving the chassis. Concurrently, the user begins to rise from the seated position, extending their legs and extending their thighs from horizontal to vertical. The robot reaches a stationary phase once the lower handles have attained their maximum height and forward progress has ceased. Afterwards, the user must actively transition from the lower to the upper handles, one hand at a time. Upon completion of this transfer, the user achieves an upright standing posture, grasping both upper handles.

B. Robot Vision System

In addition to the hardware for STS and walking support, SkyWalker incorporates two depth/stereo cameras (Luxonis OAK-D W [37]) for mobility-assist functions. An RGB-D camera records both color information (RGB channels) and per-pixel depth (D channel), enabling 3D pose estimation without external infrastructure. The OAK-D W camera used here also includes on-board processing, allowing the pose-estimation model to run locally without external compute hardware. The forward-facing camera facilitates environmental navigation and obstacle detection, while the user-facing camera inside the rollator performs pose estimation for adaptive control.

We adopted Google's MediaPipe framework [34] with the user-facing camera mounted on the SkyWalker robot for close-range operation. The MediaPipe BlazePose GHUM Lite model is suitable for our hardware because of its lightweight architecture [35], enabling efficient processing within the limited computational resources of the platform [38]. In our current implementation, a minimum frame rate of 15 Hz is sufficient for real-time STS monitoring and velocity modulation [39].

The OAK-D W camera is mounted in a 90° reversed configuration and captures the user's pelvis region at close range

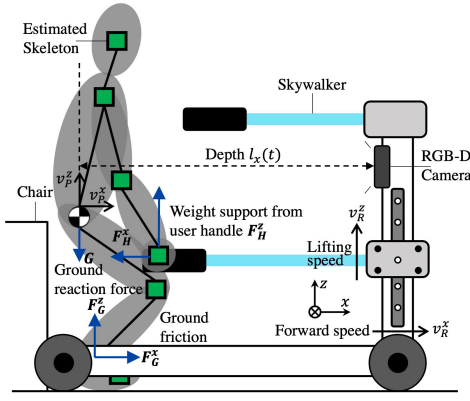


Fig. 2. A two-dimensional mathematical model describing human-robot interaction with the SkyWalker STS assistive robot.

(less than one meter). Although MediaPipe tracks multiple body landmarks, our controller uses the A-P pelvis position, following our previous evaluation showing that this landmark provides the most reliable close-proximity signal for STS phase estimation [36]. This focused choice reduces computational demand while preserving the task-relevant signal needed for control.

To ensure user safety in the event of pose estimation failure, two layers of protection are implemented. First, a software watchdog monitors the validity of the MediaPipe pelvis landmark at each frame: if no valid detection is returned for 10 consecutive frames (≈ 0.67 s at 15 Hz), the robot executes a controlled, jerk-limited deceleration to a safe stop while continuing to attempt pose recovery, avoiding any abrupt reaction on a user still in contact with the handles. Second, a hardware emergency stop mounted on the robot chassis allows an operator to immediately cut power to all actuators. During all experimental trials, a researcher was present to supervise operation and intervene if necessary.

III. METHODOLOGY

A. Mathematical Model

The mathematical model representing the physical interaction between the STS rollator and the user is illustrated in Fig. 2. For simplicity, the STS motion is projected onto a 2D sagittal plane, assuming lateral movements performed are sufficiently small to be neglected. Under this situation, the motion equations of the human-robot system in the vertical (z) and forward (x) directions are formulated as follows:

$$F_H^z + F_G^z + F_C^z - G = m \cdot \ddot{z} \quad (1)$$

$$F_H^x + F_G^x + F_C^x = m \cdot \ddot{x} \quad (2)$$

In the vertical direction, G denotes body weight, which is supported by the vertical handle force F_H^z , ground reaction force F_G^z , and chair reaction force F_C^z while the user remains in contact with the chair. In the horizontal direction, F_H^x denotes the pull/push force applied through the handles, F_G^x denotes the horizontal friction at the feet, and F_C^x denotes the horizontal friction force exerted by the chair on the user, which becomes zero after seat-off. Together, these terms determine the user's sagittal-plane accelerations $\ddot{z}$ and $\ddot{x}$.

With the exception of the handle forces F_H^z and F_H^x , the quantities in Eq. (1) and Eq. (2) were obtained from laboratory evaluation instruments: center-of-mass acceleration from the markerless Theia motion capture system, ground and chair reaction forces from the two force plates beneath the feet and chair, and body weight from a scale. These instruments were used only for offline biomechanical evaluation; they are not part of the deployed control system. The robot controller relies solely on the on-board RGB-D camera. The handle forces were then calculated from Eq. (3) and Eq. (4).

$$F_H^z = m \cdot \ddot{z} - F_G^z - F_C^z + G \quad (3)$$

$$F_H^x = m \cdot \ddot{x} - F_G^x - F_C^x \quad (4)$$

On the other hand, since the human moves together with the robot during the whole sit-to-stand process, the relative distance $l_x(t)$ is determined based on the robot speed (v_R^x) and human speed in the forward direction (v_P^x). At any time t during the STS motion, the relationship between $l_x(t)$ and the human/robot speeds is given by

$$l_x(t) - l_c^0 = \int_0^t (v_R^x - v_P^x) dt \quad (5)$$

Note that l_c^0 represents the initial distance before the human starts their motion. $l_x(t)$ can be obtained from the RGB-D camera by leveraging the MediaPipe human skeleton tracking algorithm, as introduced in [36]. We adopt the working hypothesis that a desired sit-to-stand motion requires a constant relative distance l_x , which would in turn drive the horizontal handle force F_H^x toward a minimum, avoiding any pulling or pushing of the user through the handle. The reduced horizontal handle forces measured under adaptive control in our experiments (Section V) provide empirical support for this hypothesis. We ignored the relative speed between the handle and center of mass in the vertical direction, since both velocities cause very small moments with respect to the foot and have a relatively small influence on a stable sit-to-stand motion. Based on this consideration, the control target during the sit-to-stand motion can be depicted as,

$$l_x(t) \approx l_c^0, \quad v_R^x \approx v_P^x \quad (6)$$

Eq. (6) motivates the proposed adaptive control concept: the robot's forward speed v_R^x should remain close to the user's center-of-mass speed in the forward direction v_P^x . In the following subsections, we introduce two control scenarios: predefined control, where the robot follows a fixed time-based profile, and adaptive control, where the robot modulates its speed to keep $l_x(t)$ close to the calibrated distance.

B. Predefined STS Control

The predefined STS mode allows the user to perform STS while the robot follows a predefined trajectory in both forward and vertical directions. As shown in Eq. (3) and Eq. (4), the handle forces F_H^z and F_H^x depend on the instantaneous motion in both directions. Thus, to provide appropriate motion support during STS, we introduce both predefined and adaptive control. For predefined STS control, it is crucial to ensure a

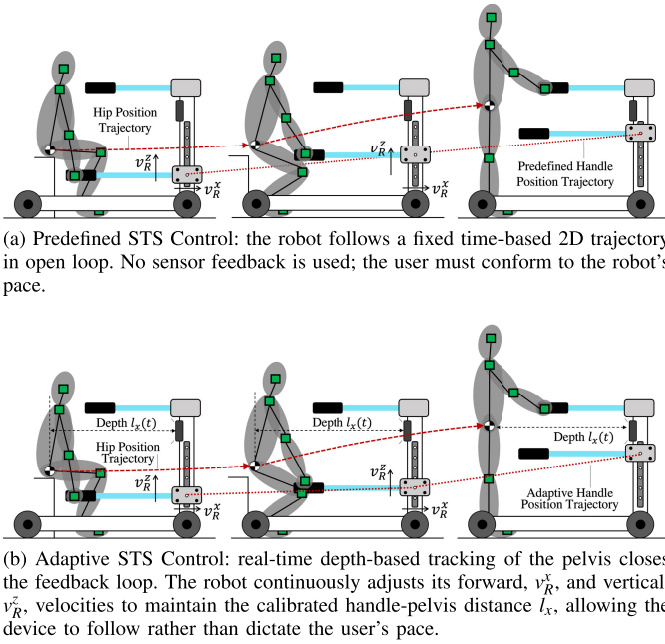


Fig. 3. Predefined and adaptive control strategies.

stable and smooth trajectory for both F_H^z and F_H^x , allowing the user to follow the robot's motion effectively.

Fig. 3a illustrates the concept of the predefined STS control strategy. In this approach, the handle position of the SkyWalker robot moves in both vertical and horizontal directions as the user transitions from the sitting phase to the standing phase. A fifth-order polynomial interpolation was employed to achieve smooth acceleration and deceleration during motion support.

$$S_{x,z}^p(t) = A_{x,z}t^5 + B_{x,z}t^4 + C_{x,z}t^3 + D_{x,z}t^2 + E_{x,z}t \quad (7)$$

Here the superscript p denotes the predefined trajectory profile. $S_{x,z}$ stands for the predefined motion trajectory in both forward (x) and vertical (z) directions. By taking the first derivative, we obtain the predefined motion velocity, which is used later for real-time motion control:

$$V_{x,z}^p(t) = 5A_{x,z}t^4 + 4B_{x,z}t^3 + 3C_{x,z}t^2 + 2D_{x,z}t + E_{x,z} \quad (8)$$

The target displacement and duration were selected from the SkyWalker hardware limits and prior implementation work, and the polynomial coefficients were then computed analytically. Note that the predefined path used here is the nominal SkyWalker S-shaped STS assistance path from our prior implementation work [5]. Its coupled forward-and-upward motion is also consistent with recent handle-trajectory evidence showing favorable support and subjective ratings for straighter and S-shaped trajectories compared with more curved paths [17]. The fifth-order polynomial is used to implement this nominal predefined path smoothly, rather than a trajectory-optimization method, and its coefficients were not individualized in this study. A general fifth-order polynomial provides six coefficients, which are sufficient for rest-to-rest motion with prescribed displacement, velocity, and acceleration boundary conditions. Because the displacement in Eq. (7) is defined relative to the initial handle position, the constant term is fixed to zero. The remaining coefficients $A_{x,z}$ to $E_{x,z}$ are determined

by $V^p x, z(0) = V^p x, z(T) = 0$, $\dot{V}^p x, z(0) = \dot{V}^p x, z(T) = 0$, and $S^p x, z(T) = S_{\text{target}}$, where S_{target} is the nominal handle lift on forward stroke and $T = 6$ s for all participants. In this study, the same coefficients were used for all participants. For predefined STS control, the vertical lift and the powered front wheels are regulated by low-level velocity PID controllers whose setpoints are $V^p z(t)$ and $V^p x(t)$, respectively, from Eq. (8). By utilizing the predefined support strategy, the user is required to firmly grasp the handle and follow the robot's motion until reaching the standing position.

C. Adaptive STS Control

The predefined STS control provides a convenient method for supporting individuals during the STS transition, without the need for additional sensors or considerations of user-specific movements. However, we observed that users, especially people with lower-extremity difficulties, prefer to perform the STS motion at their preferred timing and speed rather than simply following the robot motion. Motivated by this observation, we developed a vision-adaptive STS control strategy by incorporating a velocity feedback controller derived from real-time depth perception. Here, *adaptive* indicates that the robot modulates its velocity command based on the measured pelvis position. It does not denote classical adaptive control with online parameter identification. The proposed controller is therefore a fixed-gain, image-based velocity modulation controller.

One of the main goals of adaptive STS control is to adapt the controlled robot velocity in both directions to the user's performed motion in real time. As shown in Fig. 3b, the user first sits in front of the camera while the robot starts the calibration process by recording the user's current pelvis center position $l_x(0)$ with respect to the camera. During the early stage of standing, if the user accelerates their motion, the relative perceived depth $l_x(t)$ results in a distance deviation compared with the initial perceived distance $l_x(0)$. Considering the relative distance update between the handle and pelvis center position, we define:

$$\Delta l_x(t) = l_x(t) - l_x(0) \quad (9)$$

In the above equation, $\Delta l_x(t)$ is dynamically updated according to the user's STS motion. Ideally, when the user strictly follows the robot's motion, $\Delta l_x(t)$ is assumed to be 0. Conversely, when the user performs the STS motion independently, $\Delta l_x(t)$ becomes the control variable and must be adjusted until it converges to 0. To achieve this, we implemented a simple proportional controller to adjust the robot's speed adaptively.

$$V_{x,z}^a(t) = V_{x,z}^p(t) + \Delta l_x(t)K_p V_{x,z}^p(t) \quad (10)$$

Here the superscript a denotes the adaptive velocity command. Eq. (10) serves as a proportional controller by tracking changes of $\Delta l_x(t)$. When $\Delta l_x(t) \neq 0$, $V_{x,z}^a(t)$ is obtained by increasing or decreasing the predefined velocity $V_{x,z}^p(t)$ to follow user's movement. Otherwise, when $\Delta l_x(t) = 0$, the robot maintains its predefined velocity at that specific moment t .

$$\Delta l_x(t) = 0 \rightarrow V_{x,z}^a(t) = V_{x,z}^p(t) \quad (11)$$

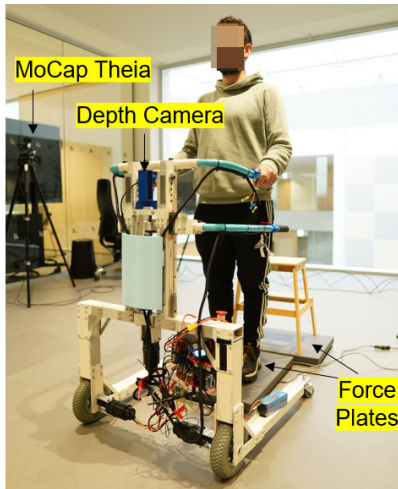


Fig. 4. Experiment setup in the motion capture lab. The individual depicted provided informed consent for the use of their image.

This means that while the user ideally follows the predefined motion without significant deviation compared to $l_x(0)$, the robot executes the predefined trajectory. Otherwise, the robot adjusts its speed, either decelerating or accelerating, until the $\Delta l_x(t)$ converges to 0. A visual comparison of the resulting movement trajectories across all experimental conditions is presented in Fig. 10.

For adaptive STS control, the vertical lift and the powered front wheels are regulated by low-level velocity PID controllers. Their setpoints are $V_z^a(t)$ and $V_x^a(t)$, respectively, from Eq. (10), which scale the predefined profile by the real-time and calibrated pelvis-distance difference. Based on this calculation, the robot increases its forward and vertical velocity setpoints when the pelvis moves beyond the calibrated distance and reduces them when the robot gets ahead of the user.

IV. EXPERIMENT

A. Protocol

The experiment was conducted with six healthy participants (five males and one female). The participants had a mean weight of 75.0 kg (SD = 11.7 kg), a mean height of 173.9 cm (SD = 12.0 cm), and a mean age of 28.0 years (SD = 7.7 years). Each participant performed Sit-to-Stand (STS) transitions using the SkyWalker robotic rollator, completing five repetitions for each condition.

The experimental setup integrated multiple measurement systems for thorough data collection, as shown in Fig. 4. Ground-truth kinematics were captured using the Theia motion capture system [40], while ground reaction forces were measured using two force plates: one positioned beneath the participant's feet and the other positioned beneath the chair. The SkyWalker's motor encoders provided odometry data, and a depth camera implementing the MediaPipe framework enabled 3D skeleton tracking for the adaptive control system. The protocol consisted of three distinct testing conditions, presented in randomized order to minimize learning and fatigue effects. In the unassisted condition, participants performed three unassisted STS transitions to capture baseline

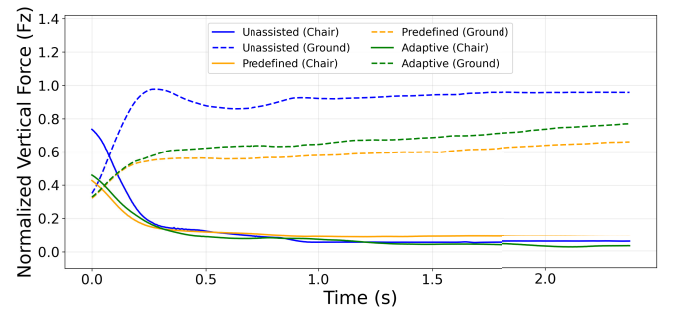


Fig. 5. Comparison of mean vertical force profiles for unassisted, predefined, and adaptive conditions in chair and ground settings. The graph shows the normalized vertical force (F_z) over time, with distinct patterns between chair (solid lines) and ground (dashed lines) conditions.

TABLE I
EVALUATION MATRIX FOR STS ASSISTANCE

Category	Metric	Description
Kinetics	Vertical Ground Reaction Forces (vGRF)	Forces measured under feet and chair, normalized to body weight
	Handle Forces	Support forces provided through robot handles during transition
Kinematics	Joint Angles	Angular displacement of ankle, knee, hip, and shoulder joints
	Vertical Position	Height changes of hip and shoulder during transition
	Center of Gravity (CoG)	Vertical displacement during STS
Temporal	Movement Duration	Time taken for complete STS transition (assisted conditions)

movement patterns. In the predefined assistance condition, participants completed five repetitions using the SkyWalker with a 3-second predefined fifth-order trajectory. In the adaptive assistance condition, participants performed five repetitions using the SkyWalker's adaptive trajectory mode, where the robot's movement continuously adjusted based on real-time user position data. Consequently, the duration of each repetition varied depending on the user's individual performance. Each condition lasted approximately 15 minutes, with appropriate rest periods provided between conditions to prevent fatigue.

All movements were simultaneously recorded using the integrated measurement systems, providing synchronized data of the participants' kinematics, kinetics, and the robot's performance throughout each transition. This comprehensive data collection approach enabled detailed comparative analysis between unassisted movement patterns and both assistance methods, with particular focus on evaluating how closely our adaptive control method could approximate unassisted STS biomechanics compared to traditional predefined trajectory assistance.

The following metrics were used to evaluate the effectiveness of both predefined and adaptive control strategies in comparison to unassisted STS movements:

V. RESULTS AND DISCUSSION

A. Kinetics Results

Fig. 5 illustrates the vertical ground reaction forces (vGRF) normalized to body weight computed as the mean of all

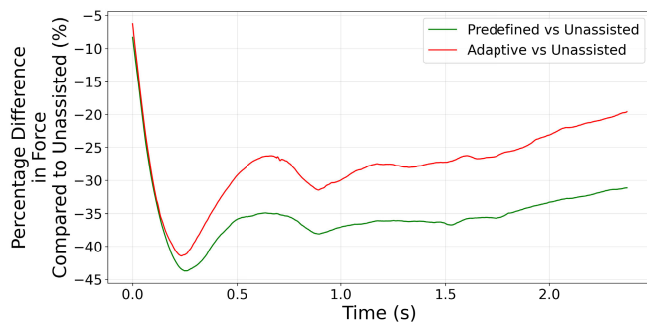


Fig. 6. Percentage difference in vertical force on the feet between predefined/adaptive methods and the unassisted baseline over time. The graph illustrates the relative deviation of force profiles from the unassisted condition.

participants ($N = 6$) across three conditions: unassisted (standing up with no assistance), predefined, and adaptive robotic assistance. The force profiles were obtained simultaneously from force plates positioned under the chair and feet.

In the unassisted condition, participants initially supported approximately 70% of their body weight on the chair, while the remaining 30% was distributed through their feet. During the transition phase ($t = 250$ ms), the average weight transferred from the chair to the ground, culminating in approximately 95% body weight registered on the ground force plate during standing. Both STS robotic assistance conditions demonstrated distinct force profiles from the unassisted condition. The predefined assistance (yellow lines) exhibited a more gradual unloading pattern from the chair, with the chair force decreasing to approximately 10% body weight over a longer duration compared to the unassisted condition. Similarly, the adaptive assistance (green dashed lines) showed a controlled weight transfer pattern, resulting in a slightly higher ground force compared with the predefined control strategy.

Fig. 6 illustrates the percentage difference in vertical ground reaction forces over time between assisted and unassisted conditions. Both robotic assistance strategies substantially reduced ground reaction forces compared to the unassisted condition, but they exhibited distinct patterns.

In Fig. 6, the predefined assistance demonstrated the largest reduction, reaching a maximum decrease of approximately 45% compared to unassisted STS at around 0.3 s into the movement. This assistance showed a rigid support pattern, maintaining a substantial difference from unassisted forces throughout the movement. This consistent deviation likely reflects its predefined trajectory approach, providing assistance regardless of the user's actual movements. While this ensures consistent support, it may keep force patterns further from unassisted movement; the robot essentially requires the user to follow its predefined path rather than adapting to the user's natural movement preferences.

In contrast, the adaptive assistance exhibited a similar initial trajectory but with a smaller peak reduction. Its force profile displayed more dynamic behavior, continuously adjusting to the user's actual position and movement preferences during the STS transition. The smaller force reduction suggests a more collaborative interaction, with the robot adapting its support based on real-time feedback. This adaptive behavior explains the more gradual return toward unassisted force

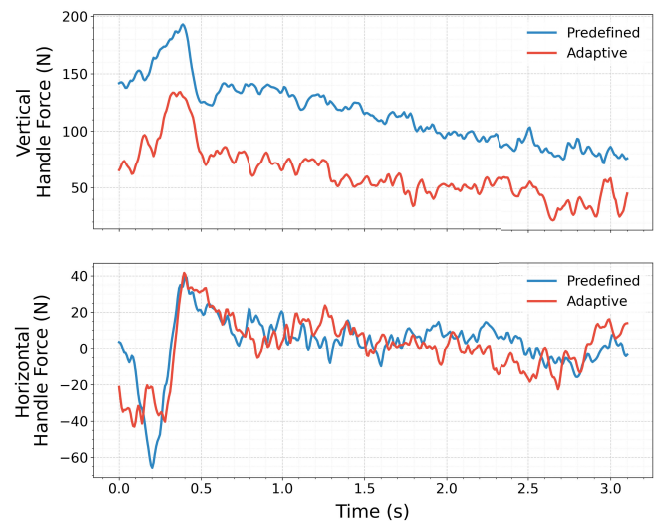


Fig. 7. Mean handle forces (N) with standard deviations comparing predefined (blue) and adaptive (red) control strategies over a 3.0 s duration. The predefined strategy exhibits consistently higher vertical and horizontal handle loads than the adaptive approach, with both showing gradual force reduction over time.

patterns, as the robot adjusts its assistance according to how the person prefers to stand up. The substantial force reductions observed in both conditions during the critical transition phase from sitting to standing indicate significant offloading of the lower extremities, which could be particularly beneficial for individuals with reduced strength.

Fig. 7 shows that during the initial seat-off phase, both strategies offered support when the user was about to lift off from the chair.

Fig. 7 further shows that adaptive control reduced both vertical and horizontal handle loads relative to predefined control. The predefined condition reached a vertical peak of approximately 190 N at ~ 0.4 s, compared with ~ 130 N under adaptive assistance. In the horizontal direction, the early resistive impulse was also smaller under adaptive control (approximately -40 N versus -65 N for predefined), indicating reduced pull-or-push interaction at the handles.

These results suggest different use cases for the two assistance modes. The adaptive mode provides less offloading and may better preserve active lower-limb contribution in users who can participate in the movement, whereas the predefined mode provides stronger and more repeatable support that may be useful when larger assistance is required.

Fig. 7 shows the mean horizontal and vertical forces on the handles. During the flexion-momentum phase (≈ 0 –0.35 s), the participant leans the trunk forward while the robot simultaneously starts translating the chassis ahead and raising the handles. That forward trunk rotation makes the hands exert a negative horizontal force, pulling the robot toward the chair to help shift the center of mass. At the same moment the arms begin supporting body weight, so vertical force rises sharply. Because the predefined trajectory does not take into account the user's position, the blue trace shows a deeper pull (≈ -60 N) and a higher vertical peak (≈ 195 N) than the adaptive red trace (≈ -40 N and ≈ 130 N), suggesting the adaptive controller slows the early motion just enough to let the user complete trunk flexion with less arm effort.

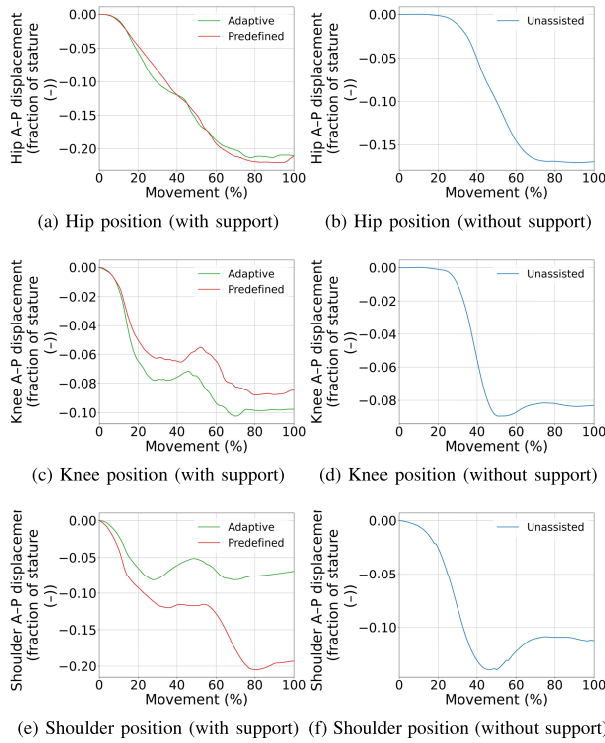


Fig. 8. Anterior-posterior position comparisons with and without robot support.

Once seat-off occurs (≈ 0.35 – 0.8 s), the horizontal force flips positive. The robot is now lifting and moving forward, so the user must push the handles away to stay centered over the feet. Vertical force begins to fall as the lower limbs take over the load. Predefined assistance still demands larger upper body involvement, about $+40$ N horizontal and 120 – 140 N vertical, whereas the adaptive response tops out around $+30$ N and 80 – 90 N. This difference implies that, by referencing real-time user position, the adaptive controller speeds up or slows down just enough to keep the handles in the participant's preferred path, trimming both the upward push and the forward shear required from the arms.

During the extension and stabilization phases (after 0.8 s), both horizontal traces hover near zero, indicating the user and robot are co-moving without appreciable push-or-pull. Vertical loads, however, remain higher in the predefined condition (drifting from approximately 120 N to 80 N) than in the adaptive one (70 N to 50 N). Lower forces under adaptive control point to smoother impedance matching and fewer corrective adjustments as the participant settles into quiet standing, highlighting the ergonomic benefit of modulating trajectory speed and position to individual user kinematics.

We observed a reduction in handle force under the adaptive support scenario. The current data suggest that movement duration alone is unlikely to account for the observed handle-force differences. Rather than producing a simple time-scaling effect, the adaptive condition changed the distribution of movement velocity and produced phase-specific differences in both vertical and horizontal handle forces. These observations suggest that the reduction in vertical handle force was more closely related to real-time pelvis-robot synchronization than to movement duration alone. Nevertheless, a duration-matched

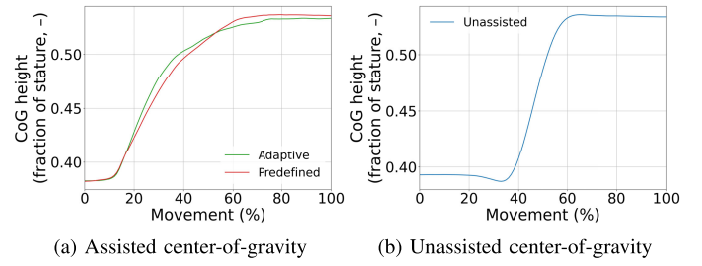


Fig. 9. Average vertical center-of-gravity position of the subjects with and without support.

predefined condition remains necessary in future work to isolate the effect of closed-loop adaptation more definitively.

In summary, predefined control produced the largest reduction in foot vGRF but required higher handle forces, suggesting stronger offloading and possible over-assistance for users who are capable of active participation. Adaptive control produced a smaller vGRF reduction but lower handle forces, suggesting a more collaborative interaction. This distinction is clinically relevant, but it must be verified in older adults and mobility-impaired participants before drawing conclusions about long-term strength preservation or fall-risk reduction.

B. Kinematics Results

Across the six healthy participants, time-normalized anterior-posterior (A-P) trajectories of the hip, knee, and shoulder shown in Fig. 8 revealed systematic differences among the adaptive, predefined, and unassisted STS methods. Both robot-assisted strategies elicited larger posterior excursions of the pelvis than the unassisted trials, reaching mean peaks of approximately -0.21 versus -0.17 stature, respectively. This additional displacement is biomechanically consistent with a momentum-generation hip hinge that increases horizontal ground reaction forces and facilitates seat-off. The adaptive controller synchronized with the natural temporal pattern of hip-knee extension: posterior translation of the hip began almost immediately after seat-off, followed in near lockstep by the knee (peaks ≈ -0.21 and ≈ -0.10 stature, respectively). In contrast, the predefined trajectory introduced a discernible phase lag: the robot's motion did not accelerate until approximately 15% of the movement, prompting users to lean markedly farther forward (shoulder peak ≈ -0.20 stature). The unassisted condition lay between these extrema; shoulder flexion peaked at ≈ -0.14 stature and hip/knee excursions were approximately 15% shallower, consistent with classical momentum-transfer STS executed without external aids [41]. Shoulder motion is where the divergence becomes most obvious. Participants using the predefined trajectory leaned forward until the shoulder displaced approximately -0.20 stature-normalized units, fully 2–3 times larger than the adaptive peak and 30% larger than the unassisted benchmark. The adaptive controller limited trunk excursion to approximately -0.05 , essentially preserving a quiet upper-body profile. The trunk motion implies that users could accomplish the STS with far less reliance on passive handle support.

The CoG traces shown in Figs. 9 show that all three conditions converge on the same final height (~ 0.535 of stature),

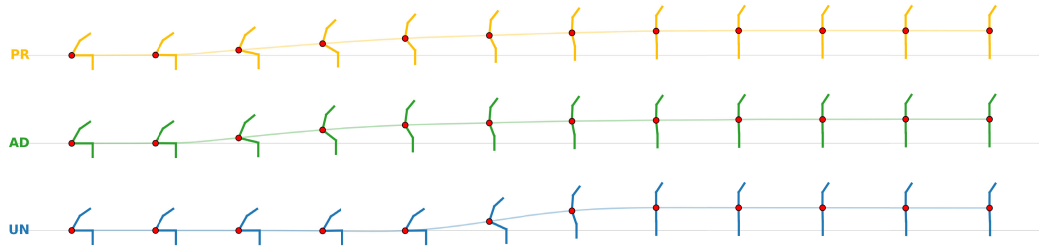
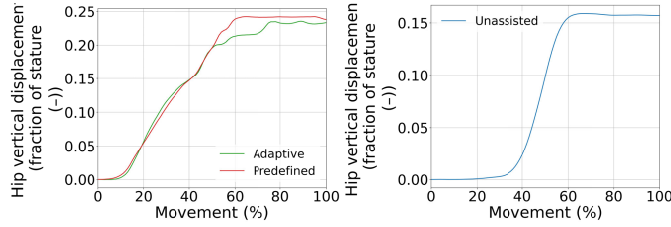
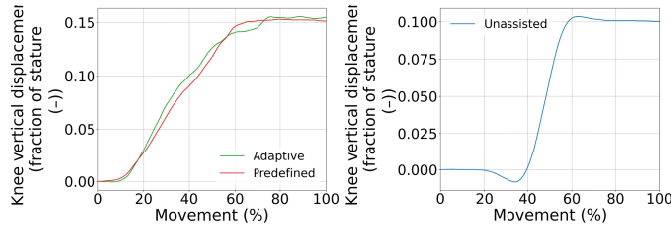


Fig. 10. Rows show the three experimental conditions: predefined (PR, yellow), adaptive (AD, green), and unassisted (UN, blue). For each condition, 12 equally spaced snapshots (0 to 100% of the subject-normalized movement duration) are displayed left-to-right. The red marker is the pelvis and is positioned at the condition's mean center-of-gravity (CoG) height; its full trajectory is drawn as the faint colored line beneath each row.



(a) Unassisted Hip vertical position (b) Assisted Hip vertical position

Fig. 11. Vertical hip position comparisons for assisted and unassisted conditions.



(a) Unassisted Knee vertical position (b) Assisted Knee vertical position

Fig. 12. Vertical knee position comparisons for assisted and unassisted conditions.

yet differ profoundly in how that height is achieved, as also illustrated in Fig. 10. In the adaptive mode, the CoG begins to rise almost immediately after seat-off and does so about 10% faster than the predefined trajectory during the first half of the stand-up phase. The predefined controller, constrained by its rigid time base, delays the lift while the user waits on the robot, then overshoots the adaptive curve by approximately 0.5% of stature between 65% and 80% of the cycle. Unassisted trials, by contrast, keep the CoG low until nearly 40% of the cycle and then execute a rapid ascent. From a control perspective, these patterns suggest that the adaptive strategy spreads the assisted rise over a user-selected interval and reduces the need for compensatory trunk motion compared with the fixed predefined profile. These data reinforce a design principle already shown by the anterior-posterior results: assistive robots should synchronize their timing to the user's own momentum transfer rather than impose a fixed trajectory when the goal is to preserve more natural hip-knee coordination.

Figs. 11 and 12 show only a subtle timing edge for the adaptive controller. Vertical hip and knee rise profiles show that the adaptive and predefined controllers behave almost identically. From roughly 10% to 50% of the movement, the

TABLE II
JOINT-LEVEL STS KINEMATICS RESULTS SUMMARY

Metric	Unit	Average $\pm$ Standard Deviation		
		Unassisted	Predefined	Adaptive
Movement duration	s	2.193 ± 0.015	3.000 ± 0.000	3.004 ± 0.282
Peak velocity	m s^{-1}	0.623 ± 0.171	0.249 ± 0.121	0.279 ± 0.124
Mean velocity	m s^{-1}	0.126 ± 0.012	0.076 ± 0.019	0.078 ± 0.014

TABLE III
COG-LEVEL STS KINEMATICS RESULTS SUMMARY

Metric	Unit	Average $\pm$ Standard Deviation		
		Unassisted	Predefined	Adaptive
Movement duration	s	2.195 ± 0.012	3.000 ± 0.000	3.004 ± 0.282
Peak velocity	m s^{-1}	0.738 ± 0.233	0.182 ± 0.044	0.214 ± 0.053
Mean velocity	m s^{-1}	0.125 ± 0.022	0.072 ± 0.010	0.075 ± 0.009

adaptive trace begins its ascent a fraction earlier, but the two curves remain within 0.3–0.5% of stature throughout the stand-up and handle-switch phases. The predefined path even overtakes the adaptive by the same small margin near the plateau, yet both conditions converge on virtually the same final height. Unassisted trials display a clearly different temporal pattern: hip and knee stay close to seat level until around 40% of the cycle and then rise steeply to final heights (hip ≈ 0.16 , knee ≈ 0.10 of stature) that are about one-third lower than in either assisted mode. This contrast highlights how handle support changes the vertical objective of the task, allowing participants to lift the pelvis and shank higher than they do when standing without assistance.

As shown in Tables II and III, both kinematic and CoG data showed a significant overall effect of condition for movement duration, peak velocity, and mean velocity (Friedman $H = 7.20$ – 12.50 , $p_{\text{FDR}} \leq 0.027$). Pair-wise Wilcoxon tests showed that assisted trials had lower peak and mean velocities than unassisted trials (all unassisted-versus-assisted comparisons $p \leq 0.048$), while movement duration was longer in both assisted modes than in the unassisted condition ($p \leq 0.012$ for both unassisted comparisons). Adaptive and predefined

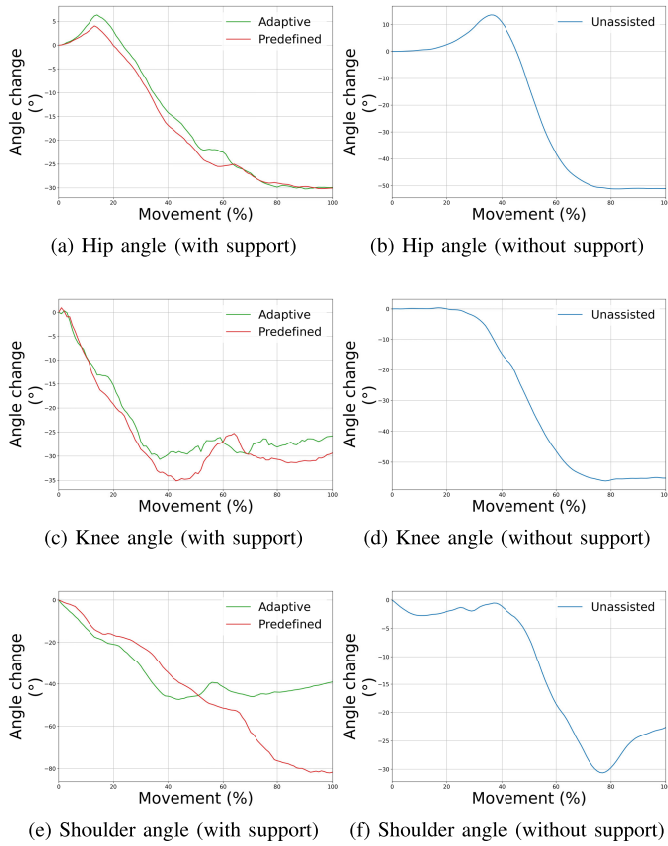


Fig. 13. Joint-angle comparisons for the assisted conditions (left) versus the unassisted condition (right).

conditions did not differ significantly for any reported metric ($p \geq 0.156$). Thus, both robot modes slowed and stabilized the STS movement relative to unassisted standing, while the kinematic differences between adaptive and predefined modes were not statistically significant in this sample.

Looking at Fig. 13 for joint angle comparisons, several key biomechanical patterns emerge across the STS transition. The unassisted condition demonstrates more pronounced angular excursions and faster transitions compared to both assisted conditions. Both robotic assistance strategies (adaptive and predefined) modify these natural movement patterns by producing more gradual joint angle changes and reduced peak velocities. Of particular biomechanical significance is the temporal coordination between joints: the unassisted condition shows a proximal-to-distal sequence (hip-knee-ankle) typical of efficient STS mechanics, while both assistance conditions alter this sequencing to provide more controlled transitions. This coordinated joint behavior in the assisted conditions suggests that the robotic support effectively redistributes the mechanical demands of the STS task, though at the cost of natural movement speed and sequencing.

The kinematic analysis indicates that robotic assistance, whether adaptive or predefined, altered the STS transition compared with unassisted movement. In the unassisted condition, users relied on a faster, momentum-based strategy with rapid anterior hip displacement and CoG elevation. In contrast, both assisted conditions produced a slower and more

controlled movement pattern. This suggests a trade-off: the robot can improve support and stability, but users must adjust their natural movement strategy to interact with the handles and the imposed support path.

C. Potential Applications

At the end of the experiment, participants were asked about their subjective experiences with the different sit-to-stand methods. They reported that the robot-assisted methods facilitated their sit-to-stand movements. In this small sample, five of the six participants preferred the adaptive method, emphasizing its responsiveness. One participant did not perceive a noticeable difference between the adaptive and predefined conditions. These subjective evaluations support the potential value of real-time pelvis-based modulation for user comfort, while larger studies are needed to confirm the preference pattern.

These impressions point to several real-world use cases. An adaptive controller embedded in rollators or lift-chairs could support older adults who live independently by matching the user's preferred pace. In contrast, predefined STS support may be useful when a simple, repeatable assistance profile is sufficient or when stronger offloading is desired. Rehabilitation settings could also use the two modes as graded assistance, with higher fixed support early in recovery and more user-paced adaptive support as lower-limb capacity improves. Because the approach relies on a single RGB-D camera and on-board computation, it may be suitable for lower-cost home or long-term-care deployments after validation in the intended population.

VI. CONCLUSION AND FUTURE WORK

This study demonstrated the feasibility of close-range, single-camera, vision-guided STS assistance on a compact mobile rollator. Both the predefined and vision-adaptive modes reduced lower-limb loading relative to unassisted STS in healthy adults. The predefined mode produced the larger peak reduction in foot vGRF (approximately 45% relative to unassisted), while the adaptive mode produced a smaller reduction (approximately 30%) with lower handle forces and more user-paced timing. The on-board vision system operated at the required 15 Hz update rate for real-time pelvis-based velocity modulation. These results provide initial evidence of the engineering feasibility of the robot and support strategies. They also help guide the further development of the robot platform and the future evaluation of adaptive STS support with older adults and individuals with mobility impairments.

Several limitations remain in this work. First, this feasibility study enrolled only healthy young adults; trials with older adults and individuals with mobility impairments are required before clinical claims can be made. Second, the experiment did not include a duration-matched predefined condition, so movement duration and closed-loop adaptation cannot be completely separated as mechanisms for handle-force reduction.

Future work will address these limitations by testing the system in the intended user population, adding matched-speed comparison conditions, and developing personalized

assistance profiles that adapt across multiple sessions. The design and validation of participant-specific coefficients will be considered in future work and are beyond the scope of the present study. Extending the framework to related tasks such as stand-to-sit transitions and balance assistance during walking would further improve its practical utility.

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