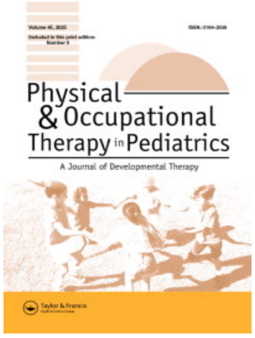

Taylor & Francis
Taylor & Francis Group

Physical & Occupational Therapy In Pediatrics

ISSN: 0194-2638 (Print) 1541-3144 (Online) Journal homepage: www.tandfonline.com/journals/ipop20

Robot-Assisted Gait Training to Improve Gait Patterns in Two Adolescents with Childhood-Onset Stroke: A Case Report

Yuichiro Hosoi , Takayuki Kamimoto , Tomoyuki Noda , Taiyo Kawaguchi , Tatsuya Teramae , Yuka Yamada , Tetsuya Tsuji & Michiyuki Kawakami

To cite this article: Yuichiro Hosoi , Takayuki Kamimoto , Tomoyuki Noda , Taiyo Kawaguchi , Tatsuya Teramae , Yuka Yamada , Tetsuya Tsuji & Michiyuki Kawakami (03 Dec 2025): Robot-Assisted Gait Training to Improve Gait Patterns in Two Adolescents with Childhood-Onset Stroke: A Case Report, Physical & Occupational Therapy In Pediatrics, DOI: 10.1080/01942638.2025.2591294

To link to this article: https://doi.org/10.1080/01942638.2025.2591294

PHYSICAL & OCCUPATIONAL THERAPY IN PEDIATRICS
https://doi.org/10.1080/01942638.2025.2591294

Taylor & Francis
Taylor & Francis Group

CASE REPORT

OPEN ACCESS Check for updates

Robot-Assisted Gait Training to Improve Gait Patterns in Two Adolescents with Childhood-Onset Stroke: A Case Report

Yuichiro Hosoi[a], Takayuki Kamimoto[a], Tomoyuki Noda[a,b], Taiyo Kawaguchi[a], Tatsuya Teramae[b], Yuka Yamada[a], Tetsuya Tsuji[a], and Michiyuki Kawakami[a]

[a]Department of Rehabilitation Medicine, Keio University School of Medicine, Tokyo, Japan; [b]Department of Brain Robot Interface, Advanced Telecommunications Research Institute International, Kyoto, Japan

ABSTRACT

Aim: Although the effectiveness of robot-assisted gait training (RAGT) in stroke has been reported, evidence in adolescents with childhood-onset stroke remains limited. This study reports the safety and clinical efficacy of RAGT using a robotized knee–ankle–foot orthosis in two adolescents with different gait patterns.

Methods: Case 1 (female, 15 years; Fugl-Meyer Assessment of Lower Extremity (FMA L/E) score 24) had moderate motor paralysis and walked with a short leg brace and cane, showing an extension-thrust pattern. Case 2 (male, 18 years; FMA L/E 26) used a short leg brace and demonstrated a stiff-knee gait. Both underwent 10 sessions of RAGT over 3 weeks. Comfortable and maximum gait speeds (10-m walking test), gait endurance (6-min walking test), gait symmetry (swing time ratio and normalized cross-correlation of knee joint angles), and safety were assessed pre- and post-intervention.

Results: Both participants completed RAGT safely. Comfortable gait speed improved from 0.78 to 0.99 m/s in case 1 and from 0.98 to 1.36 m/s in case 2. Improvements were observed in gait symmetry and kinematics, with partial correction of abnormal gait.

Conclusion: RAGT can be safely applied in adolescents with childhood-onset stroke and may contribute to improved gait performance and gait pattern.

ARTICLE HISTORY
Received 4 September 2025
Accepted 13 November 2025

KEYWORDS
Childhood-onset stroke; gait pattern; robot-assisted gait training

Childhood-onset stroke affects an estimated 1–6 per 100,000 children annually (Agrawal et al., 2009; Laugesaar et al., 2010), representing a significant pediatric neurological condition. Many survivors live with long-term disabilities (Kirton & deVeber, 2015), among which gait impairments due to motor dysfunction are particularly common and affect independence and quality of life (deVeber et al., 2000; Hill et al., 2023). Rehabilitation aimed at improving gait is, therefore, essential (Jang, 2010).

CONTACT Michiyuki Kawakami michiyukikawakami@keio.jp Department of Rehabilitation Medicine, Keio University School of Medicine, 35, Shinanomachi, Shinjuku-ku, Tokyo 160-8582, Japan

Supplemental data for this article can be accessed online at https://doi.org/10.1080/01942638.2025.2591294.

Abnormal gait is frequently addressed in post-stroke rehabilitation (Prosser et al., 2022), with distinctive patterns often seen in the affected knee joint (De Quervain et al., 1996; Mulroy et al., 2003). These include stiff-knee (excessive knee flexion) and extension thrust (excessive extension) patterns during stance (De Quervain et al., 1996), which can impair gait speed and balance (Mulroy et al., 2003), increase energy expenditure (Bleyenheuft et al., 2010), and lead to joint pain or deformity (Cooper et al., 2012; Mao et al., 2015). Similar abnormalities have been reported in young patients with childhood-onset stroke, contributing to asymmetry and limited mobility (Elnaggar et al., 2022; Hausdorff et al., 1999; Prosser et al., 2010, 2022).

Robot-assisted gait training (RAGT) has emerged as a promising strategy to deliver repetitive, task-specific lower-limb training (Chang & Kim, 2013; Nedergård et al., 2021). While it has shown benefits in improving gait speed and independence in adult patients with stroke (Mehrholz et al., 2020), its impact on abnormal gait patterns, particularly at the knee, remains unclear (Chen et al., 2024; De Luca et al., 2019).

In both pediatric and adult populations with acquired brain injury, RAGT has improved gait speed, stride length, and cadence, even in chronic phases (Drużbicki et al., 2013; Meyer-Heim et al., 2009; Volpini et al., 2022). Multi-joint robotic systems have enhanced gait symmetry and hip motion (Beretta et al., 2015, 2020), yet their effect on knee symmetry in young patients with chronic stroke is underexplored (Beretta et al., 2020).

Recently, RAGT systems capable of assisting multiple joints simultaneously, rather than single-joint support, have been reported to improve gait speed and endurance (Chen et al., 2024). Our group developed a multi-joint robotic orthosis using pneumatic artificial muscles (PAMs) to assist knee and ankle movements. This system generates higher torque and smoother support than conventional devices (Noda et al., 2018) and may inhibit knee hyperextension in adults with chronic stroke (Kamimoto et al., 2023; Takahashi et al., 2023).

Despite the diversity of abnormal gait patterns observed in young patients with childhood-onset stroke, limited evidence exists regarding the use of RAGT to address these specific impairments. In particular, the effects of RAGT on knee joint kinematics have not been sufficiently examined despite their importance in gait classification and rehabilitation planning. Therefore, this case report presents the safety and clinical effects of RAGT using a robotic knee–ankle orthosis in two young patients with childhood-onset stroke exhibiting distinct gait abnormalities.

Methods

Participants

Case 1 was a 15-year-old female who developed a cerebral hemorrhage in the left internal capsule to thalamus due to a ruptured arteriovenous malformation (AVM) at the age of 11. She was admitted to our hospital for rehabilitation 38 months after onset. She presented with moderate motor paralysis, with a Fugl-Meyer Assessment of Lower Extremity (FMA L/E) score of 24, and had no cognitive impairment affecting daily life. She attended a special-needs school and used a four-point cane and short leg brace indoors to walk independently, and was able to move outdoors using a wheelchair.

When using the cane and brace, she was able to walk outdoors under supervision, although long-distance walking was difficult. Her gait exhibited an extension thrust pattern (De Quervain et al., 1996).

Case 2 was an 18-year-old male who experienced a right subcortical hemorrhage from a ruptured AVM at the age of 14 and was admitted 43 months after onset for rehabilitation. He also presented with moderate motor paralysis (FMA L/E score: 26) and no cognitive impairment. He was enrolled in a regular high school and planned to attend college. He was able to walk independently indoors without assistive devices, and for outdoor mobility, he used a short leg brace and was also able to ambulate independently. His gait demonstrated a stiff-knee pattern (De Quervain et al., 1996).

This study was conducted in accordance with the Declaration of Helsinki and received approval from the Institutional Review Board of Keio University Hospital (approval number: 20190246). The study protocol was registered in the UMIN Clinical Trials Registry (UMIN-CTR; ID: UMIN000039299) on 29 January 2020. Written informed consent was obtained from the patients and their guardians for the publication of the case details. This case report was prepared in accordance with the CARE guidelines (Riley et al., 2017).

Clinical and Gait Assessments

All assessments were conducted the day before the start of the intervention and again on the day following its completion. During assessments, case 1 wore a plastic ankle–foot orthosis (AFO), whereas case 2 walked without any assistive device; no physical assistance was provided by therapists. The primary outcomes were comfortable and maximum gait speeds, assessed using the 10-m walking test (10MWT) (Collen et al., 1990); temporal gait symmetry, calculated using swing time ratios (SR), where a value of 1 indicated perfect symmetry (Patterson et al., 2010); and kinematic gait symmetry, assessed using normalized cross-correlation (NCC) values derived from knee joint angle waveforms (Gouwanda & Senanayake, 2011). The secondary outcomes included gait endurance, measured by the 6-minute walk test (6MWT) (Geiger et al., 2007), and gait coordination, assessed using the Gait Assessment and Intervention Tool (G.A.I.T.) (Daly et al., 2009). This tool evaluates coordinated gait components in patients with stroke, and scoring was performed by an examiner reviewing video recordings. The maximum score is 62 points, with lower scores indicating better performance. Additionally, muscle tone of the gastrocnemius muscle was assessed using the Modified Ashworth Scale (MAS), and isolated motor control was evaluated using the FMA L/E.

Data Collection and Analysis

Kinematic data collection and analysis procedures were as follows. Lower-limb kinematic data were obtained using a three-dimensional motion capture system (Vicon, Oxford, UK). Sixteen reflective markers were attached bilaterally to anatomical landmarks, including the pelvis, lower limbs, and feet. Motion data were collected at 100 Hz across five gait cycles and time-normalized to represent 0–100% of the gait cycle.

The mean knee joint angle was calculated at each of 101 time points across the cycle. All kinematic data, including SR and NCC values, were analyzed using MATLAB (MathWorks, Natick, MA).

Intervention: Robot-Assisted Gait Training

A robotized knee–ankle–foot orthosis (KAFO), developed by the Advanced Telecommunications Research Institute International (ATR, Kyoto, Japan), was used. The device comprises four main components: a metal-supported exoskeleton body, PAM actuators, an operation computer, and a control computer. The PAMs provide assistive torque for knee flexion/extension and ankle plantarflexion/dorsiflexion, and the assistance parameters can be individually adjusted according to the patient's gait pattern to facilitate more physiological movement (Figure 1).

Previous studies have suggested that this system may help correct gait abnormalities such as stiff-knee and extension thrust patterns (Noda et al., 2018; Takahashi et al., 2023). Detailed descriptions of the device's structure and control mechanisms are available in prior studies (Noda et al., 2018; Takahashi et al., 2023).

Based on previous evidence suggesting effectiveness with 10 sessions of RAGT (Hornby et al., 2008; Kang et al., 2021; Lewek et al., 2009), training was conducted for 30 min per session, 2–3 times per week, over 3 weeks (total: 10 sessions). Because the robotic orthosis was designed for treadmill-based gait training, all sessions were conducted on a treadmill, which enabled a higher training dose through repetitive, task-specific stepping with precise speed control and safe monitoring (Klassen et al., 2020; Mehrholz et al., 2017). An unloading device supported approximately 20% of body weight at the beginning, with gradual reduction. Visual feedback via a full-length mirror was provided. Treadmill speed was initially set to match the participant's comfortable overground gait speed and was gradually increased if gait was stable for at least 30 s. The final speed from the previous session was used as the starting speed in the subsequent session. Patients were instructed throughout to facilitate adaptation to the robotic assistance.

The safety review was based on safety assessments developed in previous studies and was assessed daily at the time of the intervention (see previous study for details) (Takahashi et al., 2023). The assessment consisted of three parts: before training (physical condition and risk assessment of robot wearing), during training (unexpected assistance, pain, or excessive motion), and after training (skin condition, vital signs such as blood pressure and pulse rate, and subjective fatigue). Physicians and physiotherapists performed these checks to ensure participant safety throughout all sessions.

Case 1, presenting with an extension thrust pattern, received knee flexion and ankle dorsiflexion assistance during stance, and ankle dorsiflexion assistance during swing. Case 2, with a stiff-knee pattern, was trained with knee extension and plantarflexion assistance during stance. Robotic assistance supported correction of abnormal gait patterns and facilitated gait patterns closer to normal. The system monitored joint angles in real time and adapted the assistance accordingly. As patients' control improved, assistance levels were gradually reduced and treadmill speed was progressively increased.

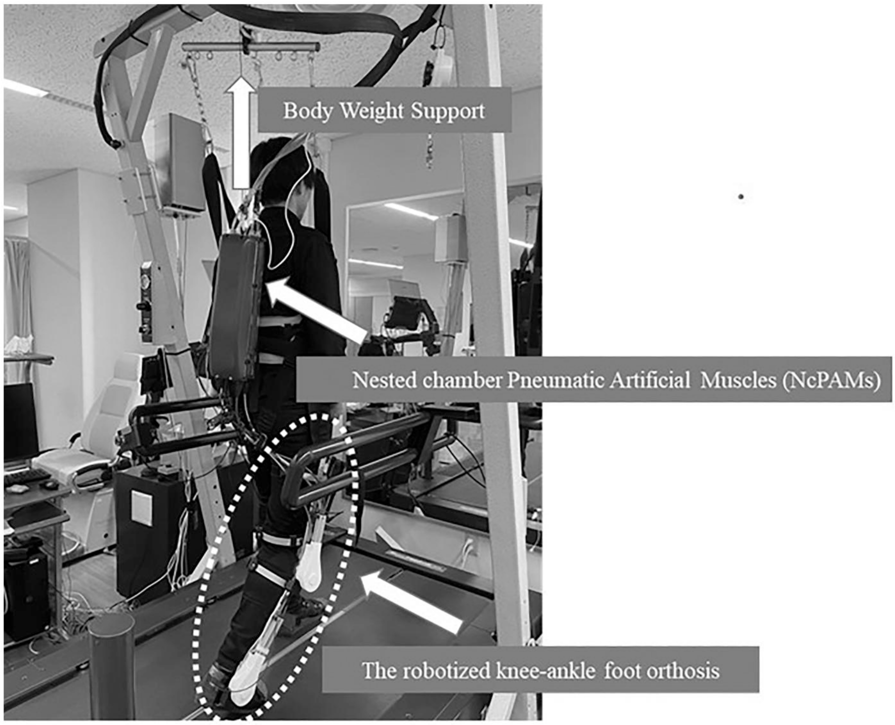

Figure 1. Robotic apparatus. The apparatus comprises an orthosis, modular exoskeletal joints, nested chamber pneumatic artificial muscles (NcPAMs), and a control personal computer. The NcPAMs unit is mounted on the patient's back and supported by a body-weight support device. The four PAMs aid in knee flexion and extension, ankle dorsiflexion, and plantarflexion.

Results

Safety of Robot-Assisted Gait Training

Both participants completed the intervention without adverse events. Vital signs—including heart rate, blood pressure, and oxygen saturation—remained stable, and neither reported fatigue or discomfort. No skin irritation, pressure sores, or device-related pain were observed. Throughout the training, physicians and physiotherapists supervised sessions to ensure safety. The device's built-in features, including an emergency stop and adjustable assistance levels, helped prevent excessive joint loading. Post-intervention evaluations confirmed no delayed adverse effects or gait instability.

Clinical and Gait Assessments

Table 1 summarizes the outcomes. Comfortable gait speed improved in both cases (case 1: 0.78–0.99 m/s; case 2: 0.98–1.36 m/s), as did maximum gait speed (case 1: 1.17–1.10 m/s; case 2: 1.66–1.93 m/s). G.A.I.T. scores decreased, indicating better gait patterns (case 1: 19–12 points; case 2: 23–15 points). Gait endurance increased in case 2 (450–514 m) but decreased slightly in case 1 (404–374 m). Temporal symmetry improved (case 1: 1.28–1.12; case 2: 1.27–1.19), as did kinematic symmetry based on knee joint angles (case 1: 0.83–0.94;

Table 1. Clinical and gait assessments pre- and post-intervention for each case.

	Case 1		Case 2	
Clinical and gait measures	Pre	Post	Pre	Post
Fugl-Meyer Assessment of Lower Extremity (points)	24	24	26	26
Modified Ashworth Scale – gastrocnemius (points)	1+	1+	1	1
Comfortable gait speed (m/s)	0.78	0.99	0.98	1.36
Maximum gait speed (m/s)	1.17	1.10	1.66	1.93
6-minute walk test (m)	404	374	450	514
Gait Assessment and Intervention Tool (point)	19	12	23	15
Swing time ratios	1.28	1.12	1.27	1.19
Normalized cross-correlation of the knee joint	0.83	0.94	0.74	0.85

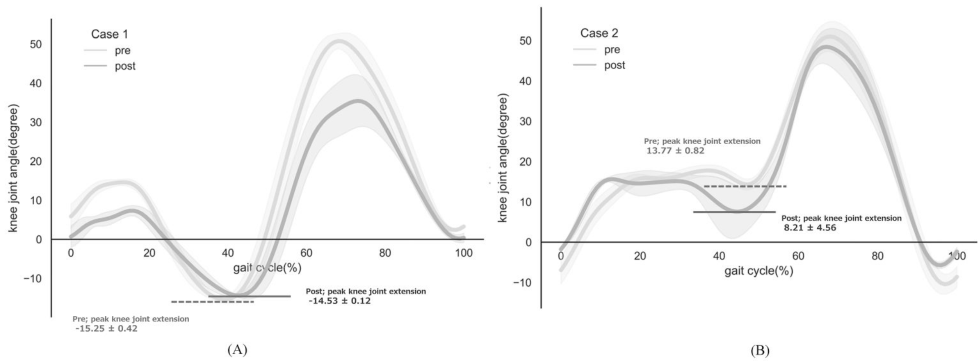

Figure 2. Changes in the knee joint angle on the affected side before and after RAGT for each case. (A) Case 1 and (B) case 2. The light gray line represents the knee joint angle before intervention, and the dark gray line represents the knee joint angle after intervention. The dashed line indicates the peak knee extension angle before intervention, and the solid line indicates the peak knee extension angle after intervention. Each curve represents the mean knee joint angle calculated across five gait cycles.

case 2: 0.74–0.85). The FMA L/E and MAS scores showed no remarkable changes between the pre- and post-training sessions in either case.

Changes in knee joint motion are presented in Figure 2. In case 1, hyperextension during stance was slightly reduced (from −15.25° ± 0.42° to −14.53° ± 0.12°), suggesting a modest tendency toward correction of the extension thrust pattern. In case 2, knee extension during stance showed a change (from 13.77° ± 0.82° to 8.21° ± 4.56°), indicating a possible shift toward a more typical mid-stance pattern. However, the knee was in a flexed position but showed insufficient flexion at the end of stance in case 1, and mild hyperextension persisted at initial contact in case 2. Supplementary material include hip and ankle kinematics pre- and post-intervention, further illustrating changes associated with RAGT.

Discussion

The findings from the two cases suggest that adolescents with childhood-onset stroke can safely perform RAGT, which may contribute to increased gait speed and improvement. The gait-assisted robot used was able to address two distinct abnormal gait patterns by individually adjusting the assist power and timing for the knee and ankle joints. Both cases showed an improvement in gait speed, exceeding the minimal clinically important difference (MCID) of 0.16–0.18 m/s reported in previous studies (Tilson et al., 2010). RAGT has been shown to improve gait speed in stroke patients, and similar results were observed in young adults with childhood-onset stroke (Calabrò et al., 2021; Nedergård et al., 2021).

Both cases showed changes in swing time symmetry and affected-side knee joint angles, consistent with previous studies reporting improved gait patterns in patients with chronic stroke following RAGT (Takahashi et al., 2023). A previous study using the Lokomat (Hocoma AG, Zurich, Switzerland) in young adults with childhood-onset stroke reported improved hip motion during gait (Beretta et al., 2015). While our findings similarly showed kinematic improvements, they differed in that they showed improvement in knee joint motion, a common abnormality in patients with stroke.

In case 1, an extension thrust pattern was addressed with knee flexion and ankle dorsiflexion assist during stance and ankle dorsiflexion assist during swing. In case 2, a stiff-knee pattern was managed with knee extension and plantarflexion assist during stance. In both cases, assist levels were gradually reduced, while gait speed increased without causing major disturbances. This may be due to repeated training with near-normal knee motion patterns.

Previous studies have shown that progressive assistance reduction facilitates gait learning more than full fixed assistance (Park et al., 2019; Srivastava et al., 2016). Furthermore, repetition of normal movement patterns is important for motor learning in young adults with childhood-onset stroke (Malone & Felling, 2020). Thus, the assist settings used in this verification may have contributed to improved gait. The robot in this study can independently adjust assist power and timing at the knee and ankle joints. Stroke-related abnormal gait often results from multi-joint impairment, not limited to the knee (Cooper et al., 2012; Knutsson & Richards, 1979). Therefore, modifying assistance based on individual gait patterns may be essential, as demonstrated in this study.

There are few reports demonstrating gait pattern improvements with RAGT in adolescents with childhood-onset stroke. In this study, two adolescents with different abnormal gait patterns showed improved gait speed and partial correction of their patterns when assistance was individually adjusted. While some abnormalities remained, the findings suggest that RAGT using a robotic knee–ankle–foot orthosis can safely support gait training and potentially promote more normal movement patterns in this population. However, given only two participants, results should be interpreted with caution. Some of the observed improvement in gait speed may also reflect the effects of repetitive treadmill practice rather than RAGT alone. Furthermore, limited changes in knee kinematics may indicate that the short training duration or long-standing compensatory gait strategies restricted further adaptation.

Although case reports are not generalizable, the observed improvements in gait performance may suggest potential benefits for daily and community ambulation, such as walking at school or in other real-world environments. However, follow-up evaluations of activity level and participation in daily life were not conducted in this case report. Future research should incorporate these outcomes to clarify the broader functional and social impact of individualized RAGT. Moreover, larger cohort studies are needed to determine its overall efficacy and optimize its clinical application in adolescents with childhood-onset stroke.

Author Contributions

CRediT: **Yuichiro Hosoi**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing; **Takayuki Kamimoto**: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing; **Tomoyuki Noda**: Conceptualization, Data curation, Methodology, Writing – review & editing; **Taiyo Kawaguchi**: Data curation, Investigation, Methodology, Writing – review & editing; **Tatsuya Teramae**: Conceptualization, Data curation, Methodology, Writing – review & editing; **Yuka Yamada**: Data curation, Investigation, Methodology, Writing – review & editing; **Tetsuya Tsuji**: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing; **Michiyuki Kawakami**: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Ethics Statement

This study followed the guidelines of the Declaration of Helsinki and received ethical approval from Keio University Hospital (approval number: 20190246) and was publicly registered in the UMIN Clinical Trials Registry (UMIN-CTR) (trial registration ID: UMIN000039299).

Funding

This work was supported by the Japan Agency for Medical Research and Development (AMED) under Grant Number JP22he2202017.

About the Authors

Yuichiro Hosoi, PT, MS, is a Specially Appointed Assistant Professor in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. His research focuses on gait rehabilitation after stroke, robot-assisted gait training, and biomechanical and machine-learning approaches for gait analysis. He collaborates across engineering and clinical fields to advance gait recovery research.

Takayuki Kamimoto, MD, is a physician in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. His clinical and research interests include rehabilitation for individuals with stroke and clinical studies related to COVID-19 and its recovery process.

Tomoyuki Noda, PhD, is a Senior Researcher in the Department of Brain Robot Interface at the Advanced Telecommunications Research Institute International (ATR) in Kyoto, Japan. His research focuses on brain–machine interfaces, robotic rehabilitation systems, human motor control, and neuromechanics, with extensive contributions to interdisciplinary engineering and clinical research.

Taiyo Kawaguchi, MD, is a physician in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. He specializes in neurorehabilitation and clinical research in neurological disorders.

Tatsuya Teramae, PhD, is a researcher in the Department of Brain Robot Interface at the Advanced Telecommunications Research Institute International (ATR), Kyoto, Japan. His work focuses on robotics and neural engineering.

Yuka Yamada, MD, PhD, is a physician in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. Her clinical and research interests include neurorehabilitation, stroke recovery, and community reintegration after neurological disorders. She is actively involved in clinical practice and interdisciplinary rehabilitation research.

Tetsuya Tsuji, MD, PhD, is a Professor in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. He is a leading expert in cancer rehabilitation and neurological rehabilitation in Japan. His clinical and research interests include functional recovery after stroke, rehabilitation oncology, and evidence-based rehabilitation medicine.

Michiyuki Kawakami, MD, PhD, is an Associate Professor in the Department of Rehabilitation Medicine at Keio University School of Medicine, Tokyo, Japan. His research focuses on neurorehabilitation, the digital transformation of rehabilitation medicine, and technology-driven interventions for neurological disorders. He leads collaborative projects integrating clinical rehabilitation with engineering innovation.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

References

Agrawal, N., Johnston, S. C., Wu, Y. W., Sidney, S., & Fullerton, H. J. (2009). Imaging data reveal a higher pediatric stroke incidence than prior US estimates. *Stroke*, *40*(11), 3415–3421. https://doi.org/10.1161/strokeaha.109.564633

Beretta, E., Romei, M., Molteni, E., Avantaggiato, P., & Strazzer, S. (2015). Combined robotic-aided gait training and physical therapy improve functional abilities and hip kinematics during gait in children and adolescents with acquired brain injury. *Brain Injury*, *29*(7–8), 955–962. https://doi.org/10.3109/02699052.2015.1005130

Beretta, E., Storm, F. A., Strazzer, S., Frascarelli, F., Petrarca, M., Colazza, A., Cordone, G., Biffi, E., Morganti, R., Maghini, C., Piccinini, L., Reni, G., & Castelli, E. (2020). Effect of robot-assisted gait training in a large population of children with motor impairment due to cerebral palsy or acquired brain injury. *Archives of Physical Medicine and Rehabilitation*, *101*(1), 106–112. https://doi.org/10.1016/j.apmr.2019.08.479

Bleyenheuft, C., Bleyenheuft, Y., Hanson, P., & Deltombe, T. (2010). Treatment of genu recurvatum in hemiparetic adult patients: A systematic literature review. *Annals of Physical and Rehabilitation Medicine*, *53*(3), 189–199. https://doi.org/10.1016/j.rehab.2010.01.001

Calabrò, R. S., Sorrentino, G., Cassio, A., Mazzoli, D., Andrenelli, E., Bizzarini, E., Campanini, I., Carmignano, S. M., Cerulli, S., Chisari, C., Colombo, V., Dalise, S., Fundarò, C., Gazzotti, V., Mazzoleni, D., Mazzucchelli, M., Melegari, C., Merlo, A., Stampacchia, G., … Italian Consensus Conference on Robotics in Neurorehabilitation (CICERONE). (2021). Robotic-assisted gait rehabilitation following stroke: A systematic review of current guidelines and practical clinical recommendations. *European Journal of Physical and Rehabilitation Medicine*, *57*(3), 460–471. https://doi.org/10.23736/s1973-9087.21.06887-8

Chang, W. H., & Kim, Y. H. (2013). Robot-assisted therapy in stroke rehabilitation. *Journal of Stroke*, *15*(3), 174–181. https://doi.org/10.5853/jos.2013.15.3.174

Chen, S., Zhang, W., Wang, D., & Chen, Z. (2024). How robot-assisted gait training affects gait ability, balance and kinematic parameters after stroke: A systematic review and meta-analysis. *European Journal of Physical and Rehabilitation Medicine*, *60*(3), 400–411. https://doi.org/10.23736/s1973-9087.24.08354-0

Collen, F. M., Wade, D. T., & Bradshaw, C. M. (1990). Mobility after stroke: Reliability of measures of impairment and disability. *International Disability Studies*, *12*(1), 6–9. https://doi.org/10.3109/03790799009166594

Cooper, A., Alghamdi, G. A., Alghamdi, M. A., Altowaijri, A., & Richardson, S. (2012). The relationship of lower limb muscle strength and knee joint hyperextension during the stance phase of gait in hemiparetic stroke patients. *Physiotherapy Research International*, *17*(3), 150–156. https://doi.org/10.1002/pri.528

Daly, J. J., Nethery, J., McCabe, J. P., Brenner, I., Rogers, J., Gansen, J., Butler, K., Burdsall, R., Roenigk, K., & Holcomb, J. (2009). Development and testing of the Gait Assessment and Intervention Tool (G.A.I.T.): A measure of coordinated gait components. *Journal of Neuroscience Methods*, *178*(2), 334–339. https://doi.org/10.1016/j.jneumeth.2008.12.016

De Luca, A., Vernetti, H., Capra, C., Pisu, I., Cassiano, C., Barone, L., Gaito, F., Danese, F., Antonio Checchia, G., Lentino, C., Giannoni, P., & Casadio, M. (2019). Recovery and compensation after robotic assisted gait training in chronic stroke survivors. *Disability and Rehabilitation. Assistive Technology*, *14*(8), 826–838. https://doi.org/10.1080/17483107.2018.1466926

De Quervain, I. A., Simon, S. R., Leurgans, S., Pease, W. S., & McAllister, D. (1996). Gait pattern in the early recovery period after stroke. *Journal of Bone and Joint Surgery*, *78*(10), 1506–1514. https://doi.org/10.2106/00004623-199610000-00008

deVeber, G. A., MacGregor, D., Curtis, R., & Mayank, S. (2000). Neurologic outcome in survivors of childhood arterial ischemic stroke and sinovenous thrombosis. *Journal of Child Neurology*, *15*(5), 316–324. https://doi.org/10.1177/088307380001500508

Drużbicki, M., Rusek, W., Snela, S., Dudek, J., Szczepanik, M., Zak, E., Durmala, J., Czernuszenko, A., Bonikowski, M., & Sobota, G. (2013). Functional effects of robotic-assisted locomotor treadmill therapy in children with cerebral palsy. *Journal of Rehabilitation Medicine*, *45*(4), 358–363. https://doi.org/10.2340/16501977-1114

Elnaggar, R. K., Alhowimel, A., Alotaibi, M., Abdrabo, M. S., & Elshafey, M. A. (2022). Accommodating variable-resistance exercise enhance weight-bearing/gait symmetry and balance capability in children with hemiparetic cerebral palsy: A parallel-group, single-blinded randomized clinical trial. *European Journal of Physical and Rehabilitation Medicine*, *58*(3), 378–386. https://doi.org/10.23736/S1973-9087.21.07324-X

Geiger, R., Strasak, A., Treml, B., Gasser, K., Kleinsasser, A., Fischer, V., Geiger, H., Loeckinger, A., & Stein, J. I. (2007). Six-minute walk test in children and adolescents. *Journal of Pediatrics*, *150*(4), 395–399, 399.e1-2. https://doi.org/10.1016/j.jpeds.2006.12.052

Gouwanda, D., & Senanayake, S. M. (2011). Identifying gait asymmetry using gyroscopes – A cross-correlation and Normalized Symmetry Index approach. *Journal of Biomechanics*, *44*(5), 972–978. https://doi.org/10.1016/j.jbiomech.2010.12.013

Hausdorff, J. M., Zemany, L., Peng, C., & Goldberger, A. L. (1999). Maturation of gait dynamics: Stride-to-stride variability and its temporal organization in children. *Journal of Applied Physiology*, *86*(3), 1040–1047. https://doi.org/10.1152/jappl.1999.86.3.1040

Hill, N. M., Malone, L. A., & Sun, L. R. (2023). Stroke in the developing brain: Neurophysiologic implications of stroke timing, location, and comorbid factors. *Pediatric Neurology*, *148*, 37–43. https://doi.org/10.1016/j.pediatrneurol.2023.08.008

Hornby, T. G., Campbell, D. D., Kahn, J. H., Demott, T., Moore, J. L., & Roth, H. R. (2008). Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: A randomized controlled study. *Stroke*, *39*(6), 1786–1792. https://doi.org/10.1161/strokeaha.107.504779

Jang, S. H. (2010). The recovery of walking in stroke patients: A review. *International Journal of Rehabilitation Research*, *33*(4), 285–289. https://doi.org/10.1097/MRR.0b013e32833f0500

Kamimoto, T., Hosoi, Y., Tanamachi, K., Yamamoto, R., Yamada, Y., Teramae, T., Noda, T., Kaneko, F., Tsuji, T., & Kawakami, M. (2023). Combined ankle robot training and robot-assisted gait training improved the gait pattern of a patient with chronic traumatic brain injury. *Progress in Rehabilitation Medicine*, *8*, 20230024. https://doi.org/10.2490/prm.20230024

Kang, C. J., Chun, M. H., Lee, J., & Lee, J. Y. (2021). Effects of robot (SUBAR)-assisted gait training in patients with chronic stroke: Randomized controlled trial. *Medicine*, *100*(48), e27974. https://doi.org/10.1097/md.0000000000027974

Kirton, A., & deVeber, G. (2015). Paediatric stroke: Pressing issues and promising directions. *Lancet. Neurology*, *14*(1), 92–102. https://doi.org/10.1016/s1474-4422(14)70227-3

Klassen, T. D., Dukelow, S. P., Bayley, M. T., Benavente, O., Hill, M. D., Krassioukov, A., Liu-Ambrose, T., Pooyania, S., Poulin, M. J., Schneeberg, A., Yao, J., & Eng, J. J. (2020). Higher doses improve walking recovery during stroke inpatient rehabilitation. *Stroke*, *51*(9), 2639–2648. https://doi.org/10.1161/STROKEAHA.120.029245

Knutsson, E., & Richards, C. (1979). Different types of disturbed motor control in gait of hemiparetic patients. *Brain*, *102*(2), 405–430. https://doi.org/10.1093/brain/102.2.405

Laugesaar, R., Kolk, A., Uustalu, U., Ilves, P., Tomberg, T., Talvik, I., Köbas, K., Sander, V., & Talvik, T. (2010). Epidemiology of childhood stroke in Estonia. *Pediatric Neurology*, *42*(2), 93–100. https://doi.org/10.1016/j.pediatrneurol.2009.08.009

Lewek, M. D., Cruz, T. H., Moore, J. L., Roth, H. R., Dhaher, Y. Y., & Hornby, T. G. (2009). Allowing intralimb kinematic variability during locomotor training poststroke improves kinematic consistency: A subgroup analysis from a randomized clinical trial. *Physical Therapy*, *89*(8), 829–839. https://doi.org/10.2522/ptj.20080180

Malone, L. A., & Felling, R. J. (2020). Pediatric stroke: Unique implications of the immature brain on injury and recovery. *Pediatric Neurology*, *102*, 3–9. https://doi.org/10.1016/j.pediatrneurol.2019.06.016

Mao, Y., Lo, W. L., Xu, G., Li, L. S., Li, L., & Huang, D. (2015). Reduced knee hyperextension after wearing a robotic knee orthosis during gait training – A case study. *Bio-Medical Materials and Engineering*, *26*(Suppl. 1), S381–S388. https://doi.org/10.3233/bme-151326

Mehrholz, J., Thomas, S., & Elsner, B. (2017). Treadmill training and body weight support for walking after stroke. *Cochrane Database of Systematic Reviews*, *8*(8), CD002840. https://doi.org/10.1002/14651858.CD002840.pub4

Mehrholz, J., Thomas, S., Kugler, J., Pohl, M., & Elsner, B. (2020). Electromechanical-assisted training for walking after stroke. *Cochrane Database of Systematic Reviews*, *10*(10), CD006185. https://doi.org/10.1002/14651858.CD006185.pub5

Meyer-Heim, A., Ammann-Reiffer, C., Schmartz, A., Schäfer, J., Sennhauser, F. H., Heinen, F., Knecht, B., Dabrowski, E., & Borggraefe, I. (2009). Improvement of walking abilities after robotic-assisted locomotion training in children with cerebral palsy. *Archives of Disease in Childhood*, *94*(8), 615–620. https://doi.org/10.1136/adc.2008.145458

Mulroy, S., Gronley, J., Weiss, W., Newsam, C., & Perry, J. (2003). Use of cluster analysis for gait pattern classification of patients in the early and late recovery phases following stroke. *Gait & Posture*, *18*(1), 114–125. https://doi.org/10.1016/s0966-6362(02)00165-0

Nedergård, H., Arumugam, A., Sandlund, M., Bråndal, A., & Häger, C. K. (2021). Effect of robotic-assisted gait training on objective biomechanical measures of gait in persons post-stroke: A systematic review and meta-analysis. *Journal of Neuroengineering and Rehabilitation*, *18*(1), 64. https://doi.org/10.1186/s12984-021-00857-9

Noda, T., Takai, A., Teramae, T., Hirookai, E., Hase, K., & Morimoto, J. (2018). Robotizing double-bar ankle-foot orthosis. In *Proceedings of the 2018 IEEE international conference on robotics and automation (ICRA)* (pp. 2782–2787). IEEE. https://doi.org/10.1109/ICRA.2018.8462911

Park, I. J., Park, J. H., Seong, H. Y., You, J. S. H., Kim, S. J., Min, J. H., Ko, H. Y., & Shin, Y. I. (2019). Comparative effects of different assistance force during robot-assisted gait training on locomotor functions in patients with subacute stroke: An assessor-blind, randomized controlled trial. *American Journal of Physical Medicine & Rehabilitation*, *98*(1), 58–64. https://doi.org/10.1097/phm.0000000000001027

Patterson, K. K., Gage, W. H., Brooks, D., Black, S. E., & McIlroy, W. E. (2010). Evaluation of gait symmetry after stroke: A comparison of current methods and recommendations for standardization. *Gait & Posture*, *31*(2), 241–246. https://doi.org/10.1016/j.gaitpost.2009.10.014

Prosser, L. A., Atkinson, H. L., Alfano, J. M., Leff, M., Kessler, S. K., Gouelle, A., & Ichord, R. B. (2022). Normalizing step-to-step variability to age in children and adolescents with hemiplegia. *Gait & Posture*, *98*, 6–8. https://doi.org/10.1016/j.gaitpost.2022.08.009

Prosser, L. A., Lauer, R. T., VanSant, A. F., Barbe, M. F., & Lee, S. C. (2010). Variability and symmetry of gait in early walkers with and without bilateral cerebral palsy. *Gait & Posture*, *31*(4), 522–526. https://doi.org/10.1016/j.gaitpost.2010.03.001

Riley, D. S., Barber, M. S., Kienle, G. S., Aronson, J. K., von Schoen-Angerer, T., Tugwell, P., Kiene, H., Helfand, M., Altman, D. G., Sox, H., Werthmann, P. G., Moher, D., Rison, R. A., Shamseer, L., Koch, C. A., Sun, G. H., Hanaway, P., Sudak, N. L., Kaszkin-Bettag, M., Carpenter, J. E., & Gagnier, J. J. (2017). CARE guidelines for case reports: Explanation and elaboration document. *Journal of Clinical Epidemiology*, *89*, 218–235. https://doi.org/10.1016/j.jclinepi.2017.04.026

Srivastava, S., Kao, P. C., Reisman, D. S., Scholz, J. P., Agrawal, S. K., & Higginson, J. S. (2016). Robotic assist-as-needed as an alternative to therapist-assisted gait rehabilitation. *International Journal of Physical Medicine & Rehabilitation*, *4*(5), 370. https://doi.org/10.4172/2329-9096.1000370

Takahashi, Y., Okada, K., Noda, T., Teramae, T., Nakamura, T., Haruyama, K., Okuyama, K., Tsujimoto, K., Mizuno, K., Morimoto, J., & Kawakami, M. (2023). Robotized knee–ankle–foot orthosis-assisted gait training on genu recurvatum during gait in patients with chronic stroke: A feasibility study and case report. *Journal of Clinical Medicine*, *12*(2), 415. https://doi.org/10.3390/jcm12020415

Tilson, J. K., Sullivan, K. J., Cen, S. Y., Rose, D. K., Koradia, C. H., Azen, S. P., Duncan, P. W., & Locomotor Experience Applied Post Stroke (LEAPS) Investigative Team. (2010). Meaningful gait speed improvement during the first 60 days poststroke: Minimal clinically important difference. *Physical Therapy*, *90*(2), 196–208. https://doi.org/10.2522/ptj.20090079

Volpini, M., Aquino, M., Holanda, A. C., Emygdio, E., & Polese, J. (2022). Clinical effects of assisted robotic gait training in walking distance, speed, and functionality are maintained over the long term in individuals with cerebral palsy: A systematic review and meta-analysis. *Disability and Rehabilitation*, *44*(19), 5418–5428. https://doi.org/10.1080/09638288.2021.1942242