Intelligent Control of a Smart Walker and its Performance Evaluation

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***Abstract*—Recent technological advances have allowed the development of force-dependent, intelligently controlled smart walkers that are able to provide users with enhanced mobility, support and gait assistance. The purpose of this study was to develop an intelligent rule-based controller for a smart walker to achieve a smooth interaction between the user and the walker. This study developed a rule-based mapping between the interaction force, measured by a load cell attached to the walker handle, and the acceleration of the walker. Ten young, healthy subjects were used to evaluate the performance of the proposed controller compared to a well-known admittance-based control system. There were no significant differences between the two control systems concerning their user experience, velocity profiles or average cost of transportation. However, the admittance-based control system required a 1.2N lower average interaction force to maintain the 1m/s target speed ($p = 0.002$). Metabolic data also indicated that smart walker-assisted gait could considerably reduce the metabolic demand of walking with a four-legged walker.**

***Index Terms*—Smart Walker, Force Control, Aging, Mobile Robots, Walking Energetics**

I. Introduction

In 2009, the world's elderly population (aged 60 and above) had risen to nearly 740 million people [1], [2] and is expected to reach over 2 billion by 2050 [2]. Since mobility impairments increase with age [3], so will the use of mobility aids [4]. Of the mobility devices used by the elderly, the walker is the second most common behind the cane [4]. The proportion of elderly persons using walkers ranges from approximately 2% (ages 65-69) to 17% (ages 85+) [4]. This, in addition to the decreasing number of people available to support the elderly and the increasing number of elderly living alone [1], [2], [5], makes mobility assistive devices a viable alternative for promoting independence and health.

Mobility plays an important role in maintaining a good quality of life and allows older adults to remain independent, perform daily tasks more easily and stay healthier [6], [7]. In addition, being upright and walking bipedally is an important ability for humans since it ameliorates quality of life and allows for a greater freedom of choice [8]. A decrease in mobility can have severe consequences; sedentary lifestyles can result in muscle atrophy and increased chances of morbidity [9], [10]. Furthermore, individuals with mobility difficulties that remain sedentary have a 50% greater relative chance of death than those that remain mobile [11]. Unfortunately, regardless of their benefits, mobility devices are often not used [12]. In fact, 30%-50% of users will cease to use them soon after receiving them [13]. This may be due to the fact that 57% of walker users feel that their devices are "difficult and/or dangerous" to use [14]. Walkers may also be discarded due to their inconvenience, lack of mobility and perceived instability [15]. For these reasons, older adults may abandon their mobility aids for devices that engender a more sedentary lifestyle such as wheelchairs or motorized scooters [16].

Some of the drawbacks associated with walkers result from the compromises that must be made when choosing between different walker types. The two types of walkers with the largest contrast in user experience are the four-legged walker and the rollator. The rollator allows faster ambulation [17] and a lower cost of transportation (COT, metabolic cost per unit of mass and distance traveled, J/kg/m) [18] than the four-legged walker since it allows bipedal walking whereas the four-legged walker needs to be picked up with each step and requires a slower, "step-to" gait [6], [18]. For example, one study that used 10 healthy young adults (mean age 25.8) walking at 0.3m/s with minimal weight bearing showed that the COT of a four-legged walker was 82% and 74% greater than unassisted and rollator-assisted walking, respectively [18]. Another study, which used 10 older adult subjects (mean age 60.3) walking at self-selected speeds with full weight bearing, found that the COT of a four-legged walker was 212% and 104% greater than unassisted and rollator-assisted walking, respectively [19]. In a similar study, it was found that a four-legged walker was 217% more metabolically demanding than unassisted gait [17]. Likely due to these reasons, the rollator is the easiest to use [20] and most preferred [21] walker in older adults compared to the four-legged walker.

However, albeit more energy efficient, the rollator is inherently less stable than the four-legged walker due to its wheels [20]. There is evidence that rollators may actually increase the chance of falling through several factors such as catching on sidewalk cracks, carpets or other objects [14], [22] or distracting users from their surroundings [6], [23]. Yet, recent advances in technology have allowed for the development of smart walkers: rollators augmented with robotics and sensors that can provide the stability of a four-legged walker while still allowing users to ambulate bipedally [20].

Although there has been a recent prominence in smart walker development [24]–[26], the intuitive force-based control of the smart walker is still a challenging problem. This

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study developed a novel intuitive rule-based controller for a smart walker and evaluated its performance in comparison to an existing admittance-based controller [24]. The user experience, speed control, interaction force and metabolic consequences of the smart walker controller were evaluated.

II. Smart Walker Model and Control Systems

The smart walker was built by modifying a Segway Robotic Mobility Platform (RMP) 50 (Segway, Bedford, New Hampshire). To acquire the interaction force for walker control, an ATI Mini45 force/torque six-axis sensor (ATI Industrial Automation, Apex, North Carolina) was installed under the left handle of the walker (Fig. 1 (A)). A laptop on top of the walker processed the force inputs to generate and send the acceleration control commands to the RMP walker at a rate of 20Hz.

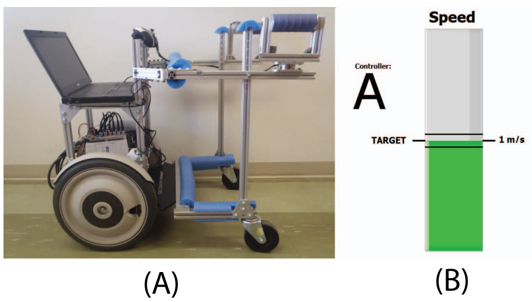

Fig. 1. (A). Photo of the RMP walker. (B). User interface of the walker experiment. The target speed region represents 1m/s $\pm 5\%$. The controller identifier, A in this instance, indicates intuitive rule-based control.

A new intuitive rule-based control scheme was developed to achieve the walker speed control. As a comparison, the admittance-based control which was originally developed in [24] was also implemented. The acceleration behaviour of the two controllers was not the same but both use the measured interaction force parallel to the walker's direction of travel as input. Since the scope of this study focused on speed control, a simple proportional control between forces orthogonal to the walker's direction of travel and the walker's turning rate was implemented for both controllers.

A. Intuitive Rule-based Control

Controlling a smart walker using interaction force is a challenging problem. Minimizing the interaction force to operate the walker throughout a range of speeds is beneficial to the user since it reduces physical exertion. However, too small of an interaction force may cause the controller to become too sensitive to noise or disturbances, resulting in a jerky control [24]. Therefore the interaction force required to operate the walker will affect user experience and satisfaction with the walker. To compromise these two factors, an intuitive rule-based control scheme was developed with an objective to reduce the interaction force required to operate the walker while accommodating perturbations in force input. A set of heuristical rules were developed to achieve the desired walker speed behavior and user control as follows: (a). The pushing force should exceed a force threshold to initiate walker movement from a standstill; (b). At a steady state, the walker speed is maintained at that speed for a predetermined range of force input; (c). The acceleration of the walker is proportional to the amount of input force that is above a speed-dependent threshold; (d). There is an upper bound on acceleration and speed. To implement these rules to control the walker acceleration, the interaction force and the current walker speed were used in a feedback control system. Based on these measurements, the acceleration characteristics of the walker were divided into five regions, which are numbered 1-5 in Fig. 2 and will be henceforth referred to as R#. Each region represents a different force-acceleration mapping for forward and backward motion of the RMP walker based on the heuristic rules. When the velocity of the RMP walker was zero, a non-zero threshold force (F_{min}) was required to initiate acceleration. Then, as the velocity became non-zero, a dynamic acceleration neutral zone was created ranging from F_{min} to F_{Dyn} (R1). The neutral zone was implemented to allow users to maintain a constant speed even under small input force variations. This neutral zone was designed to cope with the natural pushing force fluctuations caused by internal-external trunk rotation and other force disturbances. F_{Dyn} is the upper bound of the dynamic acceleration neutral zone, and it is calculated as

$$F_{Dyn}\ [N] = F_{Min} + (F_{Max} - F_{Min}) \times \frac{|V_{Curr}|}{V_{Max}} \quad (1)$$

where V_{Curr} is the current RMP walker velocity and F_{Min}, F_{Max} and V_{Max} are predetermined parameters for minimum force, maximum force and maximum velocity, respectively. When forces were within the neutral zone, the RMP walker did not accelerate. This was done in an attempt to minimize oscillatory motions that could be caused by continuously mapping force to acceleration. The neutral zone increased with speed since it was expected that greater speeds would be more susceptible to larger pushing force fluctuations. To accelerate the walker, the user had to apply a force greater than F_{Dyn} (R2, R3). The acceleration was proportional to the force applied above F_{Dyn} (R2). The new walker velocity (V) was calculated as

$$V\ [\frac{m}{s}] = V_{Curr} + \frac{F - F_{Dyn}}{F_{Max}} \times A_{Max} \times \Delta t \quad (2)$$

where A_{Max} is a predetermined parameter for maximum acceleration and Δt is the time since the previous iteration. In order to limit the maximum acceleration, the coefficient of $\frac{F-F_{Dyn}}{F_{Max}}$ in Equation 2 was limited to a maximum value of 1 when the applied force exceeded $F_{max} + F_{Dyn}$ (R3).

In order to slow down or reverse, the user decreased force below F_{Min} and the acceleration was proportional to the force applied below F_{Min} (R4, R5). In this case, the new velocity was calculated as

$$V\ [\frac{m}{s}] = V_{Curr} + \frac{F - F_{Min}}{F_{Max}} \times A_{Max} \times \Delta t \quad (3)$$

To limit the acceleration, $\frac{F-F_{Min}}{F_{Max}}$ from Equation 3 was limited to a minimum value of -1 (R5). Table I lists the parameter values used for the intuitive rule-based controller.

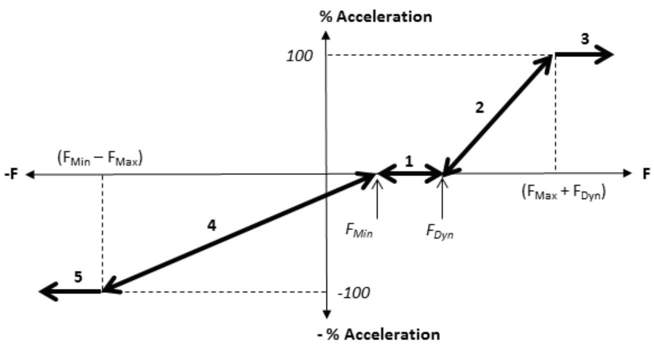

Fig. 2. Force-acceleration mapping for the intuitive rule-based controller. F is applied forward force and % Acceleration refers to the percent of A_{Max} that is applied when determining the walker's new speed. The sloped portions of the figure depend on the $\frac{F-F_{Dyn}}{F_{Max}}$ or $\frac{F-F_{Min}}{F_{Max}}$ portions of Equations 2 or 3, respectively.

TABLE I
PARAMETERS OF THE INTUITIVE RULE-BASED CONTROLLER.

Parameter	Value
F_{Min}	3N
F_{Max}	15N
V_{Max}	1.5m/s
A_{Max}	1.5m/s^2

The control parameters in Table I were determined experimentally by the researchers to ensure that the walker behaved in an intuitive manner while still minimizing the interaction force. When operated at its target speed of 1m/s, the sensitivity for accelerating and decelerating the walker was the same. At 1m/s, using Equation 1, F_{Dyn} is 11N. As shown by Fig. 2, maximum acceleration for the forward moving case occurs at an input force of 26N, resulting in a 15N range where the acceleration increased proportionally from $0-100\%$ of A_{Max}. Similarly, the range for deceleration was also 15N, ranging from F_{Min} of 3N to $F_{Min} - F_{Max}$ of -12N. This meant that at the target speed, where most of the walker use occurred, the walker behaved symmetrically and therefore intuitively, for accelerating and decelerating. As a feature of this controller, a dynamic neutral zone was implemented with the range of R1 scaling according to the walker speed. The controller had a larger input force range at lower speeds, with the range of forces used for scaling the acceleration ranging from 3N to 26N at a velocity of 0m/s, as compared a range from 11N to 26N for 1m/s. This strategy was selected based on the fact that the achievable range of interaction forces between the user and the walker is larger at slower walking speeds. Therefore, at low speeds, since the range of input forces for acceleration is larger, the acceleration is less sensitive. Finally, the usage of a dynamic neutral zone helped to provide the user with a smoother walker control irrespective to the walker's change in speed.

B. *Admittance-based control*

For comparison, the admittance-based controller implemented was based on the PAMM smart walker controller [24]. Dynamic damping was used to ensure users felt in control of the walker as they accelerated from a standstill but also to prevent fatigue while walking at a their preferred speed. The damping coefficient (B_{Dyn}) decreased proportionally to an increase in speed. Similarly to the intuitive rule-based control, a non-zero threshold force (F_{min}) was required to initiate acceleration. The following equation, which was derived from the mass-damper model, was used to determine walker speed

$$V\ [\frac{m}{s}] = \frac{F \times \Delta t + M \times V_{Curr}}{M + B_{Dyn} \times \Delta t} \quad (4)$$

where V is the new velocity, F is the applied force (after subtracting F_{Min}), Δt is the time since the previous iteration and M is the mass of the mass-damper model. V_{Curr} is the current velocity of the walker. The dynamic damping coefficient was calculated as

$$B_{Dyn}\ [\frac{N.s}{m}] = B_{Max} - (B_{Max} - B_{Min}) \times \frac{|V_{Curr}|}{V_{Max}} \quad (5)$$

where B_{Min} and B_{Max} were predetermined bounds for the damping coefficient of the mass-damper model. V_{Max} is the maximum permitted velocity of the walker. Table II lists the parameter values used during the experiments for the admittance-based controller.

TABLE II
PARAMETERS FOR THE ADMITTANCE-BASED CONTROLLER.

Parameter	Value
F_{Min}	3N
M	17.5kg
B_{Min}	3Ns/m
B_{Max}	6Ns/m
V_{Max}	1.5m/s

III. EXPERIMENTATION

A. *Subjects*

Ten young, healthy adults volunteered to participate in this study (5 male, 5 female, mean age 24.6 (SD 3.0), mean mass with equipment 79.4kg (SD 13.4)). To their knowledge, none of the subjects had any injuries, past or present, that affected their gait. As well, none of the subjects had previous experience using a rollator or smart walker. All subjects gave informed consent according to the policies of Queen's University's General Research Ethics Board.

B. *Course*

In order to create a realistic walking environment, the trials were performed by walking through the low-traffic hallways of a Queen's University building. Fig. 3 shows the ∼70m route.

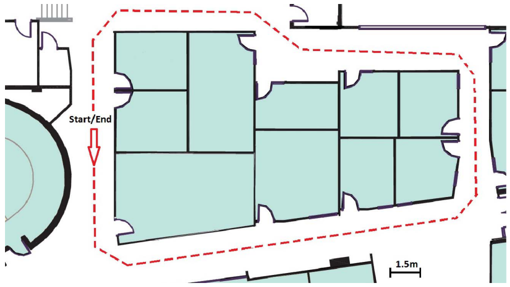

Fig. 3. Diagram of the ~70m route used for the experiments.

C. Experimental Procedure

Subjects were seated for 10 minutes before quiet standing data was collected for 5 minutes. Subjects then proceeded to train with the rollator and then the RMP walker (Controller A: intuitive rule-based control and Controller B: admittance-based control). Before use, the walkers were properly adjusted to each subject by ensuring an elbow flexion between 20 and 30 degrees [27]. Before using the RMP walker, subjects were briefly explained that the walker was controlled using the forces transmitted through the left handle and that the walker would move in the direction of applied force. No details about the control systems were given to the subjects. For both walkers, subjects were instructed to "try to reach and maintain the target speed while using as little force as possible" and to "keep both hands on the walker at all times". Since the RMP walker required rear wheel steering, the experimenter performed one lap of the course in order to instruct subjects on how to maneuver the walker. The subjects were given as much training time as necessary until they felt comfortable maintaining the target speed through the course. All subjects verbally confirmed this comfortable level with each controller after 4 laps or less.

As a comparison to the traditional walker assisted gait, a 4-wheel rollator was also instrumented and tested. The rollator used in these experiments was a Medline Ultra-Light Rollator (Medline, Mundelein, Illinois). The rollator had a mass of 5kg and wheel diameters of 15cm. A Hall effect sensor and two, small, evenly spaced magnets were added to each rear wheel of the rollator in order to keep track of the rollator's speed. A laptop on the seat of the rollator monitored the Hall effect sensors at 25Hz and displayed the rollator's speed through the same user interface as the smart walker.

The objective for the user was to regulate the pushing force on the handle and maintain the walker speed as close to 1m/s as possible. The user interface displayed a target speed region of 1m/s $\pm 5\%$ along with a controller identifier (A - Intuitive rule-based control, B - Admittance-based control, C- Rollator walking) in order to facilitate the remembrance of walker behavior from training. A screenshot of the interface, which filled the entire computer screen during trials, is shown in Fig. 1 (B).

Subjects performed a series of 4 trials in random order: walking with the rollator, walking with each of the two RMP walker controllers and walking free of aid. Each trial took approximately 7 minutes and consisted of 6 laps of the course. Before each trial, subjects were given 5 minutes of seated rest. In order to control the walking speed for the trial free of a walking aid, the subjects followed the experimenter at a constant distance while the experimenter used the rollator to control his speed to 1m/s.

D. Measurement of Energetics

To evaluate the energetics of smart walker assisted gait, oxygen consumption rates were collected using open-circuit respirometry (Cosmed K4b2, Rome, Italy). In order to allow all subjects to reach a steady state, the last 2 minutes of data from the standing trials and the data from minutes 4 to 6.5 of the walking trials were used. For each subject, the average oxygen consumption for each trial was averaged and normalized using their weight (with equipment) in order to obtain mL/kg/min of oxygen consumption. Brockway's equation [28] was used to calculate energy expenditure per unit mass and time as

$$[\frac{W}{kg}] = 20.964 \times \dot{V}\Delta O_2 \tag{6}$$

where $\dot{V}\Delta O_2$ is the rate of oxygen consumption per kg (mL/kg/s) and 20.964 is a constant representing the average metabolic fuel value of consumed oxygen (J/mL) [28]. The COT could then be calculated for each subject by dividing their energy expenditure by their average speed for each trial.

E. Performance Evaluation

The performance of the proposed controller was evaluated in the 3 following categories: (1). User experience; (2). Interaction force and walker speed; (3). Energetics. Since user experience is a subjective measure, it was evaluated using a post-trial questionnaire with a set of questions that were grouped into the 5 following categories: User comfort, Intuition, Speed control, Exertion and Overall experience. A 0 to 5 scale was used to answer the questions, with 0 as strongly disagree and 5 as strongly agree. The final score for each category was calculated as the mean values of its answers. The questionnaire is shown in Table III. After each walker trial, subjects completed the previously seen questionnaire. As a second measure of evaluation, the instantaneous pushing force and walker speed were logged for both controllers. The average and the variations for these measurements directly quantify the interaction quality between the user and the smart walker. A lower pushing force fluctuation with a smaller walker speed variation around the predefined speed indicates a smoother walker control and a better user-walker interaction. Finally, the metabolic measurements were used to evaluate the energetic consequence of walker-assisted gait.

F. Statistical Analysis

Paired t-tests were performed on the results of each category of the questionnaire, average speed, speed variation, pushing force and force variation between the two smart walker controllers. Paired t-tests were also performed on the COT between the rollator and smart walker controllers A and B. For the purposes of statistical analysis, the criterion for significance was 5%.

IV. Results

A. Questionnaire

The results of the user experience questionnaire for the intuitive rule-based controller and the admittance-based controller are shown in Fig. 4. There was no statistically significant difference between these two controllers in any of the five categories, indicating that the two control schemes functioned similarly in terms of user experience.

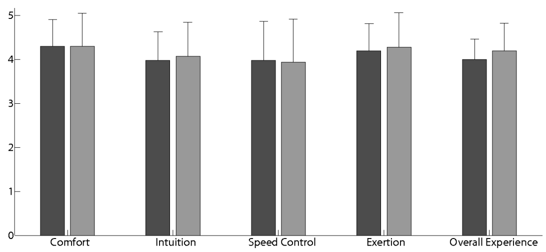

Fig. 4. The results of the post-trial questionnaire (mean and standard deviation). The intuitive rule-based controller is in dark grey, and the admittance-based controller is in light grey.

B. Walker Velocity and Interaction Force

Table IV summarizes the measured mean values and standard deviations (SD) of the walker speed and pushing force of the smart walker for the two controllers. There was no significant difference in walker speed ($p = 0.43$) and SD ($p = 0.37$) between controllers A and B. The results indicate that the intuitive rule-based controller and the admittance-based controller can both achieve a very good speed control to the targeted speed of 1m/s. The average pushing force of controller A was 1.2N larger than for controller B ($p = 0.002$), but there was no difference in the SD. Even though the mean pushing force was significantly larger for the rule-based controller, the user could not perceive a significant difference as shown by the exertion portion of the questionnaire. This may be due to the fact that under a SD of 3.8N, a 1.2N force difference is not significant enough for the user to detect.

C. Energetics

Table V shows a summary of the metabolic data for walking without aid, walking with the rollator and walking with the smart walker with controllers A and B. The mean quiet standing metabolic cost was 4.2mL/kg/min (SD 1.2). As expected, walking without aid required the lowest net COT: 1.7J/kg/m (SD 0.2). Rollator-assisted gait resulted in a 17% ($p = 0.012$) greater net COT than unassisted walking. Smart walker-assisted gait resulted in a 40% ($p = 0.0004$) and 39% ($p = 0.00001$) greater net COT than unassisted walking for controllers A and B, respectively. When compared to walking with the rollator, smart walker-assisted gait required a 20% ($p = 0.047$) and 19% ($p = 0.0006$) greater net COT for controllers A and B, respectively. There was no significant difference between the mean net COT between controllers A and B ($p = 0.68$). However, the smart walker-assisted gait increased the gross $\dot{V}O_2$ by about 1.9mL/kg/min (or 20%) compared to normal walking and by about 0.84mL/Kg/min (or 9%) compared to rollator-assisted walking. Although smart walker-assisted gait was slightly more energetically demanding than rollator-assisted gait, both smart walker controllers were still less demanding than walking with a four-legged walker. Walking with a four-legged walker at the same speed as unassisted walking and rollator-assisted walking resulted in 82% and 74% increases in net COT, respectively [18]. It is expected that smart walkers will help reduce the energetic demand of users even when used for weight bearing and support.

TABLE IV
Summary of walker velocity and interaction force.

Subject	Velocity (m/s) Controller A Mean	Velocity (m/s) Controller A SD	Velocity (m/s) Controller B Mean	Velocity (m/s) Controller B SD	Force (N) Controller A Mean	Force (N) Controller A SD	Force (N) Controller B Mean	Force (N) Controller B SD
1	1.00	0.07	1.02	0.05	6.78	3.20	5.50	3.37
2	1.02	0.04	1.01	0.05	6.97	2.84	6.55	2.60
3	0.99	0.07	0.97	0.12	7.01	3.42	5.83	4.54
4	0.95	0.19	0.99	0.04	6.51	4.07	6.16	3.08
5	1.01	0.07	1.02	0.09	6.69	4.64	4.63	5.18
6	1.03	0.07	1.00	0.09	6.80	3.60	6.33	3.25
7	1.01	0.08	1.01	0.09	6.71	4.49	4.66	4.36
8	0.99	0.13	1.01	0.03	7.05	5.22	4.34	5.13
9	0.98	0.07	1.00	0.06	6.72	3.47	5.28	3.69
10	0.99	0.06	0.99	0.04	6.62	3.02	6.39	2.61
Mean	1.00	0.08	1.00	0.07	6.79	3.80	5.57	3.78

TABLE V
Summary of metabolic data.

		Standing	Walking	Rollator	Controller A	Controller B
Gross $\dot{V}O_2$	Mean	4.23	9.30	10.14	11.21	11.19
(mL/kg/min)	SD	1.18	0.72	0.77	1.63	0.99
Gross Power	Mean	1.48	3.25	3.54	3.92	3.91
(W/kg)	SD	0.41	0.25	0.27	0.57	0.35
Net COT	Mean	-	1.74	2.04	2.44	2.41
(J/kg/m)	SD	-	0.24	0.34	0.29	0.24

n =10; SD: standard deviation

V. Future Work

Since the subjects used in this study were young and healthy, the results obtained from this study may not be representative of the typical, more elderly users of mobility aids. This study served as the first step in developing smart walker performance evaluation protocols. Future experimentation will focus on using elderly users of mobility aids as subjects.

VI. Conclusion

This study proposed a novel rule-based controller for the intuitive control of a smart walker and studied its performance. Through a comprehensive performance evaluation in the areas of user experience, speed control, interaction force and metabolic demand, we found that the proposed controller performed similarly to the state of the art admittance-based controller. This study also demonstrated for the first time the

TABLE III
POST-TRIAL QUESTIONNAIRE FOR EVALUATION SMART WALKER USER EXPERIENCE.

Category	Question	Value					
Comfort	I felt safe walking straight with the walker	0	1	2	3	4	5
	I felt safe cornering with the walker	0	1	2	3	4	5
	I did not feel nervous while operating the walker	0	1	2	3	4	5
	I did not feel afraid while operating the walker	0	1	2	3	4	5
Intuition	I felt in control of the walker while going straight	0	1	2	3	4	5
	I felt in control of the walker while cornering	0	1	2	3	4	5
	The walker was intuitive to control	0	1	2	3	4	5
Speed control	I was able to maintain a constant speed while going straight (not necessarily the target speed)	0	1	2	3	4	5
	I was able to maintain a constant speed while cornering (not necessarily the target speed)	0	1	2	3	4	5
	I was able to attain the target speed.	0	1	2	3	4	5
	I was able to maintain the target speed	0	1	2	3	4	5
Exertion	Accelerating to the target speed required little force	0	1	2	3	4	5
	Maintaining the target speed required little force	0	1	2	3	4	5
Overall Experience	Overall, my experience with this walker was good	0	1	2	3	4	5
Remark: 0-Strongly Disagree, 1-Disagree, 2-Somewhat Disagree, 3-Somewhat Agree, 4-Agree, 5-Strongly Agree							

energetic consequences of smart walker-assisted gait compared to traditional rollator-assisted gait. Although the smart walker-assisted gait was more energetically expensive than a rollator, evidence suggests that smart walkers have the potential to considerably reduce the aerobic demand of walking with a four-legged walker, while still being able to provide better stability than a rollator.

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