Gait & Posture 98 (2022) 343–354

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effectiveness of robotic exoskeletons for improving gait in children with cerebral palsy: A systematic review

Markus Hunt[a,1], Laure Everaert[b,c,*,1], Mathew Brown[a], Luiza Muraru[d], Eleni Hatzidimitriadou[e,*], Kaat Desloovere[b,c]

[a] Section of Sport, Exercise and Rehabilitation Science, School of Psychology and Life Sciences, Canterbury Christ Church University, North Holmes Road Campus, Canterbury, Kent CT1 1QU, UK
[b] Clinical Motion Analysis Laboratory, University Hospital Leuven, Weligerveld 1, 3212 Pellenberg, Belgium
[c] Department of Rehabilitation Sciences, Research Group for Neurorehabilitation (eNRGy), KU Leuven, Tervuursevest 101, 3001 Leuven, Belgium
[d] Mobilab & Care, Thomas More University of Applied Sciences, Kleinhoefstraat 4, Geel, Belgium
[e] Faculty of Medicine, Health and Social Care, Canterbury Christ Church University, North Holmes Road Campus, Canterbury, Kent CT1 1QU, UK

ARTICLE INFO

Keywords:
Robotic exoskeletons
Gait
Cerebral palsy
Assistive devices
Powered orthosis
Biomechanics

ABSTRACT

Background: Robotic exoskeletons have been developed to assist locomotion and address gait abnormalities in children with cerebral palsy (CP). These wearable assistive devices provide powered assistance to the lower-extremity joints, as well as support and stability.
Research Question: Does exoskeleton-assisted walking improve gait in children with CP?
Methods: The PRISMA guidelines were used to conduct this systematic review. Articles were obtained in a search of the following electronic databases: Embase, CINAHL Complete, PubMed, Web of Science and MEDLINE. Studies investigating spatiotemporal, kinematic, kinetic, muscle activity and/or physiological parameters during exoskeleton-assisted walking in children with CP were included. All articles were assessed for methodological quality using an adapted version of the Quality Assessment Tool for Before-After (Pre-Post) Studies with No Control Group, provided by the National Institutes of Health (NIH).
Results: Thirteen studies were included. They involved the use of the following exoskeletons: tethered knee exoskeleton, pediatric knee exoskeleton (P.REX), untethered ankle exoskeleton, WAKE-Up ankle module, WAKE-Up ankle & knee module and unilateral ankle exosuit. Methodological quality varied, with key limitations in sample size and allocated time to adapt to the exoskeleton. There was a consensus that robotic exoskeletons improve gait given careful optimisation of exoskeleton torque and sufficient exoskeleton practice time for each participant. Improvements in gait included reduced metabolic cost of walking, increased walking speed, and increased knee and hip extension during stance. Furthermore, exoskeletons with an actuated ankle module were shown to promote normal ankle rocker function.
Significance: Robotic exoskeletons have the potential to improve the mobility of CP children and may therefore increase community participation and improve quality of life. Future work should involve larger controlled intervention studies utilising robotic exoskeletons to improve gait in children with CP. These studies should ensure sufficient exoskeleton practice time for each participant.

1. Introduction

Cerebral palsy (CP) is the most common physical disability affecting children, with a prevalence rate of approximately 2–3/1000 live births [1–3]. The condition describes a ‘group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain’ [4]. These motor disorders commonly result in a delayed onset of walking and pathological gait patterns [5]. Improving the pathological gait is an important treatment goal because

---

* Corresponding authors.
E-mail addresses: markus.hunt2@canterbury.ac.uk (M. Hunt), laure.everaert@kuleuven.be (L. Everaert), mathew.brown@canterbury.ac.uk (M. Brown), luiza.muraru@thomasmore.be (L. Muraru), eleni.hatzidimitriadou@canterbury.ac.uk (E. Hatzidimitriadou), kaat.desloovere@uzleuven.be (K. Desloovere).
[1] Co-first author

https://doi.org/10.1016/j.gaitpost.2022.09.082
Received 16 September 2021; Received in revised form 12 July 2022; Accepted 19 September 2022

it is positively associated with functional independence and community participation [6–8].

Lower extremity orthoses, such as ankle-foot orthoses (AFOs), are often prescribed to children with CP to prevent contractures and address gait abnormalities [9–11], by providing stability and controlling abnormal joint alignment [12]. Studies have found that AFOs induce positive effects on gait kinematics, energy cost of walking, walking speed and stride length [10,11]. Conversely, long-term AFO use may cause further weakness in the restricted muscles [13,14]. In addition, rigid orthoses, such as solid AFOs, limit the ankle range of motion (ROM), preventing normal ankle rocker function, inhibiting the ankle in aiding propulsion during push-off [10].

To address the inherent limitations of passive devices, robotic exoskeletons are being developed. These devices assist the voluntary control of movement at the ankle, knee and/or hip, as well as providing support and stability to the joints. The assistance provided by robotic exoskeletons has been demonstrated to support normal ankle rocker function, reduce the energy cost of walking and improve walking ability [15–17]. However, robotic exoskeletons are often bulkier and heavier than passive designs, which can be metabolically detrimental [18,19].

Previous systematic reviews evaluating the effectiveness of robotic exoskeletons to improve gait in children with CP have predominately focused on studies which involve robotic-assisted gait training (RAGT) [20–23]. Devices developed for RAGT enhance gait rehabilitation by assisting stepping cycles, frequently providing body weight support and robotic assistance in one or several lower limb joints [24]. Most RAGT devices are stationary in combination with a treadmill. Studies utilising RAGT measured gait outcome parameters pre- and post-RAGT intervention and not the direct effect of the exoskeleton on gait. To complement previous literature reviews, this review focused on studies which used robotic exoskeletons designed for locomotion. The studies included in this review compared participants who walked with a robotic exoskeleton to a baseline walking condition (i.e., the participant's everyday walking condition: walking with shoes only, or shoes in combination with their AFOs). Studies that compared the effects of different magnitudes of exoskeleton torque on gait were also included in this review.

The primary aim of this review was to systematically review the literature investigating spatiotemporal, kinematic, kinetic, muscle activity and physiological parameters during exoskeleton-assisted walking in children with CP.

2. Method

2.1. Search strategy

This systematic review was conducted by two researchers (MH and LE), following the guidelines in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [25]. The following search terms were used in all databases: (1) cerebral palsy OR spastic diplegia OR spastic hemiplegia, (2) gait OR locomotion OR walking, (3) exoskeleton OR active orthoses OR powered orthoses OR robotic orthoses NOT arm exoskeleton. These search terms were combined: '(1) AND (2) AND (3)'.

2.2. Information sources

Journal articles were retrieved from searches of the following databases: Embase, CINAHL Complete, PubMed, Web of Science and MEDLINE. In addition, references of relevant articles were screened to ensure that articles overlooked by the electronic search were included. The literature search was originally performed on the 15th of May 2020 and updated on the fourth of July 2022.

2.3. Study selection

After removing duplicate studies, the two reviewers (M.H. & L.E.) independently screened journal articles based on the titles and abstracts. The second selection involved reading the full articles. Disagreements pertaining to the selection of articles were discussed between the reviewers.

The eligibility of the articles was evaluated based on the following inclusion criteria: (1) peer-reviewed experimental trials, (2) published between 2010 and 2022, (3) studies focusing on the effectiveness of robotic exoskeletons for improving gait in children with CP (ages 2–18 years), (4) gait assessment and/or metabolic cost assessment during walking, (5) treadmill or overground walking. The search was limited to 2010–2022 to ensure that only robotic exoskeletons with the latest technology were included. Exclusion criteria were (1) robotic exoskeleton walking in combination with other interventions (2) no gait assessments or metabolic assessments whilst the participant was wearing the robotic exoskeleton.

2.4. Data collection process

Both reviewers independently extracted the following information from the included studies: (1) author name(s), (2) publication year, (3) brand of exoskeleton used, (4) torque produced by the exoskeleton during stance (ST) and/or swing (SW) phase of gait, (5) intervention description, (6) sample size, (7) patient characteristics, and (8) evaluated parameter(s) with results. Disagreements pertaining to the data abstraction were discussed between the reviewers.

2.5. Study quality assessment

The quality of the studies was assessed with an adapted version of the Quality Assessment Tool for Before-After (Pre-Post) Studies with No Control Group from the National Institutes of Health (NIH) [26]. Due to the nature of the reviewed studies, some questions were removed from the quality assessment tool e.g., concealing treatment groups was not possible. Furthermore, a question regarding multiple outcome measures was removed. It was agreed that requiring participants to complete gait and/or metabolic cost assessments multiple times before the intervention (i.e., before exoskeleton familiarisation period) and multiple times after the intervention would not be feasible. This question was replaced with a question regarding condition order randomisation. The adapted quality assessment tool consisted of a list of 11 criteria questions. Reviewers selected "yes", "no", or "cannot determine/not reported/not applicable" for each criterion. When "no", "cannot determine" or "not reported" was selected, the reviewers considered the potential risk of bias.

3. Results

3.1. Search strategy yield

The first database search was completed in May 2020 and updated in July 2022. A total of 195 unique articles were retrieved from the database search, of which 68 articles were included based on their titles and abstracts. Thirteen studies were included after reviewing the full texts. The process for the study selection is presented in a flow diagram based on PRISMA (Fig. 1) [25].

3.2. Methodological quality

Table 1 displays the results of the methodological quality assessment following an adapted version of the Quality Assessment Tool for Before-After (Pre-Post) Studies with No Control Group from NIH [26]. The methodological quality of the thirteen studies assessed had a mean score of 73.84 ± 16.00%. The reviewers considered the potential risk for bias

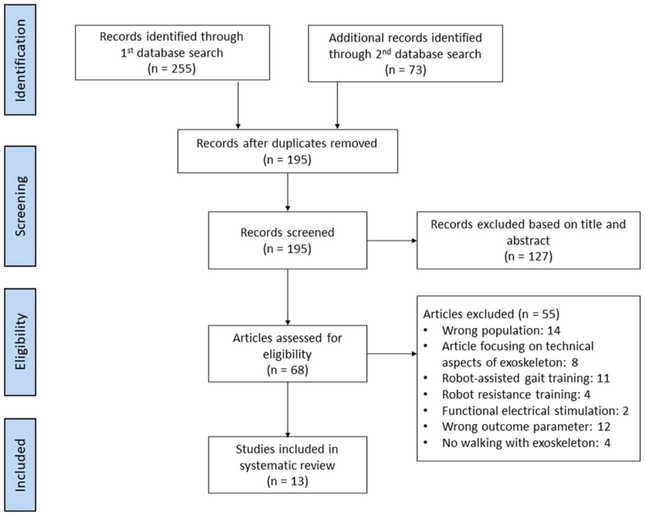


Fig. 1. PRISMA flow diagram of the systematic review.

in each instance where studies did not meet the Quality Assessment Tool requirements. This informed the reviewer’s decision for the overall quality of each study. Studies were given an overall quality rating of (*n* = 3) good [27–29], (*n* = 5) fair [16,30–33] or (*n* = 5) poor [13,15,34–36].

All studies met the following criteria: (1) clearly defined study question or objective; (3) participants were representative of those who would be eligible for the intervention in the clinical population of interest; (4) all participants met the prespecified entry criteria enrolled; (10) a participant loss to follow up after baseline 20% or less; (11) where applicable, all studies considered the use of individual-level data to determine effects at the group level [15,16,27–36]. However, six studies did not fully describe the selection criteria for participants. Three studies did not state whether participants were diagnosed with unilateral or bilateral CP [16,31,34], and three studies did not state their Gross Motor Function Classification System (GMFCS) classification [15,35,36]. Furthermore, two studies [16,36] did not describe the participants’ pathological gait pattern at baseline. None of the studies provided sample size calculations, resulting in a ‘cannot determine’ score on the criteria regarding sufficient sample size [13,15,16,27–36]. Five studies did not clearly describe the intervention [15,30,31,35,36]. More specifically, the exoskeleton adaptation time was not specified [18], or the amount of torque assistance provided by the exoskeleton was not clearly stated [15,35,36]. Four studies did not state the distance, duration and/or number of gait cycles analysed during each trial [32,33,35,36]. Condition order was randomised in six studies to avoid carry-over and/or fatigue effects [16,27–29,31,32]. One study did not provide any significance level with a p-value for differences between conditions [34]. In this study, linear regression analysis was used to determine the relationship between the magnitude of assistive torque and outcome measures. Two studies only assessed statistical significance between conditions for some of the parameters tested [15,30].

3.3. Study characteristics

All included studies were published between 2016 and 2021. Ten studies were conducted in the USA by the same research group [13,16,27–34], two studies carried out in Italy by another research group [15,35] and one study was conducted in Finland [36]. The research group from the USA includes Lerner et al. [13,27,28,31,34], Orekhov et al. [16], Fang et al. [29] and Chen et al. [30], and the research group from

Table 1
Results of the methodological quality assessment following the Quality Assessment Tool for Before-After (Pre-Post) Studies with No Control Group from NIH.

	Lerner et al., 2016 [31]	Lerner et al., 2017 [13]	Lerner et al., 2017 [34]	Lerner et al., 2017 [32]	Lerner et al., 2017 [33]	Lerner et al., 2018 [27]	Lerner et al., 2019 [28]	Fang et al., 2020 [29]	Orekhov et al., 2020 [16]	Mileti et al., 2016 [15]	Patané et al., 2017[35]	Chen et al., 2021 [30]	Thurston et al., 2021 [36]
1. Study question clearly stated	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
2. Eligibility criteria clearly described	NO	YES	NO	YES	YES	YES	YES	YES	NO	NO	NO	YES	NO
3. Representative patient population	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
4. All participants met the prespecified entry criteria enrolled	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
5. Sample size sufficiently large	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD
6. Intervention clearly described and delivered consistently	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO
7. Outcome measures clearly defined, valid, reliable, and assessed consistently	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES	NO	YES	YES
8. Condition order randomised	YES	NA	NR	YES	NR	YES	YES	YES	YES	NR	NR	NA	NA
9. Loss to follow-up after baseline 20% or less	YES	YES	YES	YES	YES	YES	YES	YES	YES	NA	NA	NA	NA
10. Statistical tests done that provided p values for differences between conditions	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
11. Individual-level data used to determine effects at the group level	NA	NA	NA	YES	YES	YES	YES	YES	YES	YES	NA	NA	NA
Overall quality rating	**Fair**	**Poor**	**Poor**	**Fair**	**Fair**	**Good**	**Good**	**Good**	**Fair**	**Poor**	**Poor**	**Fair**	**Poor**

*CD = cannot determine; NA = not applicable; NR = not reported

Table 2
Summary of exoskeleton parameters.

Citation	Type of exoskeleton	ST assist torque (Nm/kg)	SW assist torque (Nm/kg)
Lerner et al., 2016[31]	Tethered knee exoskeleton	Constant torque: 0.19	Constant torque: 0.19
Lerner et al., 2017[13]	Tethered knee exoskeleton	Constant torque: 0.18	Constant torque: 0.13
Lerner et al., 2017[34]	Tethered knee exoskeleton	Average torque: Low torque condition 0.19 High torque condition 0.27	Average torque: Low torque condition 0.13 High torque condition 0.21
Lerner et al., 2017[32]	Tethered knee exoskeleton	Average torque: ST & SW condition 0.17 ST only condition 0.07	Average torque: ST & SW condition 0.06 SW only condition 0.07
Lerner et al., 2017[33]	Tethered knee exoskeleton	Constant torque: 0.19 (EST) 0.17 (LST)	Constant torque: 0.07
Lerner et al., 2018[27]	Untethered ankle exoskeleton	Peak torque: 0.26	–
Lerner et al., 2019[28]	Untethered ankle exoskeleton	Peak torque: 0.24	–
Fang et al., 2020[29]	Untethered ankle exoskeleton	Peak torque: 0.26	Peak torque: 0.03
Orekhov et al., 2020[16]	Untethered ankle exoskeleton	Average torque: Low torque condition 0.23 Training-tuned condition 0.26 High torque condition 0.30	1–2 Nm dorsiflexion assistance to participants with footdrop
Mileti et al., 2016[15]	WAKE-Up ankle module	NR	NR
Patané et al., 2017[35]	WAKE-Up ankle & knee module	NR	NR
Chen et al., 2021[30]	P.REX	Constant torque condition (EST+MST): 0.075 Adaptive condition: torque was set at 40% of knee estimated moment	Constant torque condition (LSW): 0.075 -
Thurston et al., 2021[36]	Unilateral ankle exosuit	NR	NR

Italy includes Patané et al. [35] and Mileti et al. [15]. The included studies involved the use of the following exoskeletons: tethered knee exoskeleton, pediatric knee exoskeleton (P.REX), untethered ankle exoskeleton, WAKE-Up ankle module, WAKE-Up ankle & knee module and unilateral ankle exosuit. Table 2 summarises the exoskeleton parameters.

Table 3 displays the participants' information. The studies involved a total of 30 participants ($n = 25$ patients with CP & $n = 5$ typically developing (TD) participants). Some participants were recruited for more than one of the included studies [13,15,16,27,28,31–35]. Table 3 highlights the studies that recruited from the same pool of participants with different levels of grayscale. The sample size for each type of exoskeleton was as follows: $n = 7$ tethered knee exoskeleton, $n = 7$ untethered ankle exoskeleton, $n = 7$ WAKE-Up ankle module, $n = 7$ WAKE-Up ankle & knee module, $n = 2$ P.REX and $n = 7$ unilateral ankle exosuit. Most participants were aged 5–16 years old, however three participants were outside of the target group for this review (aged 19 or above).

A summary of the study results is presented in Table 4. In instances where studies collected data during multiple sessions, the results from the final data collection session were reported, unless stated otherwise.

3.3.1. *Description of the exoskeletons*

Five studies involved the use of the tethered knee exoskeleton [13,31–34]. This exoskeleton had a passive ankle joint, an actuated knee joint and a custom moulded thermoplastic orthotic brace. The actuated knee joint provided knee extension assistance during ST and late SW. This exoskeleton was worn on both limbs, with a combined mass of 2.6–4.48 kg. The device mass varied because of differences in assembly sizes and designs.

One study utilised the P.REX [30]. This exoskeleton is a second prototype of the tethered knee exoskeleton [13,31–34]. This new prototype is an untethered device and has three different operational modes for providing assistance, i.e., (1) constant torque control, (2) impedance control and (3) adaptive control. In this study, constant knee extension torque was applied during early ST, mid ST and late SW. Moreover, the adaptive control mode provided assistive torque proportional to the estimated internal knee moment. The mass of the device was 5.8 kg.

The untethered ankle exoskeleton was reported in four studies [16,27–29]. This device provided adaptive plantar-flexor assistance during ST. Participants with a drop-foot gait pattern were also provided with dorsi-flexor assistance during late SW. Participants wore the untethered ankle exoskeleton bilaterally. The mass of the device, including the battery, ranged from 1.73 to 2.2 kg.

Two studies assessed the use of the WAKE-Up exoskeleton [15,35]. The WAKE-Up exoskeleton is an untethered device composed of a knee and ankle module, which can be used individually or simultaneously. Mileti et al. [15] investigated the individual use of the ankle module. Patané et al. [35] investigated the simultaneous use of the WAKE-Up ankle and knee module. The ROM of the actuated joints were mechanically limited to 45° for the ankle and 100° for the knee. Both studies were performed on the same participants who wore the WAKE-Up exoskeleton on their most affected limb only. The mass of the device was not reported, although the authors stated that the mass was limited to 2.5 kg.

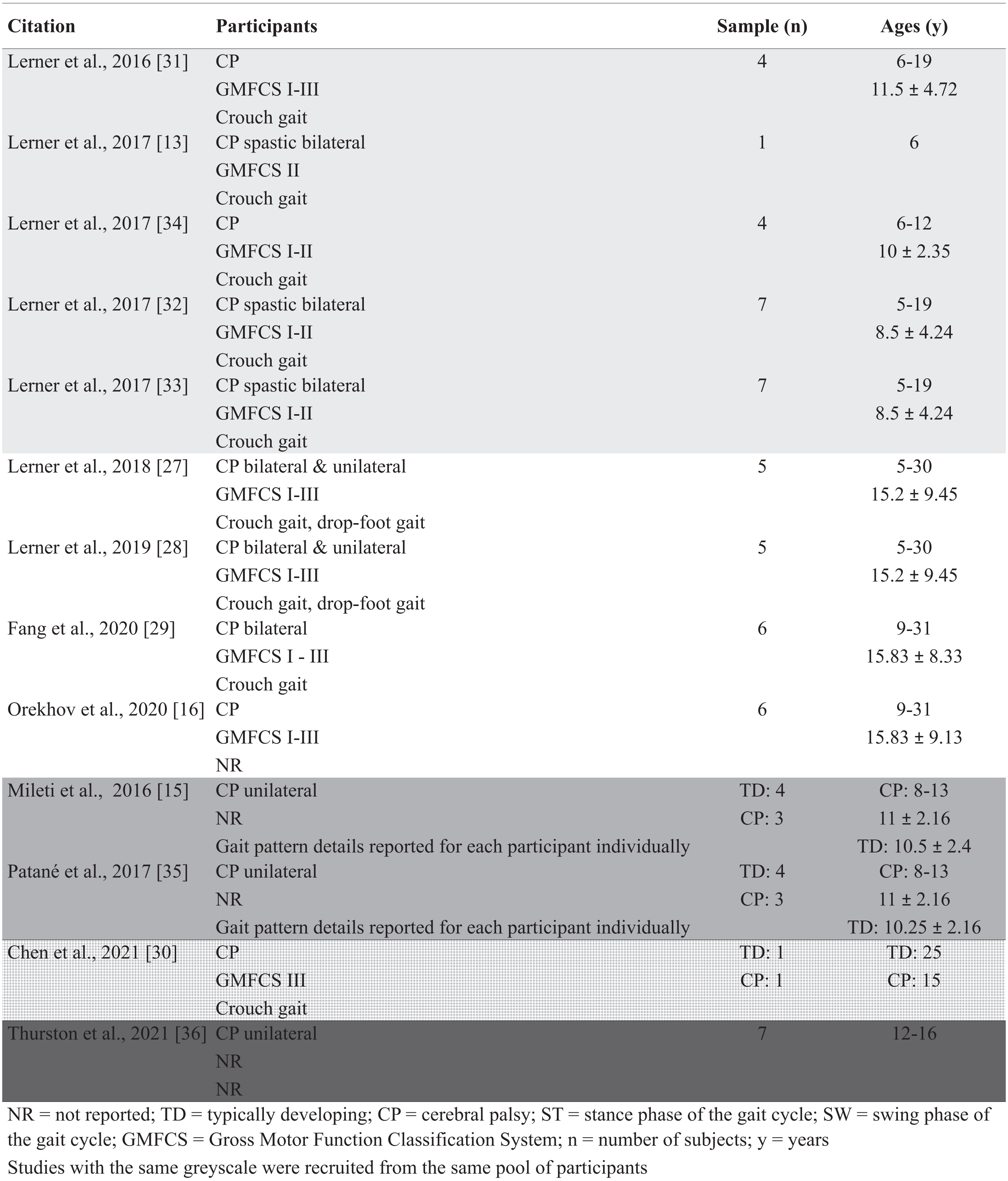
The unilateral ankle exosuit was tested in one study [36]. This device provided plantarflexion and dorsiflexion assistance at the participants affected ankle. The control strategy of the exosuit and total mass of the device was not specified. However, the exosuit motor weighed approximately 4 kg and was worn around the user's waist. It is important to note that some details of the device were missing because this study is only published as a short report.

3.3.2. *Effect on biomechanics*

3.3.2.1. Spatiotemporal parameters. Within the same research group, different results concerning how robotic exoskeleton assistance affect self-selected walking speed were reported [16,29,30,32]. Lerner et al. [32] found that after four practice sessions with the tethered knee exoskeleton, walking speed returned to baseline values (i.e., each participant's baseline walking condition). Chen et al. [30] recorded a significant decrease in walking speed with the P.REX constant torque mode in comparison to the zero torque condition, while walking speed did not significantly decrease during the adaptive mode condition. This is in contrast with the other two studies, which found that walking speed increased significantly ($p < 0.05$) with the untethered ankle exoskeleton in comparison to Shod or AFO walking [16,29]. Yet, Orekhov et al. [16] only observed an increase ($p = 0.018$) in walking speed in the high torque assistance condition (average torque: 0.3 Nm/kg), compared to Shod or AFO walking. No studies reported the effect of the WAKE-Up exoskeleton or the unilateral ankle exosuit on walking speed.

The effect of exoskeletons on walking cadence was investigated in five studies [13,15,29,32,33]. Lerner et al. reported inconsistent findings on the change in walking cadence with the tethered knee exoskeleton [13,32,33]. Fang et al. [29] found that walking cadence with the

Table 3
Summary of participant information.



Citation	Participants	Sample (n)	Ages (y)
Lerner et al., 2016 [31]	CP GMFCS I-III Crouch gait	4	6-19 11.5 ± 4.72
Lerner et al., 2017 [13]	CP spastic bilateral GMFCS II Crouch gait	1	6
Lerner et al., 2017 [34]	CP GMFCS I-II Crouch gait	4	6-12 10 ± 2.35
Lerner et al., 2017 [32]	CP spastic bilateral GMFCS I-II Crouch gait	7	5-19 8.5 ± 4.24
Lerner et al., 2017 [33]	CP spastic bilateral GMFCS I-II Crouch gait	7	5-19 8.5 ± 4.24
Lerner et al., 2018 [27]	CP bilateral & unilateral GMFCS I-III Crouch gait, drop-foot gait	5	5-30 15.2 ± 9.45
Lerner et al., 2019 [28]	CP bilateral & unilateral GMFCS I-III Crouch gait, drop-foot gait	5	5-30 15.2 ± 9.45
Fang et al., 2020 [29]	CP bilateral GMFCS I - III Crouch gait	6	9-31 15.83 ± 8.33
Orekhov et al., 2020 [16]	CP GMFCS I-III NR	6	9-31 15.83 ± 9.13
Mileti et al., 2016 [15]	CP unilateral NR Gait pattern details reported for each participant individually	TD: 4 CP: 3	CP: 8-13 11 ± 2.16 TD: 10.5 ± 2.4
Patané et al., 2017 [35]	CP unilateral NR Gait pattern details reported for each participant individually	TD: 4 CP: 3	CP: 8-13 11 ± 2.16 TD: 10.25 ± 2.16
Chen et al., 2021 [30]	CP GMFCS III Crouch gait	TD: 1 CP: 1	TD: 25 CP: 15
Thurston et al., 2021 [36]	CP unilateral NR NR	7	12-16

NR = not reported; TD = typically developing; CP = cerebral palsy; ST = stance phase of the gait cycle; SW = swing phase of the gait cycle; GMFCS = Gross Motor Function Classification System; n = number of subjects; y = years

Studies with the same greyscale were recruited from the same pool of participants

NR = not reported; TD = typically developed; CP = cerebral palsy; ST = stance phase of the gait cycle; SW = swing phase of the gait cycle; GMFCS = Gross Motor Function Classification System; n = number of participants; y = years
Studies with the same greyscale were recruited from the same pool of participants

Table 4
Summary of study results.

Citation	Name of the exoskeleton	Conditions	Outcome measures	Results
Lerner et al., [31]	Tethered knee exoskeleton	1. Baseline (AFO or Shod) 2. Exo SW & ST assist 3. Exo SW assist	Kinematics	Comparison to baseline: ↑ Max knee extension with SW & ST assist, and ST assist
		4. Exo ST assist	EMG	↓ Vastus lateralis iEMG activity during ST with ST assist ↑ Hamstrings iEMG & peak activity during ST & SW for all exo conditions
Lerner et al., [13]	Tethered knee exoskeleton	1. Baseline (AFO or Shod) 2. Exo zero torque 3. Exo assist	Spatiotemporal	Baseline and exo assist comparisons: ↓Cadence (steps/min) $p < 0.05$, no difference in step length or width
			Kinematics	↑ Peak ankle dorsiflexion $p < 0.05$ ↓ Max knee flexion angle ST $p < 0.05$ ↑ Peak knee flexion angle ST $p < 0.05$ ↑ Knee ROM during ST $p < 0.05$ no significant differences at the hip
			EMG	↑ Rectus femoris activity during late ST ↑ Semitendinosus activity during late ST ↑ Peak semitendinosus linear envelop (post-hoc test $p < 0.01$)
Lerner et al., [32]	Tethered knee exoskeleton	1. Baseline (AFO or Shod) 2. Exo SW & ST assist 3. Exo SW assist 4. Exo ST assist	Spatiotemporal	Exo improvements with practice (first assessment and final assessment comparison): ↑ Step length by 33% ($p = 0.027$) ↑ Gait speed by 32% ($p = 0.028$)
		5. Exo assist off	Kinematics	Baseline and exo SW & ST assist comparison: ↑ Mean knee extension by 13.3° MAL ($p = 0.024$) & 5.8° LAL ($p = 0.039$) ↑ Knee extension at IC by 6.8° MAL ($p = 0.004$) ↑ Knee extension by 5.3° MAL ($p = 0.003$) between assessments with exo SW & ST assist
			EMG	Comparison to baseline: ↑ Semitendinosus during SW for MAL (51%; $p = 0.001$) with exo null ↑ Vasti during SW for MAL (46%; $p = 0.002$) with exo null ↑ Vasti activity by 61% during SW for MAL ($p = 0.048$) between assessments with exo SW & ST assist ↑ Semitendinosus activity during ST by 36% ($p = 0.027$) & during SW by 55% ($p = 0.016$) for the LAL between assessments with exo SW & ST assist
Lerner et al., [33]	Tethered knee exoskeleton	1. Baseline (AFO or Shod) 2. Exo zero torque 3. Exo assist	Spatiotemporal	Walking condition had no significant effect on: cadence ($p = 0.17$), step length ($p = 0.34$), or step width ($p = 0.20$)
			Kinematics	Baselines and exo assist comparison: ↑ Knee extension on average by 6° at IC ($p = 0.012$) ↑ Max knee extension during ST 12° ($p = 0.001$) ↑ Hip extension by 8° during mid ST ($p = 0.001$)
			Kinetics	Baseline and exo assist comparison: ↓ Mean knee extension moment during early ST by 0.14 Nm/kg (36%, $p < 0.01$) & during late ST by 0.25 Nm/kg(76%, $p < 0.001$) ↑ Knee moments during SW by 0.06 Nm/kg ($p = 0.005$) ↑ Mean knee power absorption of 0.21 W/kg (269%, $p < 0.001$) during SW shift of hip moment toward the flexor direction by 0.13 Nm/kg (123%, $p = 0.004$) during early ST and 0.22 Nm/kg (86%, $p = 0.001$) during late ST ↑ Hip power absorption by 0.15 W/kg (377%, $p = 0.001$) during early ST and during late ST 0.12 W/kg (84%, $p = 0.029$) ↑ Mean hip power generation by 0.13 W/kg (133%, $p = 0.005$) during late ST, and by 0.24 W/kg (141%, $p < 0.001$) during SW
			EMG	Baseline and exo assist comparison: ↑ Semitendinosus activity by a mean of 38% ($p = 0.019$) during early ST, by 62% ($p < 0.001$) during late ST, and by 58% ($p = 0.001$) during SW ↓ Vastus lateralis activity during late ST decreased by 24 % ($p = 0.024$) ↑ Rectus femoris activity during terminal stance/early swing (75–100% of the stance and 0–50% of swing) by 61% ($p = 0.009$) ↑ Medial gastrocnemius activity by 46% ($p = 0.004$) during early ST and by 27% ($p = 0.007$) during late ST
Lerner et al., [34]	Tethered knee exoskeleton	1. Exo zero torque 2. Exo assist (low torque)	Kinematics	↓ Crouch at IC & mid ST positively associated with ↑ exo torque
		3. Exo assist (high torque)	Kinetics	↓ Mean knee extensor moment during ST positively associated with ↑ exo torque
			EMG	Vastus lateralis & semitendinosus activity positively associated with ↑ exo torque
Lerner et al., [27]	Tethered ankle exoskeleton	1. Baseline (AFO or Shod) 2. Exo zero torque 3. Exo assist	Metabolic cost	Baseline and exo assist comparison: ↓ Net metabolic cost of transport (J/mkg) by 18.7 ± 4.8% ($p = 0.011$)
Lerner et al., [28]	Untethered ankle exoskeleton	1. Baseline (AFO or Shod)	Kinematics	Baseline and exo assist comparison:

(continued on next page)

Table 4 (*continued*)

Citation	Name of the exoskeleton	Conditions	Outcome measures	Results
		2. Exo zero torque 3. Exo assist		↑ Peak ankle plantar-flexion by 5° ± 12° ($p = 0.032$) ↑ Peak knee extension in mid ST by 5° ± 8° ($p = 0.037$) Peak hip extension was not significantly different ($p = 0.187$)
			Kinetics	↓ Mean ankle moment by 27.5 ± 8.7% ($p = 0.001$) ↑ Average total ankle power generation by 43.6 ± 7.4% ($p = 0.037$) ↑ Average total ankle power absorption by 17.5 ± 3.9% ($p = 0.024$) ↓ Average biological ankle power absorption by 30.3 ± 5.3% ($p = 0.004$) ↑ Hip flexor moments by 0.10 ± 0.04 Nm/kg ($p = 0.018$) ↓ Average hip power generation 29.2 ± 6.0% ($p = 0.009$) ↓ Net hip power by 63.2 ± 15.0% ($p = 0.009$)
			EMG	↓ Mean gastrocnemius activity during ST by an average of 26 ± 6% ($p = 0.004$)
Fang et al., [29]	Untethered ankle exoskeleton	1. Baseline (Shod) 2. Exo assist	Spatiotemporal	Baseline and exo assist comparison: ↑ Walking speed by 0.28 m/s ($p = 0.023$) ↑ Stride length increased by 0.15 m ($p = 0.002$)
			EMG	Soleus, vastus lateralis and semitendinosus activity similar across all conditions
Orekhov et al., [16]	Untethered ankle exoskeleton	1. Baseline (AFO or Shod) 2. Exo zero torque 3. Exo low torque assist (LA) 4. Exo training-tuned torque assist (TTA) 5. Exo high torque assist (HA)	Spatiotemporal	Comparison to baseline: ↑ Walking speed by 5.9 ± 2.5% ($p = 0.034$) with LA, by 3.9 ± 1.9% ($p = 0.050$) with TTA, by 6.9 ± 2.4% ($p = 0.018$) with HA
			EMG	↓ Speed-normalized soleus iEMG by 21.2 ± 2.8% ($p = 0.003$) for LA, by 22.0 ± 4.5% ($p = 0.002$) for TTA, by 25.0 ± 4% ($p < 0.001$) for HA
			Metabolic cost	↓ Net metabolic cost of transport 8.5 ± 4.0% ($p = 0.042$) for HA
Mileti et al., [15]	WAKE-Up ankle module	1. Baseline (without exo) 2. Exo assist (worn on right leg) 3. Comparison with TD	Spatiotemporal	Baseline and exo assist comparison: ↓ Cadence ↑ Step length
Patané et al., [35]	WAKE-Up ankle & knee module	1. Baseline (without exo) 2. Exo assist (worn on right leg) 3. Exo assist off (worn on right leg) 4. Comparison with TD	Kinematics	WAKE-Up negatively affected the knee kinematics, especially during SW Partial recovery of hip extension before toe-off Improved foot placement at heel strike and before toe-off
Chen et al., [30]	P.REX	1.Exo zero torque 2.Constant torque (early ST + mid ST + late ST) 3.Adaptive torque	Spatiotemporal	Comparision to exo zero torque condition: Constant torque condition – ↓ walking speed by 0.06 m/s, ↓ step length LAL by 0.06 m Adaptive condition - No significant changes in spatiotemporal parameters
			Kinematics	Constant torque condition – ↑ peak knee extension MAL by 6.0° Adaptive condition - ↑ peak knee extension MAL by 9.0°, ↑ peak knee extension LAL by 11.1°
			EMG	Minimal changes across all conditions for rectus femoris, hamstrings, vastus lateralis and gastrocnemius
Thurston et al., [36]	Unilateral ankle exosuit	1.Baseline (without exo)		Exo assist comparison to baseline:
		2.Exo assist	Kinematics	↑ dorsiflexion during SW and initial contact by 6.38° ($p = 0.010$) and 9.98° ($p = 0.001$), respectively.
			Kinetics	↑ peak plantar flexion moment at toe off 8.3% ($p = 0.012$)
			Metabolic cost	Non-significant reduction

Arrows: The up and down arrows in the results column specify the changes that were reported to be significantly increased or decreased, respectively.
Results = includes results from final data collection sessions only; Baseline = participant's everyday walking condition i.e., walking with shoes only (Shod) or if prescribed their AFOs (AFO)
Abbreviations: NR = not reported; TD = typically developing; ST = stance phase of the gait cycle; SW = swing phase of the gait cycle; IC = initial contact; iEMG = integrated electromyography; MAL = most affected limb; LAL = less affected limb; exo = exoskeleton

untethered ankle exoskeleton was similar to walking with Shod or AFOs. Mileti et al. [15] observed a significant ($p < 0.05$) decrease in cadence with the WAKE-Up ankle module in comparison to walking without the exoskeleton in two out of three participants.

In addition, six studies reported the effects of robotic exoskeletons on stride length and/or step length [13,15,29,30,32,33]. Following training with the tethered knee exoskeleton, no significant differences in step length were observed between conditions [13,33]. Chen et al. [30] reported a significant decrease in step length for the less affected limb with the P.REX in the constant torque condition only. A study with the untethered ankle exoskeleton reported a significant increase ($p = 0.002$) in stride length in comparison to Shod walking [29]. Mileti et al. [15] reported a significant increase ($p < 0.05$) in both stride and step length with the WAKE-Up ankle module in comparison to Shod or AFO walking for two out of three participants.

One study calculated gait asymmetry and stride-to-stride variability using gait phase percentages and spatio-temporal parameters [15]. This study found that stride-to-stride variability decreased both for gait phase percentages as well as for spatio-temporal parameters during walking with the WAKE-Up ankle module in comparison to walking without the exoskeleton.

3.3.2.2. Kinematics. Six studies investigated ankle kinematics during robotic exoskeleton walking [13,28,33,35,36]. Studies involving the use of the tethered knee exoskeleton reported significant ($p < 0.05$) increases in peak ankle dorsiflexion for some of their participants [13,33]. An increase in peak ankle plantar flexion ($p = 0.032$) with the untethered ankle exoskeleton was reported in comparison to Shod or AFO walking [28]. A significant increase in dorsiflexion was reported during SW and initial contact with the unilateral ankle exosuit [36]. In addition, walking with the WAKE-Up ankle and knee module significantly ($p < 0.05$) increased ankle dorsiflexion at heel strike for two participants, resulting in a corrected foot placement [35]. Similarly, Mileti et al. [15] found that the WAKE-Up ankle module allowed participants to walk with a heel strike, avoiding landing with a flat foot.

Five studies of Lerner et al. investigated knee kinematics during tethered knee exoskeleton walking [13,31–34]. These studies demonstrated the following significant ($p < 0.05$) changes in knee kinematics: increased knee extension [13,31–34], increased knee ROM during ST [13] and a reduction in knee flexion during ST [13]. Significant increases in knee extension were also observed with the P.REX during the assistive modes [30]. Similarly, walking with the untethered ankle exoskeleton resulted in significant ($p = 0.037$) increases in peak knee extension during mid ST in comparison to Shod or AFO walking [28]. In contrast, the WAKE-Up ankle and knee module appeared to worsen the knee joint kinematics (i.e., deviating further from the gait of TD children) for all participants, especially during SW, resulting in significant ($p < 0.05$) increases in knee flexion during ST, decreases in knee ($p < 0.05$) flexion during mid SW and decreases ($p < 0.05$) in knee extension during terminal SW [35].

Finally, four studies of Lerner et al. investigated the effects of robotic exoskeleton walking on hip kinematics [13,28,33,35]. One study showed that walking with the tethered knee exoskeleton significantly ($p = 0.001$) increased hip extension during mid ST in comparison to Shod or AFO walking [33], while another study reported non-significant findings in hip kinematics during tethered knee exoskeleton walking [13]. A study with the untethered ankle exoskeleton reported no significant differences between conditions in hip kinematics [28]. Patané et al. [35] found that with the WAKE-Up ankle and knee module, hip extension increased ($p < 0.05$) during terminal ST for one participant and another participant exhibited a significant increase ($p < 0.05$) in hip extension during toe-off.

3.3.2.3. Kinetics. Three studies assessed ankle joint kinetics during robotic exoskeleton walking [28,33,36]. No significant differences were reported when comparing tethered knee exoskeleton walking to Shod or AFO walking [33]. In contrast, the untethered ankle exoskeleton induced the following beneficial effects: a significant increase ($p = 0.037$) in average total ankle power generation and a reduction ($p = 0.004$) in average biological ankle power absorption [28]. Biological power and moment were calculated by subtracting the contribution from the ankle exoskeleton from the total (biological + exoskeleton) joint moment and power. Thurston et al. reported a significant increase ($p = 0.012$) in peak plantar flexion moment during walking with the unilateral ankle exosuit [36]. Studies involving the WAKE-Up exoskeleton did not investigate the effects on kinetics [15,35].

Three studies of Lerner et al. reported knee joint kinetics during robotic exoskeleton walking [28,33,34]. The tethered knee exoskeleton was shown to reduce the mean knee extension moment during ST [33,34]. The reductions in mean knee extensor moment during ST were positively associated with increased torque provided by the exoskeleton ($0.60<R^2<0.70$) [34]. Furthermore, a mild to moderate negative relationship between extensor torque and mean biological extensor moment provided by the participant during SW was reported ($0.31<R^2<0.62$) [34]. Conversely, the opposite effects during SW were observed, as biological knee moments increased ($p = 0.005$) in the flexor direction with the exoskeleton assistance [33]. This increase coincided with an increase in mean knee joint energy absorption ($p < 0.001$) [33]. For the untethered ankle exoskeleton, knee joint moments and powers were not significantly different between walking conditions [28].

Two studies investigated hip joint kinetics during robotic exoskeleton walking [28,33]. The tethered knee exoskeleton assistance resulted in a significant ($p < 0.05$) increase in hip power absorption and mean hip power generation in comparison to Shod or AFO walking [33]. A significant ($p = 0.009$) reduction in average positive hip power was reported with the untethered ankle exoskeleton in comparison to baseline walking [28].

3.3.3. Effect on muscle activity

Studies utilising the WAKE-Up exoskeleton did not collect electromyography (EMG) data [15,35]. Chen et al. [30] reported the effects of the P.REX on rectus femoris, hamstrings, vastus lateralis and gastrocnemius muscle activity. In this study, muscle activation patterns were similar across exoskeleton conditions.

All five studies with the tethered knee exoskeleton showed elevated hamstring activity whilst walking with the exoskeleton [13,31–34]. A study involving the untethered ankle exoskeleton found that semitendinosus iEMG during ST was similar across all conditions [29].

The effects of the tethered knee exoskeleton on the knee extensor muscle activity during gait was reported in five studies [13,31–34]. The tethered knee exoskeleton results in comparison to Shod or AFO walking include: a significant increase ($p = 0.009$) in rectus femoris activity during terminal ST/early SW [33], a reduction ($p < 0.05$) in vastus lateralis iEMG activity during ST [31,33] and a significant ($p < 0.05$) increase in vastus lateralis activity during SW [32]. One study investigated the effects of untethered ankle exoskeleton walking on the knee extensor muscles [29]. In this study, vastus lateralis iEMG during ST was not significantly different across conditions.

Four studies of Lerner et al. collected data from the gastrocnemius and/or soleus muscles during exoskeleton-assisted walking [16,28,29,33]. Results included a 46% ($p = 0.004$) increase in medial gastrocnemius iEMG activity during early ST with the tethered knee exoskeleton [33]. Lerner et al. reported the following untethered ankle exoskeleton results in comparison to Shod or AFO walking: a decreased lateral gastrocnemius activity during ST ($p = 0.004$) [28] and a decrease in speed-normalised soleus iEMG [16]. However, Fang et al., from the same research group, [29] found that soleus iEMG activity was similar during untethered ankle exoskeleton walking and Shod walking.

Lastly, one study investigated the repeatability of muscle activity during exoskeleton walking [29]. Following four training visits with the untethered ankle exoskeleton, the soleus and vastus lateralis variance ratio was significantly ($p < 0.05$) lower, indicating higher stride-to-stride repeatability. The soleus had the greatest decrease in variability post-training: 51% for Shod walking ($p = 0.017$) and 48% for untethered ankle exoskeleton walking ($p = 0.017$). There was no significant difference in variance ratio between the Shod walking condition and untethered exoskeleton walking condition for either post- or pre-training assessments.

3.3.4. Effect on metabolic cost

Thurston et al. reported non-significant reductions in metabolic cost during unilateral ankle exosuit walking [36], whereas Lerner et al. reported significant reductions with the untethered ankle exoskeleton [16,27]. On average, net metabolic cost decreased by 18.7 ± 4.8% ($p = 0.011$) during walking with exoskeleton assistance compared to Shod or AFO walking [27]. Furthermore, another study observed a reduction ($p = 0.042$) in metabolic cost during a high torque assistance condition compared to Shod or AFO walking [16].

4. Discussion

The aim of this systematic review was to assess the effect of robotic exoskeletons on gait in children with CP. The use of robotic exoskeletons in children with CP is relatively new compared with use in other clinical populations, such as adults who suffered a stroke or spinal cord injury

[37]. Only six different robotic exoskeletons from three research groups were utilised in the included studies of this review, namely: WAKE-Up ankle module (developed by Mileti et al. [15]), WAKE-Up ankle & knee module (developed by Patané et al.[35]), unilateral ankle exosuit (developed by Thurston et al. [36]), P.REX (developed by Chen et al. [30]), untethered ankle exoskeleton and tethered knee exoskeleton (both developed by Lerner et al. [13,16,27–29,31–34]). It is important to note that Chen et al. [30] was grouped with the Lerner et al. [13,16,27–29,31–34] studies because two of the Chen et al. [30] authors were also co-authors for the Lerner papers, involving the untethered ankle exoskeleton.

It should be acknowledged that several studies were of poor [13,15,34–36] to fair quality [16,30–33]. The main reasons for methodological concerns were the lack of participant eligibility criteria description, small sample sizes, and limited descriptions of interventions and outcome measures. Moreover, several studies did not state whether the condition order was randomised [15,33–36].

4.1. *Study features*

The target group for this systematic review was children with CP. It is important to note that the enroled participants of included studies were not only children, but also adults. In addition, only participants with GMFCS I-III were included in these studies. Most of the participants had bilateral CP and a crouch gait pattern. In total, 25 patients with CP were included in this review. Some patients participated in more than one of the studies. The sample sizes for each type of exoskeleton were the following: $n = 7$ for the tethered knee exoskeleton, $n = 1$ for P.REX, $n = 7$ for the untethered ankle exoskeleton, $n = 3$ for the WAKE-Up ankle module, $n = 3$ for the WAKE-Up ankle & knee module and $n = 7$ for the unilateral ankle exosuit. All participants completed baseline walking trials and exoskeleton assist trials, except for two studies [30,34], where the effect of different magnitudes of exoskeleton knee extensor torque on gait were compared, without baseline trials. The baseline condition was defined in all the included studies as the participant's everyday walking condition (i.e., walking with their normal shoes or shoes in combination with their AFOs if prescribed).

The mass of the exoskeletons varied between 1.5 kg and 5.8 kg. A challenge in designing exoskeletons is to keep the mass of the device low, because adding mass to the body can alter gait and increase the metabolic cost of walking [27]. Previous research indicated that an exoskeleton mass of up to 2.5 kg will not noticeably alter gait in children with CP [18].

4.2. *Main findings on the effect of robotic exoskeletons on gait*

The review suggests that robotic exoskeletons have some beneficial effects on gait in children with CP. Improvements in gait seemed highly dependent on the allocated time for the participants to adapt to walking with the new device. Studies involving at least two data collection time points reported improvements accrued with robotic exoskeleton practice [29,32]. Moreover, the device adaptation time was found to be dependent on the design of the device and the exoskeleton control strategy [16,31,33,34]. Generally, the most significant improvements in gait occurred during the exoskeleton high torque conditions [16,33] and when assistance was provided during both SW and ST [13,31].

4.3. *Effect on biomechanics*

A discrepancy in spatiotemporal results was observed when comparing studies. A possible explanation for this variation is the differences in exoskeleton practice time. Namely, a decrease in walking speed was often observed in studies where participants' gait was assessed after a limited adaptation time (18 min) with the exoskeleton [13]. Lerner et al. [32] demonstrated the importance of exoskeleton adaption time. In their study, step length increased by 33% ($p = 0.027$) and gait speed increased by 32% ($p = 0.028$) across repeated assessment sessions [32].

An increase in walking speed due to robotic exoskeleton assistance is an important outcome because walking speed has been linked to functional ability and quality of life in children with CP [6]. The increase in walking speed, following training, was achieved primarily through longer strides instead of a faster cadence, which is a clinical goal in the treatment of gait pathology for individuals with CP [10,11]. Optimisation of the amount of torque provided by the exoskeleton, based on participant's weight, biological power, and adaptability to the device, appears to be a crucial factor influencing walking speed [16]. This is supported by Orekhov et al. [16], where walking speed only increased by 5.9 ± 2.5% ($p = 0.034$) with low assistance of 0.225 ± 0.014 Nm/kg, while walking speed increased by 6.9 ± 2.4% ($p = 0.018$) with high assistance of 0.300 Nm/kg compared to Shod or AFO walking. Overall, it appears that robotic exoskeletons have the potential to increase walking speed, given sufficient practice time and careful optimisation of exoskeleton torque.

The untethered ankle exoskeleton, the tethered knee exoskeleton and the P.REX induced favourable changes in kinematics for children with crouch gait. Several studies observed a significant increase in knee extension during ST [13,28,30–34] with these exoskeletons and one reported a significant increase in hip extension during ST [33], suggesting a more upright posture.

Positive effects on ankle kinematics were observed with the robotic exoskeletons which provided robotic assistance at the ankle. For example, the untethered ankle exoskeleton caused a significant increase in peak ankle plantar flexion [28]. Similarly, the WAKE-up ankle & knee module appeared to improve foot placement before toe-off for two out of three participants [35]. The unilateral ankle exosuit improved ankle mechanics by increasing dorsiflexion during SW and initial contact [36].

Robotic exoskeleton walking also had positive effects on kinetics. Key findings include a reduction in mean knee extension moment during ST with the tethered knee exoskeleton [33,34], an increase in ankle power generation with the untethered ankle exoskeleton [28] and an increase in peak plantarflexion moment at toe off with the P.REX [30]. The increase in peak plantarflexion moment addresses a limitation of solid AFOs, commonly prescribed to children with CP, whereby ankle ROM is limited, which inhibits the ankle aiding propulsion during push-off [10]. Collectively, the kinematic and kinetic findings demonstrate the ability of the untethered ankle exoskeleton to promote normal ankle rocker function. Unfortunately, studies involving the WAKE-Up exoskeleton did not collect kinetic data.

Overall, there is good evidence in spatiotemporal, kinematic, and kinetic data to support the use of the untethered ankle exoskeleton, the tethered knee exoskeleton and the P.REX in the management of crouch gait. Also, the unilateral ankle exosuit appeared to improve ankle kinematics and kinetics for children with CP. However, existing evidence for the effectiveness of the WAKE-Up exoskeleton to improve gait in children with CP is limited.

4.4. *Effect on muscle activity*

Walking with the tethered knee exoskeleton caused an increase in knee flexor and extensor muscle activity [13,31–34], with the exception of the vastus lateralis. However, the exoskeleton generally had a greater effect on knee flexor muscles than on knee extensor muscles [13,31–34]. A possible explanation of this is the required muscle activity to compensate for the added mass of the exoskeleton during SW [32]. Furthermore, increased knee flexor activity may also be a maladaptive response due to the external torque provided by the knee module exceeding the internal flexor moment [32,38]. In the contrary, EMG data was similar across conditions with the P.REX [30].

Concerning the untethered ankle exoskeleton, a reduction in the muscle activity of the plantar flexors was recorded [16,28]. This suggests that part of the biological ankle work was taken over by the exoskeleton. A reduction in muscle activation due to robotic assistance is a concern because it could lead to muscle atrophy over time [28]. However, Lerner et al. [28] note that the untethered ankle exoskeleton can also provide resistance and, therefore, can be used as a resistance gait training device intended to improve muscle strength [39]. This is an interesting area of research, although is beyond the scope of this review.

4.5. *Effect on metabolic cost*

Reduced energy expenditure during walking is an important outcome because it could facilitate greater accumulation of walking exercise and independence for children with CP [16]. Only three studies investigated the effect of robotic exoskeletons on the metabolic cost of walking [16,27,36]. A study with the unilateral ankle exosuit only reported non-significant reductions in the metabolic cost of walking. However, two studies with the untethered ankle exoskeleton reported a significant reduction in metabolic cost in comparison to baseline walking. The greatest reduction in metabolic cost occurred in the most impaired participants. Furthermore, results suggest that reductions in metabolic cost are dependent on the magnitude of robotic assistance provided and the relative exoskeleton mass [16]. Moreover, reductions in the metabolic cost of walking could be related to the reduction in the muscle activity of the plantar flexors [16,28].

5. Limitations

The use and development of robotic exoskeletons is a new area of research. Hence, this review retrieved a small number of studies from the electronic database search, predominantly from a limited number of research groups. Moreover, to limit the heterogeneity among studies, and to guarantee new steps following previous reviews, specific selection criteria were applied [20–23]. Studies were excluded from this review when they did not recruit children with CP. Moreover, studies involving the use of robotic exoskeletons for RAGT were excluded because they did not assess the direct effect of the exoskeleton on gait [20–23]. Therefore, it is not clear whether the robotic exoskeletons used in these latter studies improve gait mechanics.

As previously mentioned, the target group of this review were children with CP, but eight included studies also enrolled adult participants. Gait varies considerably with age, thus caution must be taken when generalising the results [40,41]. Furthermore, the sample sizes of the included studies were small, with a maximum of seven participants. In addition, most participants were recruited for multiple studies, which not only compromises the sample representation of a larger and more heterogenous CP population, but also, could induce carry over effects due to walking practice with other robotic exoskeletons. In addition, it should be noted that due to the limited sample sizes and the heterogeneity of the cohort, some studies described and discussed their results for each patient separately and did not conduct statistical analysis at group level [13,15,30,35].

It is important to point out that five studies conducted gait analysis during treadmill walking [27,28,33,34,36], while the other eight studies conducted gait analysis during overground walking [13,15,16,29–32,35]. Treadmill walking has been shown to decrease self-selected walking speed and increase peak angles of ankle dorsiflexion, knee extension/flexion and hip flexion compared to overground walking in children with CP [42]. Another notable difference is that walking speed on a treadmill is controlled, while participants can self-select their walking speed during overground walking.

It should be noted that several studies conducted statistical analysis at group level, although the participant groups consisted of individuals with different baseline walking conditions [16,27,28,31–33]. Furthermore, studies involving the WAKE-Up exoskeleton and the unilateral ankle exosuit did not state whether their participants walked barefoot, with shoes or shoes in combination with an AFO for their baseline walking trials [15,35,36]. Previous studies have demonstrated that AFOs significantly alter gait [9–11]. Subsequently, this should be taken into consideration when interpreting results from studies involving a baseline condition, except for one study which involved a baseline Shod condition only [31].

Another limitation was that not all studies had enough adaptation time with the exoskeleton and, therefore participants could still have been adapting to the new device and had inconsistent gait patterns [13,15,32,33,35]. Due to the variability in study design and outcome parameters, and limited sample sizes, it was not possible to complete a quantitative meta-analysis. Moreover, all the included studies only investigated biomechanical parameters in the sagittal plane, while changes in other planes may occur.

6. Future research

More research is needed to demonstrate the effectiveness of robotic exoskeletons for improving gait in children with CP. Future work should involve larger sample sizes and participants with homogeneous levels of motor impairment. Additionally, future studies should clearly describe the baseline condition and should only conduct group level statistical analysis when participant groups consist of individuals with the same baseline walking condition (i.e., Shod or AFO baseline condition, and not a combination of both).

Future studies should ensure sufficient adaptation time to the exoskeleton. Fang et al. [29] suggested that participants may need 30 – 60 min to become familiar to walking with the untethered ankle exoskeleton. This was supported by the reduction in stride-to-stride variability across gait analysis assessments and the inverse relationship between muscle variance ratio and walking speed. However, the adaptation time needed to observe improvements in gait with other devices is not clear. Future studies should monitor the stability of the gait pattern to see if participants require more adaptation time. In addition, long-term studies of the effects of robotic exoskeletons on gait in children with CP are required to observe the mechanisms of improvement over time.

There is an opportunity to conduct more studies that assess the effects of different exoskeleton control strategies on gait. Based on the heterogeneity of CP, the best control strategy for improving gait in CP will vary by individual. Control strategies which adjust assistance based on the interaction between the user and the device could be the best approach to address this challenge [30,43]. More studies are needed to demonstrate this.

7. Conclusions

In summary, lightweight robotic exoskeletons have the potential to increase knee and hip extension during stance, improve spatiotemporal parameters and reduce the metabolic cost of walking in children with CP. In addition, exoskeletons with an actuated ankle module have the potential to promote normal ankle rocker function. Collectively, these results provide evidence to support larger controlled intervention studies of robotic exoskeleton for improving gait in children with CP.

Funding

This study is part of the M.O.T.I.O.N. project, funded by the Interreg 2 Seas programme 2014–2020 and, co-funded by the European Regional Development Fund under subsidy contract (2S05–038).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This systematic review has been carried out as part of the INTERREG 2 SEAS M.O.T.I.O.N. (Mechanised Orthosis for Children with Neurological Disorders) project. The authors are grateful for the support received from M.O.T.I.O.N. project partners, namely: KU Leuven (BE), Canterbury Christ Church University (UK) and Thomas More University of Applied Sciences (BE). We would like to thank Dr Damian Coleman (Canterbury Christ Church University) for his feedback.

References

[1] C. Cans, Surveillance of cerebral palsy in Europe: a collaboration of cerebral palsy surveys and registers, Dev. Med. Child Neurol. 42 (2000) 816–824.

[2] A. Johnson, Prevalence and characteristics of children with cerebral palsy in Europe, Dev. Med. Child Neurol. 44 (2002) 633–640.

[3] E. Sellier, M.J. Platt, G.L. Andersen, I. Krägeloh-Mann, J. De La Cruz, C. Cans, M. Van Bakel, C. Arnaud, M. Delobel, J. Chalmers, V. McManus, A. Lyons, J. Parkes, H. Dolk, K. Himmelmann, M. Pahlman, V. Dowding, A. Colver, L. Pennington, K. Horridge, J. Kurinczuk, G. Surman, M.J. Platt, P. Udall, G. Rackauskaite, M.G. Torrioli, M. Marcelli, G. Andersen, S. Julsen Hollung, M. Bottos, G. Gaffney, J. De la Cruz, C. Pallas, D. Neubauer, M. Jekovec-Vrhovšek, D. Virella, M. Andrada, A. Greitane, K. Hollody, S. Sigurdardottir, I. Einarsson, M. Honold, K. Rostasy, V. Mejaski-Bosnjak, Decreasing prevalence in cerebral palsy: a multi-site European population-based study, 1980 to 2003, Dev. Med. Child Neurol. 58 (2016).

[4] R.W. Armstrong, Definition and classification of cerebral palsy, Dev. Med. Child Neurol. 49 (2007) 166.

[5] I. Novak, M. Hines, S. Goldsmith, R. Barclay, Clinical prognostic messages from a systematic review on cerebral palsy, Pediatrics 130 (2012).

[6] N.G. Moreau, A.W. Bodkin, K. Bjornson, A. Hobbs, M. Soileau, K. Lahasky, Effectiveness of rehabilitation interventions to improve gait speed in children with cerebral palsy: systematic review and meta-analysis, Phys. Ther. 96 (2016) 1938–1954.

[7] R. Schenker, W. Coster, S. Parush, Participation and activity performance of students with cerebral palsy within the school environment, Disabil. Rehabil. 27 (2005) 539–552.

[8] E. Beckung, G. Hagberg, Neuroimpairments, activity limitations, and participation restrictions in children with cerebral palsy, Dev. Med. Child Neurol. 44 (2002) 309–316.

[9] A. Caliskan Uckun, C. Celik, H. Ucan, N.K. Ordu, Gokkaya, Comparison of effects of lower extremity orthoses types on walking in children with cerebral palsy, Dev. Neurorehabil. 17 (2014) 388–392.

[10] A. Aboutorabi, M. Arazpour, M. Ahmadi Bani, H. Saeedi, J.S. Head, Efficacy of ankle foot orthoses types on walking in children with cerebral palsy: a systematic review, Ann. Phys. Rehabil. Med. 60 (2017) 393–402.

[11] J.P. Betancourt, P. Eleeh, S. Stark, N.B. Jain, Impact of ankle-foot orthosis on gait efficiency in ambulatory children with cerebral palsy: a systematic review and meta-analysis, Am. J. Phys. Med. Rehabil. 98 (2019) 759–770.

[12] M. Wingstrand, G. Hägglund, E. Rodby-Bousquet, Ankle-foot orthoses in children with cerebral palsy: a cross sectional population based study of 2200 children, BMC Musculoskelet. Disord. 15 (2014) 1–7.

[13] Z.F. Lerner, D.L. Damiano, H.-S. Park, A.J. Gravunder, T.C. Bulea, A robotic exoskeleton for treatment of crouch gait in children with cerebral palsy: design and initial application, IEEE Trans. Neural Syst. Rehabil. Eng. 25 (2017) 650–659.

[14] I. novak, S. Mcintyre, C. Morgan, L. Campbell, L. Dark, N. Morton, E. Stumbles, S. A. Wilson, S. Goldsmith, A systematic review of interventions for children with cerebral palsy: state of the evidence, Dev. Med. Child Neurol. 55 (2013) 885–910.

[15] I. Mileti, J. Taborri, S. Rossi, M. Petrarca, F. Patane, P. Cappa, Evaluation of the effects on stride-to-stride variability and gait asymmetry in children with Cerebral Palsy wearing the WAKE-up ankle module. In: Proceedings of the 2016 IEEE International Symposium on Medical Measurements and Applications, 345 E 47TH ST, NEW YORK, NY 10017 USA, 2016: pp. 286–291.

[16] G. Orekhov, Y. Fang, J. Luque, Z.F. Lerner, Ankle exoskeleton assistance can improve over-ground walking economy in individuals with cerebral palsy, IEEE Trans. Neural Syst. Rehabil. Eng. 28 (2020) 461–467.

[17] Y. Mataki, H. Kamada, H. Mutsuzaki, Y. Shimizu, R. Takeuchi, M. Mizukami, K. Yoshikawa, K. Takahashi, M. Matsuda, N. Iwasaki, H. Kawamoto, Y. Wadano, Y. Sankai, M. Yamazaki, Use of hybrid assistive limb (HAL®) for a postoperative patient with cerebral palsy: a case report, BMC Res. Notes 11 (2018).

[18] S. Rossi, A. Colazza, M. Petrarca, E. Castelli, P. Cappa, H.I. Krebs, Feasibility study of a wearable exoskeleton for children: is the gait altered by adding masses on lower limbs? PLOS One 8 (2013).

[19] E. Russell Esposito, K.A. Schmidtbauer, J.M. Wilken, Experimental comparisons of passive and powered ankle-foot orthoses in individuals with limb reconstruction, J. Neuroeng. Rehabil. 15 (2018) 1–10.

[20] C. Bayon, R. Raya, Robotic therapies for children with cerebral palsy: a systematic review, Transl. Biomed. 7 (2016).

[21] S. Lefmann, R. Russo, S. Hillier, The effectiveness of robotic-assisted gait training for paediatric gait disorders: systematic review, J. Neuroeng. Rehabil. 14 (2017).

[22] L.R. Bunge, A.J. Davidson, B.R. Helmore, A.D. Mavrandonis, T.D. Page, T. R. Schuster-Bayly, S. Kumar, Effectiveness of powered exoskeleton use on gait in individuals with cerebral palsy: a systematic review, PLOS One 16 (2021), e0252193.

[23] L.E. Cañadas Martinez, S. Montero, Efectividad de los sistemas automatizados de marcha en niños con parálisis cerebral: una revisión sistemática, Fisioterepia 42 (2020) 75–84.

[24] H. Nedergård, A. Arumugam, M. Sandlund, A. Bråndal, H. Häger, Effect of robotic-assisted gait training on objective biomechanical measures of gait in persons post-stroke: a systematic review and meta-analysis, J. Neuroeng. Rehabil. 18 (2021) 1–22.

[25] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, BMJ 339 (2009) 332–336.

[26] Study Quality Assessment Tools | NHLBI, NIH, (n.d.). https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools (accessed August 4, 2020).

[27] Z.F. Lerner, G.M. Gasparri, M.O. Bair, J.L. Lawson, J. Luque, T.A. Harvey, A. T. Lerner, An untethered ankle exoskeleton improves walking economy in a pilot study of individuals with cerebral palsy, IEEE Trans. Neural Syst. Rehabil. Eng. 26 (2018) 1985–1993.

[28] Z.F. Lerner, T.A. Harvey, J.L. Lawson, A. Battery-Powered, Ankle exoskeleton improves gait mechanics in a feasibility study of individuals with cerebral palsy, Ann. Biomed. Eng. 47 (2019) 1345–1356.

[29] Y. Fang, G. Orekhov, Z.F. Lerner, Adaptive ankle exoskeleton gait training demonstrates acute neuromuscular and spatiotemporal benefits for individuals with cerebral palsy: a pilot study, Gait Posture (2020).

[30] J. Chen, J. Hochstein, C. Kim, L. Tucker, L.E. Hammel, D.L. Damiano, T.C. Bulea, A pediatric knee exoskeleton with real-time adaptive control for overground walking in ambulatory individuals with cerebral palsy, Front. Robot. AI 8 (2021) 1–16.

[31] Z.F. Lerner, D.L. Damiano, T.C. Bulea, A robotic exoskeleton to treat crouch gait from cerebral palsy: Initial kinematic and neuromuscular evaluation. In: Proceedings of the Annual International Conference on IEEE Engineering in Medicine and Biology Society EMBS, 2016: pp. 2214–2217.

[32] Z.F. Lerner, D.L. Damiano, T.C. Bulea, A lower-extremity exoskeleton improves knee extension in children with crouch gait from cerebral palsy, Sci. Transl. Med. 9 (2017).

[33] Z.F. Lerner, D.L. Damiano, T.C. Bulea, The effects of exoskeleton assisted knee extension on lower-extremity gait kinematics, kinetics, and muscle activity in children with cerebral palsy, Sci. Rep. 7 (2017).

[34] Z.F. Lerner, D.L. Damiano, T.C. Bulea, Relationship between assistive torque and knee biomechanics during exoskeleton walking in individuals with crouch gait, in: L. Amirabdollahian, F and Burdet, E and Masia (Ed.), IEEE Int. Conf. Rehabil. Robot., IEEE, 345 E 47TH ST, NEW YORK, NY 10017 USA, 2017: pp. 492–497.

[35] F. Patané, S. Rossi, F. Del Sette, J. Taborri, P. Cappa, WAKE-up exoskeleton to assist children with cerebral palsy: design and preliminary evaluation in level walking, IEEE Trans. Neural Syst. Rehabil. Eng. 25 (2017) 906–916.

[36] M. Thurston, J.P. Kulmala, J. Nurminen, J. Avela, Beyond orthoses: using an exosuit to enhance the walking pattern of patients with unilateral Cerebral Palsy, Gait Posture 90 (2021) 271–273.

[37] F. Reyes, C. Niedzwecki, D. Gaebler-Spira, Technological advancements in cerebral palsy rehabilitation, Phys. Med. Rehabil. Clin. N. Am. 31 (2020) 117–129.

[38] Z.F. Lerner, D.L. Damiano, T.C. Bulea, Estimating the mechanical behavior of the knee joint during crouch gait: implications for real-time motor control of robotic knee orthoses, IEEE Trans. Neural Syst. Rehabil. Eng. 24 (2016) 621–629.

[39] B.C. Conner, J. Luque, Z.F. Lerner, Adaptive ankle resistance from a wearable robotic device to improve muscle recruitment in cerebral palsy, Ann. Biomed. Eng. 48 (2020) 1309–1321.

[40] D. Sutherland, The development of mature gait, Gait Posture 6 (1997) 163–170.

[41] K.J. Ganley, C.M. Powers, Gait kinematics and kinetics of 7-year-old children: a comparison to adults using age-specific anthropometric data, Gait Posture 21 (2005).

[42] T. Jung, Y. Kim, L.E. Kelly, M.F. Abel, Biomechanical and perceived differences between overground and treadmill walking in children with cerebral palsy, Gait Posture 45 (2016) 1–6.

[43] G.M. Gasparri, J. Luque, Z.F. Lerner, G. G.M, L.J. L. Z.F, Proportional joint-moment control for instantaneously adaptive ankle exoskeleton assistance, IEEE Trans. Neural Syst. Rehabil. Eng. 27 (2019) 751–759.