Gait & Posture 30 (2009) 464–468

Contents lists available at ScienceDirect

Gait & Posture

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

Effects of physical guidance on short-term learning of walking on a narrow beam[☆]

Antoinette Domingo[a,*], Daniel P. Ferris[a,b]

[a] School of Kinesiology, University of Michigan, Ann Arbor, MI, USA
[b] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

Article history:
Received 11 February 2009
Received in revised form 19 June 2009
Accepted 3 July 2009

Keywords:
Gait
Balance
Physical guidance
Motor learning
Beam walking

ABSTRACT

Physical guidance is often used in rehabilitation when teaching patients to re-learn movements. However, the effects of guidance on motor learning of complex skills, such as walking balance, are not clear. We tested four groups of healthy subjects that practiced walking on a narrow (1.27 cm) or wide (2.5 cm) treadmill-mounted balance beam, with or without physical guidance. Assistance was given by springs attached to a hip belt that applied restoring forces towards beam center. Subjects were evaluated while walking *unassisted* before and after training by calculating the number of times subjects stepped off of the beam per minute of successful walking on the beam (Failures per Minute). Subjects in Unassisted groups had greater performance improvements in walking balance from pre to post compared to subjects in Assisted groups. During training, Unassisted groups had more Failures per Minute than Assisted groups. Performance improvements were smaller in Narrow Beam groups than in Wide Beam groups. The Unassisted-Wide and Assisted-Narrow groups had similar Failures per Minute during training, but the Unassisted-Wide group had much greater performance gains after training. These results suggest that physical assistance can hinder motor learning of walking balance, assistance appears less detrimental for more difficult tasks, and task-specific dynamics are important to learning independent of error experience.

1. Introduction

Physical guidance, or force intended to reduce movement error, is often used during the rehabilitation of walking. Physical guidance may be given to a patient for a variety of reasons: to increase safety, to reduce fear, or to help complete a task that a patient may not otherwise be able to perform on their own. However, little is known about how using assistance affects motor learning of complex tasks such as walking balance. In the elderly, balance is commonly compromised, and most falls occur during walking, not standing [1,2]. For this reason, it is important to understand how assistance affects learning of walking balance. With this understanding, more effective treatments can be designed for gait rehabilitation.

Studies on the effects of physical guidance on motor learning have varied results. Physical guidance is not helpful for learning simple movements in the upper extremity [3]. Guidance improved performance during practice trials but performance improvements were not present when the guidance was removed. One possible explanation is that physical guidance did not allow for error detection and correction. Error is a critical stimulus for driving motor learning [4,5]. Another recent study examined a more complex movement and found slightly different results [6]. Subjects learned to trace a complex three-dimensional trajectory with the upper extremity using either robotic assistance or visual demonstration. The group that practiced with robotic assistance improved in performance but not any better than the group that used visual guidance alone [6]. In a task where subjects learned to bear weight on their legs asymmetrically, manual guidance provided little help [7].

In a more complex whole-body task (learning to use a ski simulator), subjects performed movements better when they practiced with ski poles for stabilizing guidance than without them [8]. The ski poles allowed the subjects to select the magnitude and timing of the assistive forces while maintaining focus on the task dynamics. Body-weight supported treadmill training, where patients are given manual assistance to move the lower extremities through the motions of walking, has been effective in helping subjects with neurological injury to re-learn how to walk [9–12]. However, none of these studies had control groups

---

[☆] A portion of the data presented in this study was also published as an abstract in the Proceedings of the North American Congress on Biomechanics, August 5–9, 2008, Ann Arbor, MI, USA.

[*] Corresponding author at: School of Kinesiology, 401 Washtenaw Avenue, Ann Arbor, MI 48109-2214, USA. Tel.: +1 734 647 3871; fax: +1 734 936 1925.

E-mail address: adomingo@umich.edu (A. Domingo).

0966-6362/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2009.07.114

where subjects practiced without assistance. These studies suggest that assistance is detrimental to learning easier tasks but may be helpful for more difficult tasks. Subjects performing very difficult tasks may benefit from using assistance because too many errors would not give the subject an appropriate example of the actual task [13].

The purpose of this study was to provide insight on the effects of physical guidance on short-term learning of walking balance and to explore if task difficulty alters those effects. We chose to study healthy subjects learning to walk on a narrow balance beam. Beam walking is similar to over ground walking, but is more challenging to dynamic balance because it exploits the lateral instability of walking [14]. We tested two groups of subjects that practiced walking on a 2.5 cm wide treadmill-mounted balance beam (Wide Beam) for 30 min, with or without lateral physical assistance at the hips. All subjects were evaluated on *unassisted* beam walking pre- and post-training. We hypothesized that subjects that received no assistance during training would have greater performance gains than subjects that received assistance. We based this hypothesis on the rationale that error drives motor learning [4,5] and assistance tends to reduce errors. To explore the confounding effects of task difficulty on the relationship between physical assistance and learning balance, we tested two more groups of subjects (with and without assistance) on a narrower balance beam (1.27 cm-wide) (Narrow Beam). We hypothesized that the difference between performance gains in the unassisted and assisted groups would be smaller for the more difficult task (Narrow Beam) than the easier task (Wide Beam). This was based on the idea that if a task is too difficult, assistance would be helpful in producing examples of the desired task.

2. Methods

2.1. Subjects

We tested 40 neurologically intact subjects (19 females, 21 males; age = 22.4 ± 4.5 years, body mass = 64.3 ± 11.4 kg, leg length = 0.90 ± 0.053; mean ± SD). Subjects were medically stable and had no history of major leg injury. The University of Michigan Institutional Review Board approved this study (IRB#-HUM00008186). All subjects gave informed consent according to the Declaration of Helsinki prior to participating. The subject appearing in the supplemental video gave informed consent to videotape the testing session and also for publication of the video.

2.2. Equipment

The equipment for this experiment consisted of a treadmill-mounted balance beam (beam-mill), a lateral assist device, force plates and a motion capture system. The beam-mill was made of interchangeable small wooden blocks attached to the treadmill belt that lined up to make a continuous balance beam (see Supplementary Content for video). One beam was 2.5 cm wide by 2.5 cm tall (Wide Beam) and the other was 1.27 cm wide by 2.5 cm tall (Narrow Beam).

The lateral assist device was made up of latex tubing and cables that attached to the subject via a padded hip belt. We chose this form of assistance because we could control the amount of assistance that provided lateral stabilization. We provided stabilization in the frontal plane because walking is passively stable in the anterior–posterior direction but unstable in the medio-lateral direction [15]. This form of stabilization has been used in other studies [14,16] during treadmill walking. A similar device has also been used in clinical settings to stabilize the torso during body-weight supported treadmill training [11]. The springs were stretched and placed laterally so that they provided a restoring force towards the center of the beam. When the subject's pelvis was centered over the beam, zero net force was applied to the subject. We had four springs of different stiffnesses. For each subject, we chose the spring that would provide the stiffness closest to the non-dimensionalized spring stiffness of 0.228. To determine the desired spring stiffness, we used the following equation:

$$k = \bar{k} \cdot \frac{l}{\mathrm{mg}}$$

where k = dimensionalized stiffness, $\bar{k}$ = non dimensionalized stiffness, l = leg length and mg = body-weight. The non-dimensionalized spring stiffness of 0.228 was based on springs used during pilot testing. These springs gave subjects feedback about their position relative to the beam but did not give them so much assistance that it completely prevented them from stepping off the beam. The average stiffness of the springs used was 160.96 N/m. We placed single-axis tension/compression load cells (1200 Hz; Omega Engineering, Stamford, CT, USA) in series with the springs on both sides of the subject to measure the force produced by the springs during walking. The lateral assist device provided an average net force of $<3.0\%$ of body-weight onto the subject during the training period while walking on the beam.

The treadmill was placed above two force plates (sampling rate 1200 Hz; Advanced Mechanical Technology Inc., Watertown, MA, USA) so that we could calculate center of pressure from the forces and moments produced by the subject while walking [17].

We used a four-camera video system (frame rate 120 Hz; Motion Analysis Corporation, Santa Rosa, CA, USA) to record the positions of four reflective markers placed on the subject's pelvis, neck and shoulders during walking.

2.3. Procedures

Four groups of 10 subjects walked on the beam-mill for a 3 min pre-training evaluation, a 30 min training period, and a 3 min post-training evaluation. Two groups walked on the Wide Beam and two other groups walked on the Narrow Beam. Treadmill speed was set at 0.22 m/s. This speed was chosen based on pilot experiments. Subjects were instructed to walk on the beam for as long as possible without stepping off. They had to walk heel-to-toe with arms crossed over their torso. They were instructed not to lean forward, twist their trunk, angle their feet away from the longitudinal direction of the beam, or look down. View of the walking surface was obscured by using dribble goggles. Subjects were allowed to move their pelvis and trunk laterally to help maintain balance. All subjects wore standardized orthopedic shoes. Subjects had to wait 5 sec after stepping off the beam before attempting to walk on it again. During the training periods, one of the Narrow Beam groups and one of the Wide Beam groups were given assistance via the lateral assist device (Assisted-Narrow, Assisted-Wide), and the other two groups were not given any assistance (Unassisted-Narrow, Unassisted-Wide). The training duration was 30 min with rest breaks every 10 min. During the pre- and post-evaluation periods, all subjects walked without assistance and were made aware of this at the beginning of the experiment.

We recorded the number of times the subject stepped off the beam per minute. We then divided this quantity by the fraction of time the subject was on the beam (not touching the treadmill surface with either foot). This quotient, Failures per Minute, was our primary performance metric because it took into account the number of errors with respect to the amount of time the subject was successfully able to walk on the beam, both indicators of learning and performance. We also calculated the standard deviation (SD) of the medio-lateral movement of markers placed at the sacrum and the neck (Motion Analysis Corporation, Santa

Rosa, CA; 120 Hz) as a measure of movement variability at the upper trunk and pelvis. We calculated percent change of the performance variables by subtracting the pre-training value from the post-training value and dividing by the pre-training value for each subject to normalize to pre-training performance.

For the pre- and post-training periods, we recorded data for the duration of the 3 min trial. For the 30 min training period, we collected only 20 s of data per each minute of training. We used a fourth order, zero-lag low pass Butterworth filter with a cutoff frequency of 6 Hz to smooth center of pressure data. Values for SD of markers were calculated only using the data from when subjects were on the beam.

2.4. Statistical analysis

To evaluate whether Narrow Beam walking was more difficult than Wide Beam walking, we performed a 2×2 Analysis of Variance (ANOVA) (assist, beam) to compare results for Failures per Minute between the Narrow Beam groups and the Wide Beam groups during pre-training (JMP IN software, SAS Institute, Inc., Cary, NC). We also used this information to determine if both Assisted groups and both Unassisted groups had similar pre-training scores to each other.

We performed a 2×2 ANOVA (assist, beam, assist*beam) to test for differences between the groups and any interaction effect for each of the following dependent variables: percent change for Failures per Minute, sacral marker SD and neck marker SD. For *post hoc* analysis, we performed *t*-tests to compare results within each beam group as needed to delineate the differences between assist groups, and adjusted the alpha level for multiple comparisons using the Bonferroni correction ($\alpha = 0.05$/number of tests).

We used generalized estimating equations (GEE) to test for differences in the time series data between each group during training (SPSS software, SPSS, Inc., Chicago, IL). We also performed contrast tests using pairwise comparisons to delineate which groups were different from each other.

3. Results

Pre-training results showed that walking on the Narrow Beam was more difficult than walking on the Wide Beam. The Narrow Beam groups had significantly more Failures per Minute (30.4 ± 1.7, mean ± SEM) than the Wide Beam groups (19.2 ± 1.2) in pre-training (ANOVA, beam: $P < 0.0001$, power > 0.99) (Fig. 1). Both Wide Beam groups had similar pre-training scores, as did both the Narrow Beam groups (ANOVA, assist: $P = 0.6871$).

The assistance used during training greatly hindered learning of the unassisted task compared to those that did not use assistance. The results showed that the Unassisted groups had $49.0 \pm 4.6\%$ less Failures per Minute after training, and the Assisted groups had $2.88 \pm 11.6\%$ more Failure per Minute after training (ANOVA, assist: $P = 0.0002$). *Post hoc* tests showed that the Unassisted-Wide group was different than the Assisted-Wide group (*t*-test: $P = 0.0045$), and that the Unassisted-Narrow group was different than the Assisted-Narrow group (*t*-test: $P = 0.0030$). Power for *post hoc* tests were greater than 0.85. The interaction effect (assist*beam) approached significance (ANOVA: $P = 0.0712$). The Assisted-Wide group had more failures after training (13.4% more failures from pre- to post-training).

Most subjects decreased frontal plane movement variability in the upper body and increased movement variability at the pelvis during post-training compared to pre-training. The percent change in standard deviation of neck marker movement in the medio-lateral direction was significantly different between groups (ANOVA, assist: $P = 0.0017$) (Fig. 2B). *Post hoc* tests showed that the percent change in movement variability at the neck marker was significantly different between the Assisted-Wide and Unassisted-Wide groups (*t*-test: $P = 0.0235$). The Narrow Beam groups were also significantly different from each other (*t*-test: $P = 0.0200$). Because subjects in the Assisted groups had little or no improvements after training, the decrease in neck marker movement variability after training in the Assisted groups suggests that movement at the upper trunk was correlated with the ability to maintain balance during beam walking. There were no significant differences between groups for sacral marker movement variability (ANOVA: $P = 0.4355$) (Fig. 2C).

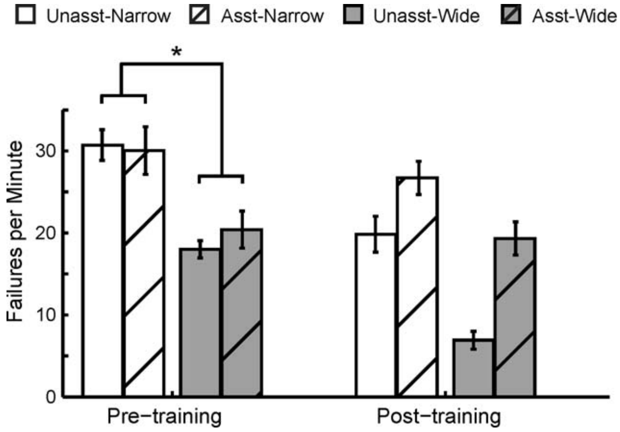

Fig. 1. Averaged pre- and post-training values for Failures per Minute. Error bars are ±1 standard error of the mean (SEM). Significant differences are indicated by *. Statistical analyses of post-training data not presented.

There were significant differences in the Failures per Minute during training between groups (ANOVA: $P < 0.0001$), but *post hoc* tests showed that that the Unassisted-Wide and Assisted-Narrow were not significantly different than each other (*t*-test: $P = 0.9158$) (Fig. 3A). All other comparisons were significant ($P < 0.0083$) except Assisted-Narrow compared to Assisted-Wide ($P = 0.0373$). All significant findings for these comparisons had a power greater than 0.9. GEE analysis showed similar results when comparing the time series data during training (GEE: $P < 0.001$) (Fig. 3B). Pairwise comparisons showed that there were differences between all groups in Failures per Minute ($P < 0.05$) except for the Unassisted-Wide and Assisted-Narrow groups ($P = 0.943$).

Movement variability at the sacral marker in frontal plane during training for the different groups (Fig. 3C) paralleled their respective improvements in performance (Fig. 2A).

4. Discussion

Our main result was that practice with assistance hindered short-term learning of a walking balance task compared to unassisted practice. We also found that using assistance during practice while walking on the Narrow Beam did not hinder learning as much as while walking on the Wide Beam. Thus, assistance appears more beneficial when used during more difficult motor tasks. This is consistent with what is considered best practices in clinical rehabilitation: that assistance should only be given as much as is needed to complete the task [18]. It is also consistent with the challenge point framework for motor learning that states that task difficulty should be adjusted to the learner's skill level [19].

Physical guidance was clearly detrimental to learning to walk on the Wide Beam. The Unassisted-Wide group had the largest percentage decrease in Failures per Minute for the post-test compared to the pre-test (Fig. 2A). The post-test performances were in direct contrast to performances during training. The greater amount of learning by the unassisted group could be

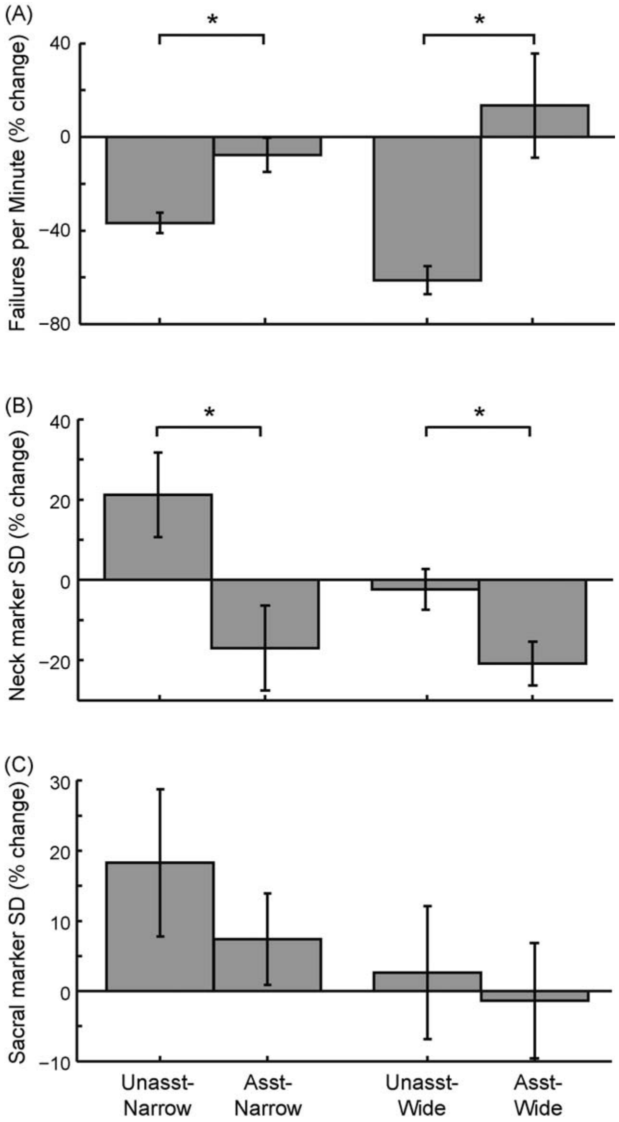

Fig. 2. Significant differences are indicated by *. Averaged percent change between pre- and post-training for (A) Failures per Minute, (B) standard deviation of the neck marker in the frontal plane, and (C) standard deviation of the sacral marker in the frontal plane.

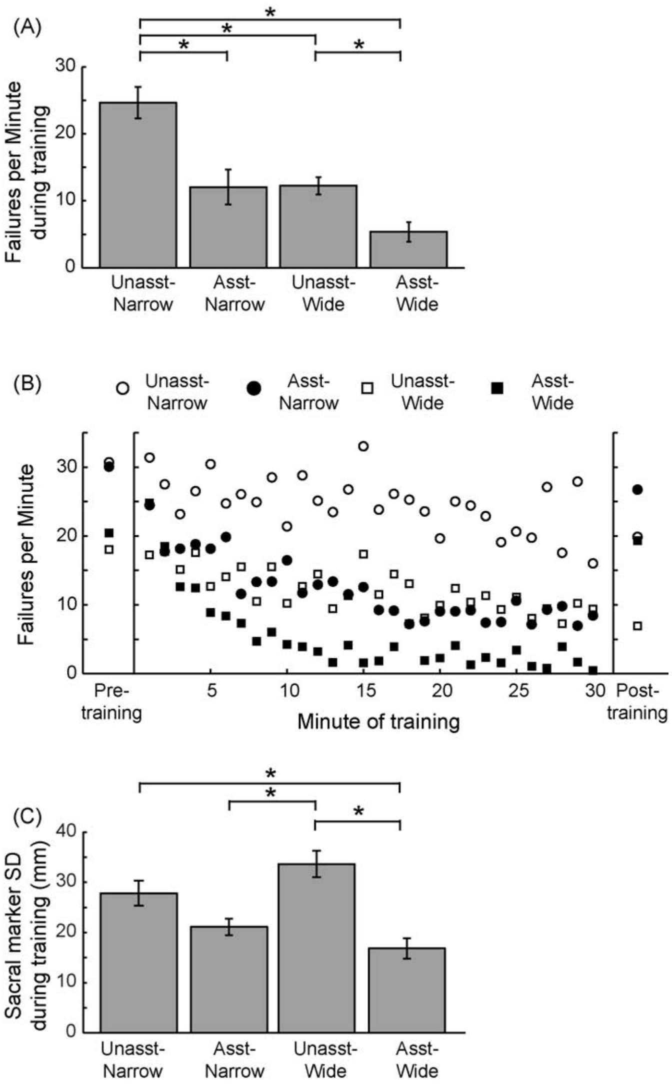

Fig. 3. Significant differences are indicated by *. During the training period: (A) averaged Failures per Minute, (B) Failures per Minute during each minute, and (C) averaged standard deviations of sacral marker movement in the frontal plane.

attributed to experiencing more errors during the training period (Fig. 3A and B).

The results were different in groups that learned the more difficult task (walking on the Narrow Beam). There was a smaller difference between the performance gains after training for the Assisted-Narrow and Unassisted-Narrow groups (Fig. 2A), despite having relatively similar error experience during training as the Wide Beam groups (Fig. 3A and B). The interaction effect of assist and beam approached significance. Thus, for more difficult tasks, physical assistance seems to be less detrimental to motor learning.

It is important to dissociate the effects of the mechanical interactions of physical guidance and the error experienced during practice on motor learning. Error experience is proportional to motor learning [20,21]. Because physical guidance reduces errors, it would follow that physical guidance would hinder motor learning. However, the mechanical interaction itself may affect learning. To make this distinction, we examined the performance of two groups of subjects that experienced similar amounts of error during training, but one group had assistance (Assisted-Narrow) and the other did not (Unassisted-Wide) (Fig. 3A). The Unassisted-Wide group had a larger percent change in Failures per Minute than the Assisted-Narrow group (Fig. 2A). This suggests that another factor is important to motor learning of this task other than the amount of errors.

Another possible explanation for the differences in motor learning gains between Assisted and Unassisted groups is that the training for the Unassisted groups had more task-specific dynamics. According to the specificity of practice hypothesis, motor learning is specific to the available afferent feedback during practice [22]. Having task dynamics more similar to the desired task would allow subjects to explore the state-space of position and velocity parameters and develop the ability to better control balance. Additionally, groups that had greater sacral marker movement variability during training (Fig. 3C) had greater performance improvements after training (Fig. 2A). This suggests that when subjects explored their limits of stability, they were better able to learn how to balance. This idea is in agreement with a recent theoretical construct for detecting loss of balance [23].

Previous studies show little correlation between static and dynamic balance or standing and walking balance [24,25]. It is imperative to devise assessment tools and rehabilitation strategies that specifically target balance during walking. We developed the beam-mill to specifically assess walking balance and it has potential to be used as a means to improve balance during walking. Future studies should test long-term retention, include wider ranges of difficulty levels and amounts of assistance, and test clinical populations.

Acknowledgements

The authors would like to thank Kurt Sieloff for assistance with device construction and design, data collection and processing, and the other members of the Human Neuromechanics Laboratory for their assistance with data collection and processing. This work was supported by the Rackham Graduate Student Research Grant, the Foundation for Physical Therapy PODS II Scholarship, and NIH F31 HD056588-01.

Conflict of interest statement

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2009.07.114.

References

[1] Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SB, Arie TH, Fentem PH, Bassey EJ. Falls by elderly people at home: prevalence and associated factors. Age Ageing 1988;17(6):365–72.
[2] Niino N, Tsuzuku S, Ando F, Shimokata H. Frequencies and circumstances of falls in the National Institute for Longevity Sciences, Longitudinal Study of Aging (NILS-LSA). J Epidemiol 2000;10(1 Suppl):S90–94.
[3] Armstrong TR. Training for the production of memorized movement patterns, in Psychology. Ann Arbor: University of Michigan; 1970.
[4] Lisberger SG. The neural basis for learning of simple motor skills. Science 1988;242(4879):728–35.
[5] Rumelhart DE, Hinton GE, Williams RJ. Learning representations by back-propagating errors. Nature 1986;323(6088):533–6.
[6] Liu J, Cramer S, Reinkensmeyer D. Learning to perform a new movement with robotic assistance: comparison of haptic guidance and visual demonstration. J Neuroeng Rehab 2006;320.
[7] Sidaway B, Ahn S, Boldeau P, Griffin S, Noyes B, Pelletier K. A comparison of manual guidance and knowledge of results in the learning of a weight-bearing skill. J Neurol Phys Ther 2008;32(1):32–8.
[8] Wulf G, Shea CH, Whitacre CA. Physical guidance benefits in learning a complex motor skill. J Motor Behav 1998;30367–80.
[9] Wernig A, Nanassy A, Muller S. Maintenance of locomotor abilities following Laufband (treadmill) therapy in para- and tetraplegic persons: follow-up studies. Spinal Cord 1998;36(11):744–9.
[10] Dobkin B, Apple D, Barbeau H, Basso M, Behrman A, Deforge D, Ditunno J, Dudley G, Elashoff R, Fugate L, Harkema S, Saulino M, Scott M. Weight-supported treadmill vs over-ground training for walking after acute incomplete SCI. Neurology 2006;66(4):484–93.
[11] Behrman AL, Harkema SJ. Locomotor training after human spinal cord injury: a series of case studies. Phys Ther 2000;80(7):688–700.
[12] Dietz V, Colombo G, Jensen L, Baumgartner L. Locomotor capacity of spinal cord in paraplegic patients. Ann Neurol 1995;37(5):574–82.
[13] Sanger TD. Failure of motor learning for large initial errors. Neural Comput 2004;16(9):1873–86.
[14] Donelan JM, Shipman DW, Kram R, Kuo AD. Mechanical and metabolic requirements for active lateral stabilization in human walking. J Biomech 2004;37(6):827–35.
[15] Bauby CE, Kuo AD. Active control of lateral balance in human walking. J Biomech 2000;33(11):1433–40.
[16] Chang CL, Ulrich BD. Lateral stabilization improves walking in people with myelomeningocele. J Biomech 2008;41(6):1317–23.
[17] Collins SH, Adamczyk PG, Ferris DP, Kuo AD. A simple method for calibrating force plates and force treadmills using an instrumented pole. Gait Posture 2009;29(1):59–64.
[18] Ryerson S, Levitt K. Functional Movement Reeducation. New York: Churchill Livingstone; 1997.
[19] Guadagnoli MA, Lee TD. Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. J Mot Behav 2004;36(2):212–24.
[20] Scheidt RA, Dingwell JB, Mussa-Ivaldi FA. Learning to move amid uncertainty. J Neurophysiol 2001;86(2):971–85.
[21] Thoroughman KA, Shadmehr R. Learning of action through adaptive combination of motor primitives. Nature 2000;407(6805):742–7.
[22] Proteau L, Marteniuk RG, Levesque L. A sensorimotor basis for motor learning: evidence indicating specificity of practice. Q J Exp Psychol A 1992;44(3):557–75.
[23] Ahmed AA, Ashton-Miller JA. Is a loss of balance a control error signal anomaly? Evidence for three-sigma failure detection in young adults. Gait Posture 2004;19(3):252–62.
[24] Shimada H, Obuchi S, Kamide N, Shiba Y, Okamoto M, Kakurai S. Relationship with dynamic balance function during standing and walking. Am J Phys Med Rehab 2003;82(7):511–6.
[25] Owings TM, Pavol MJ, Foley KT, Grabiner MD. Measures of postural stability are not predictors of recovery from large postural disturbances in healthy older adults. J Am Geriatr Soc 2000;48(1):42–50.