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Muscle activity and hip kinematics during robot-assisted hip abduction after total hip arthroplasty: a preliminary single-arm study

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Muscle activity and hip kinematics during robot-assisted hip abduction after total hip arthroplasty: a preliminary single-arm study

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Abstract

Background

This preliminary study examined the technical feasibility of early postoperative robot-assisted hip abduction after total hip arthroplasty and described task-specific differences in muscle activity and hip kinematics. Clinical rehabilitation effectiveness is not established in this report.

Methods

Forty participants were enrolled, 36 started training, and 35 completed four sessions within two weeks after surgery. Each session included 10 unassisted repetitions followed by 50 assisted repetitions; 10 further unassisted repetitions were performed after session 4. For biomechanical comparisons, the 10 unassisted repetitions were compared with the first 10 HAL-assisted repetitions. Surface electromyography of the gluteus medius and tensor fasciae latae was normalized to each muscle's maximum unassisted root mean square value within each session. Paired t-tests or Wilcoxon signed-rank tests compared conditions and time points; surgical-approach comparisons were exploratory. Hip abductor force and adverse events were assessed.

Results

Assisted movement showed greater hip abduction in all four sessions and lower hip flexion in sessions 1–3. Normalized tensor fasciae latae activity was lower in all sessions, whereas normalized gluteus medius activity was lower in sessions 1–3. The normalized gluteus medius/tensor fasciae latae ratio was numerically higher during assistance. The ratio in unassisted movement after session 4 differed from that before session 1 (1.27 versus 1.02; $P = 0.006$), although session-specific normalization limits longitudinal interpretation. Hip abductor force increased from 8.6 to 11.2 kgf ($P = 0.005$). No serious adverse events were reported; one participant discontinued because of postoperative wound pain.

Conclusions

The protocol was deliverable in 35 of 36 participants who started training. Observed EMG and kinematic differences describe performance under repetition-matched but sequential task

conditions and do not isolate an effect of robotic assistance. The uncontrolled design cannot distinguish longitudinal changes from natural recovery and concurrent rehabilitation. Clinical benefit, motor learning, and equivalence across surgical approaches remain unestablished.

Trial registration

Japan Registry of Clinical Trials, jRCTs032240437, registered 28 October 2024.

Keywords: total hip arthroplasty; hip abduction; robotic rehabilitation; gluteus medius; tensor fasciae latae; electromyography

Background

Hip osteoarthritis causes pain, restricted motion, impaired activities of daily living (ADL), and gait abnormalities. Total hip arthroplasty (THA) improves pain and ADL [1,2], gait speed, symmetry, and joint motion up to 12 months postoperatively [3].

However, muscle atrophy and contracture can accompany persistent gait abnormalities [4,5]. Gluteus medius (Gmed) dysfunction is relevant to Trendelenburg gait [6], and stable gait remains an important goal after surgery [7]. Abductor weakness [8] and altered tensor fasciae latae (TFL) activity or morphology [9,10] provide a rationale for studying hip abduction exercises.

Conventional rehabilitation includes resistance exercises, range-of-motion exercises, and manual therapy. A device that assists repeated abduction when voluntary movement is limited warrants technical evaluation, but changes during an assisted exercise cannot by themselves establish improved gait or daily function.

Robot-assisted rehabilitation can support repeated movement practice [11]. HAL has been investigated in several neurological populations, although study designs and levels of evidence vary [12–17]. Coupling voluntary bioelectrical signals to assistive torque and sensory feedback provides a proposed framework for motor training [18–20]. Whether this mechanism produces motor learning or clinically meaningful recovery after THA requires direct testing.

Previous work investigated HAL-assisted hip extension after THA [21]. At our institution, modified single-joint HAL attachments have been used for shoulder [22] and ankle [23] movement. A hip abduction HAL system was subsequently developed and evaluated in healthy adults [24]. Evidence in healthy adults does not establish feasibility or clinical effectiveness during early recovery after THA.

This preliminary single-arm study examined delivery and tolerability of early postoperative hip abduction HAL training and described muscle activity and kinematics under unassisted and assisted conditions. Changes across the training period and comparisons by surgical approach were interpreted as exploratory observations rather than evidence of clinical efficacy.

Methods

Study design and participants

This preliminary single-arm study enrolled 40 participants undergoing primary unilateral THA for unilateral hip disease with preoperative gait abnormalities. Four withdrew before intervention; 36 started training, and one discontinued because rehabilitation exacerbated postoperative wound pain. The final analysis included 35 completers (Figure 1). No concurrent control group was included.

Exclusions were previous lumbar, pelvic, or hip surgery; bleeding tendency or cardiopulmonary contraindications; active infection; moderate/severe involuntary movements, ataxia, or postural reflex disorders; height outside 150–190 cm or weight outside 40–100 kg; skin disease preventing electrode placement; cognitive impairment preventing comprehension; absent consent; or physician-determined unsuitability.

The study was conducted at University of Tsukuba Hospital in accordance with the Declaration of Helsinki. Approval was obtained from the Clinical Research Review Board of the University of Tsukuba Hospital (approval number TCRB24-016). Written informed consent was obtained from all participants before enrollment. The study was registered with the Japan Registry of Clinical Trials (jRCTs032240437) on 28 October 2024, before the actual first-enrollment date of 16 January 2025.

The present report describes a prespecified subanalysis of the registered study, whose primary analysis focuses on lateral pelvic tilt during gait after total hip arthroplasty. This subanalysis examines muscle activity and hip kinematics during HAL-assisted hip abduction performed within the study's intervention protocol. The primary gait outcome is outside the scope of this report; the present findings do not establish effects on pelvic control during walking. No formal sample size calculation was performed for this subanalysis.

Hip abduction device

The single-joint Hybrid Assistive Limb (HAL; CYBERDYNE Inc., Tsukuba, Japan) was modified as previously described [24]. Its knee-joint distal segment was fixed to a tripod platform using a shoulder-device attachment; the proximal segment was secured to the thigh with the standard belt (Figure 2). Patients lay sideways near the platform. The power unit axis aligned with the greater trochanter, the device with the femoral axis, and the unit rested against the gluteal region. Position and height were adjusted for smooth abduction–adduction (Figure 3).

The control electrode was placed over the Gmed belly. An orthopedic surgeon and physical therapist applied and removed the device. Donning, training, and doffing required approximately 15–20 minutes per session.

Hip abduction training protocol

Daily standard rehabilitation included gait training and exercises; hip abduction began on postoperative day 3. Assisted sessions occurred on days 7 ± 1, 9 ± 1, 11 ± 1, and 14 ± 1 (Figure 4).

On non-assisted days, patients performed 5 sets of 10 abductions with physical therapist assistance during usual rehabilitation.

On assisted days, side-lying training comprised 10 unassisted repetitions (pre HAL), followed by 5 sets of 10 assisted repetitions (HAL). Session 4 included 10 additional unassisted repetitions afterward (post HAL). The 50 HAL-assisted repetitions constituted the main training component of the intervention protocol, whereas the 10 unassisted repetitions were added as a reference assessment to characterize muscle activity and hip kinematics before robotic assistance. The unassisted and assisted conditions were not designed as dose-matched training interventions. However, for the biomechanical analyses, the 10 unassisted repetitions were compared with the first 10 repetitions of HAL-assisted exercise. Thus, the number of repetitions included in the EMG and kinematic analyses was matched between conditions, although the total training volume differed. The unassisted assessment was incorporated into the existing intervention protocol

without replacing or reducing the prescribed HAL-assisted training volume. Before assistance, maximal abduction was measured with a goniometer; target angle and assistance were adjusted toward this range as tolerated. Pace and rest were individualized, and pain and fatigue were assessed verbally to avoid excessive fatigue and performance deterioration.

Electromyographic assessment

Wireless surface electromyography (EMG; Ultium EMG, Noraxon) recorded Gmed and TFL, both of which contribute to hip abduction. TFL also contributes to hip flexion. After alcohol cleansing, bipolar Ag–AgCl electrodes (1-cm diameter; 2.5-cm spacing) were applied. Following SENIAM recommendations [25], electrodes were placed midway between the iliac crest and greater trochanter for Gmed and at the proximal one-sixth between the anterior superior iliac spine and lateral femoral condyle for TFL.

Signals were filtered at 20–500 Hz and smoothed using a 100-ms root mean square (RMS) window. Abduction from neutral to maximum was time-normalized to 0–100% of the movement cycle. Mean cycle RMS was amplitude-normalized to each muscle's maximum pre HAL RMS within that session and expressed as a percentage. This reference was task-derived, not a maximal voluntary contraction. Each muscle had its own denominator, and the reference was re-established in each session. For each session, EMG data from all 10 unassisted repetitions and the first 10 HAL-assisted repetitions were included in the within-session comparison. The remaining 40 HAL-assisted repetitions were part of the training protocol but were not included in this comparison.

Muscle activity reduction for each muscle/session was calculated as:

$$\text{Reduction rate} = \frac{\text{pre HAL EMG} - \text{HAL EMG}}{\text{pre HAL EMG}} \times 100$$

The Gmed/TFL ratio used normalized mean EMG values [26]:

$$\text{Ratio} = \frac{\text{normalized Gmed EMG}}{\text{normalized TFL EMG}}$$

Higher ratios indicated the Gmed activation relative to the TFL. Ratios were calculated for both conditions in each session; session-1 pre HAL and session-4 post HAL were compared.

Kinematic assessment

Wireless inertial motion analysis (Ultium Motion, Noraxon) used sensors over the sacrum, anterior mid-thigh, and proximal anterior shank. Abduction was the angle between the limb axis and a perpendicular line in the frontal plane; flexion was the trunk–thigh angle in the sagittal plane. EMG and motion data were synchronized. Peak abduction and flexion angles for each neutral-to-maximum repetition were averaged by session and condition. Kinematic comparisons were based on the same 10 unassisted and first 10 HAL-assisted repetitions used for the EMG analyses.

Hip abductor strength

Hip abductor force was measured in sessions 1 and 4 using a handheld dynamometer (μTas F-01, ANIMA Corp.). Participants lay supine with neutral hip abduction/adduction and full knee extension; the pad contacted the operated lateral distal lower leg. Three approximately 5-second maximal isometric efforts were separated by 10-second rests. The maximum force (kgf) was analyzed; 1 kgf = 9.80665 N.

Safety assessment

Blood pressure, heart rate, and peripheral oxygen saturation (SpO_2) were measured immediately before and after each session. Pain intensity/location were assessed before, during, and after training; increased pain or participant request prompted interruption or discontinuation. Approach-specific institutional hip precautions were followed. Dislocations and complications potentially affecting rehabilitation or hospitalization were recorded.

Statistical analysis

JMP 19.0.4 (SAS Institute Inc., Cary, NC, USA) was used. Paired comparisons evaluated normalized EMG and angles between conditions; reduction rates between muscles; session-1 pre

HAL versus session-4 post HAL ratios; vital signs before/after assistance across sessions; and hip abductor force between sessions 1 and 4. The biomechanical analyses included the 35 completers. Shapiro–Wilk testing assessed normality of paired differences. Normally distributed differences underwent paired t-tests; otherwise, Wilcoxon signed-rank tests were used. Within-session comparisons were based on an equal number of analyzed repetitions in the unassisted and HAL-assisted conditions. However, because the conditions were performed sequentially and differed in robotic assistance and potentially in movement characteristics, these analyses were interpreted as descriptive comparisons rather than estimates of the isolated causal effect of HAL.

Post hoc exploratory analyses averaged each participant's pre HAL and HAL values over sessions 1–4. The Kruskal–Wallis test compared participant-level mean changes (HAL minus pre HAL) between surgical approaches. P values were adjusted across the five outcomes using the Benjamini–Hochberg procedure.

The nominal significance threshold was $P < 0.05$; figure/table symbols were *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

Results

Participant characteristics

The 35 completers included 9 men and 26 women. Mean age was 62.1 years (range, 41–78), height 1.60 m (1.50–1.77), weight 65.9 kg (43.6–95.9), and body mass index 25.6 kg/m² (17.5–38.9). All were within device size limits, without size-related application or operational restrictions.

Diagnoses were osteoarthritis (27), femoral head osteonecrosis (7), and rheumatoid arthritis (1). Approaches were posterolateral (PL; 14), direct anterior (DAA; 11), and anterolateral supine (ALS; 10).

Muscle activity

Normalized EMG (n-EMG: pre HAL/HAL; Figure 5) was:

1st session: Gmed 49.9 ± 12.7% / 44.2 ± 16.0%, TFL 50.3 ± 9.5% / 39.4 ± 16.5%

2nd session: Gmed 51.4 ± 11.2% / 47.9 ± 20.1%, TFL 53.3 ± 9.7% / 42.5 ± 12.4%

3rd session: Gmed 50.9 ± 10.6% / 42.5 ± 14.9%, TFL 48.7 ± 11.4% / 40.9 ± 15.0%

4th session: Gmed 53.5 ± 11.3% / 52.3 ± 18.5%, TFL 48.6 ± 12.3% / 43.6 ± 13.6%

Both muscles showed reduced activity with assistance. Gmed reductions were significant in sessions 1–3 ($P = 0.03$, 0.02, and 0.002); TFL reductions were significant in all sessions ($P < 0.0001$, $P < 0.0001$, $P = 0.003$, and $P = 0.01$).

Reduction rates (Gmed/TFL; Figure 6) were 12.2 ± 19.3%/24.7 ± 20.7% (session 1; $P = 0.04$), 12.7 ± 20.1%/21.4 ± 16.8% (session 2; $P = 0.04$), 16.8 ± 20.8%/20.2 ± 20.4% (session 3; $P = 0.8$), and 11.2 ± 21.2%/12.9 ± 17.5% (session 4; $P = 0.3$). TFL reductions exceeded Gmed significantly only in sessions 1 and 2.

Pre HAL Gmed/TFL ratios were 1.02 ± 0.32, 0.97 ± 0.22, 1.09 ± 0.29, and 1.15 ± 0.33 across sessions; assisted ratios were 1.28 ± 0.68, 1.15 ± 0.42, 1.16 ± 0.53, and 1.24 ± 0.39 (Figure 7). Ratios were numerically higher with assistance in each session. Session-4 post HAL was 1.27 ± 0.31 compared with session-1 pre HAL 1.02 ± 0.32 ($P = 0.006$).

Kinematic outcomes

Mean abduction angles (pre HAL/HAL; Figure 8A) were:

1st session: 7.6 ± 7.9° / 13.6 ± 8.6°

2nd session: 10.1 ± 6.7° / 16.1 ± 9.8°

3rd session: 12.0 ± 6.2° / 18.0 ± 9.8°

4th session: 12.8 ± 7.2° / 19.1 ± 10.4°

Increases were significant in all sessions ($P = 0.002$, 0.0001, 0.0003, and 0.0001).

Mean flexion angles (pre HAL/HAL; Figure 8B) were:

1st session: 15.4 ± 17.1° / 5.3 ± 22.6°

2nd session: 10.8 ± 12.2° / 6.2 ± 17.0°

3rd session: 13.4 ± 9.5° / 8.6 ± 16.5°

4th session: 6.2 ± 17.1° / 3.4 ± 14.8°

Flexion decreased toward neutral significantly in sessions 1–3 (P = 0.03, 0.02, and 0.02).

Hip abductor strength

Hip abductor force increased from 8.6 ± 3.4 kgf in session 1 to 11.2 ± 3.9 kgf in session 4 (P = 0.005).

Safety

No statistically significant changes in vital signs were reported (Table 1). Nonsignificant tests do not establish physiological equivalence or exclude uncommon adverse events.

Muscle soreness in the gluteal, quadriceps, or adductor regions was reported for 31, 23, 9, and 3 participants in successive sessions. It caused no reported discontinuations, interference with gait training/usual rehabilitation, or prolonged hospitalization. No dislocations or serious adverse events were reported. Of 36 participants who started training, one requested discontinuation because rehabilitation exercise exacerbated postoperative wound pain and 35 completed the protocol.

Exploratory analysis by surgical approach

Approach-stratified participant-level averages are shown in Table 2. Between-approach tests did not detect differences in Gmed n-EMG, TFL n-EMG, Gmed/TFL ratio, abduction, or flexion. With 14 PL, 11 DAA, and 10 ALS participants, these exploratory comparisons cannot establish equivalence or similar responsiveness across approaches.

Discussion

Four findings emerged: HAL-assisted abduction was associated with a higher Gmed/TFL activity ratio, which was also observed during unassisted movement immediately after the final session; abduction angles were greater and flexion angles were lower during assistance; measured hip abductor force increased over the observation period; and early postoperative training was completed by 35 of 36 participants who started the protocol, with no serious adverse events reported.

An important consideration in interpreting these findings is the distinction between the prescribed training protocol and the reference assessment. The 50 HAL-assisted repetitions represented the main intervention, whereas the preceding 10 unassisted repetitions were included to characterize movement performance without robotic assistance. Although the total number of training repetitions differed between conditions, the biomechanical analyses compared the 10 unassisted repetitions with the first 10 HAL-assisted repetitions. Therefore, the number of repetitions included in the EMG and kinematic comparisons was matched between conditions. The observed differences consequently describe task-specific biomechanical characteristics during unassisted and robot-assisted hip abduction rather than differences arising simply from averaging unequal numbers of repetitions.

Nevertheless, matching the number of analyzed repetitions does not eliminate other potential confounding factors. The two conditions were performed in a fixed sequence, and movement excursion, movement speed, and muscular effort were not standardized. Although robotic assistance may intrinsically influence movement excursion and muscular effort, the present design cannot determine the extent to which the observed differences were attributable specifically to robotic assistance rather than other task-related factors. Accordingly, these findings should be interpreted as preliminary evidence of task-specific biomechanical differences during robot-assisted hip abduction, rather than as proof of an isolated therapeutic effect of HAL.

Gmed and TFL both contribute to hip abduction, but their relative contributions depend on joint position. Anatomical and biomechanical studies have shown that Gmed, consisting of anterior, middle, and posterior fibres, has the greatest abduction moment arm in mid-range or slight adduction positions and acts as the primary abductor stabilizing the femoral head in the acetabulum during early stance [27]. In contrast, TFL contributes to abduction as well as flexion and internal rotation. In hip flexion and external rotation positions, the line of action of TFL becomes more laterally oriented, increasing its contribution to abduction [26, 27]. These

anatomical observations provide context for interpreting hip position but do not establish the relative muscle forces or functional significance of the changes observed here.

Patients in the early post-operative period after THA often fear hip movement because of post-operative pain and concern about dislocation [28, 29]. The “movement adaptation to pain” model proposed by Hodges and Tucker suggests that, in the presence of pain, activity of agonist muscles directly involved in the painful movement may be reduced, while activity is redistributed to other muscles, and movement patterns are altered, such as reduced movement speed [30]. Accordingly, pain and fear-avoidant behaviour provide possible explanations for variation in muscle activity, although their relationships to Gmed and TFL activity were not examined in this subanalysis.

Patients with hip osteoarthritis and after THA frequently present with hip flexion contracture due to pain and range-of-motion limitation [31]. Previous studies have also described muscle weakness, altered activation, and changes in muscle morphology [8–10]. These findings provide background for examining muscle activity during abduction but do not establish that a flexed hip position represents a pathological TFL-dominant pattern in the present participants. In the present study, during HAL-assisted training, EMG activity in both Gmed and TFL was lower on average, but the reduction in TFL was greater in the early sessions, alongside a higher Gmed/TFL ratio. This suggests that the relative balance of normalized activity between Gmed and TFL differed during HAL use. The significant increase in the Gmed/TFL ratio in the fourth-session post HAL condition compared with baseline pre HAL describes a difference between these assessment points; it does not demonstrate acquisition or retention through motor learning. Each muscle was normalized to its own session-specific pre HAL reference, which also limits longitudinal interpretation. The proposed interactive biofeedback framework links assistance to voluntary bioelectrical activity and repeated sensory feedback [20], but its contribution to the present observations was not established.

Increased hip abduction and reduced flexion during HAL use describe differences in the assisted movement trajectory. Greater joint excursion occurred alongside differences in normalized muscle

activity, but a causal relationship between these observations was not examined. As flexion approached neutral, hip position differed in a way that may alter muscle mechanics according to anatomical descriptions [27]. Together with the increased Gmed/TFL ratio, these kinematic changes suggest that HAL-assisted abduction was associated with a higher Gmed/TFL ratio, lower TFL activity, and differences in hip angles.

These findings can be considered alongside previous HAL studies examining muscle activity during assistance. Lafitte et al. reported that in patients with shoulder elevation dysfunction of cervical origin, training with a shoulder HAL reduced EMG activity of both the deltoid and trapezius, but the reduction was greater in the trapezius, leading to an increased deltoid/trapezius ratio and a reduction in compensatory shoulder shrugging [32]. They interpreted this as normalisation of the muscle coordination pattern, in which excessive compensatory muscle activity was suppressed while the primary agonist was relatively emphasised. Similarly, in the present study, the combination of reduced TFL activity, increased Gmed/TFL ratio, and reduced hip flexion angle during HAL use indicates concurrent task-specific differences in normalized EMG and kinematics, rather than evidence of a more physiological or Gmed-dominant abduction pattern.

The observed increase in hip abductor force over a short period may partly reflect the natural recovery process after THA, as patients were in the early postoperative recovery phase. Concurrent rehabilitation, changes in pain, and test familiarization are additional possible explanations. Although the force increase occurred over the same observation period as the EMG and kinematic differences, the single-arm design does not establish a causal relationship between them. Unlike conventional resistance training that may require high effort, HAL generates assistive torque based on voluntary EMG signals, enabling repetitive training with appropriate loading on the primary agonist while avoiding excessive co-contraction or compensatory activation. Previous studies have reported that decreases in co-contraction are associated with increased output of the agonist muscles [33]. In the present study, suppression of excessive co-

contraction induced by the HAL may therefore have contributed to more efficient strengthening of the gluteus medius and to increase in hip abductor force. However, because antagonist muscle activity and co-contraction were not quantified in this study, the mechanisms underlying the observed strength gains cannot be fully determined. Future studies should evaluate not only strength outcomes but also broader muscle activation patterns, including antagonist muscles, and assess muscle cross-sectional area using CT- or MRI-based measurements.

No statistically significant changes in vital signs or serious adverse events were reported, providing preliminary information on tolerability under clinical monitoring. Soreness decreased over successive sessions, but this observation does not establish adaptation to loading or improved motor efficiency. Early post-operative rehabilitation must balance sufficient training against pain, dislocation risk and tissue healing. No interference with usual rehabilitation or prolonged hospitalization associated with soreness was reported during the short side-lying sessions beginning around one week after surgery. One participant nevertheless withdrew because exercise exacerbated wound pain.

This study has several limitations. Because this was a small single-arm interventional study without a control group, the observed changes cannot be attributed to HAL or distinguished from natural postoperative recovery and concurrent rehabilitation. The training protocol comprised 50 HAL-assisted hip abduction repetitions per session, with 10 additional unassisted repetitions performed beforehand as a reference assessment. Although the total training volume differed, the biomechanical analyses compared an equal number of repetitions: 10 unassisted repetitions and the first 10 HAL-assisted repetitions. Therefore, unequal numbers of analyzed repetitions were not a source of difference between the calculated condition means. Nevertheless, the fixed task order and lack of standardization of movement speed, movement excursion, and muscular effort remain potential confounding factors. In addition, fatigue was not quantitatively assessed. Consequently, the observed EMG and kinematic differences cannot be attributed exclusively to robotic assistance. Future studies should employ repetition-matched, order-controlled

comparisons with standardized movement speed and quantitative fatigue assessment to better isolate the biomechanical contribution of robotic assistance. This limitation is consistent with the broader orthopaedic HAL literatures, in which many studies remain small, single-center, or uncontrolled [20]. Future randomized controlled trials comparing HAL-assisted rehabilitation with conventional rehabilitation are needed to evaluate the additive effects of HAL. This cohort included patients treated with different surgical approaches (PL, ALS, and DAA), which may involve varying degrees of trauma to the abductor muscles. Previous reports suggest that abductor dysfunction and Trendelenburg gait may differ by approach [34]. Our exploratory analysis did not detect between-approach differences in mean pre-HAL-to-HAL changes in muscle activity or hip angles. However, the subgroup sizes of 14 PL, 10 ALS, and 11 DAA participants limit the precision of these comparisons; the absence of statistically significant differences does not establish equivalence among approaches. Future studies should include larger cohorts with prespecified analyses stratified by surgical approach or more homogeneous surgical populations.

This study assessed muscle activity and hip kinematics during early postoperative hip abduction, but did not evaluate whether the observed changes persisted beyond the immediate assessment period. Although maintenance of gait ability over five years has been reported in patients with spinal and bulbar muscular atrophy receiving repeated gait training with bilateral lower-limb HAL [35], that finding cannot establish the durability of changes associated with single-joint hip abduction HAL after THA. Whether these changes persist after training ends or require continued or repeated training remains unknown.

The clinical relevance of the observed changes also remains uncertain. Changes in EMG activity and hip angles during abduction may not translate into improvements in gait or daily function. The primary gait outcome of the registered study is outside the scope of this report. The present subanalysis does not establish improvements in patient-reported function, quantitative gait outcomes, pelvic stability, or Trendelenburg gait, or demonstrate associations between these clinical outcomes and the observed exercise-task differences. Future controlled studies should

assess these clinical outcomes alongside muscle activity and kinematics over longer follow-up periods to determine both the persistence and clinical relevance of the findings.

Conclusions

Early postoperative hip abduction HAL training was completed by 35 of 36 participants who started the protocol. Assisted abduction showed task-specific differences in normalized EMG and hip angles under repetition-matched but sequential comparison conditions. Hip abductor force increased during an uncontrolled observation period. These preliminary findings concern protocol delivery and biomechanical observations; they do not establish motor learning, clinical effectiveness, superiority over conventional rehabilitation, or equivalence across surgical approaches.

List of abbreviations

ADL, activities of daily living; ALS, anterolateral supine; CI, confidence interval; DAA, direct anterior approach; DBP, diastolic blood pressure; EMG, electromyography; Gmed, gluteus medius; HAL, Hybrid Assistive Limb; HR, heart rate; n-EMG, normalized electromyography; NS, not significant; PL, posterolateral; RMS, root mean square; SBP, systolic blood pressure; SD, standard deviation; SpO_2, peripheral oxygen saturation; TFL, tensor fasciae latae; THA, total hip arthroplasty.

Declarations

Ethics approval and consent to participate

This study was approved by the Clinical Research Review Board of the University of Tsukuba Hospital (approval number TCRB24-016). Written informed consent was obtained from all participants prior to enrollment. The study was registered with the Japan Registry of Clinical Trials (jRCTs032240437) on 28 October 2024, before the actual first-enrollment date listed in the public registry (16 January 2025).

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

FH: conceptualization, data curation, formal analysis, investigation, resources, validation, visualization, and writing—original draft. YS: formal analysis, funding acquisition, investigation, project administration, validation, and writing—review and editing. TN: funding acquisition, project administration, resources, and writing—review and editing. YSh: funding acquisition, project administration, and writing—review and editing. SY: resources. RW and TY: resources and writing—review and editing. HM: funding acquisition, resources, supervision, and writing—review and editing. YH: supervision and writing—review and editing.

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References

1. Siopack JS, Jergesen HE. Total Hip Arthroplasty. West J Med. 1995;162(3):243-9.

2. Gogia PP, Christensen CM, Schmidt C. Total hip replacement in patients with osteoarthritis of the hip: improvement in pain and functional status. Orthopedics. 1994;17(2):145-50. https://doi.org/10.3928/0147-7447-19940201-10.

463 3. Mendiolagoitia L, Rodríguez MÁ, Crespo I, Del Valle M, Olmedillas H. Kinematic Gait
464 Analysis After Primary Total Hip Replacement: A Systematic Review: Gait After Total Hip
465 Replacement: A Systematic Review. Indian J Orthop. 2020;54(6):767-75.
466 https://doi.org/10.1007/s43465-020-00101-x.
467 4. Foucher KC, Hurwitz DE, Wimmer MA. Preoperative gait adaptations persist one year after
468 surgery in clinically well-functioning total hip replacement patients. J Biomech.
469 2007;40(15):3432-7. https://doi.org/10.1016/j.jbiomech.2007.05.020.
470 5. Grimaldi A, Richardson C, Stanton W, Durbridge G, Donnelly W, Hides J. The association
471 between degenerative hip joint pathology and size of the gluteus medius, gluteus minimus and
472 piriformis muscles. Man Ther. 2009;14(6):605-10. https://doi.org/10.1016/j.math.2009.07.004.
473 6. Hardcastle P, Nade S. The significance of the Trendelenburg test. J Bone Joint Surg Br.
474 1985;67(5):741-6. https://doi.org/10.1302/0301-620X.67B5.4055873.
475 7. Fujita K, Makimoto K, Hotokebuchi T. Qualitative study of osteoarthritis patients' experience
476 before and after total hip arthroplasty in Japan. Nurs Health Sci. 2006;8(2):81-7.
477 https://doi.org/10.1111/j.1442-2018.2006.00253.x.
478 8. Loureiro A, Constantinou M, Diamond LE, Beck B, Barrett R. Individuals with mild-to-
479 moderate hip osteoarthritis have lower limb muscle strength and volume deficits. BMC
480 Musculoskelet Disord. 2018;19(1):303. https://doi.org/10.1186/s12891-018-2230-4.
481 9. Schmidt A, Stief F, Lenarz K, Froemel D, Lutz F, Barker J, et al. Unilateral hip osteoarthritis:
482 Its effects on preoperative lower limb muscle activation and intramuscular coordination patterns.
483 Gait Posture. 2016;45:187-92. https://doi.org/10.1016/j.gaitpost.2016.01.028.
484 10. Rodríguez-Roiz JM, Bori G, Tomas X, Fernández-Valencia JA, García-Díez AI, Pomés J, et
485 al. Hypertrophy of the tensor fascia lata muscle as a complication of total hip arthroplasty. Eur J
486 Orthop Surg Traumatol. 2017;27(2):255-9. https://doi.org/10.1007/s00590-016-1854-z.

11. Turner DL, Ramos-Murguialday A, Birbaumer N, Hoffmann U, Luft A. Neurophysiology of robot-mediated training and therapy: a perspective for future use in clinical populations. Front Neurol. 2013;4:184. https://doi.org/10.3389/fneur.2013.00184.

12. Wall A, Borg J, Palmcrantz S. Clinical application of the Hybrid Assistive Limb (HAL) for gait training-a systematic review. Front Syst Neurosci. 2015;9:48. https://doi.org/10.3389/fnsys.2015.00048.

13. Endo Y, Mutsuzaki H, Mizukami M, Yoshikawa K, Kobayashi Y, Yozu A, et al. Long-term sustained effect of gait training using a hybrid assistive limb on gait stability via prevention of knee collapse in a patient with cerebral palsy: a case report. J Phys Ther Sci. 2018;30(9):1206-10. https://doi.org/10.1589/jpts.30.1206.

14. Jansen O, Grasmuecke D, Meindl RC, Tegenthoff M, Schwenkreis P, Sczesny-Kaiser M, et al. Hybrid Assistive Limb Exoskeleton HAL in the Rehabilitation of Chronic Spinal Cord Injury: Proof of Concept; the Results in 21 Patients. World Neurosurg. 2018;110:e73-e78. https://doi.org/10.1016/j.wneu.2017.10.080.

15. Saita K, Morishita T, Arima H, Hyakutake K, Ogata T, Yagi K, et al. Biofeedback effect of hybrid assistive limb in stroke rehabilitation: A proof of concept study using functional near infrared spectroscopy. PLoS One. 2018;13(1):e0191361. https://doi.org/10.1371/journal.pone.0191361.

16. Kubota S, Abe T, Kadone H, Shimizu Y, Funayama T, Watanabe H, et al. Hybrid assistive limb (HAL) treatment for patients with severe thoracic myelopathy due to ossification of the posterior longitudinal ligament (OPLL) in the postoperative acute/subacute phase: A clinical trial. J Spinal Cord Med. 2019;42(4):517-25. https://doi.org/10.1080/10790268.2018.1525975.

17. Ezaki S, Kadone H, Kubota S, Abe T, Shimizu Y, Tan CK, et al. Analysis of Gait Motion Changes by Intervention Using Robot Suit Hybrid Assistive Limb (HAL) in Myelopathy Patients After Decompression Surgery for Ossification of Posterior Longitudinal Ligament. Front Neurorobot. 2021;15:650118. https://doi.org/10.3389/fnbot.2021.650118.

513 18. Morishita T, Inoue T. Interactive Bio-feedback Therapy Using Hybrid Assistive Limbs for
514 Motor Recovery after Stroke: Current Practice and Future Perspectives. Neurol Med Chir
515 (Tokyo). 2016;56(10):605-12. https://doi.org/10.2176/nmc.st.2016-0094.
516 19. Sankai Y, Sakurai T. Exoskeletal cyborg-type robot. Sci Robot. 2018;3(17):eaat3912.
517 https://doi.org/10.1126/scirobotics.aat3912.
518 20. Miura K, Soma Y, Shimizu Y, Kadone H, Kubota S, Ezaki S, et al. Hybrid Assistive Limb in
519 orthopaedic rehabilitation: cybernic treatment developed in Japan for neuromotor functional
520 restoration. Int Orthop. 2026;50(11):2815-22. https://doi.org/10.1007/s00264-026-07011-x.
521 21. Setoguchi D, Kinoshita K, Kamada S, Sakamoto T, Kise N, Kotani N, et al. Hybrid Assistive
522 Limb improves restricted hip extension after total hip arthroplasty. Assist Technol.
523 2022;34(1):112-20. https://doi.org/10.1080/10400435.2020.1712498.
524 22. Makihara T, Kadone H, Onishi S, Kubota S, Hada Y, Shimizu Y, et al. Shoulder motion
525 assistance using a single-joint Hybrid Assistive Limb® robot: Evaluation of its safety and validity
526 in healthy adults. J Orthop Surg (Hong Kong). 2017;25(3):2309499017727951.
527 https://doi.org/10.1177/2309499017727951.
528 23. Kubota S, Kadone H, Shimizu Y, Koda M, Noguchi H, Takahashi H, et al. Development of a
529 New Ankle Joint Hybrid Assistive Limb. Medicina (Kaunas). 2022;58(3):395.
530 https://doi.org/10.3390/medicina58030395.
531 24. Hirose F, Nishino T, Shimizu Y, Soma Y, Haginoya A, Yasunaga S, et al. Assessment of Hip
532 Abduction Motion Assistance Using a Single-Joint Hybrid Assistive Limb Robot: Feasibility and
533 Safety Evaluation in Healthy Adults. J Clin Med. 2025;14(2):454.
534 https://doi.org/10.3390/jcm14020454.
535 25. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for
536 SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol. 2000;10(5):361-74.
537 https://doi.org/10.1016/s1050-6411(00)00027-4.

538 26. Lee JH, Cynn HS, Choi SA, Yoon TL, Jeong HJ. Effects of different hip rotations on gluteus
539 medius and tensor fasciae latae muscle activity during isometric side-lying hip abduction. J Sport
540 Rehabil. 2013;22(4):301-7. https://doi.org/10.1123/jsr.22.4.301.
541 27. Gottschalk F, Kourosh S, Leveau B. The functional anatomy of tensor fasciae latae and
542 gluteus medius and minimus. J Anat. 1989;166:179-89.
543 28. Alsaleem MK, Alkhars AM, Alalwan HA, Almutairi A, Alonayzan A, AlYaeesh IA.
544 Kinesiophobia Post Total Hip Arthroplasty: A Retrospective Study. Cureus. 2021;13(6):e15991.
545 https://doi.org/10.7759/cureus.15991.
546 29. Dong S, Guo X, Zhou Y, Chen Y, Wang C, Peng S, et al. Construction and validation of a
547 predictive model for post-operative kinesiophobia in total hip arthroplasty patients. Front Med
548 (Lausanne). 2025;12:1699157. https://doi.org/10.3389/fmed.2025.1699157.
549 30. Hodges PW, Tucker K. Moving differently in pain: a new theory to explain the adaptation to
550 pain. Pain. 2011;152(3 Suppl):S90-S98. https://doi.org/10.1016/j.pain.2010.10.020.
551 31. Tateuchi H. Gait- and postural-alignment-related prognostic factors for hip and knee
552 osteoarthritis: Toward the prevention of osteoarthritis progression. Phys Ther Res. 2019;22(1):31-
553 7. https://doi.org/10.1298/ptr.R0003.
554 32. Lafitte MN, Kadone H, Kubota S, Shimizu Y, Tan CK, Koda M, et al. Alteration of muscle
555 activity during voluntary rehabilitation training with single-joint Hybrid Assistive Limb (HAL) in
556 patients with shoulder elevation dysfunction from cervical origin. Front Neurosci.
557 2022;16:817659. https://doi.org/10.3389/fnins.2022.817659.
558 33. Gabriel DA, Kamen G, Frost G. Neural adaptations to resistive exercise: mechanisms and
559 recommendations for training practices. Sports Med. 2006;36(2):133-49.
560 https://doi.org/10.2165/00007256-200636020-00004.
561 34. Baker AS, Bitounis VC. Abductor function after total hip replacement. An electromyographic
562 and clinical review. J Bone Joint Surg Br. 1989;71(1):47-50. https://doi.org/10.1302/0301-
563 620X.71B1.2915004.

35. Iijima K, Watanabe H, Nakashiro Y, Iida Y, Nonaka M, Moriwaka F, et al. Long-term effects of the gait treatment using a wearable cyborg hybrid assistive limb in a patient with spinal and bulbar muscular atrophy: a case report with 5 years of follow-up. Front Neurol. 2023;14:1143820. https://doi.org/10.3389/fneur.2023.1143820.

Tables

Table 1. Vital signs before and after HAL training

Variable	Before Mean±SD	After Mean±SD	P value
SBP (mmHg)	131.4 ± 19.5	132.1 ± 18.9	NS
DBP (mmHg)	75.4 ± 11.7	77.2 ± 12.9	NS
HR (beats/min)	79 ± 10.2	78.2 ± 10	NS
SpO_2 (%)	98 ± 0.7	98.4 ± 0.6	NS

Values are mean ± SD. SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate; SpO_2, peripheral oxygen saturation; NS, not significant; HAL, Hybrid Assistive Limb.

Table 2. Muscle activity and hip kinematics by surgical approach

Outcome	Approach	n	pre HAL Mean ± SD	HAL Mean ± SD	Mean change [95% CI]	Between-approach P value
Gmed (%)	PL	14	50.87 ± 8.44	50.65 ± 12.43	-0.22 [-5.92, 5.47]	0.102
	DAA	11	53.10 ± 10.66	46.65 ± 14.66	-6.45 [-13.35, 0.46]	
	ALS	10	50.21 ± 3.14	42.66 ± 6.12	-7.55 [-12.30, -2.79]	

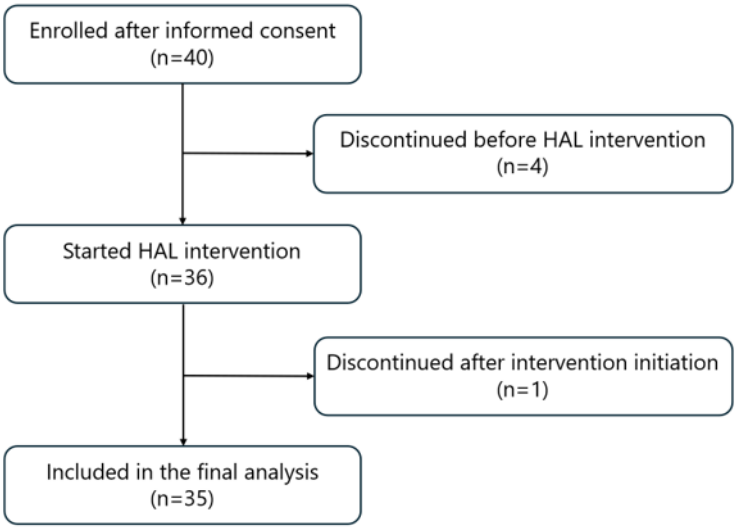
Outcome	Approach	n	pre HAL Mean ± SD	HAL Mean ± SD	Mean change [95% CI]	Between-approach P value
TFL (%)	PL	14	48.69 ± 9.91	43.92 ± 10.93	-4.77 [-9.55, -0.004]	0.093
	DAA	11	53.52 ± 8.32	47.16 ± 10.59	-6.36 [-9.54, -3.18]	
	ALS	10	47.89 ± 5.15	35.43 ± 5.15	-12.46 [-18.29, -6.63]	
Gmed /TFL ratio	PL	14	1.123 ± 0.234	1.226 ± 0.201	0.10 [-0.03, 0.24]	0.256
	DAA	11	1.000 ± 0.091	1.019 ± 0.252	0.02 [-0.13, 0.17]	
	ALS	10	1.084 ± 0.177	1.285 ± 0.249	0.20 [0.02, 0.39]	
Abduction (°)	PL	14	8.61 ± 3.81	14.13 ± 5.94	5.52 [3.34, 7.71]	0.988
	DAA	11	11.22 ± 5.92	16.61 ± 4.97	5.38 [2.01, 8.76]	
	ALS	10	12.01 ± 5.76	19.64 ± 10.13	7.63 [1.37, 13.88]	
Flexion (°)	PL	14	13.62 ± 13.19	6.42 ± 12.56	-7.20 [-13.19, -1.21]	0.784
	DAA	11	16.18 ± 14.13	9.24 ± 15.58	-6.94 [-11.28, -2.61]	
	ALS	10	14.37 ± 10.02	5.40 ± 14.90	-8.97 [-15.87, -2.08]	

Each participant's values were averaged over sessions 1–4. Change denotes HAL minus pre HAL; EMG changes are percentage points. Between-approach tests used the Kruskal–Wallis test, with Benjamini–Hochberg adjustment described for five outcomes.

HAL, Hybrid Assistive Limb; SD, standard deviation; CI, confidence interval; Gmed, gluteus medius; TFL, tensor fasciae latae; PL, posterolateral; ALS, anterolateral supine; DAA, direct anterior approach.

Figures and legends

Figure 1. Participant flow



Forty participants were enrolled; four withdrew before HAL training, 36 started training, one discontinued because postoperative wound pain was exacerbated during rehabilitation, and 35 were included in the completer analysis. HAL, Hybrid Assistive Limb.

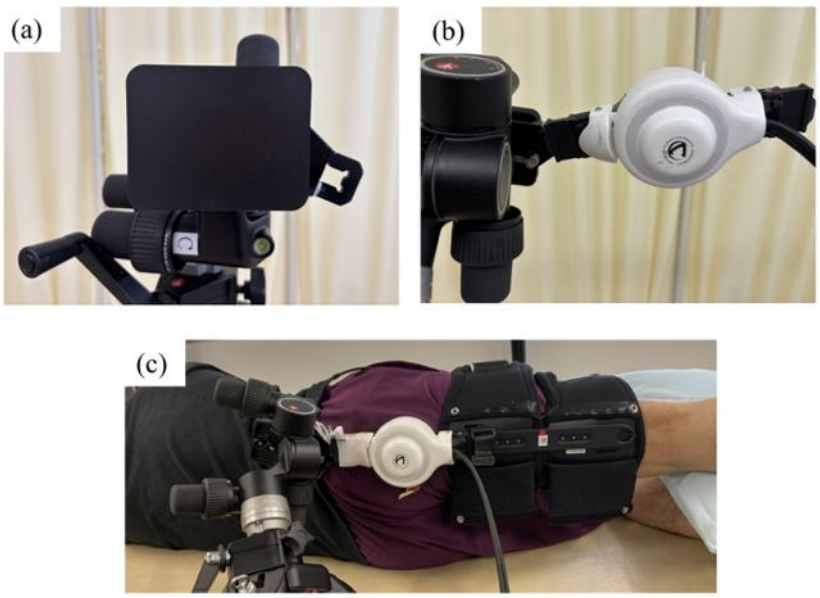
Figure 2. Components of the hip abduction HAL



The hip abduction HAL system consists of (a) control device, (b) battery, (c) manual controller, (d) electrode cable, (e) power unit, (f) thigh belt, (g) tripod-based platform, and (h) attachment. HAL, hybrid assistive limb robot.

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603 Figure 3. Hip abduction HAL setup



604



605

606 (a, b) The distal portion of the single-joint HAL is attached to a tripod-based platform using a

607 custom attachment. (c) The proximal portion is secured to the thigh using the standard belt.

608 Participants lie on their side near the platform. The device is aligned with the femoral axis, with

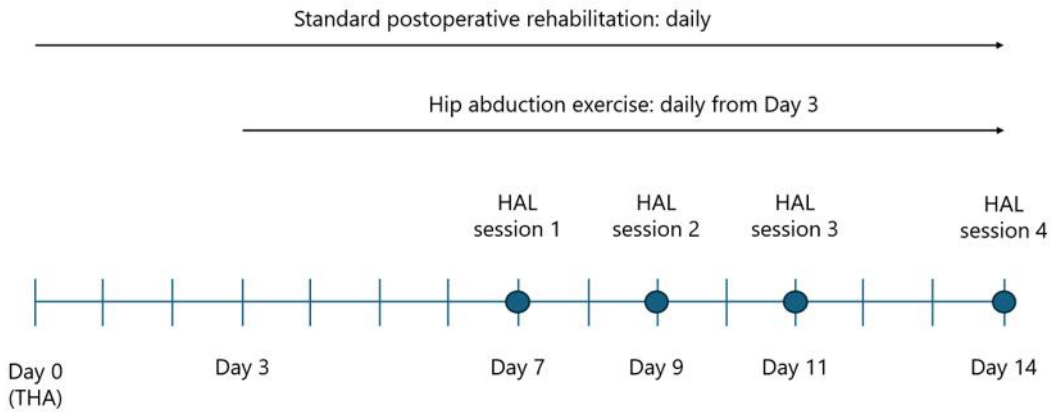
609 the power unit positioned at the greater trochanter against the gluteal region. (d) The setup permits

610 assisted abduction–adduction. HAL, Hybrid Assistive Limb.

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612 License.

613 Figure 4. Postoperative rehabilitation and HAL training schedule



614

615 Standard postoperative rehabilitation was provided daily. Hip abduction exercise was initiated on

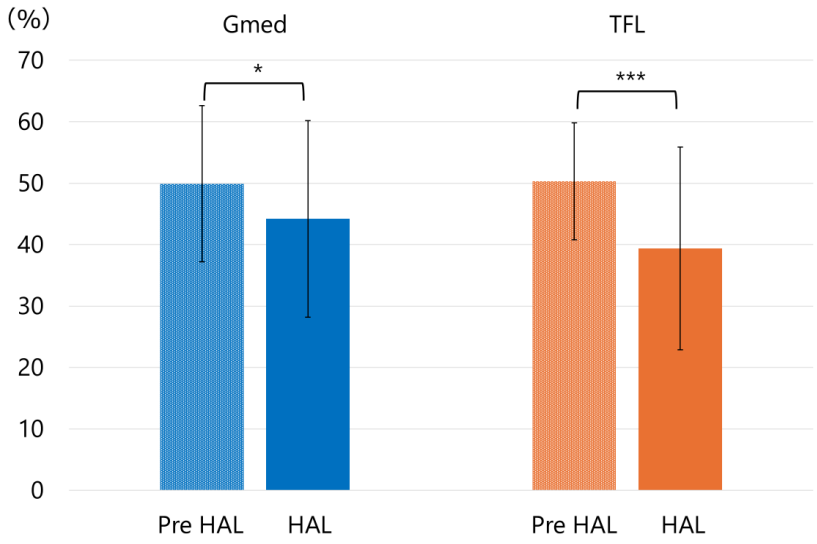
616 postoperative Day 3. HAL-assisted sessions were performed on Days 7 ± 1, 9 ± 1, 11 ± 1, and 14

617 ± 1. HAL, Hybrid Assistive Limb.

618

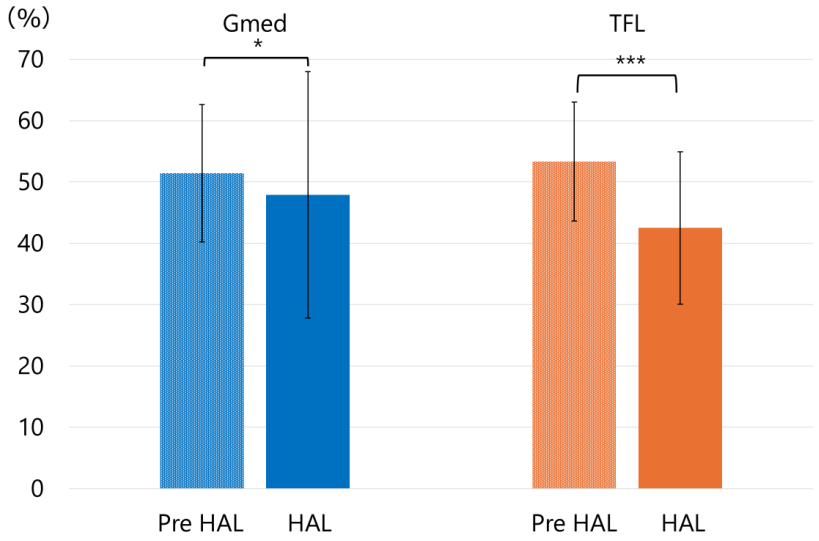
619 Figure 5. Normalized muscle activity during unassisted and assisted abduction

620 1st session

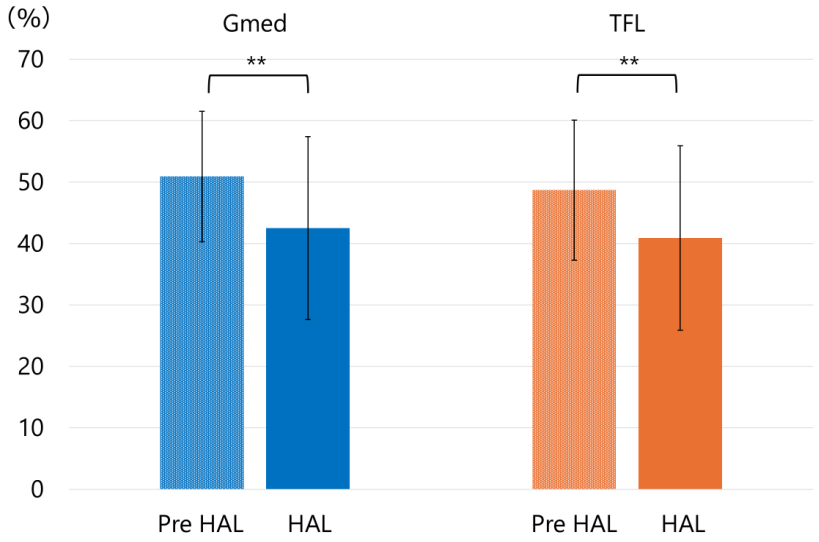


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622 2nd session

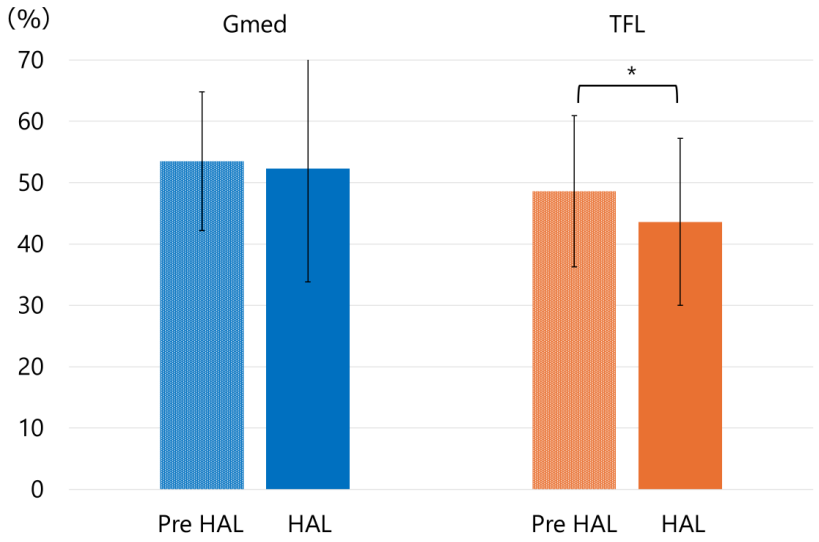


623
624 3rd session



625

626 4th session



627

628 Gmed and TFL activity during 10 unassisted repetitions (pre HAL) followed by 50 assisted

629 repetitions (HAL) in sessions 1–4. EMG was normalized to each muscle's maximum pre HAL

630 RMS within the same session; time was normalized over neutral-to-maximum abduction. Bars

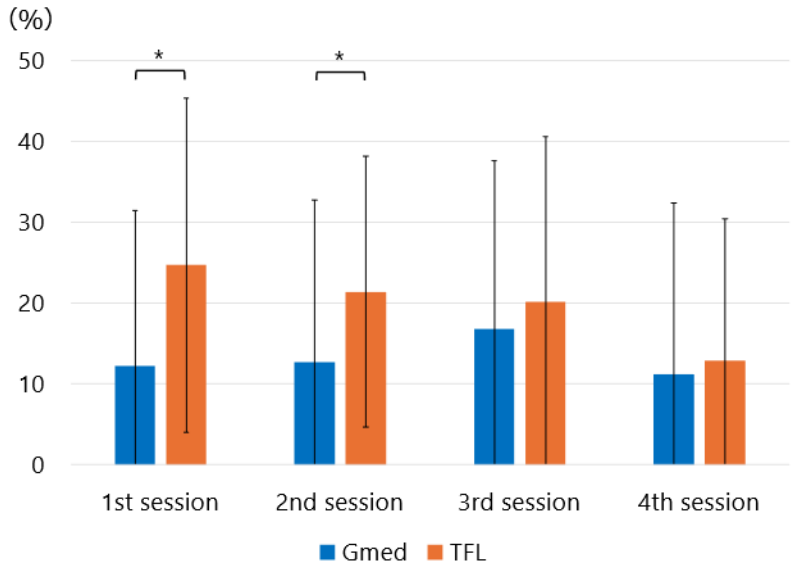
631 represent means, and error bars indicate standard deviations (n = 35 participants).

632 Gmed, gluteus medius; TFL, tensor fasciae latae; HAL, Hybrid Assistive Limb; n-EMG,

633 normalized electromyography; RMS, root mean square. The unequal repetition counts and fixed

634 order limit attribution to assistance alone.

635 Figure 6. Relative reduction in normalized EMG during HAL use



636

637 Reduction was calculated as 100 × (pre HAL − HAL)/pre HAL for each muscle and session. Bars

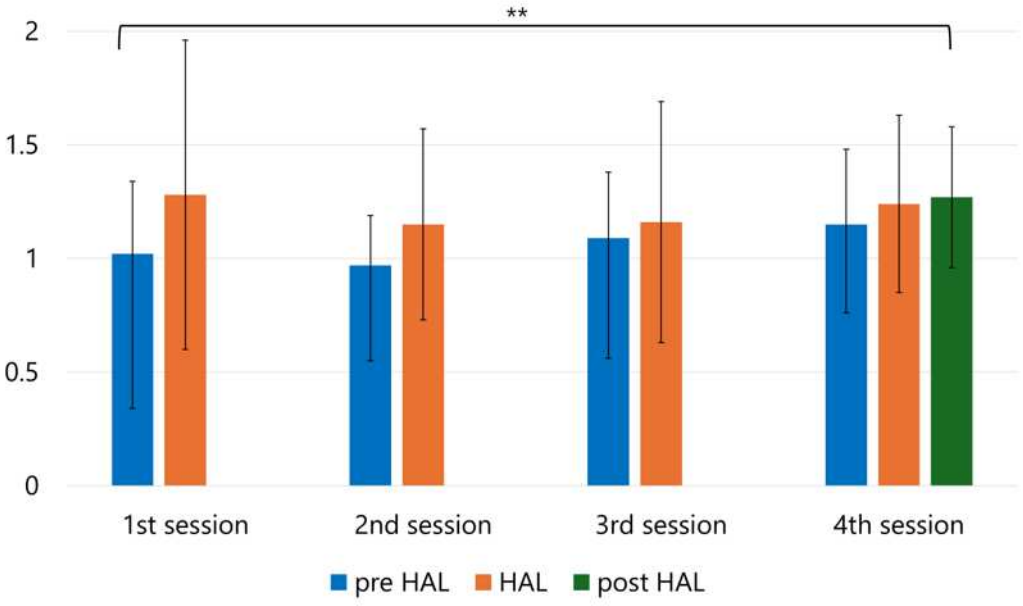
638 represent means, and error bars indicate standard deviations (n = 35 participants).

639 Gmed, gluteus medius; TFL, tensor fasciae latae; HAL, Hybrid Assistive Limb; EMG,

640 electromyography. Comparisons are between the two muscles' participant-level reduction rates.

641

642 Figure 7. Ratio of separately normalized Gmed and TFL activity



643

644 The Gmed/TFL ratio was calculated from separately normalized EMG values in each session.

645 Post HAL denotes unassisted repetitions immediately after session 4. Session-1 pre HAL and

646 session-4 post HAL used session-specific references. Bars represent means, and error bars

647 indicate standard deviations (n = 35 participants).

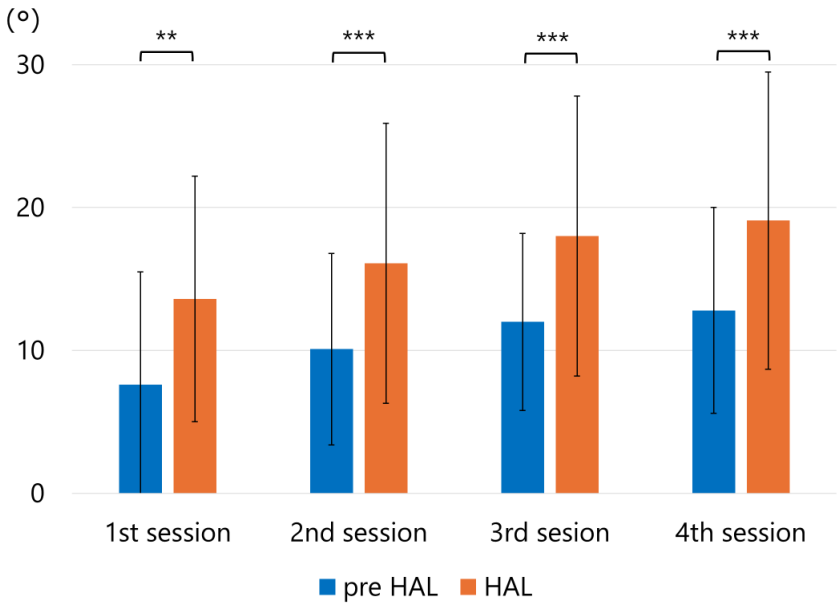
648 Gmed, gluteus medius; TFL, tensor fasciae latae; HAL, Hybrid Assistive Limb. The ratio does not

649 measure relative muscle force or establish motor learning.

650

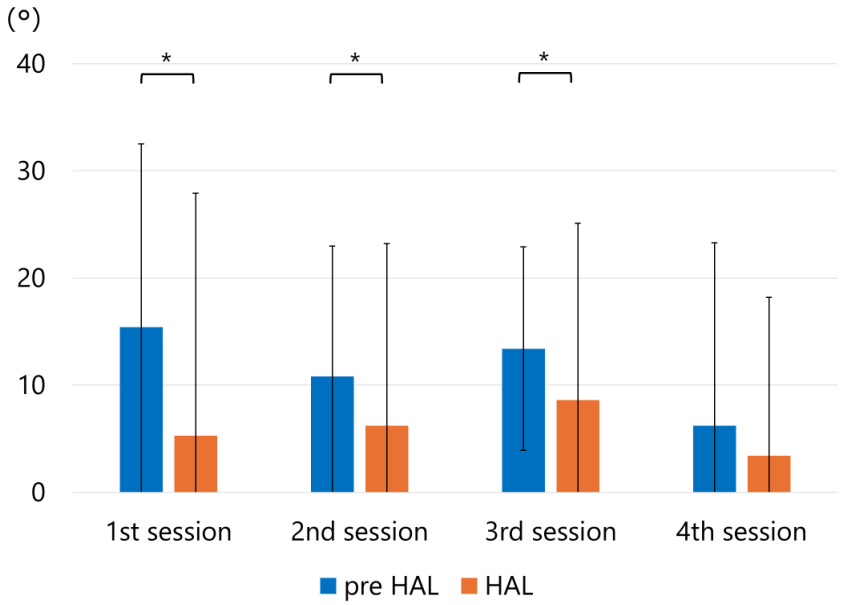
651 Figure 8. Hip angles during unassisted and assisted abduction

652 (A) Hip abduction angle



653

654 (B) Hip flexion angle



655

656 (A) Comparison of hip abduction angle with and without HAL in each session.

657 (B) Hip flexion angles. Pre HAL denotes 10 unassisted repetitions before 50 HAL-assisted

658 repetitions. Values summarize peak angles over neutral-to-maximum abduction. Bars represent

659 means, and error bars indicate standard deviations (n = 35 participants).

660 HAL, Hybrid Assistive Limb.