Gait & Posture 73 (2019) 168–172

Contents lists available at ScienceDirect

Gait & Posture

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

Full length article

Effects of functional power training on gait kinematics in children with cerebral palsy

Laura M. Oudenhoven[a,*], Liesbeth F. van Vulpen[a,b], Annet J. Dallmeijer[a], Sonja de Groot[b,c], Annemieke I. Buizer[a], Marjolein M. van der Krogt[a]

[a] Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rehabilitation Medicine, Amsterdam Movement Sciences, de Boelelaan 1117, Amsterdam, the Netherlands
[b] Amsterdam Rehabilitation Research Center, Reade, Amsterdam, the Netherlands
[c] University of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, the Netherlands

ARTICLE INFO

Keywords:
Rehabilitation
Biomechanics
Muscle weakness
Spasticity

ABSTRACT

Background: Muscle weakness is one of the most prevalent symptoms in children with cerebral palsy (CP). Although recent studies show that functional power training can improve strength and functional capacity in young children with CP, effects on specific gait parameters have not previously been reported.

Research question: What are the effects of functional power training on gait in children with CP? Specifically, we investigated effects of training on gait kinematics and spatiotemporal parameters, and whether these were dependent on walking speed.

Methods: Ten children with CP (age 5–10 years, GMFCS I–II) participated in a functional power training program. At the start and end of the program, children underwent 3D gait analysis on a treadmill at a gradual range of walking speeds (70–175% of their comfortable walking speed). Multilevel (linear mixed model) analysis was used to evaluate effects pre-post training at different walking velocities.

Results: Although children's self-chosen comfortable walking speed improved (0.71 ± 0.25 to 0.85 ± 0.25 m/s, $p < .05$), effects on gait kinematics at similar speed were limited and only exceeded statistical and clinically meaningful thresholds when children walked at higher walking speed. At fast speeds, improvements up to 5° were found in knee and hip extension during stance ($p < .01$).

Significance: This study demonstrates that gait kinematics can improve after functional power training, but the magnitude of effects is dependent on walking speed. In this light, improvements are underestimated when evaluating gait at pre-training comfortable walking speed only.

Muscle weakness is one of the most prevalent motor symptoms in children with cerebral palsy (CP). Especially weakness of the ankle plantar flexors seems to play a major role in gait impairments, as it is associated with gait stability as well as forward propulsion [1,2]. Weakness of the plantar flexors is associated with gait deviations, including excessive knee flexion and ankle dorsiflexion during the stance phase, as often seen in children with CP [3–5].

Although historically treatment to improve gait in children with spastic CP was primarily aimed to reduce effects of spasticity by further weakening muscles through interventions such as denervating hyperreflexic muscles [6], recently, there appears to be a shift towards more activating forms of therapy [4,7,8]. Different studies evaluated effects of strength training in children with CP, but results were conflicting [8–14]. Although improvements have been reported in multiple domains including isometric and isokinetic strength [10,15–18], few studies showed improvement in functional capacity [15,16,18,19] and none of the studies showed effect on gait kinematics or spatiotemporal parameters [8,10–12,16,19].

Several hypotheses have been previously raised why the relation between strength training and gait improvement is weak [20]. Firstly, most strength training programs target the knee extensors [7,8,10,18]. Although improvements have been found for knee extension strength, it was argued that the knee extensors may not be the limiting factor causing gait impairments [3]. In fact, in children who walk with a flexed knee gait pattern, the knee extensors may be constantly trained during regular gait, because of the high demands on this muscle group to deliver an internal knee extension moment.

Secondly, it has been proposed that gait in children with CP is not

* Corresponding author.
E-mail addresses: l.oudenhoven@vumc.nl (L.M. Oudenhoven), l.v.vulpen@reade.nl (L.F. van Vulpen), a.dallmeijer@vumc.nl (A.J. Dallmeijer), s.d.groot@reade.nl (S. de Groot), ai.buizer@vumc.nl (A.I. Buizer), m.vaderkrogt@vumc.nl (M.M. van der Krogt).

https://doi.org/10.1016/j.gaitpost.2019.06.023
Received 15 February 2019; Received in revised form 25 April 2019; Accepted 28 June 2019
0966-6362/

primarily limited by a lack of strength, but rather by a lower rate of force development, related to impaired ankle push off power [4]. Based on these ideas, a functional power training was developed for young children with CP by Van Vulpen et al. [21]. They performed an intervention study, where children were trained inducing fast movements related to daily life activities of children, such as running and playing, with added load, rather than repetitive single-joint exercises at a slow velocity as frequently done in previous strength training studies. A special focus of this program was to improve weakness of the calf muscles. They found large increases in strength at the level of body function (24–27% increase in plantar flexor strength), as well as improvement in the domain of activities, including the muscle power sprint-test (83%) and 1-min walk test (13%) [22]. The positive effects of this recent study suggest that functional power training might be one of the paths towards improvement of activities. However, whether this is also reflected in improved gait performance and what the effect of this improved calf muscle strength is on their knee kinematics, is yet unknown.

One of the principles of high intensity power training, is that exercises are performed at a high velocity. In studies describing positive effects of training interventions in CP, exercises typically comprise running, jumping and stair climbing and children are challenged to perform all exercises as fast as they can [15,22]. Although such a training type is designed to improve children's walking capacity, evaluation is often through gait analysis at comfortable walking speed, which does not evaluate maximum walking capacity but rather performance at a submaximal level. In this light, it could be argued that children improve their capacity by training, but this only becomes visible when they tested during high demanding circumstances in gait analysis, for example by inducing faster walking velocities.

Therefore, the aim of the present study is to evaluate the effects of functional power training on gait in children with CP. Outcomes are evaluated at comfortable walking speed (CWS) as well as at a range of different walking speeds. We hypothesize that after training, more knee extension and less ankle dorsiflexion will occur during stance. In addition, we hypothesize that these effects are more pronounced if children are challenged to walk at higher walking velocities, because of the higher demands.

1. Methods

1.1. Participants

For this study, we investigated a subset (n = 10) of the group of young children with CP as described by Van Vulpen et al. [20,22]. Children were selected for the functional power training program by their physician or physiotherapist because they had a treatment goal related to walking capacity. Children had to be motivated and able to follow instructions. Exclusion criteria were treatment with botulinum toxin-A or serial casting within six months before the start of the training program and selective dorsal rhizotomy less than a year before the start of the training program. All parents gave written informed consent before the start of the study. The protocol was approved by the Medical ethics committees of the VU University Medical Center, Reade Rehabilitation Research Center Amsterdam and Slotervaart Medical Center.

1.2. Intervention

Children followed the training protocol as described by Van Vulpen et al. [20,22]. The training comprised a period of fourteen weeks with sessions of 60 min, three times a week located at the local rehabilitation centre. The progressive power training was specifically designed to strengthen the plantar flexors during functional exercises in small groups (3–6 children) with a personal supervising therapist for each child. Power exercises were characterized by progressive loaded multi-joint exercises at a high speed. All exercises were translatable to daily life activities of the children, such as running and walking with a focus on the ankle push-off.

1.3. Data collection

Before and after the training protocol, children underwent clinical gait analysis on an instrumented treadmill (GRAIL system, Motekforce Link BV Amsterdam). During gait analysis, children walked at a gradual range of walking velocities, including CWS at a self-paced mode or fixed speed mode [23], as well as slower/faster velocities. Comfortable walking speed was determined on the treadmill. For all children, belt speed was varied with an within-individual range of 50–175% of comfortable walking speed, with the prerequisite that at maximal imposed speeds children were still walking (no transition to running). Walking velocities were imposed in a randomized order, with rest in-between trials if needed. Walking trials lasted for at least 30 s each. A habituation trial was included before the start of the measurement, for as long as necessary for individual children. During all trials, a harness was used for safety reasons and children walked on textile shoes with a flexible sole without support, which can be considered as barefoot walking.

3D-Motion capture was used to collect passive marker data (Vicon, Oxford, UK, sample frequency 100 Hz). Kinematics and spatiotemporal parameters were calculated with the human body model (HBM [24]) in combination with custom-written scripts (in Matlab). Kinetic data was collected simultaneously, but excluded from further analysis due to hardware issues.

For functional outcomes, the muscle power sprint test [25], shuttle run test [26] and one minute walk test were evaluated [27]. The results of these tests have previously been reported for a larger group [20,22].

1.4. Data processing

Valid strides were selected based on visual inspection. Strides were excluded from the analysis if children were running, standing still, tripping or were distracted. All valid strides were time normalized from initial contact to consecutive initial contact. Initial contacts were based on the heel and pelvis markers according to Zeni et al. [28]. Data were evaluated for the most affected leg only, based on a physical examination.

Walking speed, stride length and time, stance percentage and cadence were calculated for each stride, based on the absolute trajectory of the heel markers corrected for the belt speed. Walking speed was normalized to the mean comfortable walking speed before training (CWS). In this way, we were able to make a direct comparison between gait outcomes before and after training, at the exact same walking speed.

Marker data were low-pass filtered at 6 Hz and knee and ankle kinematics were calculated with HBM-2. Specific clinically relevant outcome parameters were calculated for all joints, including: maximal knee flexion/extension during stance, maximal ankle dorsiflexion during stance and swing, and knee and ankle angles at initial contact.

1.5. Statistical analysis

To assess the difference in gait kinematics between pre- and post-test at different walking speeds, multilevel analysis was used (IBM SPSS Statistics 22.0). This method wat chosen since includes individual intercepts for participants and is relatively robust for missing data [29]. A linear scale response was used with as a dependent variable the gait kinematics parameter and as evaluated predictors: pre-post (dichotomous variable, 0 = pre/1 = post), the gradual range of relative walking speeds (% CWS) as a covariate, as well as their interaction (pre-post*walking speed). Statistical analyses were performed to evaluate main effects of individual factors, as well as interactions when predictors were combined within the model. Intercepts were allowed to vary between subjects, whereas coefficients were fixed. For all tests, a significance level of $p < 0.01$ was set. For interpretation of coefficients, relative walking speed was centred, meaning that 0 equals CWS before training. Effects were considered to be clinically meaningful when they exceeded a threshold of 5° for joint kinematics [30], or 0.1 m / 0.1 s / 5% for spatiotemporal parameters. Functional outcomes before and after training were compared using paired sampled t-tests.

Since effects of walking speed on pre-post differences are not by definition linear, additional post-hoc tests were performed for normalized walking speed intervals of: 50–75%, 75–100%, 100–125%, 125–150% and 150–175% of CWS, evaluating pre-post main effects within each interval, with Bonferroni correction to account for multiple comparisons.

2. Results

Ten children with spastic CP (GMFCS I (n = 2) or GMFCS II (n = 8), hemiplegic (n = 3), diplegic (n = 7), age 7.3 years (range: 5–10), 5 girls) were included in the study. All children able to walk independently on even surface, although some children used a wheelchair (n = 3) or walker (n = 2) for walking longer distances (> 500 m). During daily life, all children wore orthoses. All children were able to walk at the imposed walking velocities (50–175% CWS).

Results of the multilevel analysis are presented in Table 1, based on 186 up to 585 strides for each individual participant.

Concerning spatiotemporal parameters, increases were found for step length and cadence with faster walking speeds, but no pre-post effect nor interaction effects were found. For relative stance time (% gait cycle), a significant interaction effect was found ($p < .01$), indicating a relative longer stance time at faster walking velocities post-training. However, this effect remained below the clinically pre-determined threshold of 5%, and did not reach significance in any of the velocities for post-hoc testing.

For sagittal hip joint angles/kinematics, no pre-post effects were found ($p < .01$). Walking speed was significantly related to increased hip flexion at initial contact and increased maximal/minimal hip flexion during stance ($p < .01$). Significant interaction effects were found between pre-post effects and walking speed, showing larger improvements at higher speeds for hip flexion at initial contact as well as maximum/minimum hip flexion during stance (Table 1). Post-hoc analysis revealed more hip extension after training at 150–175% CWS exceeding the predefined threshold of > 5° (pre: 15 ± 9° post: 9 ± 7°; p = < .01) (Fig. 1).

For the knee joint, small but significant pre-post effects and significant effects of speed were found (Table 1). The interaction effects were significant for all knee angle parameters, indicating that changes in knee angle after training were larger when evaluated at higher speeds. Post-hoc analyses revealed an increase in maximal knee extension at 150–175% CWS exceeding the predefined threshold of > 5° (pre: 15 ± 11° flexion vs. post: 10 ± 10° flexion, $p < 0.01$) (Fig. 1).

For ankle kinematics, small but significant pre-post and speed effects were found for ankle angles at initial contact as well as maximum dorsiflexion, indicating less dorsiflexion after training, as well as less dorsiflexion at faster walking velocities (Table 1). For ankle angle at initial contact, a significant interaction effect was found indicating less decrease in ankle angle at faster walking velocities after training. However, this effect was limited (regression coefficient = 1.3, SE = 0.34) and did not reach significance during post-hoc testing (Fig. 1).

In line with the group results presented in the previous study by Van Vulpen [19], also for this subgroup of children significant and large improvements were found for the 1-min walk test (pre: 69.7 ± 14.1 m vs. post: 84.5 ± 9.8 m; $p < 0.01$), Shuttle Run Test (pre: 7.3 ± 2.1 stages vs. post: 12.5 ± 4.1 stages; $p < 0.01$) and mean power during Muscle Power Sprint Test (pre: 24.6 ± 22.0 W vs. post 58.7 ± 51.3 W; $p < 0.01$). Self-chosen CWS during gait analysis increased with on average 21% (mean pre: 0.71 ± 0.25 m/s; post: 0.85 ± 0.24 m/s; $p < 0.05$).

3. Discussion

The aim of the present study was to investigate the effects of functional power training on gait kinematics in children with CP. Since we expected improvements to become more pronounced when children were challenged, effects were compared for comfortable walking speed

Table 1
Results of multilevel analysis for the effect of functional power training on gait parameters and the relation with walking speed. Pre-post effects were evaluated by a dichotomous variable (0 = pre/1 = post). If no significant interaction effect was found, models are presented for main effects only. For interpretation of the presented results, walking speed was normalized to comfortable walking speed (CWS) before training and centered, where a zero equals CWS in the regression formula. Hence, in case of significant interaction-effects, pre-post coefficients can be interpreted as effects at pre-training CWS. CWS = comfortable walking speed.

Parameter	Intercept	pre-post effect			walking speed			walking speed*pre-post		
	Estimate 1	Estimate 2	SE	p-value 2	Estimate 3	SE	p-value 3	Estimate 4	SE	p-value 4
Spatiotemporal										
Cadence (strides/sec)	1.80	−0.01	0.01	0.14	0.69	0.01	< 0.01*	–	–	n.s.
Stride length (m)	0.79	−0.00	0.00	0.65	0.35	0.00	< 0.01*	–	–	n.s.
Stance time (% gait cycle)	67	0.25	0.10	0.01	−6.9	0.17	< 0.01*	0.58	0.22	0.01
Sagittal kinematics										
Hip										
positive = flexion/negative = extension										
Initial contact (°)	46.6	0.42	0.22	0.06	6.69	0.38	< 0.01*	1.67	0.50	< 0.01*
Minimal stance (°)	3.1	−0.74	0.29	0.01	−1.84	0.49	< 0.01*	−5.56	0.65	< 0.01*
Maximal stance (°)	48.3	0.36	0.22	0.11	6.60	0.39	< 0.01*	1.54	0.51	< 0.01*
Knee										
positive = flexion/negative = extension										
Initial contact (°)	31.6	0.98	0.25	< 0.01*	1.6	0.43	< 0.01*	2.2	0.57	< 0.01*
Minimum in stance (°)	12.3	−1.0	0.28	< 0.01*	3.2	0.47	< 0.01*	−4.2	0.63	< 0.01*
Maximum in stance (°)	48.2	−2.6	0.20	< 0.01	1.9	0.34	< 0.01*	1.3	0.45	< 0.01*
Maximum in swing (°)	67.4	−1.5	0.20	< 0.01*	4.4	0.35	< 0.01*	−2.2	0.46	< 0.01*
Ankle										
positive = dorsiflexion/negative = plantarflexion										
Initial contact (°)	2.3	−0.33	0.15	0.03	−1.5	0.26	< 0.01*	1.3	0.34	< 0.01
Maximal dorsiflexion stance (°)	17	−0.61	0.12	< 0.01*	−1.5	0.16	< 0.01*	–	–	n.s.

*Significant effect ($p < 0.01$).

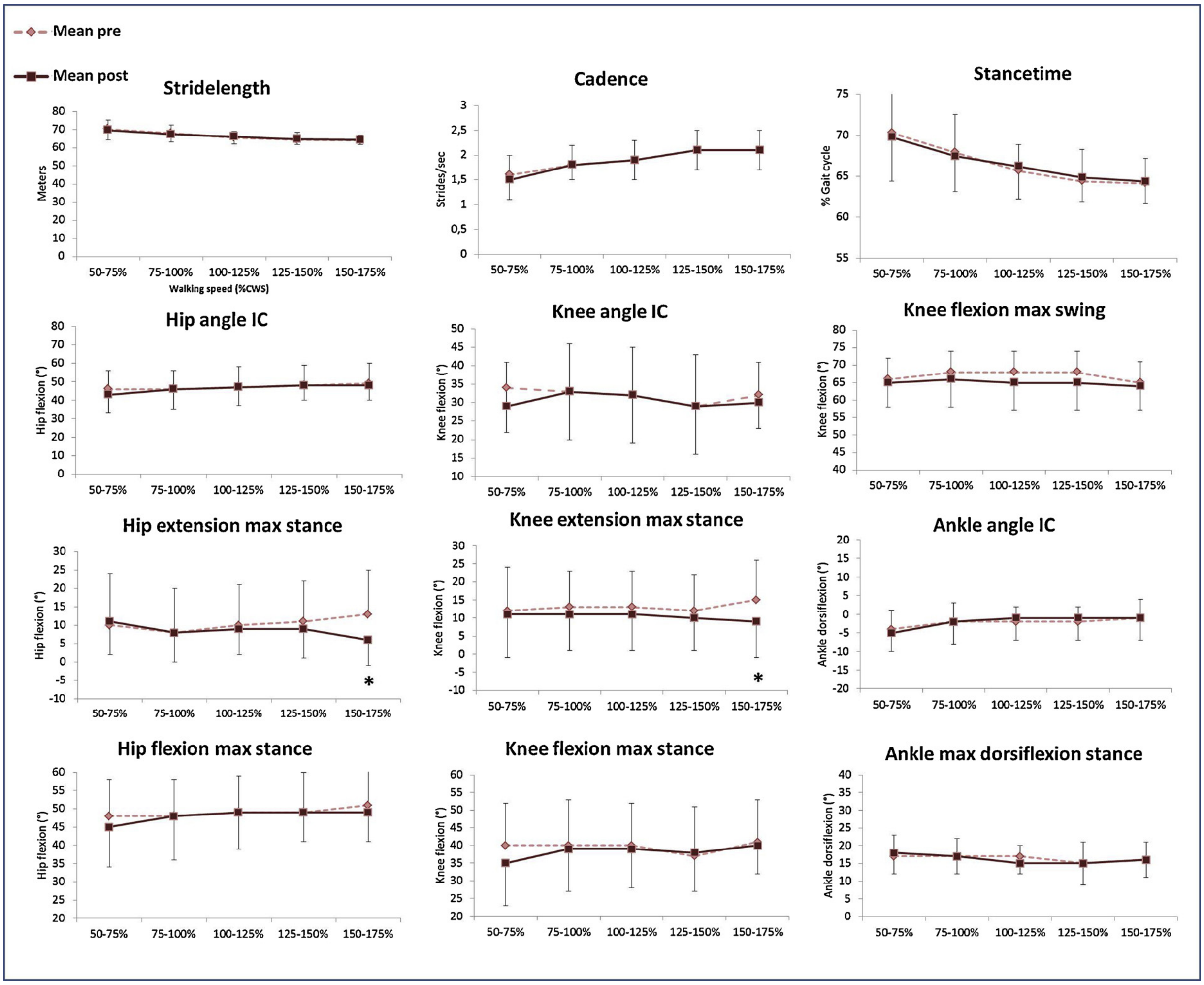

Fig. 1. Averaged group values + SD for spatiotemporal parameters and gait kinematics, before (dashed) and after (solid) training, at different walking velocities. Stars indicate significant changes > 5°, as indicated from post-hoc tests per interval. Positive values represent flexion/dorsiflexion. Walking speed was normalized to comfortable walking speed (CWS) before training (%). IC: initial contact (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

as well as a range of faster/slower walking velocities. Although some main effects of training were found for kinematics at CWS, in line with previous studies [4,8,10], effects were small (1–3°) and remained below a clinically meaningful threshold of 5° [30]. In line with a recent study by Gillet et al. [19], post-hoc analysis revealed no significant differences for any of the outcome parameters around comfortable walking speed (CWS).

In contrast, when inducing faster walking velocities, pre-post effects in sagittal knee and hip kinematics d better knee (5° at 150–175% CWS) and hip extension (6° at 150–175%) after the training program (Fig. 1), exceeding the predefined clinically relevant threshold of five degrees. Concerning the increased knee extension during stance, improved calf muscle strength (as previously reported by van Vulpen et al. [20,22]) might allow children to reach better knee extension by prevention of excessive tibia inclination during loading response [22]. Since walking speed in children with CP is often impaired to 75% of CWS in typically developing children [31], changes as found at faster speeds might be a good representative of daily life activities in children, for example while keeping up with peers. Thus, although the current clinical practice is to evaluate gait just at comfortable walking speed, this may lead to an underestimation of improvement.

Our statistical method to incorporate the effect of walking speed, including multiple individual data-points within children to evaluate effects of training in CP, is different from previously reported studies. Due to the use of treadmill walking, we analysed a relatively large number of strides (range 186–585 for individual children) at a gradual range of walking velocities. This allowed us to compare effects at a matched pre-post speed, but also to include their 'new' improved walking speed, representing functional mobility after the training program. The large number of strides and the use of a mixed model design with random intercept, further allowed to analyse data if pre-post velocities were not equally matched [29,32]. The significant results indicate that effects were consistent between children and strides, nevertheless it is important to keep in mind that the magnitude of effects was small and did not reach a clinically relevant threshold for all parameters. Given this precaution, we can conclude that although children with CP can improve gait kinematics after functional power training, effects are small and are only visible if children are challenged to walk at faster walking velocities.

In line with findings reported in a previous study, our participants improved significantly on all functional measures, even doubling their scores on the Shuttle Run Test and Muscle Power Sprint Test [22]. In addition, children's self-chosen comfortable walking speed increased, indicating that functional walking capacity improved. Given the discrepancy between the large effects seen in functional tests and CWS, versus small effects seen in kinematics, it is likely that changes occurred more prominent in the underlying mechanisms of neuromuscular motor control or physiological fitness, than in the motion performance itself as quantified by kinematics. By increasing maximal capacity through improved muscle strength or physiological fitness, in theory, motor tasks can be performed at a lower relative percentage of a child's maximum, leading to less fatigue. In the present study, this was originally tested for muscle activation, through collection of maximal voluntary contractions and electromyography during gait. However, due to problems with performing isolated movements during MVC [33,34], results were found to be unreliable and further excluded from analysis. However, we would like to encourage future research to explore alternative methods of quantifying maximal activation, as well as into include measures for energy expenditure.

Some caution should be taken when interpreting results of the present study. Effects of the functional power training were evaluated with a pre-post design, without inclusion of a control group or control period. Therefore, improvements might be influenced by natural development. In addition, even though walking on a treadmill results in a comparable gait pattern as overground walking [35] and treadmill habituation was included, effects post-training might have been influenced by learning effects of treadmill walking. Besides, although, the previous study by van Vulpen found comparable results on functional outcomes with inclusion of a control period [19,21], we cannot distinguish whether effects were driven by this particular type of power training and whether improvements would be different for another type or of strength training or training frequency. Another clear limitation of the present study is the absence of joint kinetics. Unfortunately, we cannot conclude whether ankle push-off power during gait improved after training. Besides, since gait features at different velocities were collected in different short trials, we cannot address whether less muscle fatigue occurred after training. It will be interesting for future research to look into these factors, providing more in-depth insights in the underlying changes leading to functional improvement.

In conclusion, our study demonstrates that gait kinematics can improve after functional power training, although the magnitude of improvement is smaller than effects on functional outcomes. Improvements after training were only visible when walking at faster speeds, and therefore effects of training may be underestimated when evaluating gait at comfortable walking speed alone. This emphasizes the need to challenge children during gait analysis, for example by incorporating a range of velocities when evaluating training outcomes directed at improving walking ability.

Declaration of Competing Interest

None.

Acknowledgements

A special thanks to all children for participating in the project and undergoing the additional gait analysis. A special thanks to all MegaPower trainers as well!

The authors would like to acknowledge Marjolein Piening for data collection and measurement organization.

This project was funded in part by the MD-Paedigree project: A Model-Driven Paediatric European Digital Repository, partially funded by the European Commission under P7-ICT-2011-9 program (600932).

References

[1] M.Q. Liu, F.C. Anderson, M.H. Schwartz, S.L. Delp, Muscle contributions to support and progression over a range of walking speeds, J. Biomech. 41 (15) (2008) 3243–3252.
[2] J.L. Honeine, M. Schieppati, O. Gagey, M.C. Do, The functional role of the triceps surae muscle during human locomotion, PLoS One 8 (1) (2013) e52943.
[3] M.M. van der Krogt, S.L. Delp, M.H. Schwartz, How robust is human gait to muscle weakness? Gait Posture 36 (1) (2012) 113–119.
[4] N.G. Moreau, M.J. Falvo, D.L. Damiano, Rapid force generation is impaired in cerebral palsy and is related to decreased muscle size and functional mobility, Gait Posture 35 (1) (2012) 154–158.
[5] K.M. Steele, M.M. van der Krogt, M.H. Schwartz, S.L. Delp, How much muscle strength is required to walk in a crouch gait? J. Biomech. 45 (15) (2012) 2564–2569.
[6] J.G. Becher, Pediatric rehabilitation in children with cerebral palsy: general management, classification of motor disorders, JPO 14 (2002).
[7] D.L. Damiano, Activity, activity, activity: rethinking our physical therapy approach to cerebral palsy, Phys. Ther. 86 (11) (2006) 1534–1540.
[8] K.J. Dodd, N.F. Taylor, D.L. Damiano, A systematic review of the effectiveness of strength-training programs for people with cerebral palsy, Arch. Phys. Med. Rehabil. 83 (8) (2002) 1157–1164.
[9] D. Damiano, M.F. Abel, Functional outcomes of strength training in spastic cerebral palsy, Arch. Phys. Med. Rehabil. 79 (1998) 119–125.
[10] V.A. Scholtes, J.G. Becher, Y.J. Janssen-Potten, H. Dekkers, L. Smallenbroek, A.J. Dallmeijer, Effectiveness of functional progressive resistance exercise training on walking ability in children with cerebral palsy: a randomized controlled trial, Res. Dev. Disabil. 33 (1) (2012) 181–188.
[11] R.N. Boyd, Functional progressive resistance training improves muscle strength but not walking ability in children with cerebral palsy, J. Physiother. 58 (3) (2012) 197.
[12] J.G. Gillett, R.N. Boyd, C.P. Carty, L.A. Barber, The impact of strength training on skeletal muscle morphology and architecture in children and adolescents with spastic cerebral palsy: a systematic review, Res. Dev. Disabil. 56 (2016) 183–196.
[13] A.S. Papavasiliou, Management of motor problems in cerebral palsy: a critical update for the clinician, Eur. J. Paediatr. Neurol. 13 (5) (2009) 387–396.
[14] A. Scianni, J.M. Butler, L. Ada, L.F. Teixeira-Salmela, Muscle strengthening is not effective in children and adolescents with cerebral palsy: a systematic review, Aust. J. Physiother. 55 (2) (2009) 81–87.
[15] C. Schranz, A. Kruse, T. Belohlavek, G. Steinwender, M. Tilp, T. Pieber, et al., Does home-based progressive resistance or high intensity circuit training improve strength, function, activity or participation in children with cerebral palsy? Arch. Phys. Med. Rehabil. (2018).
[16] K.J. Dodd, N.F. Taylor, H.K. Graham, A randomized clinical trial of strength training in young people with cerebral palsy, Dev. Med. Child Neurol. 45 (10) (2003).
[17] J.R. Engsberg, S.A. Ross, D.R. Collins, Increasing ankle strength to improve gait and function in children with cerebral palsy: a pilot study, Pediatr. Phys. Ther. 18 (4) (2006) 266–275.
[18] J.F. Morton, M. Brownlee, A.K. McFadyen, The effects of progressive resistance training for children with cerebral palsy, Clin. Rehabil. 19 (3) (2005) 283–289.
[19] J.G. Gillett, G.A. Lichtwark, R.N. Boyd, C.P. Carty, L.A. Barber, The effect of combined functional anaerobic and strength training on treadmill gait kinematics and kinetics in ambulatory young adults with cerebral palsy, Gait Posture 70 (2019) 323–329.
[20] L.F. van Vulpen, S. de Groot, E.A.A. Rameckers, J.G. Becher, A.J. Dallmeijer, Effectiveness of functional power training on walking ability in young children with cerebral palsy: study protocol of a double-baseline trial, Pediatr. Phys. Ther. 29 (3) (2017) 275–282.
[21] L.F. Van Vulpen, S. De Groot, J.G. Becher, G.S. De Wolf, A.J. Dallmeijer, Feasibility and test-retest reliability of measuring lower-limb strength in young children with cerebral palsy, Eur. J. Phys. Rehabil. Med. 49 (2013) 1–11.
[22] L.F. van Vulpen, S. de Groot, E. Rameckers, J.G. Becher, A.J. Dallmeijer, Improved walking capacity and muscle strength after functional power-training in young children with cerebral palsy, Neurorehabil. Neural Repair 31 (9) (2017) 827–841.
[23] L.H. Sloot, M.M. van der Krogt, J. Harlaar, Self-paced versus fixed speed treadmill walking, Gait Posture 39 (1) (2014) 478–484.
[24] A.J. van den Bogert, T. Geijtenbeek, O. Even-Zohar, F. Steenbrink, E.C. Hardin, A real-time system for biomechanical analysis of human movement and muscle function, Med. Biol. Eng. Comput. 51 (10) (2013) 1069–1077.
[25] O. Verschuren, B.C. Bongers, J. Obeid, T. Ruyten, T. Takken, Validity of the muscle power sprint test in ambulatory youth with cerebral palsy, Pediatr. Phys. Ther. 25 (1) (2013) 25–28.
[26] O. Verschuren, T. Takken, M. Ketelaar, J.W. Gorter, P.J.M. Helders, Reliability and validity of data for 2 newly developed shuttle run tests in children with cerebral palsy, Phys. Ther. 86 (8) (2006) 1107–1117.
[27] O. Verschuren, M. Ketelaar, D. Keefer, V. Wright, J. Butler, L. Ada, et al., Identification of a core set of exercise tests for children and adolescents with cerebral palsy: a Delphi survey of researchers and clinicians, Dev. Med. Child Neurol. 53 (5) (2011) 449–456.
[28] J.A. Zeni Jr, J.G. Richards, J.S. Higginson, Two simple methods for determining gait events during treadmill and overground walking using kinematic data, Gait Posture 27 (4) (2008) 710–714.
[29] J.W.R. Twisk, Longitudinal data analysis. A comparison between generalized estimating equations and random coefficient analysis, Eur. J. Epidemiol. 19 (8) (2004) 769–776.
[30] J.L. McGinley, R. Baker, R. Wolfe, M.E. Morris, The reliability of three-dimensional kinematic gait measurements: a systematic review, Gait Posture 29 (3) (2009) 360–369.
[31] M.F. Abel, D. Damiano, Strategies for increasing walking speed in diplegic cerebral palsy, J. Pediatr. Orthop. 16 (6) (1996) 753–758.
[32] J. Twisk, M. de Boer, W. de Vente, M. Heymans, Multiple imputation of missing values was not necessary before performing a longitudinal mixed-model analysis, J. Clin. Epidemiol. 66 (9) (2013) 1022–1028.
[33] K. Tedroff, L.M. Knutson, G.L. Soderberg, Synergistic muscle activation during maximum voluntary contractions in children with and without spastic cerebral palsy, Dev. Med. Child Neurol. 48 (10) (2006) 789–796.
[34] E.G. Fowler, L.A. Staudt, M.B. Greenberg, Lower-extremity selective voluntary motor control in patients with spastic cerebral palsy: increased distal motor impairment, Dev. Med. Child Neurol. 52 (3) (2010) 264–269.
[35] M.M. van der Krogt, L.H. Sloot, J. Harlaar, Overground versus self-paced treadmill walking in a virtual environment in children with cerebral palsy, Gait Posture 40 (4) (2014) 587–593.