JMST

Effects of a Wearable Hip Exoskeleton on Gait Performance in Patients After Hip Surgery

Hojin Choi, PT[1]; Sunghoon Jung, PT, Ph.D[1,2]

[1]Department of Physical Therapy, Graduate School of Health Science and Welfare, Baekseok University, Seoul, South Korea
[2]Department of Physical Therapy, Division of Health Science, Baekseok University, Cheonan, South Korea

Background Patients after hip surgery often demonstrate reduced gait speed and limited independence at hospital discharge, which may hinder rehabilitation planning and safe return to the community. Walking speed is also an important prognostic indicator of functional recovery after total hip arthroplasty.

Purpose To investigate the immediate effects of overground walking with a wearable hip exoskeleton (WHE) on functional mobility and spatiotemporal gait parameters in inpatients after hip surgery.

Study design Single-group, within-subject comparison

Methods Participants performed the Timed Up and Go (TUG) test and the 10-Meter Walk (10MWT) Test at self-selected and fast speeds under two conditions: unassisted walking and walking with a WHE. Total steps and time over the 10-m section were used to calculate gait speed, cadence, and step length. Each test was performed twice, and the mean value was used for analysis. Within-subject differences were analyzed using paired *t*-tests. For the 10MWT at fast speed, the Wilcoxon signed-rank test was used because the paired differences were not normally distributed. Statistical significance was set at $\alpha=0.05$.

Results For the TUG, WHE-assisted walking reduced time from 29.68±17.55 to 25.77±14.45 s ($p=0.015$). During the 10 MWT at self-selected speed, WHE-assisted walking reduced step count from 25.67±7.63 to 23.83±7.40 ($p=0.024$) and time from 21.78±10.76 to 18.96±8.63 s ($p=0.003$), and increased gait speed from 0.59±0.31 to 0.64±0.29 m/s ($p=0.039$) and step length from 0.42±0.13 to 0.46±0.14 m ($p=0.015$). At fast speed, WHE-assisted walking reduced time from 16.14±7.57 to 14.35±6.84 s ($p<0.001$) and increased gait speed from 0.78±0.38 to 0.87±0.41 m/s ($p<0.001$).

Conclusions In inpatients after hip surgery, WHE-assisted walking was associated with immediate improvements in overground walking performance, including shorter 10MWT time and higher gait speed at both self-selected and fast speeds. Given the single-session design and fixed testing order, these findings should be interpreted as immediate performance changes observed while the WHE was worn.

Key words Gait speed; Hip arthroplasty; Hip fracture; Rehabilitation; Robotics.

J Musculoskelet Sci Technol
2026; 10(1): 52-59

pISSN 2635-8573
eISSN 2635-8581

Article History
Received 17 Dec 2025
Revised 26 Dec 2025 (1st)
Revised 4 Mar 2026 (2nd)
Accepted 9 Mar 2026

CONTACT
shjung@bu.ac.kr
Sunghoon Jung
Department of Physical Therapy, Division of Health Science, Baekseok University, Cheonan, South Korea

INTRODUCTION

Hip surgery is frequently followed by impaired walking ability during the early postoperative period. Many patients demonstrate reduced gait speed and limited independence at hospital discharge, which can complicate rehabilitation

https://doi.org/10.29273/jmst.2026.10.1.52

planning and safe reintegration into the community.[1] In patients undergoing total hip arthroplasty, gait speed at hospital discharge is markedly reduced and has been identified as a key target of early postoperative rehabilitation.[1] Moreover, maximal gait speed has been identified as a simple and useful prognostic indicator of functional recovery after total hip arthroplasty.[2] Early postoperative gait parameters may also be associated with longer-term patient-reported outcomes following hip arthroplasty.[3] Recovery after hip fracture involves improvements across multiple functional domains, with ambulation and independence being critical for successful return to the community.[4] Effective postoperative rehabilitation programs are essential during the early recovery period to optimize functional outcomes and facilitate safe reintegration into the community.[5] These findings underscore the clinical importance of interventions that safely facilitate walking performance during early rehabilitation.

Wearable robotic devices have recently been introduced as potential adjuncts to gait rehabilitation. Previous studies have reported that gait training using a wearable hip exoskeleton (WHE) may promote earlier recovery of walking ability after lower-extremity surgery.[6] Systematic reviews and meta-analyses have suggested that robot-assisted rehabilitation following hip or knee replacement surgery provides additional functional benefits compared with conventional rehabilitation alone.[7] A narrative review further concluded that WHE-assisted gait and support rehabilitation across a wide range of populations.[8] In community-dwelling older adults, exercise programs using WHE have been associated with improvements in physical function and walking efficiency.[9-11] Advances in device design have also focused on optimizing assistive torque while minimizing mechanical burden during walking.[12] In addition, prior work evaluating an assistive walking device reported that measurable changes occurred even after a single exposure in neurological populations, thereby supporting the rationale for examining immediate performance effects.[13]

Despite these developments, clinical evidence for WHE–assisted gait rehabilitation has accumulated primarily in neurological populations (e.g., chronic stroke), community-dwelling older adults, and patients undergoing total knee arthroplasty (TKA), rather than in inpatients after hip surgery. For example, a pilot randomized controlled trial in individuals with chronic stroke reported that gait training with a WHE improved spatiotemporal gait parameters and walking efficiency.[14] In surgical populations, a case-control clinical trial suggested that WHE–assisted walking exercise may promote earlier recovery of walking ability after TKA.[6] Moreover, systematic reviews and meta-analyses of robot-assisted rehabilitation after joint replacement have indicated potential functional benefits compared with conventional rehabilitation, while also emphasizing the need for higher-quality studies and verification of long-term effects, particularly in hip replacement populations.[7] Consequently, evidence specifically addressing WHE use during early postoperative inpatient rehabilitation after hip surgery remains limited. In particular, it remains unclear whether overground walking with a WHE produces measurable immediate improvements in functional mobility and spatiotemporal gait parameters compared with unassisted walking in this early postoperative inpatient population.

Therefore, the purpose of this study was to investigate the immediate effects of overground walking with a WHE on functional mobility and spatiotemporal gait parameters in inpatients after hip surgery. We hypothesized that WHE-assisted walking would lead to immediate improvements in overground walking performance in inpatients after hip surgery.

METHODS

Participants

Twenty inpatients undergoing rehabilitation after hip surgery were initially recruited. Two inpatients declined participation in gait assessments; therefore, 18 participants were included in the final analysis. Table 1 summarizes the participant characteristics, and Table 2 classifies the participants by type of hip surgery.

The eligibility criteria were as follows: (1) hip surgery

Table 1. Characteristics of the patients (n=18)

Characteristics	Value
Gender (male/female)	7/11
Age (years)	76.2±15.24 (39–95)
Weight (kg)	54.94±8.50 (51–60)
Height (cm)	160.04±6.80 (155–167)
Affected side (right/left)	11 / 7
K-MMSE (score)	25.88±3.23
K-MBI (score)	61.07±11.09
BBS (score)	16.50±13.70

K-MMSE, Korean version of the mini-mental state examination; K-MBI, Korean version of the modified barthel index; BBS, Berg balance scale.

Values are presented as mean±standard deviation (SD) and interquartile range (IQR), where applicable.

Table 2. Distribution of hip surgery procedures among participants (n=18)

Type of surgery	n
Total hip arthroplasty	5
Bipolar hemiarthroplasty	5
Intramedullary nailing	6
Plate-and-screw fixation	2

within the previous 30 days; (2) medical clearance for ambulation by an orthopedic or rehabilitation physician; (3) ability to ambulate at least 14 m with a walking aid; and (4) sufficient cognitive function to follow instructions, defined as a score greater than 17 on the Korean version of the Mini-Mental State Examination.[15,16] Exclusion criteria included non–weight-bearing status, unstable cardiopulmonary conditions, neurological disorders affecting gait, active infection, or any other condition that could interfere with safe participation.

The study protocol was approved by the Institutional Review Board of Baekseok University (BUIRB-202505-HR-026), and all participants provided written informed consent before participation.

Wearable hip exoskeleton

The WHE used in this study was WIM (WIRobotics Inc., Republic of Korea), a device designed to provide bilateral hip flexion–extension assistance during walking (Figure 1). The device employs a single actuator to assist sagittal-plane hip motion in both limbs using an anti-phase torque symmetry strategy, whereby hip flexion assistance is applied to the advancing limb and hip extension assistance to the trailing limb during gait. This assistance pattern is intended to support limb advancement during the swing phase and propulsion during late stance.[11,12] The WIM features an ultra-lightweight, compact design, with a total device weight of approximately 1.6 kg and main body dimensions of 21.7 × 11.0 × 5 cm. The thigh frames are foldable to reduce storage volume. The main unit, which integrates a single electric motor, battery, and controller, is positioned at the anterior pelvis and secured using an adjustable waist belt (66.0–91.4 cm) and bilateral thigh frames adjustable from approximately 160 to 350 mm to accommodate individual anthropometric characteristics.[11,12] The device operates based on detection of the hip joint angular waveform during walking and generates bilaterally symmetric assistive torques. Torque control is achieved using a current-based estimation method without a dedicated torque sensor. The actuator is designed to minimize passive resistance when assistance is inactive, thereby reducing interference with natural gait mechanics.[11,12]

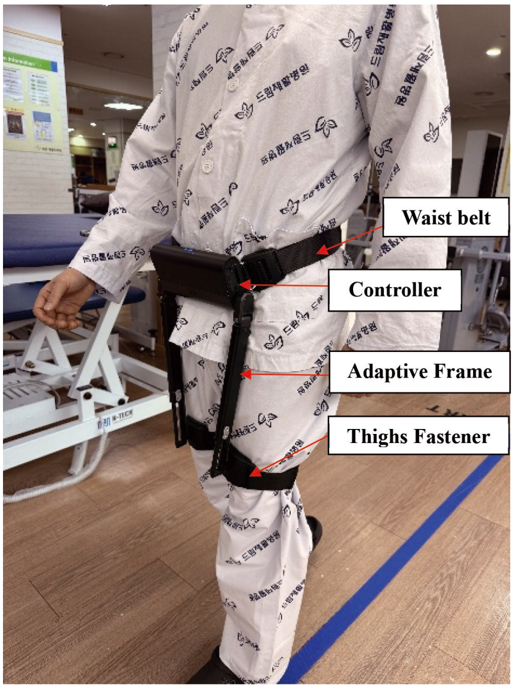

Figure 1. Participant wearing the wearable hip exoskeleton.

Based on manufacturer specifications, previously published evaluations, and pilot tolerability testing in early postoperative inpatients, the device was operated in Assist mode at a fixed assist level (Assist Level 2; peak assistive torque of 4.0 Nm) for all participants.[11,12] The reported peak assistive torque capacity of the device ranges from approximately 4 to 5 Nm depending on operating conditions.[11] In early postoperative ambulation, where balance reserve is limited and fall risk is heightened, inappropriate assistance timing or excessive assistance can perturb natural gait control; exoskeleton parameters have been shown to modify stride-to-stride gait variability, and some configurations can adversely affect reactive balance responses to slip- and trip-like perturbations.[17,18] In addition, human-in-the-loop optimization studies indicate that meaningful reductions in walking energy cost can be achieved with relatively low assistance magnitudes, and that "more assistance" is not necessarily better across outcomes.[19,20] Therefore, Assist Level 2 was selected to provide moderate assistance while avoiding excessive torque that could disrupt gait mechanics or increase perceived instability during early postoperative ambulation. No individualized torque adjustment was performed to ensure standardized exposure across participants.

Participants were fitted with the device in a standing position under the supervision of a physical therapist. The rotational axis of the device was aligned as closely as possible with the anatomical hip joint axis, and the waist belt and thigh straps were adjusted to minimize movement or slippage during walking.

Outcome measures and calculations

Functional mobility and gait performance were assessed using the Timed Up and Go (TUG) test and the 10-Meter Walk Test (10MWT). The TUG measured the time required to stand up from a chair, walk 3 m, turn around, return to the chair, and sit down, with shorter times indicating better functional mobility.[21,22] The 10MWT was conducted using a walkway that allowed for acceleration and deceleration, and walking time was recorded over the central 10 m.[23] Both the 10MWT and TUG have demonstrated good reliability and validity in patients following total hip arthroplasty, supporting their use in this population.[24] Total step count and walking time were used to calculate spatiotemporal gait parameters as follows: gait speed (m/s)=10 m ÷ time (s); cadence (steps/min)=(steps ÷ time) × 60; and step length (m)=10 m ÷ total steps. Step count was recorded as the total number of steps without differentiation between the left and right limbs.

Procedure

This single-session study used a within-subject design comparing unassisted walking and WHE-assisted walking in the same inpatients. The testing sequence was standardized for all participants and was fixed from the unassisted condition to the WHE-assisted condition. This fixed order was selected to prioritize safety in early postoperative inpatients who had limited independent ambulation and an elevated risk of instability and falls. In addition, first-time use of the WHE and initial apprehension during donning could increase safety risk if device-assisted walking was tested first. Therefore, unassisted assessments were completed first, followed by WHE-assisted assessments.

Using a walker for all assessments was intended to ensure safety and minimize variability related to assistive device selection across conditions. All assessments were supervised by a physical therapist with more than 2 years of clinical experience in gait rehabilitation. Participants were monitored for pain exacerbation, excessive fatigue, skin irritation, near-falls, and discontinuation during all trials.

1) Preparation and assistive device control

All participants performed gait assessments using a walker, and the same assistive device was used across both unassisted and WHE-assisted conditions for each participant.

2) Unassisted condition assessments

Under the unassisted condition, participants completed the TUG test and 10MWT at self-selected speed (SSS) and fast speed (FS). Each test condition was performed twice, and the mean of the two trials was used for analysis.

3) Rest between trials

Participants rested in a seated position for at least 1 minute between trials, with additional rest provided as needed to minimize fatigue and maintain safe performance during repeated gait-speed testing.[12]

4) Wearing the WHE

After completion of all unassisted assessments, participants were fitted with the wearable hip exoskeleton.

5) Standardized familiarization

A standardized familiarization period was conducted to ensure safety and facilitate initial adaptation, during which participants walked along a flat indoor corridor (approximately 40 m per circuit) and completed one circuit. This familiarization was intended to promote safety and comfort and to allow initial adaptation rather than to serve as a training intervention.[25]

6) Rest after familiarization

Following familiarization, participants rested for approximately 3 minutes before formal testing to minimize fatigue and ensure safe repeated gait testing.[23]

7) WHE-assisted condition assessments

Participants then completed the same sequence of assessments while wearing the WHE: TUG, 10MWT at SSS, and 10MWT at FS. Each test condition was performed twice, and the mean of the two trials was used for analysis.

Statistical analysis

Statistical analyses were performed using SPSS version 18.0 (IBM Corp., Armonk, NY, USA). Continuous variables are presented as mean ± standard deviation. Normality of paired differences was assessed using the Shapiro–Wilk test and visual inspection of Q–Q plots. Paired t tests were used for outcomes that met the normality assumption. Because the paired differences for 10MWT FS time violated the normality assumption, a Wilcoxon signed-rank test was used for that outcome. Statistical significance was set at $\alpha=0.05$, and exact p values are reported unless $p<0.001$. Effect sizes and 95% confidence intervals were also reported to support practical interpretation beyond p values. Cohen’s d was used for paired t-tests, and r was used for the Wilcoxon signed-rank test; absolute values were reported for all effect sizes.

RESULTS

Eighteen inpatients completed both unassisted and WHE-assisted gait assessments and were included in the analysis. No adverse events, including near-falls, device-related discomfort, or discontinuation, were observed during testing. Functional mobility and spatiotemporal gait parameters under unassisted and WHE-assisted conditions are presented in Table 3. TUG time was significantly shorter during WHE-assisted walking (p=0.015). During the 10MWT at SSS, WHE-assisted walking significantly reduced step count (p=0.024) and walking time (p=0.003) and increased gait speed (p=0.039) and step length (p=0.015). Cadence did not differ significantly between conditions. At FS, WHE-assisted walking significantly reduced walking time (p<0.001) and increased gait speed (p<0.001). Step count, step length, and cadence did not differ significantly between conditions.

DISCUSSION

Wearing the WHE was associated with immediate improvements in straight-line walking after hip surgery. The clearest effects were observed in the 10MWT. At SSS, gait speed increased, accompanied by shorter walking time, fewer steps, and longer step length. This pattern suggests a more efficient spatial gait strategy over a fixed distance and is consistent with the intended role of hip flexion–extension assistance in facilitating limb advancement and forward progression.[8,12] Prior studies using WHE in older adults have similarly reported improvements in gait performance and functional outcomes.[9-11] In addition, WHE gait training has been shown to improve metabolic walking efficiency in older adults, supporting the broader plausibility of performance gains associated with hip-assist technology.[26] At FS, walking time decreased and gait speed increased, whereas step-derived metrics changed less markedly. Safety constraints during inpatient walking may partly explain this finding, including routine walker use and cautious maximal effort, which can limit spatiotemporal adaptation.[31,32]

WHE-assisted gait speed increased by 0.05 m/s at SSS and 0.09 m/s at FS. The clinical relevance of these changes can be evaluated against established minimal clinically important difference (MCID) thresholds.[27] In older adults, an improvement of approximately 0.05 m/s represents a small clinically important difference, whereas an improvement of approximately 0.10 m/s constitutes a substantial clinically important difference.[27] Interpreted within this framework, the 0.05 m/s improvement at SSS meets the threshold for a small MCID, whereas the 0.09 m/s improvement at FS closely approaches the threshold for a substantial clinically important difference. Beyond its value as a functional performance measure, gait speed independently predicts survival and long-term outcomes in older adults, underscoring the prognostic relevance of even

Table 3. Gait and functional mobility assessments

			Unassisted	WHE-assisted	Mean difference (95% CI)†	p	Effect size‡
TUG (s)			29.68±17.55	25.77±14.45	−3.91 (−6.96 to −0.86)	0.015	0.64
10MWT	SSS	Steps (count)	25.67±7.63	23.83±7.40	−1.83 (−3.40 to −0.27)	0.024	0.58
		Times (s)	21.78±10.76	18.96±8.63	−2.82 (−4.53 to −1.10)	0.003	0.82
		Speed (m/s)	0.59±0.31	0.64±0.29	0.05 (0.00 to 0.10)	0.039	0.53
		Steps length (m)	0.42±0.13	0.46±0.14	0.033 (0.007 to 0.059)	0.015	0.64
		Cadence (steps/min)	80.27±25.29	82.32±21.04	2.05 (−4.73 to 8.84)	0.531	0.15
	FS	Steps (count)	21.72±7.03	21.06±7.26	−0.67 (−2.38 to 1.05)	0.423	0.19
		Time (s)	16.14±7.57	14.35±6.84	−1.79 (−2.65 to −1.04)	< 0.001	0.86
		Speed (m/s)	0.78±0.38	0.87±0.41	0.09 (0.05 to 0.13)	< 0.001	1.07
		Steps length (m)	0.51±0.17	0.53±0.17	0.016 (−0.03 to 0.06)	0.495	0.16
		Cadence (steps/min)	89.82±27.40	96.43±25.66	6.62 (−1.46 to 14.69)	0.102	0.41

TUG, timed up and go; 10MWT, 10-meter walk test; SSS, self-selected speed; FS, fast speed; WHE, wearable hip exoskeleton.

Values are presented as mean±standard deviation (SD).

† Mean difference indicates WHE-assisted minus unassisted.

‡ Effect size represents the absolute value of Cohen’s d for paired t tests and the absolute value of r for the Wilcoxon signed-rank test; the Wilcoxon signed-rank test was applied only to 10MWT FS time.

modest improvements.[28] Nevertheless, interpretive caution remains warranted because early postoperative gait assessment is inherently sensitive to testing protocol (e.g., start condition, acceleration and deceleration allowance, and measurement environment), which may introduce variability in performance estimates.[23-25,29] Furthermore, in post–total hip arthroplasty populations, reliability characteristics of the 10MWT can vary by condition (e.g., indoor vs outdoor), indicating that measurement error may be nontrivial in early recovery settings.[24] Accordingly, the present results are most appropriately characterized as an immediate assistive effect of the WHE during device use rather than as evidence of durable functional recovery. Longitudinal follow-up and randomized, counterbalanced designs are required to determine whether these acute assistive gains translate into sustained improvements throughout rehabilitation.

Cadence did not change significantly despite faster walking. This finding suggests that speed gains were driven primarily by spatial adjustments, such as longer step length, rather than by increased step frequency. In exoskeleton gait training on real-world terrain, speed gains have been reported to be more strongly associated with increased stride length than with higher cadence, supporting the plausibility of a predominantly spatial mechanism.[30] Walker use may further limit cadence modulation in inpatients. Assistive devices can alter gait parameters while imposing stability demands and increasing upper-limb load.[31,32]

Functional mobility improved on the TUG with WHE assistance. The TUG is a composite task consisting of sit-to-stand, straight walking, turning, return walking, and sitting.[21] Total time reflects both gait and transitional control demands. Instrumented TUG studies have demonstrated that subcomponents can contribute differently across patients and conditions.[33] The 10MWT improvement likely contributed to performance during the straight-walking segments of the TUG. Hip assistance may also support dynamic stability during turning and directional changes. Prior WHE interventions have reported improvements in TUG performance and related functional outcomes in older adults.[9,11] A single-subject case study of hip-assist gait training following total hip arthroplasty reported improved TUG performance, supporting the clinical plausibility of WHE-related mobility gains in the hip surgery population.[34]

Several limitations affect inference. First, the test order was fixed; therefore, learning effects may have influenced performance. Second, the TUG was not analyzed by phase, so the primary contributor to improvement remains unclear. Third, surgical heterogeneity may have increased variability. Fourth, walker use may have constrained spatiotemporal adaptations. Fifth, the exact postoperative day was not recorded for each participant. Therefore, it was not possible to examine whether the magnitude of the immediate WHE effect varied according to time since surgery, which may have contributed to between-participant variability. Despite these constraints, the results support that WHE use can acutely enhance straight-line gait (10MWT) and composite mobility (TUG) in early inpatient rehabilitation after hip surgery. Future studies should use randomized, counterbalanced designs. Longitudinal protocols are needed to evaluate retention beyond the immediate assistive effect observed during device wear.

CONCLUSIONS

In inpatients after hip surgery, overground walking with a WHE was associated with immediate improvements in walking performance, including shorter 10MWT time and higher gait speed at both self-selected and fast walking speeds. These findings suggest that WHE-assisted walking produces measurable, immediate changes in gait performance while the device is worn.

Key Points

Question Does WHE–assisted overground walking immediately increase 10MWT gait speed and improve TUG performance in early postoperative inpatients after hip surgery compared with unassisted walking?

Findings In a single-group, within-subject study (n=18), WHE-assisted walking significantly reduced TUG time. During the 10MWT, WHE-assisted walking significantly reduced self-selected speed step count and time, and increased gait speed and step length. At fast speed, time and gait speed improved.

Meaning WHE may be a practical adjunct to early inpatient rehabilitation after hip surgery by acutely increasing 10MWT gait speed and improving TUG performance while the device is worn.

Article information

Conflict of Interest Disclosures: None.

Funding/Support: This work was supported by the Baekseok University Research Fund.

Acknowledgment: None.

Ethic Approval: The study was approved by the Institutional Review Board of Baekseok University (BUIRB-202505-HR-026).

Data Availability: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Informed consent for publication of the images was obtained from the patient.

Author contributions

Conceptualization: SH Jung.
Data acquisition: HJ Choi.
Design of the work: HJ Choi.
Data analysis: HJ Choi.
Project administration: SH Jung.
Interpretation of data: HJ Choi.
Writing – original draft: HJ Choi.
Funding acquisition: SH Jung.
Writing–review&editing: HJ Choi, SH Jung.

REFERENCES

1. Morri M, Natali E, Tosarelli D. At discharge gait speed and independence of patients provides a challenges for rehabilitation after total joint arthroplasty: An observational study. *Arch Physiother*. 2016;6:6.
2. Shibuya M, Nanri Y, Kamiya K, et al. The maximal gait speed is a simple and useful prognostic indicator for functional recovery after total hip arthroplasty. *BMC Musculoskelet Disord*. 2020;21(1):84.
3. Okazawa K, Hamai S, Fujita T, et al. Effect of early postoperative gait parameters after total hip arthroplasty on Forgotten Joint Score-12 at 2-year follow-up. *Geriatrics (Basel)*. 2025;10(1):7.
4. Magaziner J, Hawkes W, Hebel JR, et al. Recovery from hip fracture in eight areas of function. *J Gerontol A Biol Sci Med Sci*. 2000;55(9):M498-M507.
5. Lee KJ, Um SH, Kim YH. Postoperative rehabilitation after hip fracture: a literature review. *Hip Pelvis*. 2020;32(3):125-131.
6. Koseki K, Mutsuzaki H, Yoshikawa K, et al. Early recovery of walking ability in patients after total knee arthroplasty using a hip-wearable exoskeleton robot: A case-controlled clinical trial. *Geriatr Orthop Surg Rehabil*. 2021;12:21514593211027675.
7. Yoo JI, Oh MK, Lee SU, et al. Robot-assisted rehabilitation for total knee or hip replacement surgery patients: a systematic review and meta-analysis. *Medicine (Baltimore)*. 2022;101(40):e30852.
8. Cha JM, Hong J, Yoo J, et al. Wearable robots for rehabilitation and assistance of gait: a narrative review. *Ann Rehabil Med*. 2025;49(4):187-195.
9. Lee SH, Lee HJ, Kim K, et al. Effect of exercise using an exoskeletal hip-assist robot on physical function and walking efficiency in older adults. *J Pers Med*. 2022;12(12):2077.
10. Lee SH, Kim J, Lim B, et al. Exercise with a wearable hip-assist robot improved physical function and walking efficiency in older adults. *Sci Rep*. 2023; 13(1):7269.
11. Shin JH, Byeon N, Yu H, et al. Effect of 4-weeks exercise program using wearable hip-assist robot (EX1) in older adults: one-group pre- and post-test. *BMC Geriatr*. 2023;23(1):724.
12. Lim B, Choi B, Roh C, et al. Ultra-lightweight robotic hip exoskeleton with anti-phase torque symmetry for enhanced walking efficiency. *Sci Rep*. 2025;15:10850.
13. Satoh Y, Yamada T, Arai Y, et al. The immediate effect of the Honda Walking Assist Device on foot and ankle function in hemiplegic stroke patients. *J Phys Ther Sci*. 2020;32(6):405-409.
14. Lee HJ, Lee SH, Seo K, et al. Training for walking efficiency with a wearable hip-assist robot in patients with stroke: a pilot randomized controlled trial. *Stroke*. 2019;50(12):3545-3552.
15. Tombaugh TN, McIntyre NJ. The mini-mental state examination: a comprehensive review. *J Am Geriatr Soc*. 1992;40(9):922-935.
16. Folstein MF, Folstein SE, McHugh PR. “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12(3):189-198.
17. Antonellis P, Galle S, De Clercq D, Malcolm P. Altering gait variability with an ankle exoskeleton. *PLOS One*. 2018;13(10):e0205088. Published 2018 Oct 24.
18. Dooley S, Kim S, Nussbaum MA, Madigan ML. A passive leg-support exoskeleton adversely affects reactive balance after simulated slips and trips on a treadmill. *J Biomech*. 2023;151:111533.
19. Lakmazaheri A, Song S, Vuong BB, Biskner B, Kado DM, Collins SH. Optimizing exoskeleton assistance to improve walking speed and energy economy for older adults. *J Neuroeng Rehabil*. 2024;21(1):1. Published 2024 Jan 2.
20. Kim J, Quinlivan BT, Deprey LA, et al. Reducing the energy cost of walking with low assistance levels through optimized hip flexion assistance from a soft exosuit. *Sci Rep*. 2022;12(1):11004. Published 2022 Jun 29.
21. Podsiadlo D, Richardson S. The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc*. 1991;39(2):142-148.
22. Barry E, Galvin R, Keogh C, et al. Is the Timed Up and Go test a useful predictor of risk of falls in

community dwelling older adults: A systematic review and meta-analysis. *BMC Geriatr*. 2014;14:14.

23. Moore JL, Potter K, Blankshain K, et al. A core set of outcome measures for adults with neurologic conditions undergoing rehabilitation: a clinical practice guideline. *J Neurol Phys Ther*. 2018;42(3):174-220.
24. Temporiti F, Casirati C, Adamo P, et al. indoor and outdoor 10-meter walk test and timed up and go in patients after total hip arthroplasty: a reliability and comparative study. *Arch Physiother*. 2024;14:90-95.
25. Cleland BT, Perez-Ortiz A, Madhavan S. Walking test procedures influence speed measurements in individuals with chronic stroke. *Clin Biomech (Bristol, Avon)*. 2020;80:105197.
26. Martini E, Crea S, Parri A, et al. Gait training using a robotic hip exoskeleton improves metabolic gait efficiency in the elderly. *Sci Rep*. 2019;9(1):7157.
27. Perera S, Mody SH, Woodman RC, Studenski SA. Meaningful change and responsiveness in common physical performance measures in older adults. *J Am Geriatr Soc*. 2006;54(5):743-749.
28. Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. *JAMA*. 2011;305(1):50-58.
29. Stuck AK, Bachmann M, Füllemann P, et al. Effect of testing procedures on gait speed measurement: a systematic review. *PLOS One*. 2020;15(6):e0234200.
30. Tagoe EA, Fang Y, Williams JR, et al. Exoskeleton gait training on real-world terrain improves spatiotemporal performance in cerebral palsy. *Front Bioeng Biotechnol*. 2024;12:1503050.
31. Mundt M, Batista JP, Markert B, et al. Walking with rollator: A systematic review of gait parameters in older persons. *Eur Rev Aging Phys Act*. 2019;16:15.
32. Bateni H, Maki BE. Assistive devices for balance and mobility: benefits, demands, and adverse consequences. *Arch Phys Med Rehabil*. 2005;86(1):134-145.
33. Ortega-Bastidas P, Gómez B, Aqueveque P, et al. Instrumented Timed Up and Go Test (iTUG)—more than assessing time to predict falls: a systematic review. *Sensors (Basel)*. 2023;23(7):3426.
34. Koseki K, Mutsuzaki H, Yoshikawa K, et al. Gait training using the Honda Walking Assistive Device® in a patient who underwent total hip arthroplasty: A single-subject study. *Medicina (Kaunas)*. 2019;55(3):69.