Evaluation of Lower Body Positive Pressure Supported Treadmill Training for Children With Cerebral Palsy

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Purpose: To examine the feasibility of using lower body positive pressure supported (LBPPS) treadmill training to improve the walking abilities, balance and lower extremity strength of children with cerebral palsy (CP). **Methods:** Nine children with CP (GMFCS II-IV) participated in LBPPS treadmill training 2 days per week for 6 weeks. Pre and post training measures of preferred walking speed, spatiotemporal kinematics, lower extremity strength, and the BESTest were used to assess potential improvements from LBPPS treadmill training. **Results:** LBPPS treadmill training resulted in significantly faster walking speed, less time in double support, improved overall balance, and strength of the lower extremity antigravity musculature. **Conclusions:** It is feasible to use LBPPS treadmill training to improve the walking performance, balance, and strength of children with CP. **(Pediatr Phys Ther 2011;23:232–239)** *Key words: balance, biomechanics, body weight support, cerebral palsy, child, gait, gait training, locomotion, physical therapy, strength training*

INTRODUCTION

More than 3 of every 1000 children born in the United States have cerebral palsy (CP), and the prevalence of the disorder is on the rise worldwide.[1] Cerebral palsy typically results from a defect or insult to white matter of the periventricular area during birth or shortly after,[2] which reduces the fidelity of information that is transmitted along the thalamocortical and corticospinal tracts that are involved in the control of movement.[3] Although the brain insult does not progressively worsen, often musculoskeletal impairments accumulate as the child develops. Compared with children who are typically developing, these impairments result in a slower gait pattern with a shorter stride length and more time spent in double support.[4–6] Presumably these gait deviations are a result of poor balance, reduced strength of the antigravity musculature, and inadequate motor control of the lower extremity movement patterns.

A considerable amount of neurophysiologic evidence from animal models and humans with neurological damage has shown that walking on a treadmill with body weight partially supported has the potential to promote neuroplasticity in the damaged nervous system.[7,8] This reorganization is partly driven by afferent somatosensory cues that are triggered via the action of the treadmill belt. For example, as the trailing limb approaches the terminal portion of stance phase, the muscle spindles sense elongation of the hip flexor muscles, and Golgi tendon organs in the plantarflexor muscles sense unloading as weight is transferred forward onto the opposite limb. These sensory cues are powerful signals that bring about stance-to-swing phase transitions and contribute to rhythmic, alternating lower extremity movements during gait.[9–12] Insights from these

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studies have inspired the use of body weight–supported treadmill training (BWSTT) for improving the walking performance of children with CP. Several investigations have shown that the sensorimotor experience from BWSTT can improve walking speed, stride length, postural balance, and walking endurance of these children.[13–17] Furthermore, a functional magnetic resonance imaging investigation has shown that BWSTT can alter the activation of the primary sensorimotor cortices of children with CP while performing an ankle dorsiflexion task.[18] Overall the current scientific evidence suggests that BWSTT may be an efficacious therapy for improving the walking performance of children with CP.

Traditionally, BWSTT is performed by supporting an individual's body weight with a chest corset that has straps positioned under the groin area or around the proximal thighs. The lifting forces provided by the straps can be uncomfortable,[19,20] which may reduce the duration of the training sessions and hinder a patient's compliance with the training protocol. Despite their usefulness for gait rehabilitation, limited efforts have been made to improve how these devices support an individual's body weight. Recently, a lower body positive pressure support (LBPPS) system has emerged as an alternative means for supporting an individual's body weight during treadmill training (Figure 1).[20–23] This system consists of a treadmill that is enclosed in an inflatable bag. The subject wears a pair of neoprene shorts that are zipped into the bag. The amount of body weight supported is dependent upon the air pressure in the bag, which provides a lifting force on the body. The air pressure is uniformly distributed over the lower body, which reduces the uncomfortable pressure points that typically occur in more traditional body weight support systems.[20] Recent experiments have shown that LBPPS systems have similar physiologic and biomechanical responses as the more traditional harness-based body weight support systems.[20,23] No experiments however, have explored the feasibility of using an LBPPS as an alternative means for supporting the body weight of children with CP during treadmill training. These insights are necessary before this technology can begin to be integrated into mainstream physical therapy practice.

Recent advancements in body weight support technology may provide an opportunity to improve on the BWSTT therapeutic protocols that are being used for gait training in children with CP.[20–23] The primary purpose of this investigation was to initially examine the feasibility of using LBPPS treadmill training to improve the preferred walking speed of children with CP. Our secondary purpose was to evaluate the feasibility of LBPPS treadmill training for improving balance, spatiotemporal kinematics, and strength of the lower extremity antigravity musculature.

METHODS

Subjects

A total of 9 children (age = 13.8 ± 3 y; height = 1.45 ± 4 m; mass = 53 ± 9 kg; leg length = 0.77 ± 0.03 m) with CP who had Gross Motor Function Classification System (GMFCS) levels that ranged from II to IV[24] were recruited to participate in this investigation. One child had spastic hemiplegic involvement, and the remaining 8 children were diagnosed with spastic diplegia. Five of the children did not require assistive device for mobility (GMFCS II), 1 child used a wheeled walker (GMFCS III), and 3 of the children primarily used power mobility (GMFCS IV). Further details on the participating children are listed in Table 1. The parents of the children gave their written consent for their child's participation in the investigation, and the university's Committee for the Protection of Human Subjects approved the experimental protocol.

Intervention

LBPPS was provided by a commercially available system that consisted of a treadmill that was enclosed in a pressurized bag (Figure 1) (G-Trainer Pro; Alter-G Inc., Fremont, CA). The child wore a pair of neoprene shorts that were zipped into the bag, and the amount of body weight supported was dependent upon the bag's air pressurization. The air pressure was uniformly distributed over the lower body, which reduced the uncomfortable pressure points that typically occur in more traditional body weight support systems.[20] Furthermore, no support was provided around the torso as would be the case with more conventional body weight support systems. This freedom allowed the child to practice controlling the displacement of the torso's mass during the training sessions. The child was able to freely swing her/his arms during the training sessions or had the option to hold on to handrails that were at the front of the treadmill. Manual assistance for the legs was not provided during any of the training sessions because the child was enclosed in the LBPPS system. Therefore, any modification in the stepping pattern occurred through verbal feedback from the therapist or visual feedback that was provided by a mirror positioned on the right side of the treadmill perpendicular to the LBPPS system. The bag material does not allow for the child to see the legs when looking down. However, the bag does have translucent material on the side panels that allows the therapist to see the child's lower limbs, and the mirror allowed the child to also see his/her stepping pattern through the side panels.

The children participated in an LBPPS treadmill training program that was performed 2 days per week for 6 weeks, with a minimum of 1 day of rest between the training sessions. This protocol was based on a previous BWSTT study that showed that this training paradigm can improve the preferred walking speed of children with CP.[17] The general guidelines of the therapeutic prescription consisted of initially supporting 40% of the child's body weight, and gradually reducing it to 10% by the completion of the therapy. The speed of the treadmill was initially set at 90% of the child's over ground walking speed, and was gradually increased in each training session with a minimum goal of reaching a target speed of 0.89 m/s (2 miles/h) at the end of the therapy. This minimum speed was chosen because

Fig. 1. Alter-G, Inc., lower body positive pressure system, which consisted of a treadmill that is enclosed in an inflatable bag. Pressurizing the bag provides a lifting force that supported children's body weight as they walked on a treadmill that was enclosed in the bag.

TABLE 1
Participant Characteristics

Subject	Age (y)	Gender	Type	GMFCS	Walking Device	Orthoses
1	12	Male	Spastic diplegia	II	None	None
2	8	Male	Spastic diplegia	II	None	Bilateral solid AFOs
3	16	Female	Spastic diplegia	II	None	Bilateral articulated AFOs
4	15	Female	Hemiplegia	II	None	Unilateral articulated AFO
5	16	Male	Spastic diplegia	II	None	Bilateral solid AFOs
6	14	Female	Spastic diplegia	III	Wheeled walker	Bilateral solid AFOs
7	10	Male	Spastic diplegia	IV	Power mobility	Bilateral solid AFOs
8	18	Female	Spastic diplegia	IV	Power mobility	Bilateral solid AFOs
9	16	Female	Spastic diplegia	IV	Power mobility	Bilateral solid AFOs

Abbreviations: AFOs, ankle foot orthoses; GMFCS, Gross Motor Function Classification System level.

it represented the minimal walking speed for community ambulation.[25] Although this target speed minimum was prescribed, many of the children exceeded this speed during the training sessions. For each training session, the child accumulated a total of 30 minutes of walking (not including breaks). The children wore heart rate monitors and rest breaks were provided as needed; however, the children were encouraged to walk as long as possible. Rest was required if the child's heart rate exceeded 75% of age-predicted heart rate maximum. The amount of rest varied as the children progressed through the training sessions. Early training had more rest sessions that lasted 2 to 3 minutes. However, as the children's fitness level improved, the later training sessions had fewer rest periods.

All sessions were performed barefoot to increase the amount of cutaneous sensory feedback the nervous system was receiving about the stepping pattern. This rationale is supported by animal BWSTT studies that have shown that cutaneous feedback from the foot is necessary for shaping the appropriate foot placement, balance, and changes in the amount of weight supported by the limbs.[26,27] In addition, we suspected that the additional sensory feedback would be important for children with CP because they have a diminished thalamocortical response to peripheral tactile stimulation.[28]

Although the general LBPPS and walking speed guidelines were followed, these variables were not kept constant during the therapy sessions. Rather the training variables were manipulated within the training session to challenge the child's ability to maintain as normal a walking pattern as possible based on the therapist's judgment. Some of the key components the therapist focused on for this judgment were maintaining an upright lower limb posture, ankle push-off during terminal stance, and clearing the toe during swing. In addition, the children were instructed to alter their stepping patterns to explore different couplings of the lower extremity degrees of freedom. For example, the children were instructed to modify their step length and height of their steps and to alter their step width. Likewise, children who were GMFCS III-IV were encouraged to not hold onto the handrails and see how many steps they could complete. This approach allowed the children to explore how the degrees of freedom of their legs could be modified to meet the task constraints. All of the training sessions were supervised and instructions given by a pediatric physical therapist.

Some of the participants were receiving conventional physical therapy upon enrollment in the investigation. These participants were allowed to continue their therapy; however, they were asked to refrain from working on any lower extremity strength, flexibility, and gait-related training while in the study.

Outcome Measures

The participants walked along a 16-m walkway at a self-selected pace while a photocell timing system monitored their speed. The measured walking speed was normalized by $\sqrt{L\ gravity}$, where L is the child's leg length and gravity is 9.81 m/s.[2,29] The data were nondimentionalized to equate the outcome measures because they were collected from the children who had different anthropometrics and levels of motor impairments (GMFCS II-IV) that would influence their walking biomechanics.[29]

Children with a GMFCS level of III to IV used a wheeled walker during gait analysis. All other children walked unassisted during gait analysis. Pre-post data for analyses were assessed while the child was barefoot. Reflective markers were placed bilaterally on the heel and toe, and were tracked by an 8-camera motion capture system (120 Hz; Vicon, Centenial, CO). The 3-dimensional positions of the marker coordinates were smoothed with a zero-lag low-pass Butterworth filter at 6 Hz. The occurrences of foot contact and foot-off for the legs were determined from the local minimums of the heel and toe makers. Horizontal and lateral displacements of the right- and left-foot heel markers at foot contact were used to calculate the child's step length and width. These displacement values were normalized using subject leg length to adjust for differences in stature.[29] Foot contacts and foot-offs of the legs were used to calculate the stride and double support times. Similar to walking velocity, respective gait timings were normalized by $\sqrt{L\ gravity}$. The mean spatiotemporal values for each child were calculated from 5 representative walking trials.

Bilateral strength measurements of the lower extremity antigravity musculature were obtained with a hand-held dynamometer (Hoggan Health Industries, West Jordan, UT). Hip extensor strength was assessed in the supine position with the hip flexed 90°; knee extensor strength was measured in the sitting position with the hip and knee each flexed 90°; and ankle plantarflexor strength was measured in the supine position with the hip and knee extended and the ankle in a neutral position. Strength measurements were performed in the same order during the baseline and postassessments. Strength measures were taken a minimum of 2 times to ensure that the measures were consistent. Furthermore, the measures were taken by a physical therapist (BC) proficient in the use of the hand-held dynamometer. To create a composite score, strength measures for each leg were summed and divided by the child's body weight.

The Balance Evaluation System Test (BESTest) was used to assess the overall balance of the children who had a GMFCS level II or III.[30] The BESTest contains a series of separate evaluations that assess the child's balance on the basis of biomechanical constraints, stability limits, postural responses, sensory orientation, and gait stability. The total score from each of the subtests was used to assess overall change in the child's balance after BWSTT.

All of the outcome measures were log-transformed before undergoing statistical analysis to ensure that the values were normally distributed. The Kolomogrov-Smirnov tests confirmed that the log-transformed data sets were normally distributed ($P > .05$). Student t tests were used to determine whether there were significant differences pre- and postoutcome measures. A P value less than .05 was considered to be statistically significant. All results in the graphs and text are not log-transformed and are presented as the mean $\pm$ SEM. Cohen d was calculated to determine the effect size of the change in the outcome measures. The calculated effect sizes are interpreted as 0.2, small; 0.5, medium; and greater than 0.8, large.[31] Medium to large effects are clinically relevant because they are large enough to be observed.[32]

RESULTS

Only subjects 4 and 7 continued to participate in conventional physical therapy during the investigation. Self-report from the parents of these children indicated that they refrained from outside gait training, lower extremity strength training, and lower extremity flexibility exercises during the study.

There was 100% compliance with the training sessions. Overall, children and families responded positively to the experience. Participants were eager to get started and seemed to enjoy the opportunity to move in the system. Frequently when the participants were standing in the system they would spontaneously experiment with a movement they would ordinarily be unable to perform in full gravity such as bouncing, single-leg stance, kicking, jumping, and tall-kneeling to stand transfers. Caregivers frequently expressed interest in continued use of the system at the conclusion of the study and felt that their children had benefited from the experience. Barefoot walking was well tolerated by the participants. Although minimal, a few children experienced a skin abrasion when the foot was not appropriately cleared during swing. There were also instances when a participant would express discomfort, but this was usually resolved by pausing the treadmill and allowing the child or caregiver to adjust the seams of the shorts until comfortable and walking was then resumed.

Group outcomes indicated that the preferred walking speed of the children was significantly faster by 15% after LBPPS treadmill training (P = .01; Pre = 0.25 ± 0.04; Post = 0.27 ± 0.03; Cohen d = 0.58). The faster walking speed was accompanied by significantly less time spent in the double support phase (P = .01; Pre = 0.79 ± 0.2; Post = 0.62 ± 01; Cohen d = 0.84), and a trend for a longer step length (P = .06; Pre = 0.51 ± 0.05; Post = 0.54 ± 0.05; Cohen d = 0.54). No significant changes were found after LBPPS treadmill training in overall step width (Pre = 0.21 ± 0.03; Post = 0.19 ± 0.02; P = .20), stride time (Pre = 4.5 ± 0.3; Post = 4.2 ± 0.4; P = .11), or cadence (Pre = 43.9 ± 2.8 steps/min; Post = 46.3 ± 3.1 steps/min; P = .13).

The group results indicated a significant improvement in the BESTest scores of the children at GMFCS levels II-III after the LBPPS treadmill training (P = .008; Pre = 71 ± 9 points, Post = 82 ± 8 points; Cohen d = 1.17). Lastly, the group results show a significant improvement in the overall strength of the lower extremity antigravity musculature (P = .03; Pre = 0.97 ± 0.1; Post = 1.2 ± 0.1; Cohen d = 0.63).

The results for the individual participants are detailed in Table 2. The values in the table are not normalized except for the strength composite score. Participants 1 to 6 were the children who were classified at CMFCS levels II or III. Only the child with hemiplegia did not show improvements in her walking performance (subject 4). She had a slower walking speed after the LBPPS treadmill training, which was accompanied by a shorter step length and longer double support times. The remaining children with a GMFCS level II or III appeared to respond well to the LBPPS treadmill training and had a faster walking speed and improved spatiotemporal kinematics. In fact, a few of the children had as much as a 38% improvement in their walking speed. All of the children classified at GMFCS level II or III had an improvement in their BESTest scores. Participants 7 to 9 were children classified at GMFCS level IV. These children also appear to have responded well to LBPPS treadmill training. They walked faster while using a wheeled walker and spent less time in double support.

Finally, the individual results show that 7 of the children had improved strength of the lower extremity musculature after LBPPS treadmill training. The only child who did not show strength improvements was a child classified at GMFCS level IV. We were unable to collect strength data from subject 3 because she had cognitive impairments that limited her ability to understand that maximum effort was required for the strength tests.

DISCUSSION

Our results show that 6 weeks of LBPPS supported treadmill training performed twice a week promotes an improvement in the preferred walking speed of children with CP. These improvements are important because the gait patterns of children with CP are characterized as being slower than their peers, which may limit their participation in peer equivalent activities or keeping up with the walking pace required in the school environment.[5,6] The noted improvements for the group had a moderate effect size and were within the reported guidelines for a clinically meaningful change in the gait speed of a child with CP (5.7%-9.1%).[32] This suggests that it is feasible to use LBPPS treadmill training to promote improvements in the walking speed of children with CP. However, the percent change (15%) of the group's walking speed was notably lower than what has been reported (67%) from a previous body weight-supported treadmill training study by Dodd and Foley[17] using a similar training paradigm with a conventional overhead support system. Many of the children participating in this investigation typically used with ankle-foot orthoses (AFOs) while walking at school and in the community. Because AFOs have been shown to improve the walking speed of children with CP, we suspect that these children would have had a faster preferred walking speed if their tests were conducted while wearing their prescribed AFOs.[33,34] Similarly, we suspect that this may also have been the reason that subject 4 walked slower after LBPPS treadmill training, yet she had improved strength and BESTest scores.

Clinical literature fairly well establishes that children with CP have balance difficulties while walking that hinder participation in peer equivalent activities.[35–39] In some cases, these balance problems lead a child to choose power mobility over walking.[35] Although these balance problems are well documented, therapies that are efficacious in overcoming these walking balance impairments are not clearly delineated in the literature or in clinical practice. Our results show that children with CP spend less time in double support after LBPPS treadmill training. These changes partly reflect the fact that the majority of the children were walking faster.[5] However, spending more time in double support is also a signature of walking balance problems.[40] Hence, it is arguable that the shorter double support time seen in many of the children may reflect balance improvements. This notion is supported by BESTest scores from the children with GMFCS levels II or III that indicated that LBPPS treadmill training resulted in improved balance. Potentially, these improvements may indicate that these children are more capable of maintaining their balance in challenging unstable environments that they may encounter outside of the laboratory setting.

Quite often, children with CP lack the necessary strength in the antigravity musculature to support and control the displacement of their center of mass during gait.[41,42] A considerable amount of the clinical literature has focused on developing therapeutic protocols that will overcome these apparent strength deficits.[43] These approaches have included basic strength training,[44] circuit training,[45] and recumbent bicycling.[46] Our results are the first to show that LBPPS treadmill training has the potential to improve the strength of the lower extremity antigravity musculature. Short-term improvements in strength predominantly occur through changes in the motor command that governs the performance of the muscle

TABLE 2

Individual Pre-Post Lower Body Positive Pressure Supported Treadmill Training Results

Subject		Walking Speed (m/s)	Cadence (steps/min)	Stride Time (s)	Double Support (s)	Step Length (m)	Step Width (m)	BESTest (Points)	Composite Strength
1	Pre	0.88	53.3	0.95	0.17	0.45	0.19	78	0.96
	Post	0.98	55.6	0.80	0.09	0.49	0.16	89	1.23
2	Pre	0.61	44.4	1.21	0.16	0.39	0.17	69	1.56
	Post	0.69	42.4	1.28	0.16	0.44	0.17	79	1.69
3	Pre	0.77	44.2	1.15	0.22	0.38	0.17	—	—
	Post	0.89	54.4	0.94	0.21	0.39	0.15	—	—
4	Pre	1.31	55.1	0.99	0.10	0.65	0.12	80	0.96
	Post	1.11	50.9	1.09	0.10	0.59	0.13	95	1.92
5	Pre	0.80	43.7	1.78	0.14	0.48	0.10	90	1.28
	Post	0.85	43.5	1.24	0.14	0.52	0.13	93	1.35
6	Pre	0.61	42.6	1.17	0.24	0.36	0.20	39	0.78
	Post	0.83	51.2	1.05	0.14	0.41	0.15	54	1.45
7	Pre	0.18	31.0	1.46	0.50	0.18	0.22	—	0.94
	Pre	0.25	39.1	1.12	0.46	0.17	0.18	—	0.78
8	Pre	0.45	32.6	1.54	0.30	0.36	0.31	—	0.61
	Post	0.54	28.9	1.95	0.14	0.46	0.10	—	0.74
9	Pre	0.59	48.3	1.11	0.14	0.34	0.13	—	0.72
	Post	0.64	51.2	1.06	0.11	0.34	0.12	—	0.83

All data, except for the strength composite score, are not normalized.
Abbreviation: BESTest, Balance Evaluation Systems Test.

activation patterns.[47] Because the training protocol used here was short-term, we suspect that the strength changes were a result of an improved muscular coordination rather than hypertrophic factors.[47]

Body weight supported during treadmill training has become increasingly popular as a therapeutic modality that is used with patients who have a wide variety of neurological impairments (ie, stroke, spinal injuries, cerebral palsy).[13-16,48–50] Traditionally, this therapy is performed by supporting the individual's body weight with straps that are positioned under the groin area and around the torso, which can be uncomfortable.[20] All of the participating children stated that the LBPPS was comfortable during the training. This suggests that the LBPPS system may be a relevant technological advancement for supporting the body weight during treadmill training. However, the shortcoming of LBPPS technology may be that the therapist cannot provide manual cues to the legs during the treadmill training sessions. The use of manual cues has been a key component of the previous body weight–supported treadmill training studies with children with CP.[13,14,16] Probably such assistance may provide the child with movement cues that will help in the learning of proper leg and foot positioning during gait. Moreover, we suspect that the cues from the manual assistance may be important because it was a key component of the Dodd and Foley[17] study, which used the same training paradigm but had larger improvements in the group's walking speed. Alternatively, not using manual assistance may have its benefits, allowing the nervous system to self-explore and discover its own solutions for effectively coordinating the leg's degrees of freedom. Ultimately, this may allow the child to make more mistakes in selecting the proper motor command in the early learning stages, which may be essential for the natural selection of sensorimotor pathways that have the highest probability of producing a quality stepping pattern.[51–53] Although LBPPS system appears to be a technological advancement, future studies should evaluate the necessity of the cues from manual assistance to improve the walking patterns of children with various types of CP and GMFCS levels.

We cannot determine whether our results were solely due to LBPPS treadmill training because no control group was used for comparison. Although it appears that LBPPS treadmill training is feasible for improving walking speed, it is possible that these improvements may have been partly due to locomotor activities that the children performed at home or school. Moreover, because this investigation used a small and diverse group of subjects it is possible that these results may not extend to all the subtypes of children with CP. This notion is particularly evident when one considers the individual data showing the child with hemiplegic CP did not demonstrate improvements in the gait variables measured in this investigation. Hence, it is possible that LBPPS treadmill training may not be the best therapeutic prescription for this child. Further investigations of the feasibility of using LBPPS treadmill training with the different CP subtypes are necessary.

In summary, this preliminary investigation has shown that it is feasible to use LBPPS treadmill training to improve the walking abilities of children with CP. Our experiment resulted in 4 key findings. LBPPS treadmill training resulted in (1) a faster preferred walking speed, (2) changes in the temporal walking kinematics, (3) an improvement in overall balance, and (4) improved strength of lower extremity antigravity musculature. These outcomes support the use of LBPPS gait training for children with CP.

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REFERENCES

1. Yeargin-Allsopp M, Van Naarden Braun K, Doernberg NS, Benedict RE, Kirby RS, Durkin MS. Prevalence of cerebral palsy in 8-year-old children in three areas of the United States in 2002: a multisite collaboration. *Pediatrics*. 2008;121(3):547-554.
2. Bax M, Goldstein M, Rosenbaum P, et al. Proposed definition and classification of cerebral palsy, April 2005. *Dev Med Child Neurol*. 2005;47(8):571-576.
3. Hoon AH, Jr, Stashinko EE, Nagae LM, et al. Sensory and motor deficits in children with cerebral palsy born preterm correlate with diffusion tensor imaging abnormalities in thalamocortical pathways. *Dev Med Child Neurol*. 2009;51(9):697-704.
4. Johnson DC, Damiano DL, Abel MF. The evolution of gait in childhood and adolescent cerebral palsy. *J Ped Orthop*. 1997;17(3):392-396.
5. Abel MF, Damiano DL. Strategies for increasing walking speed in diplegic cerebral palsy. *J Ped Orthop*. 1996;16(6):753-758.
6. Norlin R, Odenrick P. Development of gait in spastic children with cerebral palsy. *J Ped Orthop*. 1986;6(6):674-680.
7. Dietz V. Body weight supported gait training: from laboratory to clinical setting. *Brain Res Bull*. 2009;78(1):I-VI.
8. Edgerton VR, Roy RR. Robotic training and spinal cord plasticity. *Brain Res Bull*. 2009;78(1):4-12.
9. Pang MY, Yang JF. The initiation of the swing phase in human infant stepping: importance of hip position and leg loading. *J Physiol*. 2000;528(pt 2):389-404.
10. Harkema SJ, Hurley SL, Patel UK, Requejo PS, Dobkin BH, Edgerton VR. Human lumbosacral spinal cord interprets loading during stepping. *J Neurophys*. 1997;77(2):797-811.
11. Dietz V, Muller R, Colombo G. Locomotor activity in spinal man: significance of afferent input from joint and load receptors. *Brain*. 2002;125(12):2626-2634.
12. Pearson KG, Misiaszek JE, Fouad K. Enhancement and resetting of locomotor activity by muscle afferents. *Ann New York Acad Sci*. 1998;860:203-215.
13. Schindl MR, Forstner C, Kern H, Hesse S. Treadmill training with partial body weight support in nonambulatory patients with cerebral palsy. *Arch Phys Med Rehab*. 2000;81(3):301-306.
14. Cherng RJ, Liu CF, Lau TW, Hong RB. Effect of treadmill training with body weight support on gait and gross motor function in children with spastic cerebral palsy. *Am J Phys Med Rehab*. 2007;86(7):548-555.
15. Mattern-Baxter K, Bellamy S, Mansoor JK. Effects of intensive locomotor treadmill training on young children with cerebral palsy. *Pediatr Phys Ther*. 2009;21(4):308-318.
16. Provost B, Dieruf K, Burtner PA, 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.
17. Dodd KJ, Foley S. Partial body-weight-supported treadmill training can improve walking in children with cerebral palsy: a clinical controlled trial. *Dev Med Child Neurol*. 2007;49(2):101-105.
18. Phillips JP, Sullivan KJ, Burtner PA, Caprihan A, Provost B, Bernitsky-Beddingfield A. Ankle dorsiflexion fMRI in children with cerebral palsy undergoing intensive body-weight-supported treadmill training: a pilot study. *Dev Med Child Neurol*. 2007;49(1):39-44.
19. Miyai I, Fujimoto Y, Ueda Y, et al. Treadmill training with body weight support: its effect on Parkinson's disease. *Arch Phys Med Rehab*. 2000;81(7):849-852.
20. Ruckstuhl H, Kho J, Weed M, Wilkinson MW, Hargens AR. Comparing two devices of suspended treadmill walking by varying body unloading and Froude number. *Gait Posture*. 2009;30(4):446-451.
21. Eastlack RK, Hargens AR, Groppo ER, Steinbach GC, White KK, Pedowitz RA. Lower body positive-pressure exercise after knee surgery. *Clin Orthop Relat Res*. 2005(431):213-219.
22. Cutuk A, Groppo ER, Quigley EJ, White KW, Pedowitz RA, Hargens AR. Ambulation in simulated fractional gravity using lower body positive pressure: cardiovascular safety and gait analyses. *J Appl Physiol*. 2006;101(3):771-777.
23. Grabowski AM. Metabolic and biomechanical effects of velocity and weight support using a lower-body positive pressure device during walking. *Arch Phys Med Rehab*. 2010;91(6):951-957.
24. Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Dev Med Child Neurol*. 1997;39(4):214-223.
25. Perry J, Garrett M, Gronley JK, Mulroy SJ. Classification of walking handicap in the stroke population. *Stroke*. 1995;26(6):982-989.
26. Bouyer LJ, Rossignol S. Contribution of cutaneous inputs from the hindpaw to the control of locomotion. II. Spinal cats. *J Neurophys*. 2003;90(6):3640-3653.
27. Bolton DA, Misiaszek JE. Contribution of hindpaw cutaneous inputs to the control of lateral stability during walking in the cat. *J Neurophys*. 2009;102(3):1711-1724.
28. Wingert JR, Sinclair RJ, Dixit S, Damiano DL, Burton H. Somatosensory-evoked cortical activity in spastic diplegic cerebral palsy. *Hum Brain Map*. 2010;31(11):1772-1785.
29. Hof AL. Scaling gait data to body size. *Gait Posture*. 1996;4:222-223.
30. Horak FB, Wrisley DM, Frank J. The Balance Evaluation Systems Test (BESTest) to differentiate balance deficits. *Phys Ther*. 2009;89(5):484-498.
31. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Manwah, NJ: Lawrence Erlbaum; 1998.
32. Oeffinger D, Bagley A, Rogers S, et al. Outcome tools used for ambulatory children with cerebral palsy: responsiveness and minimum clinically important differences. *Dev Med Child Neurol*. 2008;50(12):918-925.
33. Brehm MA, Harlaar J, Schwartz M. Effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy. *J Rehabil Med*. 2008;40(7):529-534.
34. Abel MF, Juhl GA, Vaughan CL, Damiano DL. Gait assessment of fixed ankle-foot orthoses in children with spastic diplegia. *Arch Phys Med Rehab*. 1998;79(2):126-133.
35. Bottos M, Gericke C. Ambulatory capacity in cerebral palsy: prognostic criteria and consequences for intervention. *Dev Med Child Neurol*. 2003;45(11):786-790.
36. Liao HF, Jeng SF, Lai JS, Cheng CK, Hu MH. The relation between standing balance and walking function in children with spastic diplegic cerebral palsy. *Dev Med Child Neurol*. 1997;39(2):106-112.
37. Burtner PA, Woollacott MH, Craft GL, Roncesvalles MN. The capacity to adapt to changing balance threats: a comparison of children with cerebral palsy and typically developing children. *Dev Neurorehab*. 2007;10(3):249-260.
38. Hsue BJ, Miller F, Su FC. The dynamic balance of the children with cerebral palsy and typical developing during gait. Part I: Spatial relationship between COM and COP trajectories. *Gait Posture*. 2009;29(3):465-470.
39. Hsue BJ, Miller F, Su FC. The dynamic balance of the children with cerebral palsy and typical developing during gait Part II: Instantaneous velocity and acceleration of COM and COP and their relationship. *Gait Posture*. 2009;29(3):471-476.
40. Gabell A, Nayak US. The effect of age on variability in gait. *J Gerontol*. 1984;39(6):662-666.
41. Wiley ME, Damiano DL. Lower-extremity strength profiles in spastic cerebral palsy. *Dev Med Child Neurol*. 1998;40(2):100-107.
42. Ross SA, Engsberg JR. Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch Phys Med Rehab*. 2007;88(9):1114-1120.

43. Fowler EG, Kolobe TH, Damiano DL, et al. Promotion of physical fitness and prevention of secondary conditions for children with cerebral palsy: section on pediatrics research summit proceedings. *Phys Ther*. 2007;87(11):1495-1510.
44. Damiano DL, Arnold AS, Steele KM, Delp SL. Can strength training predictably improve gait kinematics? A pilot study on the Effects of Hip and Knee Extensor Strengthening on Lower-Extremity Alignment in Cerebral Palsy [published online ahead of print December 18, 2009]. *Phys Ther*. 2010;(2): 269-279.
45. Scholtes VA, Becher JG, Comuth A, Dekkers H, Van Dijk L, Dallmeijer AJ. Effectiveness of functional progressive resistance exercise strength training on muscle strength and mobility in children with cerebral palsy: a randomized controlled trial. *Dev Med Child Neurol*. 52(6):e107-e113.
46. Fowler EG, Knutson LM, Demuth SK, et al. Pediatric endurance and limb strengthening (PEDALS) for children with cerebral palsy using stationary cycling: a randomized controlled trial. *Phys Ther*. 2010;90(3):367-381.
47. Akima H, Takahashi H, Kuno SY, et al. Early phase adaptations of muscle use and strength to isokinetic training. *Med Sci Sports Exerc*. 1999;31(4):588-594.
48. Barbeau H, Visintin M. Optimal outcomes obtained with body-weight support combined with treadmill training in stroke subjects. *Arch Phys Med Rehab*. 2003;84(10):1458-1465.
49. Mulroy SJ, Klassen T, Gronley JK, Eberly VJ, Brown DA, Sullivan KJ. Gait parameters associated with responsiveness to treadmill training with body-weight support after stroke: an exploratory study. *Phys Ther*. 2010;90(2):209-223.
50. Hicks AL, Adams MM, Martin Ginis K, et al. Long-term body-weight-supported treadmill training and subsequent follow-up in persons with chronic SCI: effects on functional walking ability and measures of subjective well-being. *Spinal Cord*. 2005;43(5):291-298.
51. Cha J, Heng C, Reinkensmeyer DJ, Roy RR, Edgerton VR, De Leon RD. Locomotor ability in spinal rats is dependent on the amount of activity imposed on the hindlimbs during treadmill training. *J Neurotrauma*. 2007;24(6):1000-1012.
52. Cai LL, Fong AJ, Otoshi CK, et al. Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning. *J Neurosci*. 2006;26(41):10564-10568.
53. Lewek MD, Cruz TH, Moore JL, Roth HR, Dhaher YY, Hornby TG. Allowing intralimb kinematic variability during locomotor training poststroke improves kinematic consistency: a subgroup analysis from a randomized clinical trial. *Phys Ther*. 2009;89(8):829-839.