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Gradual training reduces the challenge to lateral balance control during practice and subsequent performance of a novel locomotor task

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ABSTRACT

Locomotor balance control mechanisms and impairments have been well described in the literature. In contrast, the role of evidence-based motor learning strategies in the recovery or restoration of locomotor balance control has received much less attention. Little is known about the efficacy of motor learning strategies to improve locomotor tasks and their unique requirements, such as lateral balance control. This study examined whether gradual versus sudden training influenced lateral balance control among unimpaired adults ($n = 16$) during training and 24-h transfer performance of a novel locomotor task. This was accomplished by examining the variability of whole-body frontal plane kinematics throughout training and 24-h transfer performance of asymmetric split-belt treadmill walking. Compared to sudden training, gradual training significantly reduced the challenge to lateral balance control (exhibited by a reduction in frontal plane kinematic variability) during training and during subsequent transfer task performance. These results indicate that gradual training could play an important role in restoring locomotor balance control during physical rehabilitation.

1. Introduction

A critical aspect of safe and purposeful locomotion is the ability to maintain or restore balance during walking by controlling the whole body center of mass (COM) with respect to the base of support in response to continually changing environmental conditions and task requirements [1]. Compared to the emphasis placed on identifying locomotor balance control mechanisms [2,3] and impairments [4,5], little attention has been paid to the potential role that common motor learning strategies implemented prior to, during, or after physical practice [6] may play in the acquisition and maintenance of locomotor balance control. The studies that have begun to address this gap have demonstrated that locomotor balance control can be influenced by the selection of training strategies. Specifically, locomotor balance control appears to improve when training includes deliberate physical practice rather than observational training, and when that physical practice reduces challenges to locomotor balance control during training rather than augmenting it [7–9].

One factor limiting a greater understanding of the potential role of motor learning strategies in restoring locomotor balance control is that most research examining motor learning strategies has been performed using upper extremity motor skills [10]. Given the unique characteristics of locomotor tasks versus those of upper extremity reaching tasks, it remains unknown whether the effectiveness of these motor learning strategies generalizes to improving or restoring locomotor balance control following impairment. Research in this area can benefit the development of effective locomotor rehabilitation protocols.

One aspect of motor learning protocols that can be manipulated is the rate at which movements are modified and movement errors are produced. Sudden training is characterized by an abrupt introduction of performance requirements and the production of large movement errors [11] traditionally thought to drive motor learning [12]. In contrast, gradual training incrementally introduces performance requirements throughout practice, effectively reducing practice difficulty and minimizing the size of movement errors [11]. In spite of this reduction in movement errors and practice difficulty, gradual training is able to maintain or improve performance on adaptive reaching tasks [11], and strengthen the adaptation to novel locomotor tasks [13] when compared to sudden training. Gradual training may therefore represent an attractive training strategy for improving or restoring locomotor balance control during rehabilitation since it avoids large

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movement errors [11] that may threaten patient safety and balance confidence during locomotor rehabilitation. However, it remains unknown whether the efficacy of gradual training generalizes to the restoration or recovery of locomotor balance control, specifically lateral balance control, which is considered challenging to the central nervous system [14] and critical to successful bipedal locomotion [3].

The objective of this study was to compare the effects of gradual and sudden training on lateral balance control during initial practice and subsequent performance of a novel locomotor task, asymmetric split-belt treadmill walking. Lateral balance control was assessed by examining the variability of whole-body frontal plane kinematics, as quantified by the standard deviation of the frontal inclination angle (FIA) [15] at heel-strike. This metric describes the variation in lateral foot placement with respect to the whole-body COM on a step-by-step basis, and thus captures the challenge to lateral balance control based on the need to continually alter the base-of-support to ensure that whole-body COM remains within it. It was hypothesized that compared to sudden training, gradual training would reduce the challenge to lateral balance control during training and subsequent performance of the novel locomotor task.

2. Methods

2.1. Recruitment

Inclusion criteria were age between 18 and 50, and the ability to walk continuously for 20 min on a treadmill without assistance. Exclusion criteria were self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions and any previous split-belt walking experience. Institutional Review Boards approved all protocols, and informed consent was obtained prior to enrollment.

2.2. Experimental protocol

A 15-min treadmill acclimation phase, during which participants walked on a Bertec split-belt instrumented treadmill (Bertec, Columbus, OH) with both belts at 0.7 m/s (1:1 walking), was used to promote gait consistency [16]. Twenty additional strides were then performed to characterize baseline 1:1 walking performance. Participants were then randomly allocated to either the gradual or sudden training cohorts. Noise-canceling earphones and eyewear that blocked the lower visual field (i.e., dribble goggles) were worn throughout the experiment to minimize acoustic feedback from treadmill motors and visual feedback from treadmill belts.

During training all subjects practiced the same novel locomotor task, asymmetric split-belt treadmill walking, where one leg is driven at a faster velocity than the other [17]. This task was selected for its novelty, an essential feature of a valid motor learning study as it allows for an unbiased assessment of both training strategies. For subjects allocated to sudden training, the novel locomotor task (split-belt treadmill walking) was introduced via a single abrupt change in belt velocity. The belt under the dominant leg was accelerated at 10.0 m/s^2 to reach a velocity of 1.4 m/s (2:1 walking) between heel-strikes. The condition of 2:1 walking was then maintained for the remainder of training, totaling 720 consecutive strides. The gradual training cohort was introduced to 2:1 walking by incrementally increasing the belt speed under the dominant leg such that every 20 strides, belt velocity was increased by 0.02 m/s using an acceleration of 0.001 m/s^2. This continued until the dominant leg belt velocity reached 1.4 m/s (2:1 walking), a transition that took 700 strides (35 blocks of 20 strides). Twenty additional 2:1 walking strides were then performed by the gradual cohort, for a total of 720 strides during training. The magnitude of the velocity changes and the acceleration were chosen to minimize detection of the incremental changes and represent the lower limits of treadmill motor control. Participants were given the same instructions, to maintain or restore a comfortable, rhythmic walking pattern. Participants were naive to the novel locomotor task, 2:1 walking, and to their allocation to gradual or sudden training.

To examine how well lateral balance control strategies generalized to a similar locomotor task following gradual or sudden training, a transfer test was performed 24 h post-training to allow sufficient time for stabilization and consolidation of motor memories acquired during training [18]. Prior to transfer testing all participants were provided 5 min to re-acclimate to the treadmill at 1:1 walking. The transfer test was performed with a sudden re-introduction, and consisted of a modification of the original locomotor task, wherein the velocity of the dominant leg belt was three times that of the non-dominant leg belt, 2.1 m/s (producing 3:1 walking). The transfer test was performed for 400 strides.

2.3. Data collection

Fifty-seven reflective markers were placed on participants' bony landmarks [19]. Throughout all phases of the experimental protocol, three-dimensional marker coordinate data were collected at 120 Hz using a 12 camera Vicon MX motion capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from the treadmill force platforms at 1200 Hz Demographics including age, height, weight, sex, self-selected walking speed (SSWS) and limb dominance were recorded.

2.4. Data analysis

Marker coordinate data were filtered (4th order Butterworth with 5 Hz low-pass cut-off) and combined with anthropometric data adapted from Dempster [20] to build a 15 segment whole-body model in Visual 3D (C-Motion, Germantown, MD) [19]. Whole-body COM position was calculated using the weighted sum approach. Ground reaction forces were filtered (4th order Butterworth with 45 Hz low-pass cut-off) and used for heel-strike detection.

The frontal inclination angle (FIA) (Fig. 1), a measure of limb endpoint control relative to the COM, was chosen as the metric of lateral balance control. It can be defined as the angle formed by a vector from the COM to the lateral malleolus with respect to the vertical in the frontal plane [15],

$$\theta = \sin^{-1}\left(\frac{\vec{J}_{\text{ankle to COM}} \times \vec{J}_{\text{vertical}}}{|\vec{J}_{\text{ankle to COM}}|}\right)$$

where $\vec{J}_{\text{ankle to COM}}$ is the vector from the ankle (lateral malleolus) to the COM in the frontal plane, and $\vec{J}_{\text{vertical}}$ is the unit vector of the vertical.

The FIA was selected as the metric for lateral balance control because lateral foot placement relative to the COM is a critical factor affecting frontal plane whole-body balance [3,21], and the primary means of altering COM deviations in the frontal plane [3]. The FIA is also sensitive to gait imbalance [15].

Using custom MATLAB™ (MathWorks, Natick, MA) code, discrete values for the FIA were calculated on a stride-by-stride basis at ipsilateral heel-strike for the fast (dominant) and slow (non-dominant) legs. This event in the gait cycle was chosen because of the importance it presents to maintaining frontal plane balance control during locomotion [3,19]. The standard deviation (SD) of the FIA was then calculated for every 20 strides during baseline 1:1 walking, 2:1 training, and 3:1 transfer performance.

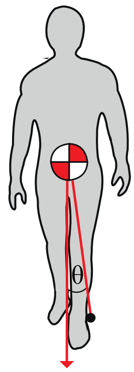

Fig. 1. The frontal inclination angle (FIA) is formed by a vector from the whole-body COM to the lateral malleolus with respect to the vertical.

The SD reflects the amount of variability in the movement pattern [22]. The amount of variability in the frontal plane movement pattern is considered a useful metric for assessing the maintenance or recovery of sensorimotor control of lateral balance [14] because it describes the challenge presented to lateral balance by a locomotor task [14,23–25] by quantifying the need to constantly adjust foot placement relative to the COM on a step-by-step basis to ensure that the COM remains within the base-of-support, thus ensuring safe locomotion.

To determine whether gradual versus sudden training influenced the challenge to lateral balance control, we calculated the average uncertainty residual (AuR) of the FIA for the fast (dominant) and slow (non-dominant) legs during 2:1 training and 3:1 transfer performance. The AuR was defined as the mean difference in FIA variability (SD) between each block of 20 strides during 2:1 training or 3:1 transfer and baseline 1:1 walking (20 strides) (Supplement A). The lower the AuR during 2:1 training and 3:1 transfer, the closer the amount of variability in the whole-body frontal plane kinematic movement pattern to that of baseline 1:1 walking, and thus the lower the challenge to lateral balance control while performing the novel locomotor task.

Supplementary data related to this article found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2013.04.019.

2.5. Statistical analysis

To evaluate the effect of gradual versus sudden training on the challenge to lateral balance control, the AuR for the fast and slow legs were compared between the gradual and sudden cohorts using a multivariate analysis of variance (MANOVA) during training and transfer performance (1-sided test, $\alpha = 0.05$). Differences in FIA variability between 2:1 training and baseline 1:1 walking were assessed with one-sided paired t-tests ($\alpha = 0.05$). All statistical tests were conducted using SPSS (V.19; SPSS, Inc., Chicago, IL).

3. Results

Sixteen adults without impairment were recruited and participated in the study (Table 1). During 2:1 training, the AuR of the FIA for the fast and slow legs was found to be significantly larger for the sudden versus the gradual cohort (fast leg, $p < 0.001$; slow leg, $p = 0.042$) (Figs. 2 and 3; Table 2). Additionally, the average variability of the FIA during 2:1 training was found to be significantly larger than during baseline 1:1 walking for the fast and slow legs among the sudden cohort (fast leg, $p < 0.001$; slow leg, $p < 0.001$), but not during gradual training (fast-leg, $p = 0.060$; slow leg, $p < 0.101$) (Figs. 2 and 3; Table 2). During transfer performance the AuR values of the fast and slow legs were significantly larger for the sudden than the gradual cohort (fast-leg $p = 0.005$; slow leg $p = 0.035$) (Figs. 2 and 3; Table 2).

4. Discussion

This study sought to determine whether gradual versus sudden training influenced lateral balance control during training and subsequent performance of a novel locomotor task, asymmetric split-belt treadmill walking. The average uncertainty residual (AuR) of the frontal inclination angle (FIA) was calculated to quantify the challenge to lateral balance control during 2:1 training and 3:1 transfer performance. Based upon previous interpretation of metric variability to describe the challenge to lateral balance control [14,23–25], the significantly smaller AuR of the fast and slow legs during gradual 2:1 training (Figs. 2 and 3; Table 2) observed in the present study indicates that the gradual cohort experienced significantly less challenge to lateral balance control during 2:1 training than the sudden cohort. Furthermore, the lack of any significant difference in the amount of variability in the FIA between baseline 1:1 walking and 2:1 training among the gradual cohort indicates that the challenge to lateral balance control during 2:1 gradual training was no greater than during baseline 1:1 walking.

During transfer testing, the AuR of the fast and the slow leg were both significantly greater among those individuals who had received sudden training the previous day (Figs. 2 and 3; Table 2). This indicates that those individuals in this study who received gradual training had less difficulty controlling lateral balance when learning was transferred to a different version of the locomotor task the following day. These results demonstrate that the manner by which participants were initially trained influenced the challenge to lateral balance control during training, and more importantly, during subsequent performance of a similar locomotor task. Therefore, gradual training promotes the development of a balance control strategy that offers greater generalizability.

These results agree with the previous studies that found that locomotor balance control could be influenced by the selection of specific motor learning strategies [7–9]. Similar to the results presented in this study, Domingo and colleagues found that control of lateral balance could be improved by reducing the challenge to locomotor balance control during training rather than augmenting it, provided that this did not involve physical guidance [8,9]. Based

Table 1
Participant demographics.

Cohort		Height (m)	Mass (kg)	Age (years)	Sex[a]	SSWS (m/s)	Dominant leg[b]
Gradual ($n = 8$)	Mean (*SD*)	1.79 (*0.07*)	76 (*12*)	28 (*5*)	7M, 1F	1.42 (*0.10*)	7R, 1L
	Range	1.65–1.88	56–91	23–36		1.25–1.51	
Sudden ($n = 8$)	Mean (*SD*)	1.67 (*0.12*)	67 (*9*)	28 (*4*)	2M, 6F	1.43 (*0.17*)	7R, 1L
	Range	1.52–1.85	55–83	24–36		1.12–1.70	

[a] M, male; F, female.
[b] R, right; L, left.

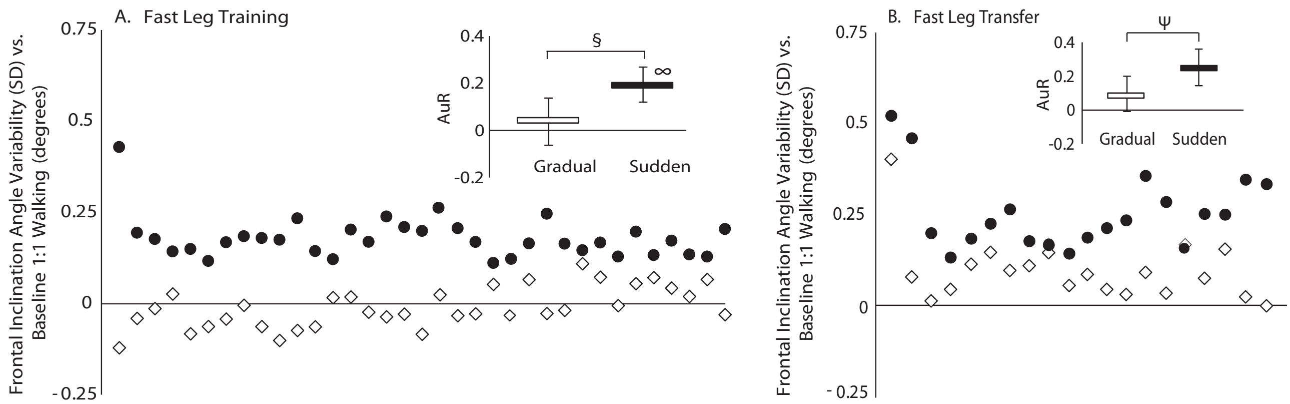

Fig. 2. Frontal inclination angle (FIA) variability (SD) of the fast (dominant) leg minus that of baseline 1:1 walking for the gradual (◇) and sudden (●) cohorts during 2:1 training (A) and 3:1 transfer performance (B). Each data point represents the average variability over 20 strides with respect to baseline 1:1 walking. Inset is the resulting average uncertainty residual (AuR) with error bars equal to ±1SD. (A) The AuR of the fast (dominant) leg during 2:1 training was significantly larger during sudden than gradual training ($p < 0.001$)§. The amount of variability in the fast leg FIA during 2:1 training was significantly greater than during baseline 1:1 walking for sudden ($p < 0.001$)$^{\infty}$ but not gradual training. (B) The AuR of the fast leg was significantly larger for the sudden than the gradual cohort during 3:1 transfer performance (fast leg transfer, $p = 0.005$) $^{\Psi}$.

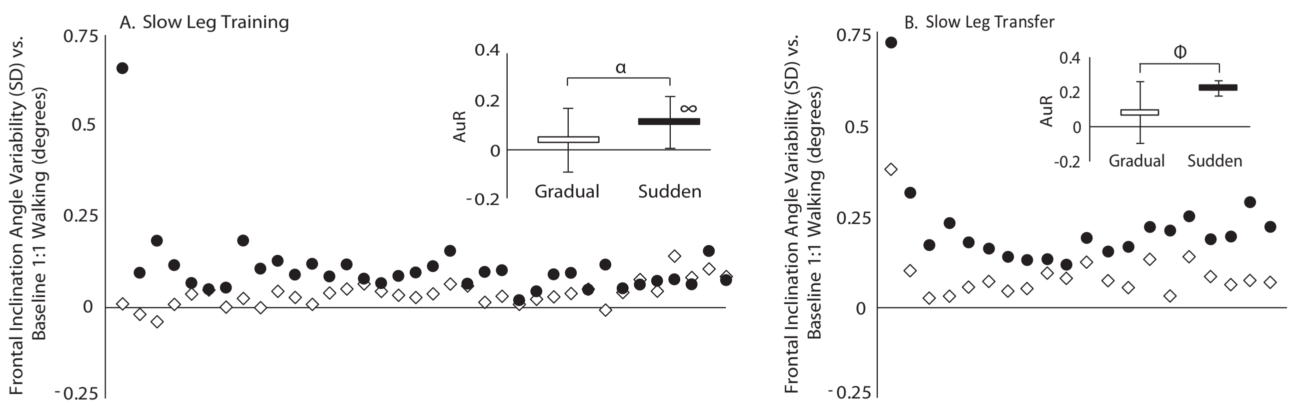

Fig. 3. Frontal inclination angle (FIA) variability of the slow (non-dominant) leg minus that of baseline 1:1 walking for the gradual (◇) and sudden training (●) cohorts during 2:1 training (A) and 3:1 transfer performance (B). Each data point represents the average variability over 20 strides with respect to baseline 1:1 walking. Inset is the resulting average uncertainty residual (AuR) with error bars equal to ±1SD. (A) The AuR of the slow (non-dominant) leg during 2:1 training was significantly larger during sudden than gradual training ($p = 0.042$)$^{\alpha}$. The amount of variability in the slow leg FIA during 2:1 training was significantly greater than during baseline walking for sudden ($p < 0.001$)$^{\infty}$ but not gradual training. (B) The AuR of the slow leg was significantly larger for the sudden than the gradual cohort during transfer ($p = 0.035$)$^{\Phi}$.

on the results of the current study and previous research, rehabilitation protocols aimed at improving lateral balance control should avoid practice conditions which introduce considerable challenge to lateral balance or rely on physical guidance. Rather, they should be designed to provide a degree of difficulty or challenge that learners are able to manage independently. The finding that 2:1 gradual training did not pose significantly more challenge to lateral balance control than baseline 1:1 walking, yet led to superior control of lateral balance the next day indicates that the ideal level of practice difficulty is closer to that experienced within an individual's normal repertoire. Specifically, gradual training may allow individuals to explore and develop a balance control strategy over time without risking a loss of balance. The use of a sudden training strategy, particularly for a complex task such as walking, forces individuals to respond immediately to address the threat to balance presented by the abrupt introduction of task requirements. This prevents individuals from thoroughly exploring all of the possible solutions and experiencing the true nature of the task, thus selecting a balance control strategy that while successful (i.e. prevents falls), may not be the most effective [26]. Gradual

Table 2
The frontal inclination angle (FIA) average uncertainty residual (AuR) of the fast (dominant) and slow (non-dominant) legs during 2:1 training and 3:1 transfer performance.

Phase	Sudden training cohort		Gradual training cohort	
	Fast leg AuR (SD)	Slow leg AuR (SD)	Fast leg AuR (SD)	Slow leg AuR (SD)
2:1 training	0.20 (0.07)[a]	0.11 (0.10)[b]	0.04 (0.10)[a]	0.04 (0.12)[b]
3:1 transfer	0.26 (0.11)[c]	0.22 (0.04)[d]	0.10 (0.10)[c]	0.09 (0.18)[d]

[a] A comparison of the fast leg AuR between gradual and sudden cohorts during 2:1 training, $p < 0.05$.
[b] A comparison of the slow leg AuR between gradual and sudden cohorts during 2:1 training, $p < 0.05$.
[c] A comparison of the fast leg AuR between gradual and sudden cohorts during 3:1 transfer, $p < 0.05$.
[d] A comparison of the slow leg AuR between gradual and sudden cohorts during 3:1 transfer, $p < 0.05$.

training may also promote the development of greater self-efficacy regarding balance control and thus balance confidence [27], in turn promoting superior lateral balance control the following day.

The results of this study have applications to the design of rehabilitation protocols for individuals with balance impairments. For example, perturbation training, which involves the repeated introduction of balance threats (i.e. slips) with the goal of improving responses to perturbations through practice, has recently been established as a successful means to improve locomotor balance control and reduce falls [28]. To date, perturbation training has only utilized a single perturbation magnitude that has been abruptly introduced [28]. The results of the present study indicate that perturbation training may benefit from gradually introducing the magnitude of the perturbation during training, particularly among individuals prone to or with a history of falls.

While necessary to perform this study, the use of a treadmill may have affected the results. The loss of optic flow that is characteristic of treadmill walking could have altered the variability of foot placement, while the slow baseline walking speed may have increased the medial–lateral COM motion, thereby influencing the assessment of whole-body frontal plane kinematics. However, previous research has demonstrated that the amount of variability in foot placement during treadmill walking is comparable to that of overground walking [29]. The 15-min acclimation period was intended to minimize both of these concerns. While the goal of using the AuR metric was to capture the average variability in the frontal plane movement pattern and thus the challenge to lateral balance control over specified periods of interest (i.e. training and transfer performance), some resolution may have been lost. In future work it may be of value to examine changes in the average amount of variability over shorter time periods rather than over the entire training, or transfer session. Such an approach could yield information regarding how and when to manage practice difficulty. Lastly, a greater number of strides may be necessary to fully capture the variability of the lateral movement pattern [30].

Additional research is necessary to determine whether the differences in whole kinematic movement strategies observed in this study are accompanied by differences in kinetic strategies as well as individual joint kinematics, and whether the ability of gradual training to reduce the challenge to lateral balance control can be retained over an extended period of time. The ability of gradual and sudden training to improve responses to discrete as well as continuous perturbations requires further analysis, as does the degree to which gradual but not sudden training promotes equivalent challenge to lateral balance control in each leg.

5. Conclusion

This study found that gradual training reduced the challenge to lateral balance control during training, and perhaps more importantly during subsequent performance of a novel locomotor task. These results indicate that motor learning strategies are capable of altering aspects of locomotor balance control and their selection should receive greater attention during the development of locomotor balance control rehabilitation protocols.

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Conflict of interest statement

The authors attest to having no conflict of interest regarding this submitted work.

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