Int Clin Neurosci J. 2023;10:e14 Original Article

doi:10.34172/icnj.2023.14

Effectiveness of Gait Training Using Dynamic Bodyweight Support System on Locomotor Abilities of Ambulatory Children With Different Neural Disorders

Afsaneh Zeinalzadeh[1], Reza Lotfi[2,3], Hasan Barmaki[3], Mohammad Lotfi[3], Alireza Shadman[4], Ali Asadi[3], Hamid Reza Kobravi[5*]

[1]Department of Physiotherapy, School of Paramedical and Rehabilitation Sciences, Mashhad University of Medical Sciences, Mashhad, Iran
[2]Electrical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran
[3]Payamavaran Payamavaran Corporation, Mashhad, Iran
[4]Department of Industrial Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[5]Research Center of Biomedical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran

Abstract

Background: In this study, we evaluated the efficacy of dynamic bodyweight-supported training on the gait quality of children with different neural disorders.

Methods: Seventeen ambulatory children, aged 3 to 11 years, experiencing gait limitations, were selected to participate in the designed gait training program. Each child participated in 10 practice sessions held three days a week, with each training session using the dynamic body weight support system, comprising three stages, and lasting 20 minutes. Clinical assessments were conducted using four functional tests: "Five Time Sit to Stand Test (FSST)", "Modified Time Up and Go (MTUG)", "Time Up and Down Stairs (TUDS)", and "Pediatric Berg Balance Scale" (BBS).

Results: Statistical tests demonstrated a significant increase in the post-values of the BBS after gait training. Notably, children with higher relative cognitive abilities showed more improvement. Additionally, there was a significant enhancement in the assigned score for the level of independence. As all participants had received conventional physical therapies for more than three years, reaching their maximum obtainable improvements with conventional training methods, the observed improvements could be attributed to the designed training protocol even without a control group.

Conclusion: Designed gait training protocol using a dynamic weight support system proved effective in enhancing balance, improving gait quality, and increasing the level of independence during performing functional tests in ambulatory children suffering from different locomotor disabilities.

Keywords: Gait; Child; Walk; Postural balance; Rehabilitation.

Received: January 8, 2023 **Accepted:** November 12, 2023 **Published online:** December 20, 2023

Citation: Zeinalzadeh A, Lotfi R, Barmaki H, Lotfi M, Shadman A, Asadi A, et al. Effectiveness of gait training using dynamic bodyweight support system on locomotor abilities of ambulatory children with different neural disorders. Int Clin Neurosci J. 2023;10:e14. doi:10.34172/icnj.2023.14.

Introduction

Gait rehabilitation in children with cerebral palsy (CP) employs various approaches including exoskeletons, functional electrical stimulation (FES), and body-weight supported system (BWSS).[1-3] Genuine rehabilitation involves the emergence of motor learning, and the effectiveness of the potentially impactful approaches can be evaluated based on their ability to foster motor learning. The exoskeletons are promising devices.[1,4] However, they restrict participants' natural degree of freedom, which may hinder the development of musculoskeletal synergetic patterns emerging from exercise and necessary for generating a normal gait. Additionally, there is some evidence suggesting that FES, as a well-known rehabilitation strategy, has beneficial effects on muscle strength, muscle activation, and the learning of movement in children with CP.[3, 5] Nevertheless, the use of FES can expedite muscle fatigue. [3] Moreover, using FES requires long training periods before starting the gait-related intervention.[6] Such limitations impede its effectiveness.

In comparison to exoskeleton systems and FES systems, the bodyweight support systems not only provide users with full kinematic freedom but also facilitate active participation, which is necessary for motor learning. Therefore, several prominent works have focused on gait recovery using the BWSS.[2,7-10] Particularly, BWSS has shown potential benefits for CP children.[11-13] It has been shown that treadmill training with partial body weight

*Correspondence to: Hamid Reza Kobravi, Email: hr.Kobravi@iau.ac.ir

support is a promising treatment for nonambulatory CP children.[13] This is evidenced by increased values in important clinical measures such as the functional ambulation category and gross motor function measure following the intervention.[12] Also, some research reports suggest that intensive and prolonged bodyweight-supported treadmill training (BWSTT) could be a beneficial interventional treatment for improving gait speed and endurance in children with different degrees of CP.[11] Furthermore, intriguing evidence has been presented demonstrating the positive effect of BWSTT on the endurance and functional gait of six CP children.[11] Researchers have also explored the feasibility of home-based BWSTT for three CP children,[2] with post-intervention improvements in the functional mobility of two participants.[2] Additionally, evidence supports the effectiveness of BWSTT in improving gait impairments and level of participation for individuals with CP.[13]

Interestingly, researchers have unveiled the positive impact of a BWSTT-based intervention on the Segmental Assessment of Trunk Control (SATCo) in three young children with CP.[12] Furthermore, some examinations have demonstrated the significant effect of BWSTT on gait and gross motor skill development in children with developmental delays.[10,14] In another study, the efficacy of exercising based on partial bodyweight-supported treadmill training (PBWSTT) was evaluated in thirty-four CP children.[15] The results elucidated the safety of PBWSTT for implementation in a special school setting, but it is no more effective than over-ground walking for improving walking speed.[15] It has been emphasized that concurrent over-ground walking alongside the PBWSTT boosts the improvement of over-ground walking.[15] Additionally, some studies prove the positive benefits of PBWSTT in walking speed over short distances, particularly for CP children with more severe walking disabilities and in the motor skills of children with spastic CP. [8,13]

In addition to the BWSTT, the influence of walking training based on body weight unloading (BWU) on gait characteristics was also investigated.[16] The evidence reveals more rigorous influence of BWU on the kinetic characteristics of gait compared to a treadmill or over-ground walking.[16] In particular, for CP children, the effectiveness of over-ground walking practices based on BWU using a rehabilitation robot called Andago has been assessed.[17] It has been shown that inter-joint coordination increased in Andago compared to treadmill walking.[17]

Nevertheless, some researchers find it challenging to draw decisive conclusions regarding the BWSS due to the small number of participants and the heterogeneous level of abilities of participants reported in the studies.[18] Furthermore, in the majority of the presented works body weight–support was used alongside treadmill training.[18-21] While the gait dynamics during treadmill training differ from those during over-ground walking, dynamic body-weight support system (DBWSS) could have an effective impact on rehabilitation outcomes.[22] Incorporating a treadmill, however, eliminates these capabilities. Thus, in this study, a BWSS endowed with a dynamic bodyweight supporting mechanism has been designed and implemented for gait rehabilitation in children with CP. In this study, the effectiveness of the designed DBWSS on the gait quality of CP children has been evaluated in terms of different functional indexes.

Methods

Participants

In the current study, the gait quality of the selected participants was evaluated once before and once after conducting gait exercises using the DBWSS. Participants were recruited through a specialized pediatric neurorehabilitation clinic in Mashhad (Iran). The selected participants included 17 children aged 3 to 11 years. The rational and acceptable sample size was designated compared to similar works. An expert team selected the children based on a study of their medical files and examinations. The participants suffered from spastic CP, motor delay disorder, CP due to atrophy of the cerebellum, CP due to Dandy-Walker syndrome, CP due to hydrocephalus, CP along with microcephaly, and motor disorder due to genetic disorders. The parents of each child filled out an informed consent form before participating in this study. A local ethics committee approved the study. The participant selection process was conducted under the supervision of expert physiographists, physical therapists, and *occupational therapists*. Each participant has met specific inclusion criteria. The main criterion was the value of the Gross Motor Function Measure (GMFM), which quantifies the severity of movement disability in CP children.[10,12,14] Children rated as level 3 or 4 of the GMFM, with no cardiovascular dysfunction, bone deformities, fixed contracture, and visual/auditory disorder were chosen.

Tests and Outcomes

In this study, gait and stability performance were evaluated once at baseline and once after five weeks of physical therapy using the designed DBWSS. The mentioned assessments were conducted by performing four functional tests including “Five Time Sit to Stand Test (FSST)”, “Modified Time Up and Go (MTUG)”, “Time Up and Down Stairs (TUDS)”, and “Pediatric Berg Balance Scale” (BBS).[23-26]

Functional Tests

FSST: In the FSST, the child rises from a standard seat five times as quickly as possible, then sits down, and the time duration is recorded. With a short break, the test is repeated. After three test performances, the average of three recorded time durations is taken as the output measure.[23]

MTUG: In the MTUG, the child travels three meters after rising from the standard seat, returns, and sits back in the seat. The test time is recorded. After a short rest, the test is repeated, and after the third time, the shortest time is recorded as the output measure.[24]

TUDS: In the TUDS test, the child climbs and returns on standard four steps stairs. The time from the beginning of the ascent to the descent from the last step is recorded as the output measure.[25]

Pediatric Berg Balance Scale (BBS): In the BBS, 14 functional tests are administered to the child. The score of each test item ranges from 0 to 4. A score of 0 indicates the lowest ability and a score of 4 indicates the maximum ability of the participant to perform the test. The test items include getting up from a chair, sitting on a chair, moving, standing without assistance and support, sitting on a chair without assistance and support, standing with closed eyes, standing with legs crossed, standing one step ahead, standing on one leg, 360-degree rotation, rotation to see behind, lifting the object from the ground from a standing position, alternating stepping on the step, and bending forward to grasp the object. Finally, the total score is recorded as the result of this test.[26]

The Implemented DBWSS

Figure 1 illustrates the structure of the designed and implemented DBWSS. In this system, there is a moving suspension unit connected to the harness. A trolley rail system transports this unit. Also, the implemented DBWSS is equipped with an intelligent propelling system. Thanks to this mechanism as children take one step forward, the position of the moving unit moves forward to align with the participant's position. This allows each child to walk freely at a preferred speed without imposing any speed restriction on the musculoskeletal system. We believe that removing this restriction could pave the way for the gradual relearning of the desired musculoskeletal synergy pattern that needs to be elicited during stable walking. This synergy pattern might be participant-specific and designated automatically during a gait training process. In other words, over-ground walking using a BWSS without removing speed restrictions may not yield such automatic designation by the neuromusculoskeletal system. Additionally, the value of bodyweight support can be easily adjusted between 0 to 22 pounds through mobile-based application software with a weight resolution of about 0.22 pounds. The determined percentage of body weight support is continuously adjusted by an embedded intelligent closed-loop system. This ensures that the determined percentage of body weight support remains unchanged as the participant goes up and down. Using a DBWSS, a gait training process can be performed in the presence of different obstacles and stairs, expediting the motor learning process.

Figure 1. A View of the Utilized Intelligent Dynamic Body-Weight Support System (DBWSS)

This intelligent DBWSS is suitable for children weighing up to about 88 pounds with a maximum height of 4.5 feet. In addition, the system can record various kinematic and gait-related quantities such as deviation angles and the number of strides, which can be used for supplementary analysis. It's worth noting that all technical reliability and technical repeatability tests have been certified by relevant organizations and experts.

Training Protocol

There were ten practice sessions for each child, usually held three days a week and continuously. Before starting the ten-session training period, one to three sessions of familiarity with the device and exercises were considered for each person. In these sessions, the child was introduced to the machine and the harness, and the therapist explained how to perform the exercises, preparing the child to start the main practice sessions. In each training session with the device, three steps of gait training were performed, including normal walking (gait) for ten minutes, going up and down on a sloping surface for 5 minutes, and going up and down 4 stairs for 5 minutes. Thanks to the dynamic body-weight system, the bodyweight support percent has been preserved during going up and down. During each step, the distance traveled by the child, the number of strides, and the maximum forward, right, left, and back deviation angles were measured and stored for further analysis. The number of times the child walked in different directions was also recorded. The physiotherapist was responsible for accompanying the child in all stages of the training and recording the results. Figure 2 shows a child conducting three steps of gait training using DBWSS.

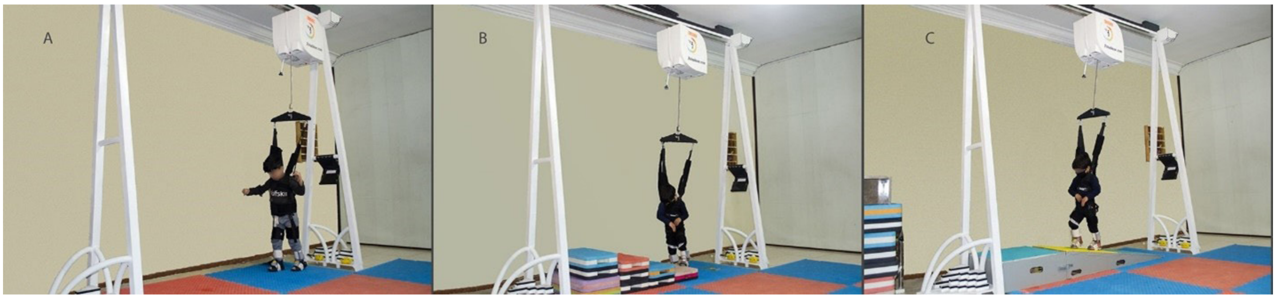

Figure 2. Three steps of gait training exercises (A: normal walking, B: going up and down 4 stairs, C: going up and down on a sloping surface)

Data Analysis

Means and standard deviations were calculated for all computed scores related to the functional tests. Before and after the physical therapy using the DBWSS, none of the children could afford to perform the functional tests independently, except for the Berg Balance Test. In this study, to quantify this important progression, a measure called the level of independence (LI) was envisioned. The assigned quantized number ranged from 0 to 3, where a score of zero means the child could not conduct the test even with assistance, and a score of 3 means the child could perform the test independently without any assistance.

The gait training process was filmed, and a group of experts determined the scores after reviewing the recorded films. Thus, the Wilcoxon signed-rank test was adopted to examine whether differences existed between week one and week five for the possible progression of the balance situation using the BBS. In addition, the MARGINAL HOMOGENEITY TEST was used to examine whether differences existed between week one and week five for possible increasing the LI values.

Results

Table 1 shows the level of GMFM and some important descriptive characteristics related to the type of diagnosed CP, assistive devices and orthoses, and prior physical therapy that each child had received. The results of individual and group analyses will be elaborated on in the following subsections.

Group Results

Table 2 shows the results of the Berg Balance test for the group. The result of the Wilcoxon signed-rank test indicates significant differences between the pre-values and post-values of the pediatric BBS (P value < 0.001). Figure 3 shows the related box plot graphically delineating the observed difference. According to Figure 3, the median of the BBS increased after physical therapy using DBWSS. Therefore, one can conclude that balance quality significantly improved after participating in the training sessions using DBWSS. Also, Table 2 presents the results of determining the LI values for participating children. A distinct LI value has been assigned to each functional test. The marginal homogeneity test showed significant differences between the pre-values and post-values of LI related to FSST (P = 0.012), and TUDS (P = 0.020). However, no significant differences were observed between the pre-values and post-values of LI related to MTUG (P = 0.052). Nevertheless, other analyses elucidated that although the values of MTUG have not changed significantly, their values have increased relatively. Overall, according to Table 3, the LI values increased significantly (relatively) after conducting the physical therapeutic interventions using DBWSS.

Table 1. Participant Demographics

Participant	Age	Gender	Weight	Diagnosis	GMFCS Level
1	6	Male	15	Spastic diplegia	3
2	6	Male	24	Spastic quadriplegia	4
3	3	Female	9	Genetic disorder	4
4	11	Male	22.5	Cerebellar atrophy	4
5	4	Female	14	Dandy-Walker syndrome	2
6	8	Male	22	Spastic diplegia	4
7	5	Female	12	Genetic disorder	3
8	4	Female	12	Spastic diplegia	3
9	4	Male	13	Weakness	3
10	3	Female	11	Cerebral palsy	4
11	3	Female	15	Motor delay	4
12	6	Female	10	Cerebral palsy (Microcephaly)	4
13	4	Male	14	Spastic diplegia	4
14	6	Female	15	Cerebral palsy	3
15	4	Male	13	Spastic diplegia	3
16	3	Male	10	Hydrocephaly	4
17	4	Female	15	Weakness	4

Individual Results

Table 3 presents the pre-post-values of the BBS and the LI values related to the FSST, MTUG, and TUDS calculated for each child separately. The balance scale increased for all children. Furthermore, the most significant improvement was observed for participant number 6

Table 2. The Results of Statistical Tests Related to the Berg Balance Scale (BBS), Five Time Sit to Stand Test (FSST), Modified Time Up and Go (MTUG), and Time Up and Down Stairs (TUDS)

	Mean ± SD	**Median (IQR)**	***P* value**
BBS			
Pre	26.41 ± 16.32	28.0 (34.0)	
Post	34.12 ± 12.52	35.0 (21.5)	
Difference (Post-pre)	7.71 ± 6.52	6.0 (8.5)	< 0.001
FSST			
Pre	1.65 ± 1.17	2.0 (2.5)	
Post	2.24 ± 0.75	2.0 (1.0)	
Difference (Post-pre)	0.59 ± 0.79	0.0 (1.0)	0.012
MTUG			
Pre	1.71 ± 1.16	2.0 (2.5)	
Post	2.12 ± 0.70	2.0 (1.0)	
Difference (Post-pre)	0.41 ± 0.79	0.0 (0.5)	0.052
TUDS			
Pre	1.41 ± 0.87	2.0 (1.5)	
Post	1.82 ± 0.53	2.0 (0.5)	
Difference (Post-pre)	0.41 ± 0.62	0.0 (1.0)	0.020

IQR: Interquartile range, SD: Standard deviation.
* Significant at $P < 0.05$.

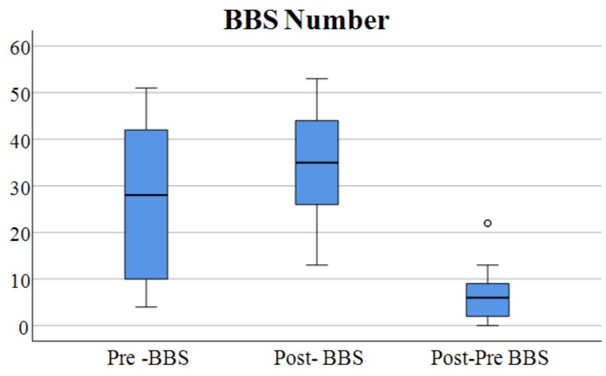

Figure 3. Graphically Description of the Observed Difference Between the Group Medians on Pre-values and Post-values of the Berg Balance Scale (BBS)

(22) and the next highest improvement was observed for participant number 15 (13). Interestingly, their cognitive abilities were lower compared to most participants. The first is a child with spastic quadriplegia CP and the latter is not a CP child and suffers from another disorder. The least increase was observed for participants number 1, 4, 6, and 7 (2). The pre-test Berg Balance Scale obtained for the mentioned children was more than 40. These results show that the balance-preserving capability in children, whose pre-test balance quality was considerable, did not increase significantly. Also, according to Table 3, the LI values either increased or did not change. As explained previously, overall, the post-values of LI increased significantly.

Considering this result, analyzing Table 3 reveals an interesting point. The most significant improvement was observed for participant number 12. He could not perform any functional tests independently before conducting the gait training exercises. After training, the scores of FSST and MTUG improved to 2. The situation of participant number 16 is also similar to participant number 12. Participant number 12 suffers from CP due to microcephalus and participant number 16 suffers from CP due to hydrocephalus. Furthermore, it is worth noting that after training, participants number 1 and 7 could walk independently without a walker.

Table 3. pre-values and post-values of the Berg Balance Scale (BBS) and the LI values related to the Five Time Sit to Stand Test (FSST), Modified Time Up and Go (MTUG), and Time Up and Down Stairs (TUDS) calculated for each child separately

Participant	**TUDS**		**MTUG**		**FSST**		**BBS**	
	Pre-test	**Post-test**	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**
1	2	2	3	3	3	3	45	43
2	2	2	2	2	1	2	35	30
3	1	1	1	1	2	2	15	6
4	2	2	2	2	1	3	43	38
5	2	3	3	3	3	3	53	51
6	0	1	0	2	0	1	26	4
7	2	2	3	3	3	3	52	48
8	2	2	2	2	2	2	38	30
9	2	2	3	3	3	3	44	42
10	0	1	0	1	0	1	13	4
11	2	2	2	2	2	2	31	23
12	1	2	0	2	0	2	32	10
13	0	1	1	1	1	1	20	14
14	2	2	3	3	3	3	45	43
15	2	2	2	2	2	3	41	28
16	0	2	0	2	0	2	19	7
17	2	2	2	2	2	2	28	28

Discussion

Velocity can be an influential contributor to movement dynamics.[27] Therefore, asking participants to move slowly fails to take into account the interaction between speed and physical properties that play a key role in producing momentums,[27] let alone limiting the gait velocity. According to the aforementioned reasons, using dynamic weight support while the child walks freely over the ground alongside a bodyweight support system could be a prelude to accomplishing an associative learning process. Ambulatory children can do the exercises at their preferred (different) speeds. Thus, in this study, an intelligent DBWSS was used to conduct the gait training process in ambulatory children with gait limitations. As expected, the achieved results testify to the presumptions because the Berg Balance Scale and the level of LI during performing the functional test have increased significantly. After training, some of the children were able to walk even without a walker. Such observations could prove that sensory-motor integration has been boosted which we believe arises from motor learning. After training, the children were able to walk with much better quality repeatedly, becoming able to walk independently with or without a walker. This result elucidates that after the physical therapy, the children could perform the designated functional tests with considerably more independence. Performing such movement skills repeatedly needs a synergetic collaboration among the involved muscle-joint systems, guaranteeing balance. Emerging such musculoskeletal synergetic collaboration could be a sign of modifying motor programs. This achievement elucidates that gait training using DBWSS yielded improved neuromuscular coordination giving rise to a more stable gait and boosted balance quality during the gait. In addition, scrutinizing different aspects of the individual results can reveal intriguing and interesting points. As explained previously, the least increase in the Berg Balance Scale was observed mostly in the participants whose score was more than 40. The balance preserving emerges from cooperation among the muscles leading to the control of the center of pressure (CoP). Therefore, boosting this ability means enhancing the processing of received proprioceptive information transferred from muscles to the upper level of the central nervous system. This means empowering neurocognitive processing. Since the severity of pediatric traumatic brain injury has a significant impact on neurocognitive outcomes,[28] brain trauma could limit the possible balance improvement. The mentioned participants had received classical physical therapies for about one year and according to the situation of their brain trauma they had reached the maximum possible improvement. Nevertheless, training using DBWSS has caused enhancing the aforementioned information processing in the mentioned participants albeit it was less than most of the participants. Another intriguing point is the significant increase in the BBS in the children whose post-value of LI has not changed significantly. However, after training, all children could walk independently with or without a walker. This can prove the positive effect of training using DBWSS on sensory-motor coupling because preserving the balance during supported/unsupported standing or during supported/unsupported gait needs such communication between sensory and motor systems. In other words, this observation shows that even though the locomotor abilities have not changed significantly, the sensory-motor integration improved. Because properly conducting the Berg balance test needs proper communication between the motor and sensory systems. In addition, it seems that utilizing a dynamic weight support mechanism could engage the specific intact neural networks of the brain involved in associative learning. This could cover the cognitive shortages. This finding aligns with recent research showing improvement in children with considerable cognitive shortages because all of them elucidate the influential role of gait training using the DBWSS in enhancing the process of receiving information through senses, interpreting, and organizing it. Nevertheless, our results show that the participants whose cognitive abilities were relatively higher compared to the others (participants number 1 and 7) could walk without a walker after training. It could be justifiable because some evidence proves the impact of cognitive impairment on specific gait parameters and static balance.[29] Furthermore, the planned physical therapy even if has not had a positive effect on a child, yet it has not degraded the achievements related to prior training exercises received by that child. Such findings could certify the posed presumption regarding the necessity of dynamic weight support and intelligent propelling. Because such a system could pave the way for conducting the training under conditions that elicit motor learning.

One limitation of this research was the lack of a control group. Two control groups could be constituted. One group comprises a sample of children with the neural disorder who only received classical physical therapy, and another group is comprised of children who conducted BWSTT. Owing to this limitation, the generalizability of the findings is limited. Furthermore, the superiority of training using DBWSS to body weight-supported treadmill training cannot be proved decisively. Nevertheless, all participating children had received classical physical therapies for about one year and the pediatric physical therapists believed that they reached the maximum improvement. Thus, observing the mentioned improvements may show the relative efficacy of the proposed gait training strategy in comparison to the classical physical therapies. In addition, although there were no participants who received BWSTT, at least, the mentioned findings can certify the purported expectations regarding eliciting motor learning using DBWSS. Furthermore, the authors have not found dazzling and prominent research related to DBWSS which has been published so far. Nevertheless, it is emphasized again on the necessity of constituting two mentioned control groups in future works. Another limitation of this study was the nonuniform distribution of participants. In other words, the number of spastic CP, motor delay disorder, CP due to atrophy of the cerebellum, CP due to Dandy-Walker syndrome, CP due to hydrocephalus, and CP along with microcephaly was not equal. In this study, children with different neural disorders participated and the number of participants was more than the number of participants reported in some of the distinguished works.[10,11] Although this might generalize the findings partially, the number of children with different neural disorders was not equal. This issue has to be also addressed in future studies. It would be rather the participants are categorized uniformly into different groups in terms of the type of disorder. In a manner that at least three participants are assigned to each group.

Authors' Contribution

Conceptualization: Afsaneh Zeinalzadeh, Reza Lotfi, Hamid Reza Kobravi.
Data curation: Hamid Reza Kobravi, Alireza Shadmehri, Reza Asadi.
Formal analysis: Hamid Reza Kobravi.
Funding acquisition: Mohammad Lotfi.
Investigation: Afsaneh Zeinalzadeh, Hamid Reza Kobravi, Reza Asadi.
Methodology: Afsaneh Zeinalzadeh.
Project administration: Mohammad Lotfi.
Resources: Mohammad Lotfi, Reza Lotfi.
Software: Alireza Shadmehri.
Supervision: Reza Lotfi.
Validation: Hamid Reza Kobravi.
Visualization: Hamid Reza Kobravi.
Writing–original draft: Hamid Reza Kobravi, Hasan Barmaki.
Writing–review & editing: Hasan Barmaki.

Competing Interests

None declared.

Ethical Approval

The ethical committee of Ferdwosi University of Mashhad has certified that all applicable institutional regulations concerning the ethical use of human volunteers were addressed in this research (Ethical Committee Code: IR.UM.REC.1400.099). Furthermore, the children's parents filled out the informed consent form. In addition, the authors declare that they have no conflict of interest.

Funding

Payamavaran Corporation, Mashhad, Iran.

References

1. Shideler BL, Bulea TC, Chen J, Stanley CJ, Gravunder AJ, Damiano DL. Toward a hybrid exoskeleton for crouch gait in children with cerebral palsy: neuromuscular electrical stimulation for improved knee extension. J Neuroeng Rehabil. 2020;17(1):121. doi: 10.1186/s12984-020-00738-7.
2. Kenyon LK, Westman M, Hefferan A, McCrary PPD, Baker B. A home-based body weight supported treadmill training program for children with cerebral palsy: a case series. Physiother Theory Pract. 2017;33(7):576-85. doi: 10.1080/09593985.2017.1325956.
3. Singleton C, Jones H, Maycock L. Functional electrical stimulation (FES) for children and young people with cerebral palsy. Paediatr Child Health. 2019;29(11):498-502. doi: 10.1016/j.paed.2019.07.015.
4. Zhu F, Kern M, Fowkes E, Afzal T, Contreras-Vidal JL, Francisco GE, et al. Effects of an exoskeleton-assisted gait training on post-stroke lower-limb muscle coordination. J Neural Eng. 2021;18(4). doi: 10.1088/1741-2552/abf0d5.
5. Mukhopadhyay R, Mahadevappa M, Lenka PK, Biswas A. Effect of FES in rehabilitation of cerebral palsy children by analysis of surface EMG in tibialis anterior muscle. In: 2014 IEEE 19th International Functional Electrical Stimulation Society Annual Conference (IFESS). Kuala Lumpur, Malaysia: IEEE; 2014. p. 1-5. doi: 10.1109/ifess.2014.7036755.
6. del-Ama AJ, Gil-Agudo Á, Bravo-Esteban E, Pérez-Nombela S, Pons JL, Moreno JC. Hybrid therapy of walking with Kinesis overground robot for persons with incomplete spinal cord injury: a feasibility study. Rob Auton Syst. 2015;73:44-58. doi: 10.1016/j.robot.2014.10.014.
7. Gama GL, Celestino ML, Barela JA, Forrester L, Whitall J, Barela AM. Effects of gait training with body weight support on a treadmill versus overground in individuals with stroke. Arch Phys Med Rehabil. 2017;98(4):738-45. doi: 10.1016/j.apmr.2016.11.022.
8. Ganesan M, Sathyaprabha TN, Pal PK, Gupta A. Partial body weight-supported treadmill training in patients with Parkinson disease: impact on gait and clinical manifestation. Arch Phys Med Rehabil. 2015;96(9):1557-65. doi: 10.1016/j.apmr.2015.05.007.
9. Willoughby KL, Dodd KJ, Shields N. A systematic review of the effectiveness of treadmill training for children with cerebral palsy. Disabil Rehabil. 2009;31(24):1971-9. doi: 10.3109/09638280902874204.
10. Lowe L, McMillan AG, Yates C. Body weight support treadmill training for children with developmental delay who are ambulatory. Pediatr Phys Ther. 2015;27(4):386-94. doi: 10.1097/pep.0000000000000172.
11. Provost B, Dieruf K, Burtner PA, Phillips JP, Bernitsky-Beddingfield A, Sullivan KJ, et al. Endurance and gait in children with cerebral palsy after intensive body weight-supported treadmill training. Pediatr Phys Ther. 2007;19(1):2-10. doi: 10.1097/01.pep.0000249418.25913.a3.
12. Flores MB, Da Silva CP. Trunk control and gross motor outcomes after body weight supported treadmill training in young children with severe cerebral palsy: a non-experimental case series. Dev Neurorehabil. 2019;22(7):499-503. doi: 10.1080/17518423.2018.1527862.
13. Mattern-Baxter K. Effects of partial body weight supported treadmill training on children with cerebral palsy. Pediatr Phys Ther. 2009;21(1):12-22. doi: 10.1097/PEP.0b013e318196ef42.
14. Su IY, Chung KK, Chow DH. Treadmill training with partial body weight support compared with conventional gait training for low-functioning children and adolescents with nonspastic cerebral palsy: a two-period crossover study. Prosthet Orthot Int. 2013;37(6):445-53. doi: 10.1177/0309364613476532.
15. Willoughby KL, Dodd KJ, Shields N, Foley S. Efficacy of partial body weight-supported treadmill training compared with overground walking practice for children with cerebral palsy: a randomized controlled trial. Arch Phys Med Rehabil. 2010;91(3):333-9. doi: 10.1016/j.apmr.2009.10.029.
16. Apte S, Plooij M, Vallery H. Influence of body weight unloading on human gait characteristics: a systematic review. J Neuroeng Rehabil. 2018;15(1):53. doi: 10.1186/s12984-018-0380-0.
17. van Hedel HJA, Rosselli I, Baumgartner-Ricklin S. Clinical utility of the over-ground bodyweight-supporting walking system Andago in children and youths with gait impairments. J Neuroeng Rehabil. 2021;18(1):29. doi: 10.1186/s12984-021-00827-1.
18. Mutlu A, Krosschell K, Spira DG. Treadmill training with partial body-weight support in children with cerebral palsy: a systematic review. Dev Med Child Neurol. 2009;51(4):268-75. doi: 10.1111/j.1469-8749.2008.03221.x.
19. Kawasaki S, Ohata K, Yoshida T, Yokoyama A, Yamada S. Gait improvements by assisting hip movements with the robot in children with cerebral palsy: a pilot randomized controlled trial. J Neuroeng Rehabil. 2020;17(1):87. doi: 10.1186/s12984-020-00712-3.
20. Pignolo L, Basta G, Carozzo S, Bilotta M, Todaro MR, Serra

S, et al. A body-weight-supported visual feedback system for gait recovering in stroke patients: a randomized controlled study. Gait Posture. 2020;82:287-93. doi: 10.1016/j.gaitpost.2020.09.020.

21. Begnoche DM, Pitetti KH. Effects of traditional treatment and partial body weight treadmill training on the motor skills of children with spastic cerebral palsy. A pilot study. Pediatr Phys Ther. 2007;19(1):11-9. doi: 10.1097/01.pep.0000250023.06672.b6.
22. Huber JP, Sawaki L. Dynamic body-weight support to boost rehabilitation outcomes in patients with non-traumatic spinal cord injury: an observational study. J Neuroeng Rehabil. 2020;17(1):157. doi: 10.1186/s12984-020-00791-2.
23. Wang TH, Liao HF, Peng YC. Reliability and validity of the five-repetition sit-to-stand test for children with cerebral palsy. Clin Rehabil. 2012;26(7):664-71. doi: 10.1177/0269215511426889.
24. Verbecque E, Vereeck L, Boudewyns A, Van de Heyning P, Hallemans A. A modified version of the timed up and go test for children who are preschoolers. Pediatr Phys Ther. 2016;28(4):409-15. doi: 10.1097/pep.0000000000000293.
25. Chrysagis N, Skordilis EK, Tsiganos G, Koutsouki D. Validity evidence of the Lateral Step Up (LSU) test for adolescents with spastic cerebral palsy. Disabil Rehabil. 2013;35(11):875-80. doi: 10.3109/09638288.2012.711896.
26. Franjoine MR, Gunther JS, Taylor MJ. Pediatric balance scale: a modified version of the berg balance scale for the school-age child with mild to moderate motor impairment. Pediatr Phys Ther. 2003;15(2):114-28. doi: 10.1097/01.pep.0000068117.48023.18.
27. Shumway-Cook A, Woollacott MH. Motor Control: Translating Research into Clinical Practice. Lippincott Williams & Wilkins; 2007.
28. Goh MSL, Looi DSH, Goh JL, Sultana R, Goh SSM, Lee JH, et al. The impact of traumatic brain injury on neurocognitive outcomes in children: a systematic review and meta-analysis. J Neurol Neurosurg Psychiatry. 2021;92(8):847-53. doi: 10.1136/jnnp-2020-325066.
29. Hanlon RE. Motor learning following unilateral stroke. Arch Phys Med Rehabil. 1996;77(8):811-5. doi: 10.1016/s0003-9993(96)90262-2.