Feasibility and Effects of a Soft-Wearable Robotic Suit Assisting Hip Extension in Older Adults: A Pilot Study

Hyun Iee Shin, Ho Seok Lee, Na Young Yun, Kyeongmin Lim, Jaeha Yang, Giuk Lee, *Member, IEEE*, and Don-Kyu Kim

***Abstract*— Background: The global population of older adults is rapidly increasing, leading to a higher prevalence of gait impairment and fall risk. Soft-wearable robotic suits have emerged as alternatives to rigid exoskeletons; however, evidence of their effects in older adults remains limited. This pilot study evaluated the feasibility and effects of a cable-driven soft-wearable robotic suit (H-Medi) assisting hip extension during gait training in community-dwelling older adults. Methods: This single-center, single-arm study recruited 22 community-dwelling older adults (age≥ 65 years). Participants completed six exercise sessions over three weeks, each consisting of 20 minutes of robot-assisted gait training and 20 minutes of strength training. Feasibility was assessed through session adherence and safety monitoring. Functional outcomes were measured before and after the intervention without robotic assistance, including gait speed using the 4-meter walk test (4MWT), Timed Up and Go test (TUG), Short Physical Performance Battery (SPPB), Berg Balance Scale (BBS), and lower-limb joint range of motion (ROM). Pre–post comparisons were performed using paired t-tests or Wilcoxon signed-rank tests, and a linear mixed-effects model analyzed gait speed. Results: Twenty-one of 22 participants completed all sessions with no adverse events. Gait speed increased from 1.00[0.80 – 1.10] to 1.10[1.00 – 1.20] m/s (Δ= 0.10[0 = 0.20] m/s, p<0.001). TUG time decreased from 11.1 ± 1.8 to 9.7 ± 1.4 sec (p<0.001). Ankle sagittal-plane ROM increased significantly (p= 0.015). The mixed-effects model identified time and age as significant determinants of gait speed (ICC= 0.65). Conclusions: Short-term training using a soft-wearable robotic suit assisting hip extension was safe, feasible, and improved gait speed and mobility in older adults.**

***Index Terms*— Soft-wearable robotic suit, hip extensor assistance, older adults, gait.**

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I. Background

THE global population of older adults is rapidly increasing [1], [2]. Structural and functional changes with aging, such as altered joint mechanics, gait alterations, and sarcopenia, contribute to impaired balance and gait function, and increase fall risk [3], [4]. Older adults typically exhibit slower gait speed, shorter step length, and increased cadence, reflecting neuromuscular deterioration and altered lower limb joint mechanics [5], [6]. These changes may result from reduced mechanical work and decreased joint range of motion (ROM) in the lower limbs, leading to compromised gait efficiency and stability. Specifically, older adults show reduced ankle push-off power, which is often compensated by increased reliance on hip extensors during early stance phase, reflecting a distal-to-proximal shift in propulsion [7]. Consequently, the hip extensors assume a greater role in forward progression and trunk stabilization with age. While enhancing hip-generated work can help compensate for deteriorating ankle function and maintain gait performance, it may also increase mechanical demand and metabolic cost if excessively relied upon [3], [7]. In a previous study, Beijersbergen et al. demonstrated that lower-limb power training can improve gait speed by optimally increasing hip mechanical output while preserving efficient ankle contribution [7]. It is well known that faster gait speed consistently predicts longer survival and better health outcomes [8]. Even small increases in usual gait speed (e.g., 0.1 m/s) significantly improve survival probability, highlighting gait speed as an integrative marker of multisystem

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integrity and physiological reserve [9]. Therefore, targeted exercise interventions to increase gait speed, strengthen the hip extensors, and restore joint efficiency may improve mobility and physical performance. Previous studies incorporating exercise interventions in the older adults demonstrated improved physical performance and gait parameters, including gait speed [10], [11]. However, exercise training requires considerable man-power, leading to limitations such as being time-consuming, costly, and often restricted to in-hospital or specialized settings. Consequently, wearable robots have emerged as a solution to address these issues. Moreover, these devices have become an important component of healthcare, with the potential to provide targeted approaches to meet the rehabilitation needs of an aging society [12], [13]. In particular, wearable robots are being used to increase activity levels, assist with daily living activities, and improve physical function, thereby playing a significant role in supporting older adults [14], [15].

Conventionally, exoskeletal robots have demonstrated effectiveness in neuromuscular rehabilitation for patients who are unable to move their lower limbs voluntarily [16], [17]. These exoskeletal robots have shown benefits for patients with spinal cord injury or stroke, including feasibility, improved strength, postural control, gait function, and reduced physical strain during rehabilitation [18], [19]. However, these robots are limited by their relatively heavy and bulky design, high cost, monotonous and unnatural joint movements, and lack of a personalized therapy approach, which restricts the range of rehabilitation [19], [20], [21]. Specifically, rigid exoskeletal robots rely on limb-mounted rigid linkages that may become misaligned with the user's anatomical joint centers, generating unintended interaction forces, increased mechanical impedance, and greater rotational inertia. As a result, they can restrict natural multi-planar movements, including pelvic rotation, thereby altering physiological gait patterns [19], [21]. In addition, each patient may require individualized rehabilitation protocols, yet conventional robots often struggle to adapt flexibly to these varying needs, potentially limiting the efficacy of rehabilitation [22]. Therefore, wearable robotic systems have recently emerged for gait training and have demonstrated significant effects [15], [23], [24], [25]. However, these wearable devices still commonly employ rigid thigh frames or structured exoskeletal components to support and transmit assistive forces, which may constrain natural lower-limb movement.

To overcome these limitations, soft-wearable robotic suits have been developed. Unlike conventional rigid exoskeletons, soft wearable robots are typically lightweight, compliant, and designed in the form of clothing, thereby improving comfort and reducing restrictions on natural movement [14], [26], [27]. These systems commonly employ cable-driven or textile-based actuation mechanisms to deliver assistive forces while minimizing mechanical impedance and limb inertia [26]. In addition, soft wearable robots can adapt more flexibly to individual body shapes and gait patterns because of their compliant structures and wearable sensor systems [14], [27]. They also commonly incorporate real-time gait event detection using wearable sensors to synchronize assistive force with the user's movement, thereby enabling task-specific and individualized gait assistance [27], [28].

However, clinical benefits of gait training using soft-wearable robotic suits in older adults have not yet been fully established. In populations beyond older adults, studies have demonstrated effects of soft wearable robots in individuals with stroke or Parkinson's disease, though these only involved small samples [29], [30]. Therefore, this study aimed to evaluate the feasibility of incorporating a soft-wearable robotic suit employing a cable-driven actuator that provides hip extension assistance into a gait training program for older adults, and to investigate the functional improvements associated with this training protocol. Furthermore, this study sought to determine whether training with robotic assistance would lead to improvements in gait function even during unassisted walking. By assisting hip extension, we hypothesized that users may experience improvements in gait function, primarily gait speed. To our knowledge, this is the first study to examine the usability of a cable-driven soft-wearable robot assisting hip extension for gait training in older adults.

II. Methods

A. Study Setting and Design

This was a pilot study to evaluate the feasibility and effects of the soft-wearable robotic suit in older adults. The study was conducted at a single-center (Chung-Ang University Hospital) using a single-arm design. This study was approved by the Institutional Review Board (IRB) of Chung-Ang University Hospital (IRB number 2401-020-587). All participants provided written informed consent. Participants were recruited between March and November 2024, and the final assessments were completed in December 2024.

B. Participants

We recruited community-dwelling older adults. Inclusion criteria were as follows: 1) Age $\geq$ 65, and 2) agreed to participate in the study. Exclusion criteria were as follows: 1) patients with cognitive impairment (Korean version of Mini-mental status examination [K-MMSE] <24), 2) patients with neuromuscular diseases that affect gait function, 3) patients having unstable medical condition that affects activities of daily living, 4) patients with vestibular diseases or having dizziness that could increase the risk of fall, and 5) other condition confirmed by investigators that patients could not participate in this study.

Sample size was calculated based on gait speed. A previous study suggested that the minimal clinically important difference (MCID) in gait speed for older adults is 0.1 m/s, with a standard deviation (SD) of 0.15 m/s [31], [32]. The power was set at 80% with a two-tailed significance level of 0.05. Accordingly, the required sample size was calculated to be 20 participants. Allowing for a 10% loss to follow-up, we planned to recruit 22 participants.

C. Exercise Protocol

The exercise program was primarily designed to enhance gait speed of older adults [33]. The 45-minute exercise

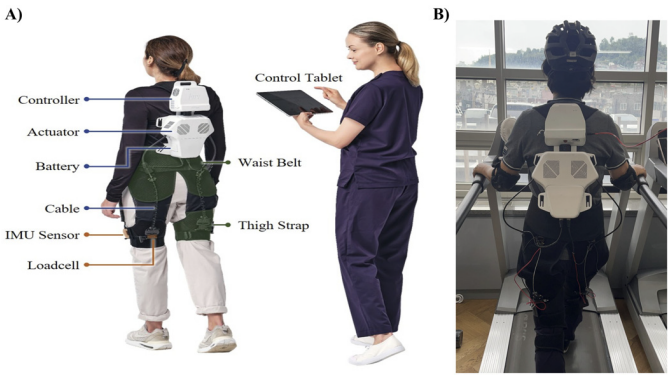


Fig. 1. The cable-driven soft-wearable robotic suit (H-Medi). **A)** Schematic of H-Medi, **B)** H-Medi applied to participant (back-view).

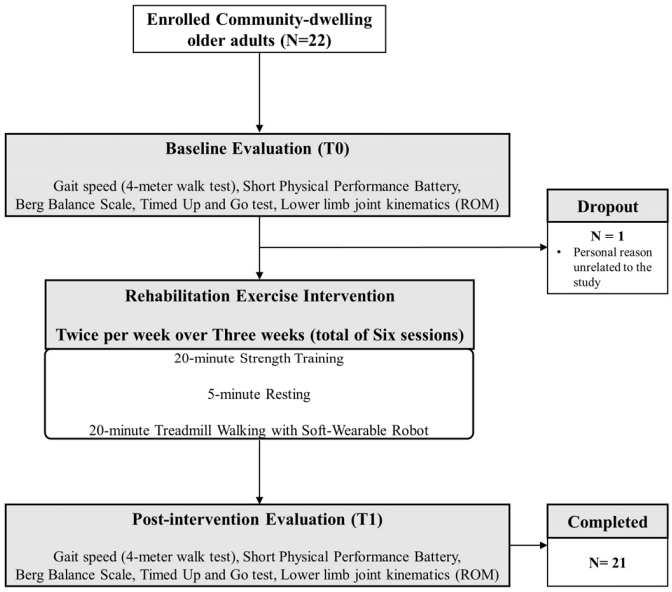


Fig. 2. Flowchart of the study.

program consisted of 20 minutes of gait training using the soft-wearable robotic suit, a 5-minute of rest period, and a subsequent 20 minutes of strength training. During gait training, participants walked at an individually self-selected speed within target of a moderate-intensity range, defined as 11-13 on Borg Rating of Perceived Exertion (RPE) scale [34], [35]. RPE was recorded at 10 and 20 minutes to monitor exercise intensity. Gait training was performed on a treadmill with handrail support. Strength training was conducted in a one-on-one setting with a skilled physical therapist and included hamstring and quadriceps stretching, single-leg bridging, hip abductor strengthening, quadriceps strengthening, bird-dog exercises, squats, and single-leg standing exercises. Participants were scheduled to participate in the exercise program twice weekly over a three-week period, for a total of six sessions.

D. Soft-Wearable Robotic Suit (H-Medi)

Gait training was conducted using the H-Medi (HUROTICS Inc., Seoul, Republic of Korea), a cable-driven soft-wearable robotic suit [36]. This system was selected to address the intrinsic mechanical limitations of conventional rigid exoskeletal robots. The H-Medi employs a frame-free architecture that fundamentally eliminates these inertial constraints. This compliant design helps preserve intrinsic gait patterns and allows natural kinematic variability, which is particularly important for promoting motor learning and voluntary engagement in older adults [19], [26]. The robotic structure of the H-Medi also provide high mechanical transparency compared to rigid exoskeletons. Even with advanced control algorithms, they often exhibit residual friction and inertia that create parasitic resistance. The H-Medi mitigates this issue; when the Bowden cables are slack, the system exerts negligible resistance, allowing unrestricted movement similar to normal clothing [26], [37]. This transparency ensures that the device assists only when needed, without burdening the user during the rest of the gait cycle [37].

As shown in Fig 1, the device weighs less than 4.5 kg including a lumbar actuation unit, a waist belt, and thigh straps [36]. The assistive force was delivered as tension between the proximal waist and distal thigh anchors, with embedded load cells providing feedback to control the cable tension. The control algorithm tracked the Gait Cycle Percentage (GCP) using inertial measurement unit (IMU) sensor signals to synchronize assistance in real time. The gait cycle was defined based on the timing of maximum hip flexion (MHF; 0%), and the assistive force onset, peak, and offset were set to 4%MHF, 28%MHF, and 42%MHF of the cycle. The GCP algorithm identified MHF as the first positive peak in hip flexion angle following a negative peak in hip extension angle from the thigh IMU signals, following the algorithm described by Ding et al.; the assistive force timing was also selected based on the same study, which reported a timing that minimizes the biological hip extension moment [38]. When expressed relative to a heel-strike-referenced gait cycle, this force profile had an onset at 90%, a peak at 14%, and an offset at 28% of the gait cycle [39]. The assistive force followed a half-sine profile.

This assistance timing was designed to support hip extensor function during stance, thereby facilitating trunk control and stability during weight acceptance. It was intended to compensate for reduced hip extensor strength in older adults and to guide weight transfer during early stance. During swing, no active assistance was provided. The Bowden cable was maintained in a slack condition to allow natural lower-limb motion with minimal mechanical resistance. Although the maximum force capability of the H-Medi is up to 200 N, in this study assistance was applied within 30-80 N ($\approx$ 4.5 $\sim$ 12 Nm of hip extension torque). The assistance magnitude was intentionally set at a submaximal level. This was to avoid substituting voluntary muscle effort and to encourage active user participation.

To quantify the force-tracking performance of the control system and to ensure that the intended assistive force was reliably delivered, the accuracy of the cable tension control was evaluated in a pilot study involving two older adult participants (ages 71 and 65 years; heights 162.3 and 161.6 cm; weights 60.3 and 51.2 kg). The participants walked on a treadmill at 1.1 m/s while wearing the H-Medi, and reference

and actual cable tensions were logged synchronously by the on-board controller together with the gait-cycle phase derived from the thigh IMU. For each gait cycle, the root-mean-square error (RMSE) between the reference and actual force profiles, the peak force error, and the peak-instant timing error were computed and pooled across both lower limbs of the two participants. The RMSE between the reference and actual force profiles was 6.1 $\pm$ 1.5% of the reference peak force. Regarding peak force accuracy, the actual peak force exceeded the reference peak by 5.4 $\pm$ 2.2% of the reference peak force. In terms of temporal accuracy, the peak assistance timing error was -0.44 $\pm$ 1.2% of the gait cycle. These results suggest that the device provided consistent and phase-accurate hip extension assistance during the intervention sessions.

Assistive force progression followed a dual-criterion approach incorporating subjective tolerance, assessed via the RPE, and objective gait quality evaluated by the physical therapist. Assistance intensity was increased only when the participants demonstrated kinematic stability without exhibiting compensatory movements.

E. Measurements

The feasibility was assessed by participants' adherence of attending the exercise sessions. To determine the effectiveness of the robot-assisted gait training (RAGT), the following assessments were conducted at baseline (T0) and post-exercise (T1), in the absence of robotic assistance. To assess the functional levels of participants, gait speed as measured by 4-meter walk test (4MWT), Short Physical Performance Battery test (SPPB), Berg Balance Scale (BBS), and Timed-Up and Go test (TUG) were conducted. In addition, lower-limb joint kinematics during walking, including hip, knee, and ankle ROM, were assessed using Human Track gait analysis system (R. Biotech Co Ltd., Seoul, Republic of Korea).

4MWT is a validated test to measure gait speed in older adults, and therefore we used 4MWT to measure gait speed [40]. The SPPB assesses balance, walking ability, and transfers. Each component is scored on a 0–4 scale, with a total score ranging from 0 to 12, where higher scores indicate better performance [41]. The TUG evaluates gait, balance, and fall risk. Participants were asked to rise from a chair, walk 3 meters to a cone, turn around, return to the chair, and sit down at their comfortable walking speed. Completion time was recorded in seconds [42]. The BBS assesses functional standing balance through 14 tasks of increasing difficulty, including sitting, standing, single-leg stance, and positional changes. Each item is scored on a 0–4 scale, with a maximum total score of 56, where higher scores indicate better balance ability [43]. Human Track is an IMU sensor-based gait analysis system validated for detecting and analyzing gait events in older adults [44], [45]. Using this system, seven IMU sensors were placed on the dorsum of both feet, the tibial shafts, the mid-femurs, and the lower abdomen. Participants walked along a straight 10-m walkway on a flat surface. To minimize the influence of gait initiation and termination, the first and last gait cycles were excluded from the analysis. Consequently, approximately 3–6 valid gait cycles per participant were analyzed to calculate the mean ROM of lower-limb joints. For each participant, mean hip, knee, and ankle ROM values were calculated separately for the left and right limbs, and the average of both limbs was used for subsequent analyses.

All measurements were performed by two expert physical therapists, with each participant assessed by the same therapist for all sessions. Medical directors evaluated the appropriateness of the measurements. The study flowchart is shown in Fig. 2.

F. Statistical Analyses

Baseline characteristics were described in terms of frequencies and percentages for categorical variables, while means and SD were utilized for numerical variables. For the analyses of outcome measures, the Shapiro–Wilk test was used to assess normality. When a normal distribution was confirmed, paired t-tests were conducted to compare differences between T0 and T1, and the results were presented as mean $\pm$ SD. Otherwise, the Wilcoxon signed-rank tests were applied, and the results were presented as median [Interquartile range, IQR]. For paired t-tests, effect sizes were calculated using Cohen's d, defined as the standardized mean difference between paired observations based on the SD of the within-subject differences [46]. For Wilcoxon signed-rank tests, effect sizes were calculated using the rank-based effect size ($r = Z/\sqrt{N}$), defined as the standardized test statistic (Z) divided by the square root of the number of paired observations (N) [47]. In addition, linear mixed-effects model (LMM) was used to analyze repeated measures of gait speed, accounting for inter-subject variability through random intercepts while adjusting for covariates. Fixed effects included time of assessment and participants' characteristics (age and sex) as covariates.

Statistical significance was set as a two-sided $p < 0.05$ for all the conducted analyses. All analyses were performed using R Statistical Software (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria).

III. Results

Among the 22 initially recruited participants, 21 completed the study, while one did not. The participant withdrew for personal reason unrelated to the study. The baseline clinical characteristics are shown in Table I. The mean (SD) age of the participants was 72.2 $\pm$ 4.3, and 13 (61.9%) participants were female. The mean (SD) of height, weight, and BMI were 156.6 $\pm$ 8.9cm, 57.9 $\pm$ 13.8kg, and 23.4 $\pm$ 3.7kg/m^2, respectively. Regarding feasibility, all 21 participants completed all six sessions of the exercise program, and no data were missing. No adverse event was found for all participants during the study.

Regarding the outcomes, the results are shown in Table II. The median [IQR] gait speed significantly improved from 1.00 [0.80 ~ 1.10] m/s to 1.10 [1.00 ~ 1.20] m/s, indicating a relatively large effect size ($r = 0.81$, $p < 0.001$). The mean (SD) TUG also showed a significant change from 11.1 $\pm$ 1.8 sec to 9.7 $\pm$ 1.4 sec (Cohen's $d = 0.98$, $p < 0.001$), indicating improved performance. The BBS and SPPB showed no significant differences. Within the sagittal-plane, the mean

TABLE I
BASELINE CHARACTERISTICS OF PARTICIPANTS

Baseline characteristics	All participants (N = 21)
Age	72.2 ± 4.3
Sex (Male : Female)	7 (38.1%) : 13 (61.9%)
Height, cm	156.6 ± 8.9
Weight, kg	57.9 ± 13.8
Body mass index, kg/m^2	23.4 ± 3.7
K-MMSE	28.6 ± 1.2
BDI	9.0 ± 6.5
Medical history	
Hypertension	9 (42.9%)
Dyslipidemia	10 (47.6%)
Knee osteoarthritis	3 (14.3%)
Osteoporosis	2 (9.5%)
Lumbar spinal stenosis	2 (9.5%)
Cervical herniated intervertebral disc	1 (4.8%)
Angina	1 (4.8%)

K-MMSE, Korean version of Mini-mental status examination; BDI, Beck Depression Inventory.

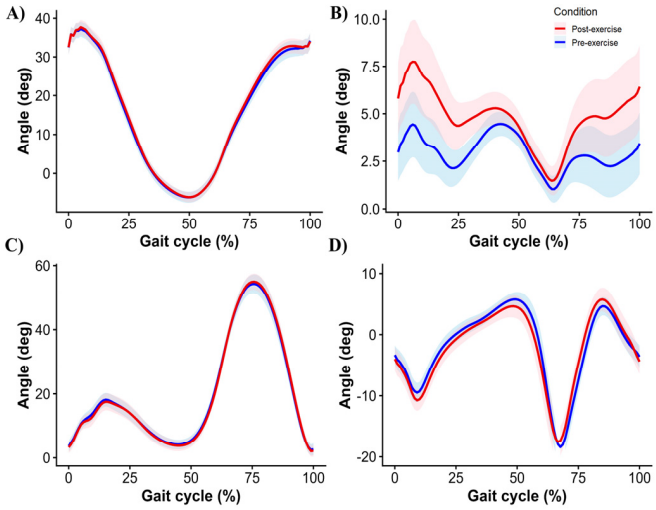


Fig. 3. The range of motion of lower-limb joints. **A)** Sagittal-plane hip, **B)** Frontal-plane hip, **C)** Sagittal-plane knee, and **D)** Sagittal-plane ankle.

(SD) ROM of the hip (from 45.3 ± 4.7° to 45.7 ± 5.6°) and knee (from 55.9 ± 6.8° to 57.5 ± 5.6°) joints showed a trend toward slight increase without statistical significance, while the ankle joint (from 33.5 ± 3.8° to 36.3 ± 6.8°; Cohen's d = 0.62, p = 0.015) demonstrating a statistically significant improvement. In frontal-plane hip joint, the mean (SD) ROM showed increasing trend from 10.3 ± 1.6° to 11.8 ± 2.7°, without statistical significance. The details are provided in Table II and Fig. 3.

When the gait speed measurements were analyzed by the LMM, time (pre- and post-exercise) and age were shown to be significantly associated factors. On average, post-exercise gait speed improved by 0.13 m/s than pre-exercise, after adjusting for age and sex ($p < 0.001$). Age was associated with a 0.02 m/s decrease in gait speed per additional year. The random-intercept variance (SD) was 0.0111 (0.106), indicating substantial between-subject heterogeneity in pre-exercise gait speed. The residual variance (SD) was 0.0060 (0.077), suggesting that within-subject variability around each individual's mean was smaller than the variability between individuals. The resulting intraclass correlation coefficient (ICC) was 0.65 [48]. The results are shown in Table III.

IV. DISCUSSION

In this pilot study, six sessions of exercise training incorporating a soft-wearable robotic suit were associated with improvement in gait function among older adults. All participants completed the full training sessions without adverse events, including falls, demonstrating the feasibility of this intervention. Post-exercise assessments showed improvements in gait speed (0.10 [0 ~ 0.20] m/s, median [IQR]) and TUG performance (−1.4 ± 1.3 sec). Lower-limb joint ROM showed a trend toward an increase, with a statistically significant improvement observed at ankle joint (2.8 ± 4.6°). For gait speed, the LMM demonstrated significant effects of time (pre- and post-exercise) and age. In addition, the ICC was 0.65, indicating that approximately 65% of the total variance in gait speed was attributable to between-individual differences. This finding underscores the importance of adjusting for between-subject heterogeneity when estimating the intervention effect.

Previously, various studies demonstrated that RAGT could enhance gait performance [49], [50]. Recently, studies utilizing wearable robotic suits other than exoskeletons also have shown effects on gait [15], [23], [24], [25]. The Gait-Enhancing Mechatronic System (GEMS) is one of the most widely studied wearable robots. GEMS demonstrated enhancement in gait speed for older adults, suggested by reductions in metabolic cost and muscle effort [23], [24]. In 2023, Lee et al. demonstrated the effects of EX1, a hip-assist wearable robot, in older adults. The results showed improvements in gait speed and kinematics (increased hip and ankle joints ROM), reduced metabolic cost via 18 exercise sessions, and improved functional level demonstrated by BBS, TUG, and SPPB [15]. Recently, Cho et al. demonstrated the effects of a wearable walking-assist robot that assists hip flexion and extension by providing torque at three predefined levels [25]. This study involved older adults undergoing 12 sessions of exercise, revealing improvements in gait speed, TUG, SPPB, and muscle strength. The authors suggest that reduced energy expenditure could be the mechanism underlying these functional improvements, as in the previous studies.

Although the wearable devices mentioned above showed promising results, the H-Medi used in this study holds several characteristics that distinguish it from previous rigid exoskeletal robots. Rigid exoskeletal devices face inherent challenges, related to misalignment between the center of robot assistance joint and the biological joint of the user. Also, rotational inertia of segments is increased due to limb-mounted hardware. In contrast, H-Medi is based on a soft, frame-free architecture that reduces sensitivity to alignment constraints and minimizes limb-mounted mass. This characteristic is beneficial to user comfort and movement compatibility in older adults.

Regarding control strategy, the torque-generation method implemented in H-Medi differs from those used in prior

TABLE II
OUTCOME ASSESSMENTS COMPARING PRE- AND POST-EXERCISE

Outcome assessments	Pre-Exercise	Post-Exercise	Delta	*p*-value*	Effect size**
Gait speed, m/s	1.00 [0.80 ~ 1.10]	1.10 [1.00 ~ 1.20]	0.10 [0 ~ 0.20]	<0.001	0.81
TUG, sec	11.1 ± 1.8	9.7 ± 1.4	-1.4 ± 1.3	<0.001	0.98
BBS	56 [55 ~ 56]	56 [55 ~ 56]	0 [0 ~ 1]	0.20	0.35
SPPB	12 [12 ~ 12]	12 [12 ~ 12]	0 [0 ~ 0]	0.23	0.29
ROM of lower-limb joints					
Hip, sagittal-plane	45.3 ± 4.7	45.7 ± 5.6	0.5 ± 3.5	0.58	0.13
Hip, frontal-plane	10.3 ± 1.6	11.8 ± 2.7	1.4 ± 3.1	0.054	0.47
Knee, sagittal-plane	55.9 ± 6.8	57.5 ± 5.6	1.5 ± 5.9	0.28	0.26
Ankle, sagittal-plane	33.5 ± 3.8	36.3 ± 6.8	2.8 ± 4.6	0.015	0.62

TUG, Timed-Up and Go test; BBS, Berg Balance Scale; SPPB, Short Physical Performance Battery; ROM, Range of motion.
Results are presented as median [Interquartile range, IQR] for non-normally distributed variables and mean ± standard deviation for normally distributed variables.
* Compared between the pre- and post-exercise values. For gait speed, BBS, and SPPB, Wilcoxon signed-rank tests were used. For TUG, and ROM of lower-limb joints, paired t-tests were used, after confirming normality.
** Effect sizes were calculated using rank-based effect size for non-normally distributed variables and Cohen's d for normally distributed variables.

TABLE III
LINEAR MIXED-EFFECTS MODEL OF GAIT SPEED

Fixed effect	Estimate	Standard error	Degrees of freedom	*p*-value
Intercept	2.05	0.44	18.27	<0.001
Time	0.13	0.02	20.00	<0.001
Age	-0.02	0.01	18.25	0.020
Sex	0.06	0.05	18.02	0.26
Random effect	**Variance**	**Standard deviation**		
Individual	0.0111	0.106		
Residual	0.0060	0.077		

wearable robots evaluated in older adults. The EX1 system described by Lee et al. employed a Delayed Output Feedback Control (DOFC) framework, in which assistive torque is generated as a function of hip joint kinematics [15]. Because DOFC intrinsically couples torque output to joint-angle amplitude and timing, its assistive profile cannot be adjusted. Similarly, GEMS utilized Particularly Shaped Adaptive Oscillator (PSAO) algorithm, which applies torque based on hip moment patterns derived from healthy adults [23], [24]. These profile-based strategies have inherent problems where they cannot apply assistance reliably when the user's walking motion deviates substantially from normative kinematics.

In contrast, the event-based strategy used in H-Medi identifies gait events to construct a user-specific gait cycle for every step. Assistance is applied at specific timings of this cycle, which can be adjusted by the user. Because this method does not depend on continuous joint-angle trajectories, the assistive torque is decoupled from the kinematic magnitude. This enables consistent delivery of assistance, even in the presence of gait impairment. The importance of providing assistance at appropriate timing within the gait cycle is supported by research from Ding et al., which showed that hip-assistance timing strongly influences the mechanical power delivered and metabolic outcomes during gait [38]. Moreover, adequate timing between the wearer's movement and the applied torque is known to reduce human–robot disagreement. Misalignment between user intent and the delivered assistance has been shown to increase interaction torque and reduce coordination between the user and robot [51].

In this study, gait training using H-Medi combined with strengthening exercises demonstrated enhancements in gait speed (0.10 [0 ~ 0.20] m/s) for older adults, exceeding the MCID [31], [32]. Despite a relatively small number of training sessions, the improvement was statistically significant and demonstrated a large effect size (r = 0.81). The improvements in gait speed could be explained by various mechanisms. First, the present intervention intentionally combined RAGT with strengthening exercises to address complementary aspects of gait impairment in older adults. The robotic assistance targeted hip extension during walking to facilitate trunk stability, weight acceptance, and forward progression during stance. The strengthening exercises were intended to improve overall lower-limb muscle capacity and postural control, which are important contributors to functional mobility and balance. Therefore, the observed improvements were likely produced by the combined effects of task-specific gait assistance and generalized neuromuscular strengthening rather than by a single intervention component alone. Second, as in previous studies, enhanced gait efficiency, such as reduced metabolic cost, may partly account for these findings, although metabolic efficiency was not assessed in this study.

Regarding the kinematic outcomes, we observed that while sagittal-plane hip and knee ROM remained relatively unchanged, frontal-plane hip and sagittal-plane ankle ROM showed increasing tendencies following the exercise. Frontal-plane hip ROM, which is often reduced in older adults, contributes to mediolateral stability, gait variability and slower walking speed [52], [53], [54]. Although the increase in frontal-plane hip ROM was not statistically significant, it was particularly apparent during early stance and late swing phases (Fig. 3-B), potentially reflecting improved activation of the hip abductors and enhanced swing-limb positioning [52], [54], [55]. Notably, hip extension assistance provided by H-Medi targets sagittal-plane motion. Therefore, the observed increase in frontal-plane hip ROM is likely attributable to secondary adaptations associated with the combined RAGT and lower-limb strengthening exercises, including changes in dynamic weight transfer, trunk stability, and lower-limb coordination during walking. Similarly, the increase in sagittal-plane ankle ROM may result from greater distal joint mobility by the strengthening program, reducing compensatory demand on the hip. These distal adaptations could facilitate forward progression and contribute to a more distal-driven gait pattern, potentially supporting improvements in gait speed. However, because the association between changes in joint ROM and gait speed was not formally examined, the improvement in gait speed cannot be attributed solely to these ROM changes. Nevertheless, these findings suggest that multiple interacting proximal and distal mechanisms, including neuromuscular coordination and strength, may contribute to gait improvement following combined RAGT and strengthening exercises. Further studies using H-Medi are needed to identify more definitive changes in the lower-limb joints that may be associated with improvements in gait speed.

Other functional measures, assessed by TUG, BBS, and SPPB, also showed a trend toward improvement, consistent with previous studies [15], [25]. Specifically, the TUG showed a statistically significant improvement (-1.4 $\pm$ 1.3 sec) with a relatively large effect size (Cohen's d = 0.98), while the other measures did not. However, the pre-exercise BBS and SPPB scores were already near the maximum values, suggesting a potential ceiling effect that may have limited the ability to detect significant improvements [56]. The improvement of the TUG is known to be related with enhanced overall functional mobility, better lower-limb strength and balance [57]. The most likely explanation for the improvement in TUG performance in this study is the enhancement of gait speed. Other components of the TUG were not directly assessed; therefore, future studies are needed to clarify the specific underlying mechanisms contributing to TUG improvement.

For gait speed, we additionally used LMM to analyze the between- and within-subject variability with adjusted covariates. The analysis revealed that time (pre- and post-exercise) and age were significant determinants of gait speed, which is consistent with the expected effects of training and aging on mobility. Additionally, the ICC of the LMM was 0.65, indicating that a substantial proportion of the total variance in gait speed was attributable to between-subject difference. This variability may have important implications for the future expansion of soft-wearable robot assisted gait training. Because individuals differ markedly in baseline gait patterns and in their response to intervention, robotic devices may need to provide personalized rehabilitation protocols rather than uniform assistance. Furthermore, the observed heterogeneity supports the development of personalized rehabilitation in which assistance is tailored to the most impaired gait mechanism according to each user's kinematic profile. Taken together, these points highlight the advantages of soft-wearable robots over rigid exoskeletons.

This study has several limitations. First, as this was designed as a pilot study, both the sample size and the exercise training period were relatively small. Additionally, the study employed a single-arm design, and the exercise sessions incorporated both RAGT and strength training. Therefore, it was not possible to determine whether the observed functional improvements were attributable primarily to the robotic assistance, the strength training, or a synergistic effect of both interventions. These factors limit the generalizability of the findings. Second, detailed assessments of kinetic gait parameters, muscle activation patterns, or metabolic efficiency were not included. Therefore, the underlying biomechanical and physiological mechanisms associated with the observed gait improvements remain unclear. Nevertheless, the present results provide preliminary evidence of beneficial effects, suggesting that future studies with larger samples and more rigorous designs could yield more robust outcomes. Third, medical history of included participants was not comprehensively assessed. Therefore, participants' heterogeneity may exist which was also suggested by the LMM result of this study (Table III). Further studies with larger, more homogeneous samples are needed to accurately evaluate the effects of soft wearable robots.

V. Conclusion

In this pilot study, short-term exercise training incorporating a soft-wearable robotic suit that assists hip extension was conducted safely in older adults. Despite the limited duration and number of sessions, the intervention led to meaningful improvements in gait pattern and speed, even when walking without robotic assistance. These findings provide preliminary evidence supporting the potential of soft-wearable robotic training to enhance mobility in older adults. Further large-scale and long-term studies are warranted to confirm these results and to explore the underlying mechanisms and optimal training protocols for clinical application.

Conflicts of Interest

Giuk Lee is employed by HUROTICS Inc., the manufacturer of the soft-wearable robot suit (H-Medi) used in this study. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The funder had no role in any aspect of the study, including its design, data collection, analyses, interpretation, writing of the manuscript, or the decision to submit for publication.

AUTHOR CONTRIBUTIONS

Hyun Iee Shin and Ho Seok Lee contributed to the study design, data analysis and interpretation, and visualization. Hyun Iee Shin and Ho Seok Lee equally contributed to writing the original draft and share first authorship. Na Young Yun, Kyeongmin Lim, and Jaeha Yang participated in data acquisition and curation and in reviewing the manuscript. Giuk Lee and Don-Kyu Kim were responsible for funding acquisition and project administration. Hyun Iee Shin, Ho Seok Lee, and Don-Kyu Kim were responsible for manuscript submission. All authors reviewed and approved the final manuscript for submission.

ETHICAL CONSIDERATIONS

Human Subject Ethics Review Approvals: This study was approved by the Institutional Review Board (IRB) of Chung-Ang University Hospital (IRB number 2401-020-587).

Informed Consent: All participants provided written informed consent.

Privacy and Confidentiality: All participant data were fully anonymized prior to analysis, and no personally identifiable information was retained in the research dataset. Therefore, individual participants cannot be identified from the data used in this study.

Compensation Details: Participants received transportation reimbursement for each study visit. The study consisted of eight visits in total (one pre-evaluation visit, six training sessions, and one post-evaluation visit). The total reimbursement amounted to 310,000 KRW per participant upon completion of all visits.

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