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Learning New Gait Patterns is enhanced by specificity of training rather than progression of task difficulty

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Abstract

The use of motor learning strategies may enhance rehabilitation outcomes of individuals with neurological injuries (e.g., stroke or cerebral palsy). A common strategy to facilitate learning of challenging tasks is to use sequential progression - i.e., initially reduce task difficulty and slowly increase task difficulty until the desired difficulty level is reached. However, the evidence related to the use of such sequential progressions to improve learning is mixed for functional skill learning tasks, especially considering situations where practice duration is limited. Here, we studied the benefits of sequential progression using a functional motor learning task that has been previously used in gait rehabilitation. Three groups of participants (N=43) learned a novel motor task during treadmill walking using different learning strategies. Participants in the specific group (n=21) practiced only the criterion task (i.e., matching a target template that was scaled-up by 30%) throughout the training. Participants in the sequential group (n=11) gradually progressed to the criterion task (from 3% to 30% in increments of 3%), whereas participants in the random group (n=11) started at 3% and progressed in random increments (involving both increases and decreases in task difficulty) to the criterion task. At the end of training, kinematic tracking performance on the criterion task was evaluated in all participants both with and without visual feedback. Results indicated that the tracking error was significantly lower in the specific group, and no differences were observed between the sequential and the random progression groups. The findings indicate

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Conflict of Interest Statement
The authors report no conflict of interest for the current study.

that the amount of practice in the criterion task is more critical than the difficulty and variations of task practice when learning new gait patterns during treadmill walking.

Keywords

locomotion; practice structure; variable; constant; gradual; variability

Introduction

The ability of humans to learn novel motor tasks is integral to development and daily function, and therefore there is a critical need to examine optimal training methods to maximize learning of new motor skills. The use of appropriate motor learning strategies to improve learning also has clinical implications because of its ability to enhance rehabilitation outcomes following neurological injury (Kitago and Krakauer, 2013; Krakauer, 2006).

Indeed, motor learning is considered to be critical for learning-dependent neuroplasticity and for restorative therapies after neurological injury, such as stroke or cerebral palsy (Winstein et al., 2014). This is because acquisition of new skills in many ways is similar to re-learning of lost skills after a damage to the neuromotor system. Thus, the way that the therapy session has to be structured (i.e., practice structure), the activities that are to be performed, as well as their order and relative amounts (i.e., dosage) are all critical components for re-learning of lost motor functions (Winstein et al., 2014). However, there has been limited research on optimal strategies to facilitate learning of leg motor tasks, particularly during gait.

From a clinical standpoint, a key issue in gait rehabilitation is the issue of retention (i.e. how well performance on the trained task is retained after practice). Retention is especially critical in the context of addressing specific impairments (e.g. stiff knee gait) where a specific movement coordination is desired after rehabilitation. Thus, examining the optimal methods to facilitate motor learning during gait is not only interesting from a theoretical standpoint of how movements are learned and retained for future use, but also from a therapeutic standpoint because of its relevance to gait rehabilitation in individuals with neurological or musculoskeletal injuries.

One factor in particular that influences learning is the progression of task difficulty (Capio et al., 2013; Christiansen et al., 2018). Typical rehabilitation paradigms emphasize sequential progression of the task from easy to difficult. In the motor learning literature, the support for such sequential progression is mixed - there is some evidence that 'errorless' learning, which occurs during sequential progression promotes implicit learning that is robust to external situations (Capio et al., 2013; Kessels and Hensken, 2009; Maxwell et al., 2001; Winning et al., 2018). However, other studies have not found such benefits (Lin et al., 2018; Mount et al., 2007; Orrell et al., 2006).

Moreover, despite the large body of work elucidating the role of task difficulty in skill learning, two critical issues remain unanswered - (i) from a dosing standpoint, if the amount of practice time is controlled, then practicing on easy versions of the task might be suboptimal because it necessarily means that practice time on the criterion task is reduced, (ii) if sequential progression does facilitate learning, it is not clear if the benefit is due to sequential progression, or simply because of practicing multiple task variations (Turnham et al., 2012). If it is only practice variation that facilitates learning, then a random progression of task difficulty to the criterion task should also yield similar benefits as sequential progression.

In this study, we examined these questions using a novel foot-trajectory tracking task that has been previously used in gait rehabilitation. We found that sequential progression of task difficulty was not superior to random progression and that specific practice at higher task difficulty was superior to sequential progression of task difficulty for learning a new gait pattern during walking.

Methods

2.1 Participants

Participants included 43 healthy adults (Age: 22.7±5.4 years; Height: 1.72±0.10 meters; Weight: 67.3±13.1 kilograms) with no history of major orthopedic or neurological conditions, injuries in their lower extremities, uncontrolled illnesses, and/or medication changes in the past 3 months. All participants were classified right-foot dominant based on the leg with which they preferred to kick a ball (Krishnan, 2015; Krishnan et al., 2017; Ranganathan et al., 2016). Participants provided informed, written consent prior to participation, and all protocols received approval from the University of Michigan Institutional Review Board.

2.2 Study protocol

A schematic of the experimental procedure is shown in Figure 1. The motor learning task was performed while the participants walked on a motorized treadmill at 0.89m/s (2mph) while a camera (C920 Pro HD Logitech Webcam, Logitech, Newark, CA, USA) tracked kinematics in real-time via reflective markers placed on the lateral side of the hip, knee, and ankle joints (Krishnan et al., 2015). The motor learning task involved learning a new gait pattern that necessitated greater hip and knee flexion angles during swing phase of the gait. The experiment began by first having the participant walk normally on the treadmill to obtain ensemble averages of their right hip and knee angles across the entire trial. The ensemble averaged normal walking hip and knee trajectories were then scaled (3% to 30%) to create target templates, which were projected in the end-point space (i.e., as a foot-trajectory template, which represents the spatial path of the participant's lateral malleolus relative to the hip [local coordinate system] on the sagittal plane) (Krishnan et al., 2017; Krishnan et al., 2018; Ranganathan et al., 2016) using the following forward kinematic equation.

$$\begin{bmatrix} X_a \\ Y_a \end{bmatrix} = \begin{bmatrix} \sin(\theta_h) & -\sin(\theta_k - \theta_h) \\ -\cos(\theta_h) & -\cos(\theta_k - \theta_h) \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}$$

where X_a and Y_a are the x and y positions of the ankle lateral malleolus (referred to as the foot-trajectory) relative to the hip, l_1 is the distance between hip and knee markers, l_2 is the distance between knee and ankle markers, θ_h and θ_k are the hip and knee angles. The forward kinematic model was used instead of simply tracking and scaling the ankle marker in the global coordinate system because the relative position of the participant on the treadmill will not affect the foot-trajectory.

The participant then performed nine blocks of target-matching trials with each block lasting for one minute. Each block was separated by a one-minute rest period. The target template representing the ankle path over one stride was projected onto a monitor placed in front of the participant. The participant was asked to adjust their gait patterns to match the scaled template to the best of their ability. The real-time actual trajectory of the participant was displayed concurrently along with the target template as the participant attempted to alter their gait pattern on the right leg to match the target template. The visual feedback on the screen was adjusted such that the participant could see the entire trajectory produced over the previous gait cycle.

Participants were assigned to one of three training groups: specific (n=21), sequential progression (n=11), or random progression (n=11), referring to the manner (i.e., order) in which the tasks were introduced (Figure 1D). This sample size provided us with a power $\beta >$ 80% to detect statistical significance with an effect size of f=0.5 (computed from our prior study) at a significance level of $\alpha = 0.05$ (computed with unequal sample sizes in G*power 3.1) (Krishnan et al., 2018). Participants in the specific training group were required to match a 30% scaled template (criterion task) immediately at the beginning of training and for all target-matching trials including the criterion task. The template for the sequential progression group started at a 3% and increased in increments of 3% until they reached the criterion task. Participants in the random progression group also initially practiced at the 3% template, but subsequent trials were pseudo-randomly scaled by factors of three between 3% and 30% — ending on 30% for the criterion task. Two pseudo-random orders (Random 1: n=6 and Random 2: n=5) were used in order to ensure that any differences observed were not simply due to chance. Thus, both sequential and random progression groups performed essentially the same tasks with the same variation in task practice, except the order in which the tasks were performed differed between the groups. The total amount of practice was constant across all groups; however, both the sequential and random groups received a lower amount of practice on the criterion task than the specific group. At the end of training, participants in all the groups performed the criterion task (i.e., matching a 30% target template), first with visual feedback (VF) and then with no visual feedback (NVF).

2.3 Analysis Protocol

Participant performance during target-matching was evaluated by computing the amount of tracking error during each block. To compute tracking error (see supplemental section), the difference in area (computed in pixels) between the actual and intended trajectory for each stride was found and normalized to the area of the criterion task-template trajectory (also computed in pixels) (Figure 1C). The error for each stride was then averaged across all strides in a trial to determine the average tracking error during each training block.

2.4 Statistical Analyses

All statistical analyses were performed in SPSS for Windows version 24 (SPSS Inc., Chicago, IL, USA). Differences in tracking error in the criterion task (i.e., 30% target template) during target-matching with and without visual feedback were used as the primary variables for all analyses. Non-parametric tests were used because the Shapiro-Wilk's test for normality indicated that the data were not normally distributed. To determine if reducing task difficulty or increasing the amount of practice in the criterion task was important for learning a new gait pattern during walking, a Kruskal-Wallis test was used to evaluate the differences in tracking error between the specific and the sequential and random progression groups. To determine if the progression of task difficulty was critical for learning a new gait pattern during walking, a Kruskal-Wallis test was used to evaluate the differences in tracking error between sequential and random progression groups. A significance level of $\alpha = 0.05$ was used for all statistical analyses.

Results

The median tracking error (and interquartile range [IQR]) when performing the criterion task with visual feedback were as follows: Specific: 11.9 (10.2 to 13.3); Sequential: 16.4 (14.0 to 19.6); Random: 14.8 (11.9 to 18.8). The median tracking error (and IQR) when performing the criterion task without visual feedback were as follows: Specific: 15.1 (13.0 to 17.9); Sequential: 20.2 (16.3 to 22.1); Random: 19.5 (14.2 to 21.6). Tracking error was significantly lower in the specific group in comparison with sequential and random progression groups for both target-matching with visual feedback (χ^2=11.736, p=0.001) and no visual feedback (χ^2=5.328, p=0.021) (Figure 2A). There were no differences in tracking error between the sequential and the random progression group for both target-matching with visual feedback (χ^2=0.786, p=0.375) and no visual feedback (χ^2=0.475, p=0.491) (Figure 2B).

Discussion

The purpose of this study was to investigate the effects of task difficulty, variations in task practice, and the amount of practice on learning of a novel motor task during walking. We found that reducing task difficulty by incrementally introducing the task requirements did not facilitate learning. This was the case irrespective of whether the task was introduced sequentially or randomly, indicating that the order of task progression did not influence the outcomes. Rather, we found that learning was facilitated when participants spent a greater amount of time practicing the criterion task, as was done in the specific training group. This observation is in contrast with prior studies that have shown that despite greater amount of practice on the criterion task in the specific training group, individuals in the random or sequential progression (aka gradual training) group perform similar to or better than those in the specific training group (Huang and Shadmehr, 2009; Kagerer et al., 1997; Sawers and Hahn, 2013; Shea and Kohl, 1990; Tang et al., 2018). Interestingly, our results suggest that reducing task difficulty may only lead to minimal learning of a novel motor task, as the final performance (i.e., at the end of training) of participants in both the sequential and random groups was similar to the initial performance of participants in the specific group (Figure

2A). Thus, if the goal is to maximize efficiency of training (such as in rehabilitation where third-party reimbursement is based on total therapy time), then specific practice is superior to sequential or random progression.

The finding that specific training is superior to sequential training is in contrast with some of the motor adaptation literature, but is consistent with studies that have utilized skill learning tasks (Lin et al., 2018; Mount et al., 2007; Orrell et al., 2006). The disparity between motor adaptation and skill learning tasks could be due to the differences in learning mechanisms between adaptation and skill learning (Krakauer and Mazzoni, 2011; Krishnan et al., 2018). For example, adaptation tasks typically involve a perturbation, where the participant must adapt their movement back to pre-perturbation levels by means of sensory-prediction errors, which are dependent on cerebellar-cerebral neural pathways (Spampinato et al., 2017). In contrast, skill acquisition tasks typically do not involve a perturbation and the participant improves performance using success-based exploration, which involves more cortical structures (Bo et al., 2008; Krakauer and Mazzoni, 2011). The results are not surprising considering that large amounts of specific practice are known to result in the emergence of effects similar to those of especial skills (Breslin et al., 2012; Lin et al., 2018), where well practiced movements lead to the development of a specific memory representation that is unique to the practiced task through use-dependent learning (Keetch et al., 2008; Ranganathan and Newell, 2013). While it is unclear whether participants in the specific training group developed a true especial skill, as the amount of practice was relatively short, prior research has shown that especial skills can emerge even with short-term repetitive practice (300 repetitions) (Breslin et al., 2012). Indeed, data from our prior studies (which used similar amount of practice) support the development of a unique skill similar to especial skills with repeated practice, as participants showed complete retention of the learned gait pattern during the delayed retention test and also exhibited substantial transfer to the opposite, untrained leg (Krishnan et al., 2017; Krishnan et al., 2018). While this improvement through repeated practice of the same task may come at the cost of poor generalization to other task variations (see potential limitations in supplementary section) (Ranganathan and Newell, 2013), this type of training may be very relevant for gait rehabilitation, where one of the goals is to minimize variability of gait patterns (Hausdorff, 2005; Hausdorff et al., 2001).

Although we found specific training to be more beneficial than sequential progression for learning our locomotor task, it should be noted that there are instances in which sequential training is the only feasible method for learning a novel skill. An example of such a circumstance is when the subject is unable to perform the criterion task safely at the beginning of training, and the only way for them to learn is to train progressively towards their goal (e.g., a gymnast learning to backflip). Also, in some situations (particularly in rehabilitation), performing the criterion task at high difficulty could decrease an individual's motivation, thereby reducing practice effectiveness or even adherence to the training program (Guadagnoli and Lee, 2004; Reinkensmeyer and Dietz, 2016).

In summary, the results of this study show that reducing task difficulty through sequential progression of task requirements is of minimal benefit, whereas performing the same task repeatedly through specific practice offers greater benefit when learning a new gait pattern during treadmill walking. The advantage of specific training appears to be primarily mediated through a greater number of practice trials on the criterion task, as increasing task difficulty through random variations of task progression did not change the outcomes. These results underscore the importance of the amount of practice, as opposed to task difficulty/variation, in learning a new gait pattern, which may have meaningful implications for gait rehabilitation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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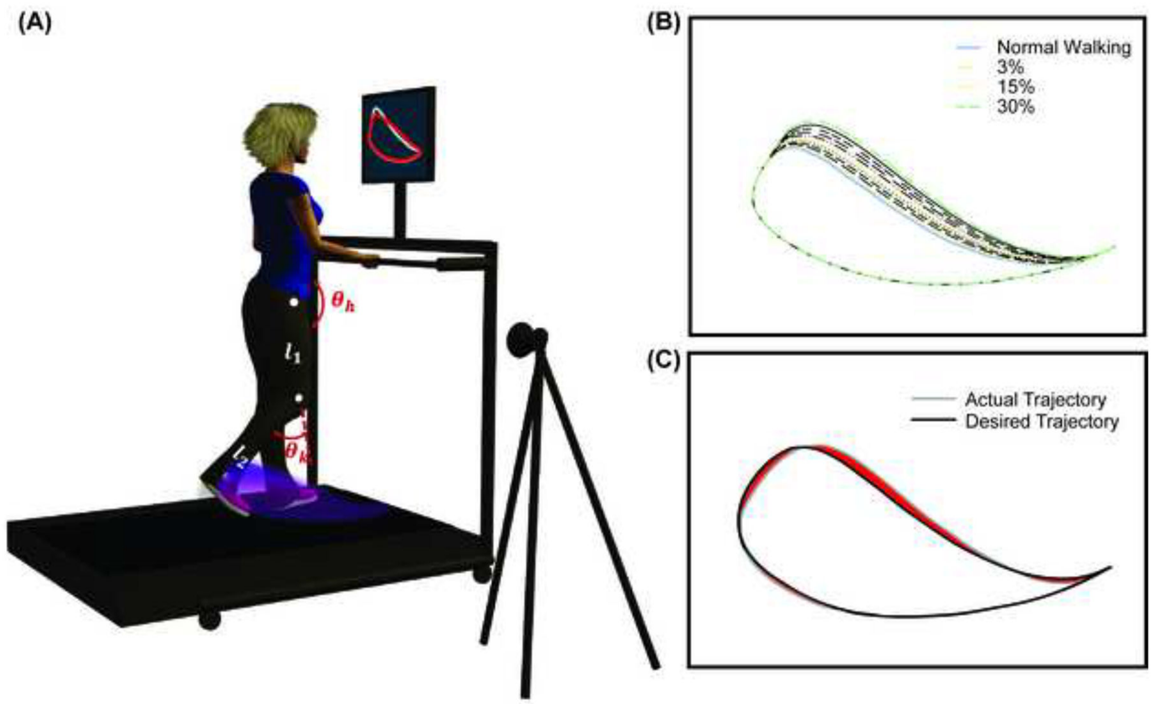

(D)

Group	Normal Walking	Target-matching									Criterion Task	
		TM 1	TM 2	TM 3	TM 4	TM 5	TM 6	TM 7	TM 8	TM 9	Feedback	No Feedback
Specific	0	30	30	30	30	30	30	30	30	30	30	30
Sequential	0	3	6	9	12	15	18	21	24	27	30	30
Random 1	0	3	27	15	9	24	6	12	18	21	30	30
Random 2	0	3	21	18	6	24	15	9	27	12	30	30

Figure 1:

A schematic of the (A) experimental set-up, (B) creation of target templates, (C) computation of tracking error (shaded region) and (D) experimental protocol. Note that figure legend for the creation of target templates only show four target trajectories for the sake of clarity. The values on the table for experimental protocol indicates the increase in template size (i.e., scaling) with respect to normal walking. For the random progression group, participants were split into two random sequences (Random 1 and Random 2). Each trial was one minute long.

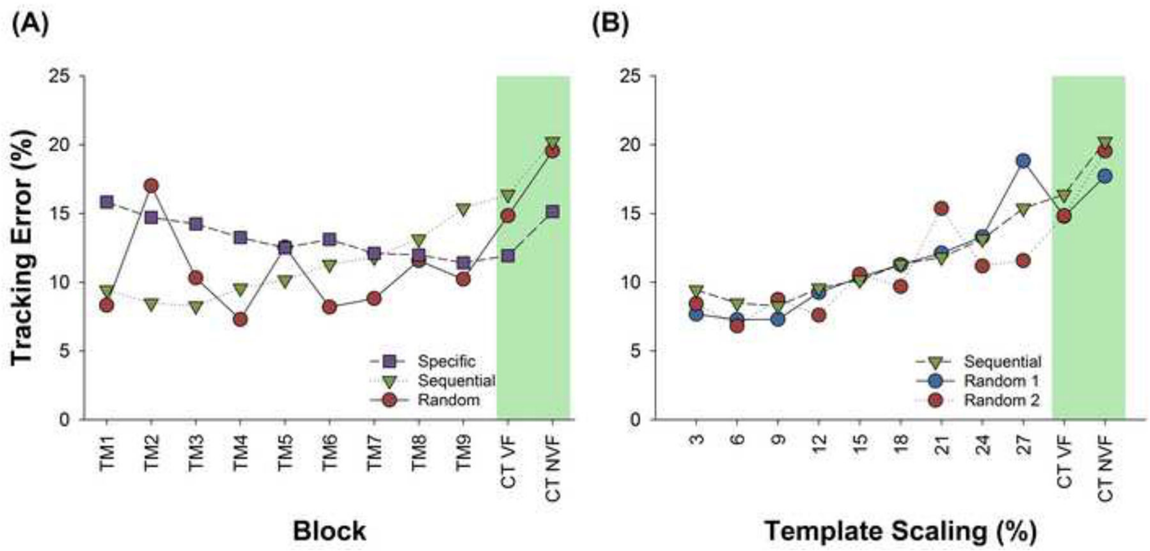

Figure 2:

(A) Median tracking error observed at each target template for the specific, sequential, and random groups, in the order of introduction (the notation of the x-axis for the non-shaded region refers target-matching [TM] blocks and the block number). **(B)** Median tracking error observed at each target template for the sequential and random groups, in the order of template size. Note the shaded region in **(A)** and **(B)** indicates the criterion task blocks with visual feedback (VF) and no visual feedback (NVF) for which comparisons were made between groups.