Gait & Posture 70 (2019) 84–89

Contents lists available at ScienceDirect

Gait & Posture

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

Learning and interlimb transfer of new gait patterns are facilitated by distributed practice across days

Chandramouli Krishnan[a,b,c,d,*]

[a] Department of Physical Medicine and Rehabilitation, Michigan Medicine, Ann Arbor, MI, USA
[b] Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA
[c] Michigan Robotics Institute, University of Michigan, Ann Arbor, MI, USA
[d] School of Kinesiology, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

Keywords:
Cross education
Intermanual
Skill learning
Spaced practice
Spacing
Consolidation

ABSTRACT

Background: Previous studies have shown that the extent to which learning with one limb transfers to the opposite, untrained limb (i.e., interlimb transfer) is proportional to the amount of prior learning (or skill acquisition) that has occurred in the training limb. Thus, it is likely that distributed practice—a training strategy that is known to facilitate learning—will result in greater interlimb transfer than massed practice.
Research question: To evaluate the effects of massed and distributed practice on acquisition and interlimb transfer of leg motor skills during walking.
Methods: Forty-five subjects learned a new gait pattern that required greater hip and knee flexion during the swing phase of gait. The new gait pattern was displayed as a foot trajectory in the sagittal plane and participants attempted to match their foot trajectory to this template. Subjects in the massed practice group (n = 20) learned the task on a single day, whereas subjects in the distributed practice group (n = 25) learned the task that was spaced over two consecutive days (training phase). Following completion of training, subjects in both groups practiced the task with their untrained, opposite leg to evaluate interlimb transfer (transfer phase).
Results: Results indicated that the amount of skill acquisition (i.e., reductions in tracking error) on the training leg was significantly higher ($P < 0.05$) in the distributed practice group when compared with the massed practice group. Similarly, the amount of interlimb transfer was also significantly higher ($P < 0.05$) in the distributed practice group both at the beginning and end of the transfer phase.
Significance: The findings indicate that acquisition and interlimb transfer of leg motor skills are significantly greater when the task was learned using distributed practice, which may have implications for gait rehabilitation in individuals with unilateral deficits, such as stroke.

1. Introduction

Interlimb transfer is the process in which training of one limb confers a benefit in performance to the opposite, untrained limb [1,2]. This ability of the neuromotor system to transfer the knowledge gained from training with one limb to the other limb is a key aspect of motor recovery in individuals with significant unilateral deficits, such as stroke or hemiparetic cerebral palsy [3,4]. Thus, understanding the processes that lead to stronger interlimb transfer may have therapeutic implications, as it can assist in the development of new treatment approaches.

Previous studies have shown that various factors (e.g., type of task, spatial reference frame, duration of training, ageing, etc.) affect the extent to which learning with one limb transfers to the opposite limb [5–9]. One such factor is the amount of learning (or skill acquisition) that has occurred with the training limb prior to testing on the opposite limb. It has been shown that the amount of interlimb transfer is proportional to the acquisition of skill in the training leg, such that interlimb transfer is greater with greater skill acquisition in the training leg [10]. Thus, it seems intuitive that training strategies that promote greater acquisition and retention will also produce greater interlimb transfer. For example, it is well known that distributed practice (i.e., a training strategy, where practice sessions are spaced over time) is superior to massed practice for acquisition and learning of novel motor tasks [11,12]. Hence, it is likely that the extent of interlimb transfer will be greater with distributed practice as opposed to massed practice.

* Corresponding author at: Neuromuscular and Rehabilitation Robotics Laboratory (NeuRRo Lab), Department of Physical Medicine and Rehabilitation, Michigan Medicine, University of Michigan, 325 E Eisenhower Parkway (Suite 3013), Ann Arbor, MI 48108, USA.
E-mail address: mouli@umich.edu.

https://doi.org/10.1016/j.gaitpost.2019.02.019
Received 23 November 2018; Received in revised form 20 February 2019; Accepted 22 February 2019
0966-6362/

However, this premise has not been verified experimentally to date.

Here, we used a novel motor learning task that has been previously used in gait rehabilitation to study the effects of massed and distributed practice on skill acquisition and interlimb transfer of new gait patterns during treadmill walking. We hypothesized that skill acquisition and interlimb transfer will be significantly greater with distributed practice than with massed practice.

2. Methods

2.1. Participants

Participants included 45 adults (Age: 22.3 ± 5.7 years; Height: 1.75 ± 0.08 m; Weight: 68.7 ± 11.6 kg; Females: 20; Males: 25) with no history of major orthopedic or neurological conditions. All participants were right leg dominant based on their preferred leg to kick a ball [10,13,14]. All participants signed a written informed consent document that was approved by the University of Michigan Institutional Review Board prior to participation.

2.2. Experimental protocol

A schematic of the experimental procedure is provided in Fig. 1. Subjects in the massed practice group (n = 20) performed the motor learning task in a single day, whereas the subjects in the distributed practice group (n = 25) performed the same task over two consecutive days that were separated by about 24 h. In both groups, about half of the participants performed the task with their right leg and half with their left leg (massed practice: 10 right leg and 10 left leg; distributed practice: 13 right leg and 12 left leg). The experiment began by having participants walk normally on a motorized treadmill at 0.89 m/s (2 mph) for one minute (Tr-NW). The hip and knee kinematics during normal walking were recorded using a camera (C920 Pro HD Webcam, Logitech, Newark, CA, USA) that tracked markers placed on the hip, knee, and ankle joints (Fig. 2A) and a reliable real-time tracking algorithm that was custom developed using LabVIEW 2011 and NI Vision Assistant (National Instruments Corp., Austin, TX, USA) [15,16]. The ensemble average of the hip and knee kinematics was then scaled (30%) during the swing phase of gait and smoothed using a Hanning window to minimize any abrupt scaling both in the beginning and at the end of swing phase (Fig. 2B). The kinematic trajectories were then projected in the endpoint space (i.e., as a foot trajectory template) using a forward kinematic equation to produce a foot trajectory tracking template [7,10,14].

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

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. Thus, when performing the motor learning task, the participant was required to alter their hip and knee joint kinematics during the swing phase of gait to successfully match the target projected on a monitor that was placed in front of them. The visual feedback on the screen was adjusted such that the participant could see their entire trajectory produced over the previous gait cycle.

The experiment consisted of two phases: (1) training phase and (2) transfer phase. During the *training* phase, the initial performance of the training leg was established by having the participant match the target template as precisely as possible for one minute (Tr-TM Pre). The participant then practiced the same task for 18 blocks of training with each block lasting for one minute (Tr-TM1 to Tr-TM18). Depending on the group, these 18 blocks of training were either performed on the same day or were equally distributed across two days (Fig. 1). A one-minute rest period was provided between each training block. At the end of the *training phase*, the changes in tracking performance of the training leg (i.e., skill acquisition) was evaluated (Tr-TM Post). During the *transfer* phase, the target template for the untrained, opposite leg was first created in the same manner as the training leg. Following which, the tracking performance of the untrained, opposite leg (i.e., interlimb transfer) was evaluated (initial transfer: Tf-TM Initial). The participant then practiced the task with their transfer leg for 8 blocks (Tf-TM1 to Tf-TM8), following which, the final performance of the transfer leg was evaluated (final transfer: Tf-TM final). Throughout the experiment, the participant was instructed to match the target as precisely as possible without altering the normal gait patterns of their opposite leg that was not involved in the target-matching task [7].

2.3. Data analyses

Motor performance during the target-matching task was evaluated by computing the tracking error (i.e., the error between the actual

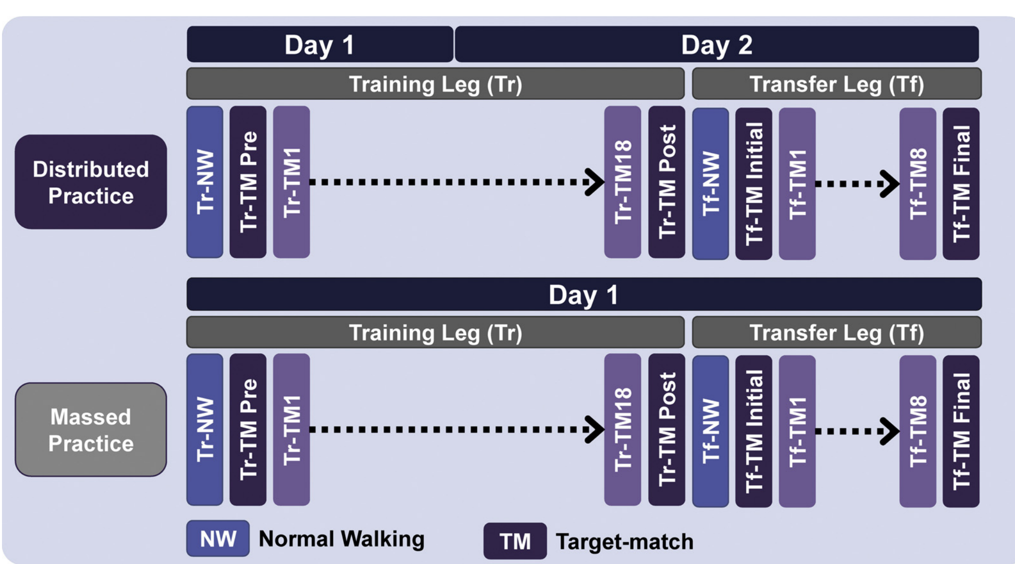

Fig. 1. Schematic of the experimental protocol. Two groups of participants volunteered for this study. Participants in the massed practice group performed the training (18 trials) in a single day and the participants in the distributed practice group performed the same task over two consecutive days that were separated by about 24 h (i.e., 9 trials on Day 1 and 9 trials on Day 2). Thus, the total practice time was constant for both groups. During normal walking (NW) trials participants walked normally on a treadmill at 0.89 m/s (2 mph). The hip and knee kinematic data recorded during the normal walking trials were used to construct the target-templates. During target-matching (TM) trials participants performed a foot trajectory tracking task that necessitated greater hip and knee flexion during the swing phase of gait. The prefixes “Tr” and “Tf” refer to the training and transfer legs, respectively. The suffixes Pre and Post refer to the initial and final training blocks, respectively. Following each block, subjects were given approximately 1 min of rest.

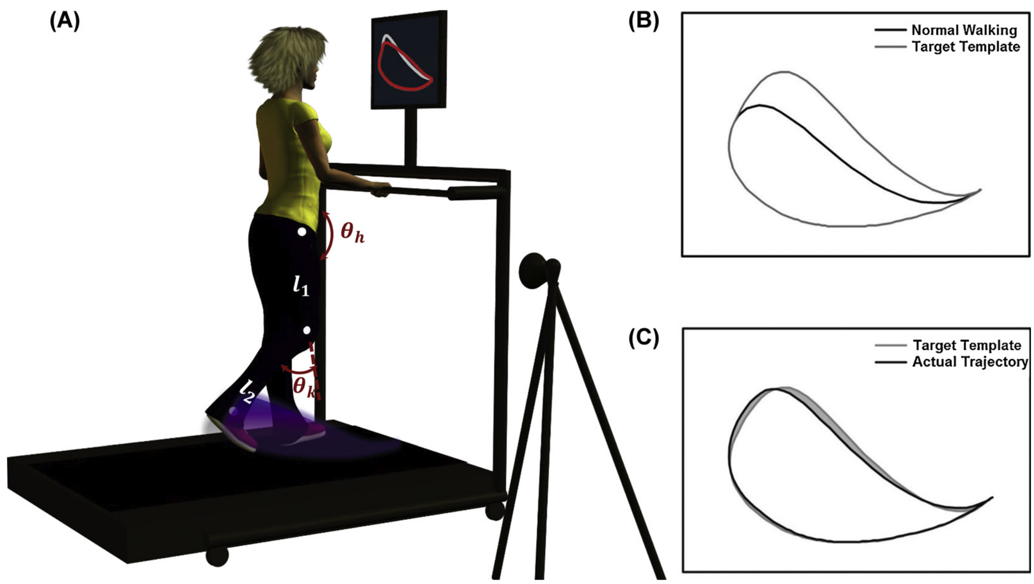

Fig. 2. (A) Schematic of the experimental set-up of the leg motor skill learning task during treadmill walking. (B) Schematic showing creation of target-template. (C) Schematic showing the computation of tracking error (shaded region).

trajectory and the target trajectory) during each training block. Tracking error was computed for each stride in the training block by calculating the difference in area (computed in pixels) between the actual and target trajectory and normalizing it to the area of the target-template trajectory (also computed in pixels) (Fig. 2C) [7,10,15]. The error for each stride was then averaged across all strides in a block 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). Analysis of Covariance (ANCOVA) was used to evaluate the effects of spacing on skill acquisition and interlimb transfer. To evaluate whether spacing affected skill acquisition, the difference in tracking error at the end of training phase (Tr-TM Post relative to Tr-TM Pre) was compared between the groups. To evaluate whether spacing affected interlimb transfer, the differences in tracking error at the beginning and end of the transfer phase were compared between the groups (i.e., initial and final tracking error of the untrained leg [i.e., transfer leg] relative to initial tracking error of the trained leg: Tf-TM initial and Tf-TM final relative to Tr-TM Pre). The initial performance of the training leg (Tr-TM Pre) was used as a covariate for all analyses [7]. We note that using ANCOVA of the error is statistically equivalent to using ANCOVA of the change in error to compare groups [17,18]. Linear regression through the origin was used to evaluate whether the amount of skill acquisition on the training leg (TrTM Pre − TrTM Post) affected the amount of interlimb transfer [(TrTM Pre − TfTM Initial) and (TrTM Pre − TfTM Final)]. A significance level of $\alpha = 0.05$ was used for all statistical analyses.

3. Results

The ensemble averages of the hip and knee flexion angles during normal walking and target-matching trials for the training and transfer legs are provided in Fig. 3. There was a significant effect of group on the amount of skill acquisition and interlimb transfer (Fig. 4). Participants in the massed practice group had higher tracking error (i.e., reduced skill acquisition) in the training leg in comparison with the distributed practice group ($F_{1,42} = 8.290$, $p = 0.006$; Fig. 5). They also had significantly lower interlimb transfer of the motor skill in their untrained, opposite leg in comparison with the distributed practice group ($F_{1,42} = 4.318$, $p = 0.044$; Fig. 5). This reduced interlimb transfer persisted even at the end of practice with their transfer leg (final transfer: $F_{1,42} = 8.976$, $p = 0.005$; Fig. 5). Regression analyses indicated that there was a significant linear relationship between the amount of skill acquisition on the training leg and the amount of transfer to the untrained, opposite leg (transfer: $\beta = 0.741$, $R^2 = 0.761$, $p < 0.001$; final transfer: $\beta = 1.020$, $R^2 = 0.931$, $p < 0.001$). Evaluation of the regression slopes indicated that for every 1% change in tracking-error on the training leg (i.e., learning) there was a change of 0.76% and 1.02% of tracking error on the transfer leg at the beginning (i.e., initial transfer) and end of the transfer phase (i.e., final transfer), respectively.

4. Discussion

The purpose of this study was to test whether acquisition and interlimb transfer of leg motor skills during walking was affected by the amount of spacing between practice sessions. Two groups (massed and distributed practice) of individuals practiced a new gait pattern that required alterations in hip and knee flexion angles during the swing phase of gait. For the massed practice group, training was performed continuously within the same day, whereas for the distributed practice group, training was distributed across two days (about 24 h spacing). The results showed that both skill acquisition and interlimb transfer were significantly higher when practice was distributed across days. Also, a large proportion of variance in the amount of interlimb transfer was explained by the amount of skill acquisition on the training leg, indicating that the enhanced performance in the transfer leg was at least partly mediated by the improved motor performance on the training leg. These results provide novel evidence indicating that spacing practice sessions across days is superior to massed practice within the same session for enhancing motor skill acquisition and interlimb transfer of new gait patterns.

The phenomenon of interlimb transfer is of particular interest to rehabilitation specialists, as it has therapeutic implications for individuals with unilateral motor deficits, such as stroke or hemiparetic cerebral palsy. For example, there is a growing interest in training the less-impaired limb to improve motor performance and functional deficits in the more-impaired limb of stroke survivors [3,4]. However, our understanding of practice strategies that could potentially enhance the transfer of motor skills from one limb to the other is limited,

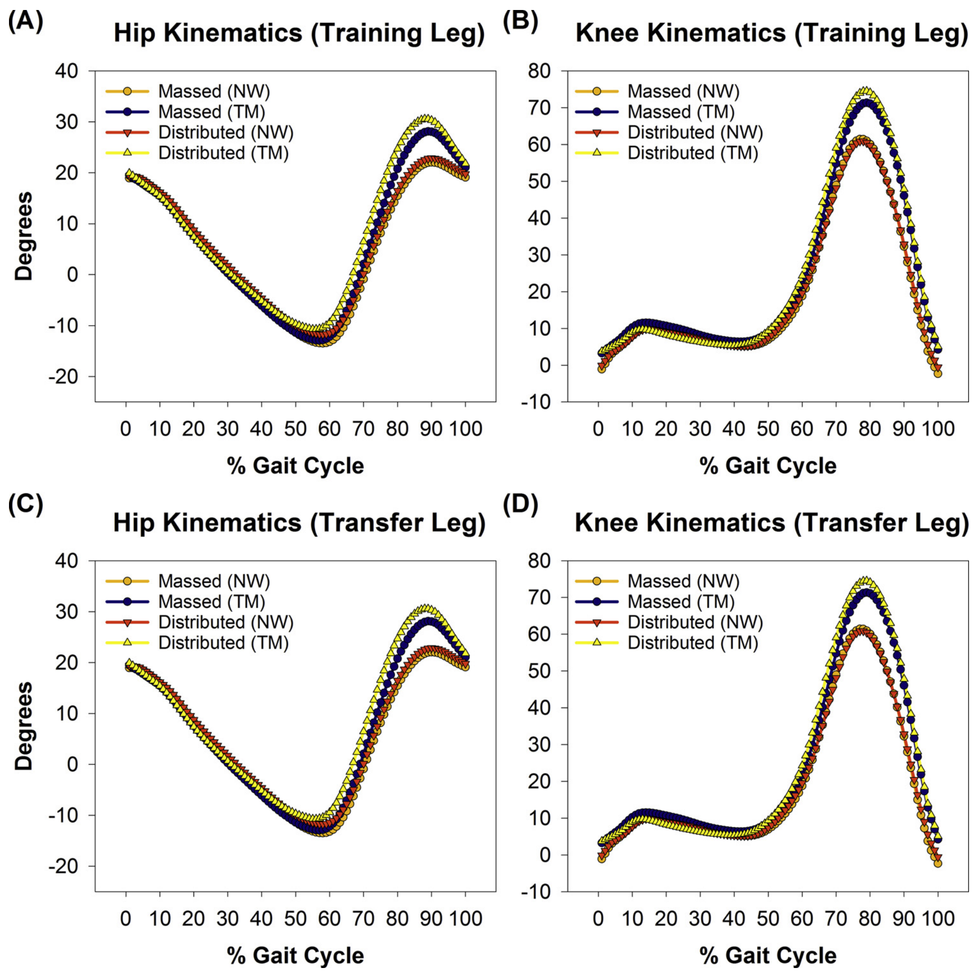

Fig. 3. Ensemble averages of the hip and knee flexion angles during normal walking (NW) and target-matching (TM) trials in the massed and distributed practice group. Panels A and B represent the training leg's ensemble averages of hip and knee flexion angles, respectively. Panels C and D represent the transfer leg's ensemble averages of hip and knee flexion angles, respectively. Note that the strategies used for performing the motor learning task were similar between groups for both the training and the transfer legs.

particularly for tasks with functional relevance, such as gait. The results of this study establish, for the first time, that distributed practice is superior to massed practice for learning new gait patterns and transferring that skill to the opposite, untrained leg. It is important to note that the motor learning task used in this study has high clinical relevance, as previous studies have shown that incorporation of this task in the rehabilitation program improves clinical outcomes after stroke [19–22].

The benefits of distributed practice for the acquisition and retention of new motor skills have been well established in the literature [23–27]. However, most of the studies have focused on the upper-extremity with virtually no research on the effects of spacing of practice sessions on learning and interlimb transfer of leg motor skills, which have particular relevance to gait rehabilitation. Here, we used a continuous skill learning task that has been previously used in gait rehabilitation to show for the first time that learning a new gait pattern can be facilitated by distributed practice than with massed practice. Using the same task, we also show that interlimb transfer of the learned skill is facilitated by distributed practice. These results extend the findings of upper-extremity studies and also underscore the importance of distributed practice during rehabilitation of individuals with motor deficits.

Motor memory consolidation has been attributed as one of the theoretical explanations for the benefits of distributed practice over massed practice on learning or acquisition of motor skills [27]. In this study, practice was evenly spaced across two consecutive days for the distributed practice group, whereas the massed practice group performed all the trials within the same day. Thus, it seems likely that the distributed practice group would have benefited by the extra time provided for motor memory consolidation. Interestingly, when comparing the tracking error in Tr-TM10 (i.e., first practice trial on Day 2 for the distributed practice group with the corresponding target-matching trial for the massed practice group) between groups, we did not find any significant difference ($p > 0.05$, Fig. 4). Rather, the tracking error reduced gradually with training on Day 2 for the distributed practice group while the massed practice group plateaued at that time-point. This suggests that factors other than consolidation could have contributed for the observed benefits in the distributed practice group.

It is to be noted that the massed practice group in this study received a small break between practice sessions (1 min). While massed practice is generally defined as practice that occurs without rest between trials [28–30], the idea of having small breaks between practice trials during massed practice is commonly accepted in the motor learning literature [31–34]. Moreover, if we consider discrete tasks (e.g., shooting a basketball or a reaching task), rest between trials is practically unavoidable in massed practice. More importantly, massed practice has been studied even in much longer time scales (e.g., days of break) than the current study [27,32,35,36]. We chose to provide a small break between practice trials in the massed practice group because this is more translatable to clinical practice and rehabilitation, as it will be difficult for individuals with poor locomotor capacity (e.g., stroke or spinal cord injury) to walk continuously without breaks. Further, even in

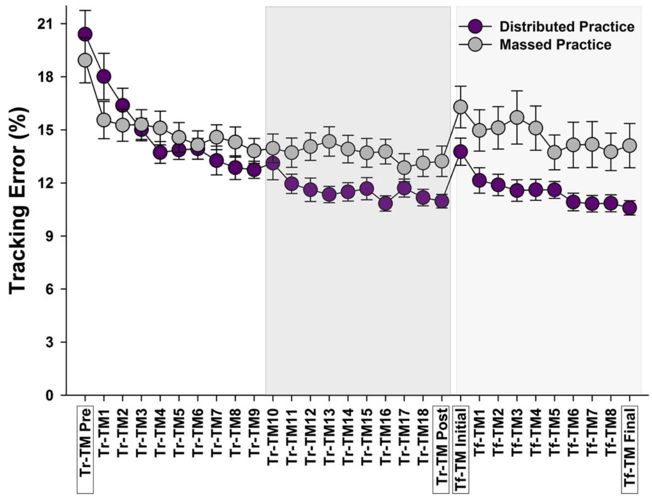

Fig. 4. Mean tracking error in the massed and distributed practice groups for each target-matching (TM) block with the training leg (Tr) and the transfer leg (Tf). The shaded regions indicate the training and testing blocks performed on Day 2 for the distributed practice group. Error bars represent the standard error of the mean. The blocks within the rectangle indicate the trials that were used in the statistical analysis. Tracking error was significantly lower in the distributed practice group when compared with the massed practice group both for the training (Tr-TM Post) and transfer legs (Tf-TM initial and Tf-TM final), indicating that skill acquisition and interlimb transfer were higher after distributed practice.

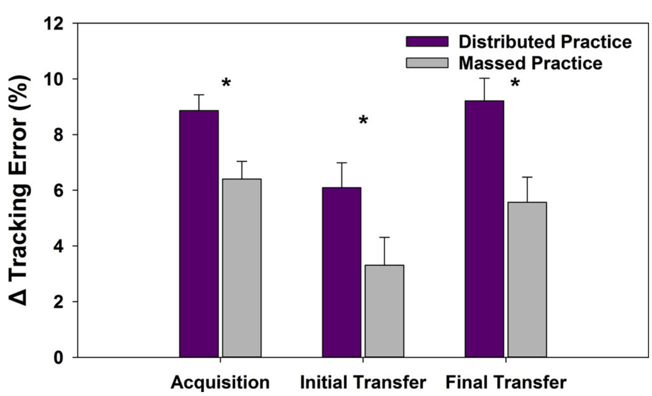

Fig. 5. Reductions in tracking error in the training (i.e., skill acquisition) and transfer legs (i.e., interlimb transfer) of the massed and distributed practice groups. Bars represent the marginal means of the change in tracking error and error bars represent standard error of the mean. Asterisks indicate a significant difference at $\alpha = 0.05$.

neurologically intact individuals, performing a continuous motor task with no rest period while walking on a treadmill could be challenging and could induce significant physical and mental fatigue that could confound the study results. Thus, we believe that by providing a small amount of rest between trials we minimized the confounding effects of fatigue. However, from a theoretical perspective, our design did not allow us to determine if massed practice with no rest period was detrimental to leg motor skill acquisition during walking. Our pilot data from both experienced and novice individuals support the general notion that motor performance degrades as a function of decreasing rest periods. However, future studies are warranted to fully understand the effects of varying levels of rest-periods on leg motor skill learning during walking.

Despite significant research on interlimb transfer, the mechanisms mediating interlimb transfer has been unclear. The two main theoretical models that have been proposed to explain interlimb transfer are the bilateral access model and the cross activation model. The bilateral access model suggests that the motor memories formed during unilateral training are not specific to the trained limb, but can also be accessed by the untrained, opposite limb (e.g., through callosal connections) [2,37–40]. The cross activation model suggests that bilateral cortical activity during unilateral training results in bilateral adaptations that facilitate subsequent performance by the untrained limb [2,41–43]. While this study did not directly evaluate the neural mechanisms underlying interlimb transfer, the observed linear relationship between the amount of learning on the training leg and the amount of interlimb transfer favors the bilateral access model and suggests that this accessibility can be strengthened by training strategies that enhance motor learning.

It is important to note that this study used a continuous task as opposed to discrete task for evaluating the effects of massed vs. distributed practice on learning and interlimb transfer. It is currently unclear whether the benefits observed for learning and transfer of continuous tasks also exist for discrete tasks (e.g., obstacle avoidance) [44,45], as research related to distribution of practice effects in the upper-extremity has yielded conflicting results [46–49]. Further research is required to examine whether there are disparities in the effects of distribution of practice in motor skill acquisition of continuous and discrete tasks.

A key limitation to this study was that the kinematics of the opposite leg (i.e., transfer leg) was not recorded to ensure that participants did not attempt to practice the task also with their contralateral leg during the training phase (which could facilitate interlimb transfer). This was not possible because the reflections of the camera light from the opposite side were substantially affecting the real-time tracking algorithm. However, we have pilot-tested this issue and have found that participants typically do not increase the hip or knee flexion angles of their opposite leg during training (Supplemental Fig. 1). Another limitation is that we do not know the relative permanency of the learning effects observed in this study. It is possible that the learning effects could washout with training session across multiple training days, although there is some evidence to suggest that distributed practice has relatively permanent influence on acquisition and retention of motor skills [32]. Moreover, even if the benefits washout, from a clinical perspective it is more efficient (and cost-effective) to reduce the amount of practice trials in a given day and space it across multiple training sessions.

In summary, this study evaluated the effects of massed and distributed practice on acquisition and interlimb transfer of a new motor skill during treadmill walking. Participants in the massed practice group learned a new gait pattern in a single session (i.e., within the same day), whereas participants in the distributed practice group learned the task across two days, but with same amount of practice. The results showed that distributed practice was superior to massed practice for learning and interlimb transfer of new gait patterns. The results also indicated that the benefits of distributed practice for interlimb transfer of leg motor skills were primarily mediated by enhanced skill acquisition on the training leg. These findings emphasize the importance of distribution of practice sessions across days during rehabilitation to facilitate locomotor outcomes in individuals with gait dysfunction.

Conflict of interest

None.

Acknowledgments

This work was partly supported by the National Institute of Child Health and Human Development of the National Institutes of Health (Grant # R21 HD092614), University of Michigan Undergraduate Research Opportunity Program (UROP), and UM Office of Research Seed Grants. The author would like to thank Mr. Tyler Johnson and Mr. Manik Tetarbe for their assistance in data collection.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.02.019.

References

[1] E. Poh, T.J. Carroll, J.A. Taylor, Effect of coordinate frame compatibility on the transfer of implicit and explicit learning across limbs, J. Neurophysiol. 116 (2016) 1239–1249.
[2] K.L. Ruddy, R.G. Carson, Neural pathways mediating cross education of motor function, Front. Hum. Neurosci. 7 (2013) 397.
[3] A. De Luca, P. Giannoni, H. Vernetti, C. Capra, C. Lentino, G.A. Checchia, et al., Training the unimpaired arm improves the motion of the impaired arm and the sitting balance in chronic stroke survivors, IEEE Trans. Neural Syst. Rehabil. Eng. 25 (2017) 873–882.
[4] R.L. Sainburg, C. Maenza, C. Winstein, D. Good, Motor lateralization provides a foundation for predicting and treating non-paretic arm motor deficits in stroke, Adv. Exp. Med. Biol. 957 (2016) 257–272.
[5] T.J. Carroll, A. de Rugy, I.S. Howard, J.N. Ingram, D.M. Wolpert, Enhanced crosslimb transfer of force-field learning for dynamics that are identical in extrinsic and joint-based coordinates for both limbs, J. Neurophysiol. 115 (2016) 445–456.
[6] W.M. Joiner, J.B. Brayanov, M.A. Smith, The training schedule affects the stability, not the magnitude, of the interlimb transfer of learned dynamics, J. Neurophysiol. 110 (2013) 984–998.
[7] C. Krishnan, E.P. Washabaugh, C.E. Reid, M.M. Althoen, R. Ranganathan, Learning new gait patterns: age-related differences in skill acquisition and interlimb transfer, Exp. Gerontol. 111 (2018) 45–52.
[8] T. Stockel, J. Wang, Transfer of short-term motor learning across the lower limbs as a function of task conception and practice order, Brain Cogn. 77 (2011) 271–279.
[9] J. Wang, A. Przybyla, K. Wuebbenhorst, K.Y. Haaland, R.L. Sainburg, Aging reduces asymmetries in interlimb transfer of visuomotor adaptation, Exp. Brain Res. 210 (2011) 283–290.
[10] C. Krishnan, R. Ranganathan, M. Tetarbe, Interlimb transfer of motor skill learning during walking: no evidence for asymmetric transfer, Gait Posture 56 (2017) 24–30.
[11] T.D. Lee, E.D. Genovese, Distribution of practice in motor skill acquisition: learning and performance effects reconsidered, Res. Q. Exerc. Sport 59 (1988) 277–287.
[12] C.H. Shea, Q. Lai, C. Black, J.-H. Park, Spacing practice sessions across days benefits the learning of motor skills, Hum. Mov. Sci. 19 (2000) 737–760.
[13] C. Krishnan, Are practice trials required for hop tests? Gait Posture 41 (2015) 960–963.
[14] R. Ranganathan, C. Krishnan, Y.Y. Dhaher, W.Z. Rymer, Learning new gait patterns: exploratory muscle activity during motor learning is not predicted by motor modules, J. Biomech. 49 (2016) 718–725.
[15] C. Krishnan, E.P. Washabaugh, Y. Seetharaman, A low cost real-time motion tracking approach using webcam technology, J. Biomech. 48 (2015) 544–548.
[16] R.J. Saner, E.P. Washabaugh, C. Krishnan, Reliable sagittal plane kinematic gait assessments are feasible using low-cost webcam technology, Gait Posture 56 (2017) 19–23.
[17] N. Laird, Further comparative analyses of pretest-posttest research designs, Am. Stat. 37 (1983) 329–330.
[18] J.R. Rausch, S.E. Maxwell, K. Kelley, Analytic methods for questions pertaining to a randomized pretest, posttest, follow-up design, J. Clin. Child Adolesc. Psychol. 32 (2003) 467–486.
[19] V. Krishnamoorthy, W.L. Hsu, T.M. Kesar, D.L. Benoit, S.K. Banala, R. Perumal, et al., Gait training after stroke: a pilot study combining a gravity-balanced orthosis, functional electrical stimulation, and visual feedback, J. Neurol. Phys. Ther. 32 (2008) 192–202.
[20] C. Krishnan, R. Ranganathan, S.S. Kantak, Y.Y. Dhaher, W.Z. Rymer, Active robotic training improves locomotor function in a stroke survivor, J. Neuroeng. Rehabil. 9 (2012) 57.
[21] S. Srivastava, P.C. Kao, S.H. Kim, P. Stegall, D. Zanotto, J.S. Higginson, et al., Assist-as-needed robot-aided gait training improves walking function in individuals following stroke, IEEE Trans. Neural Syst. Rehabil. Eng. 23 (2015) 956–963.
[22] S. Srivastava, P.C. Kao, D.S. Reisman, J.P. Scholz, S.K. Agrawal, J.S. Higginson, Robotic assist-as-needed as an alternative to therapist-assisted gait rehabilitation, Int. J. Phys. Med. Rehabil. 4 (2016).
[23] C.P. Duncan, The effect of unequal amounts of practice on motor learning before and after rest, J. Exp. Psychol. 42 (1951) 257–264.
[24] C.A. Moulton, A. Dubrowski, H. Macrae, B. Graham, E. Grober, R. Reznick, Teaching surgical skills: what kind of practice makes perfect?: a randomized, controlled trial, Ann. Surg. 244 (2006) 400–409.
[25] E. Taub, L.A. Goldberg, Prism adaptation: control of intermanual transfer by distribution of practice, Science 180 (1973) 755–757.
[26] D. Cecilio-Fernandes, F. Cnossen, D. Jaarsma, R.A. Tio, Avoiding surgical skill decay: a systematic review on the spacing of training sessions, J. Surg. Educ. 75 (2018) 471–480.
[27] C.D. Smith, D. Scarf, Spacing repetitions over long timescales: a review and a reconsolidation explanation, Front. Psychol. 8 (2017) 962.
[28] K.J. Burdick, Effects of Massed and Distributed Practice on the Learning and Retention of a Novel Gross Motor Skill, Western Illinois University, 1977.
[29] L.E. Bourne Jr., E.J. Archer, Time continuously on target as a function of distribution of practice, J. Exp. Psychol. 51 (1956) 25–33.
[30] M.R. Denny, N. Frisbey, J. Weaver Jr., Rotary pursuit performance under alternate conditions of distributed and massed practice, J. Exp. Psychol. 49 (1955) 48–54.
[31] S. Murray, B. Udermann, Massed versus distributed practice: which is better, Cahperd J. 1 (2003) 19–22.
[32] R.A. Schmidt, T.D. Lee, Motor Control and Learning: A Behavioral Emphasis, 5th ed., Human Kinetics, Champaign, IL, 2011.
[33] S.R. Wek, W.S. Husak, Distributed and massed practice effects on motor performance and learning of autistic children, Percept. Mot. Skills 68 (1989) 107–113.
[34] R.A. Schmidt, Motor Learning and Performance: From Principles to Practice, Human Kinetics, Champaign, IL, 1991.
[35] H.H. Murphy, Distribution of practice periods in learning, J. Educ. Psychol. 7 (1916) 150.
[36] A.D. Baddeley, D. Longman, The influence of length and frequency of training session on the rate of learning to type, Ergonomics 21 (1978) 627–635.
[37] K.A. Phillips, J.A. Schaeffer, W.D. Hopkins, Corpus callosal microstructure influences intermanual transfer in chimpanzees, Front. Syst. Neurosci. 7 (2013) 125.
[38] R.L. Sainburg, J. Wang, Interlimb transfer of visuomotor rotations: independence of direction and final position information, Exp. Brain Res. 145 (2002) 437–447.
[39] H.G. Taylor, K.M. Heilman, Left-hemisphere motor dominance in righthanders, Cortex 16 (1980) 587–603.
[40] J. Wang, M. Joshi, Y. Lei, The extent of interlimb transfer following adaptation to a novel visuomotor condition does not depend on awareness of the condition, J. Neurophysiol. 106 (2011) 259–264.
[41] F.A. Hellebrandt, Cross education; ipsilateral and contralateral effects of unimanual training, J. Appl. Physiol. 4 (1951) 136–144.
[42] J.I. Laszlo, R.A. Baguley, P.J. Bairstow, Bilateral transfer in tapping skill in the absence of peripheral information, J. Mot. Behav. 2 (1970) 261–271.
[43] M. Lee, M.R. Hinder, S.C. Gandevia, T.J. Carroll, The ipsilateral motor cortex contributes to cross-limb transfer of performance gains after ballistic motor practice, J. Physiol. 588 (2010) 201–212.
[44] T. Lam, V. Dietz, Transfer of motor performance in an obstacle avoidance task to different walking conditions, J. Neurophysiol. 92 (2004) 2010–2016.
[45] H.J. van Hedel, M. Biedermann, T. Erni, V. Dietz, Obstacle avoidance during human walking: transfer of motor skill from one leg to the other, J. Physiol. 543 (2002) 709–717.
[46] J.A. Garcia, F.J. Moreno, R. Reina, R. Menayo, J.P. Fuentes, Analysis of effects of distribution of practice in learning and retention of a continuous and a discrete skill presented on a computer, Percept. Mot. Skills 107 (2008) 261–272.
[47] Y.H. Kwon, J.W. Kwon, M.H. Lee, Effectiveness of motor sequential learning according to practice schedules in healthy adults; distributed practice versus massed practice, J. Phys. Ther. Sci. 27 (2015) 769–772.
[48] T.D. Lee, E.D. Genovese, Distribution of practice in motor skill acquisition: different effects for discrete and continuous tasks, Res. Q. Exerc. Sport 60 (1989) 59–65.
[49] S. Mackay, P. Morgan, V. Datta, A. Chang, A. Darzi, Practice distribution in procedural skills training: a randomized controlled trial, Surg. Endosc. 16 (2002) 957–961.