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Published in:
European journal of physical and rehabilitation medicine

DOI:
10.23736/S1973-9087.22.07539-6

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2022

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Minkes-Weiland, S., Reinders-Messelink, H. A., Boonstra, A. M., van der Woude, L. H., & den Otter, R. (2022). Effects of asymmetrical support on lower limb muscle activity during Lokomat guided gait in persons with a chronic stroke: an explorative study. *European journal of physical and rehabilitation medicine*, *58*(5), 693-700. https://doi.org/10.23736/S1973-9087.22.07539-6

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European Journal of Physical and Rehabilitation Medicine 2022 October;58(5):693-700
DOI: 10.23736/S1973-9087.22.07539-6

ORIGINAL ARTICLE

Effects of asymmetrical support on lower limb muscle activity during Lokomat guided gait in persons with a chronic stroke: an explorative study

Sylvana MINKES-WEILAND [1, 2] *, Heleen A. REINDERS-MESSELINK [2, 3],
Anne M. BOONSTRA [2], Lucas H. van der WOUDE [1, 3, 4], Rob den OTTER [1]

[1]Department of Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, the Netherlands; [2]"Revalidatie Friesland" Rehabilitation Center, Beetsterzwaag, the Netherlands; [3]University Medical Center Groningen, Center for Rehabilitation, University of Groningen, Groningen, the Netherlands; [4]Peter Harrison Centre for Disability Sport, School of Sport Exercise and Health Sciences, Loughborough University, Loughborough, UK

*Corresponding author: Sylvana Minkes-Weiland, Department of Human Movement Sciences, University Medical Center Groningen (UMCG), University of Groningen, Antonius Deusinglaan 1, 9713 AV Groningen, the Netherlands. E-mail: s.m.weiland@umcg.nl

ABSTRACT

BACKGROUND: The Lokomat, one of the most popular robotic exoskeletons, can take the asymmetry in the gait pattern of unilaterally affected patients into account with its opportunity to provide unequal levels of movement support (or 'guidance') to each of the legs. This asymmetrical guidance may be used to selectively unburden limbs with impaired voluntary control and/or to exploit the interlimb couplings for training purposes. However, there is a need to explore and understand these specific device opportunities more broadly before implementing them in training.
AIM: The aim of this study was to explore the effects of (a)symmetrical guidance settings on lower limb muscle activity in persons with post stroke hemiparesis, during Lokomat guided gait.
DESIGN: A single group, dependent factorial design.
SETTING: Rehabilitation center; a single session of Lokomat guided walking.
POPULATION: A group of ten persons with post stroke hemiparesis.
METHODS: Participants walked in the Lokomat in eight conditions, consisting of symmetrical and asymmetrical guidance situations, at both 0.28 m/s and 0.56 m/s. During symmetrical conditions, both legs received 30% or 100% guidance, while during asymmetrical conditions one leg received 30% and the other leg 100% guidance. Surface electromyography was bilaterally measured from: Biceps Femoris, Rectus Femoris, Vastus Medialis, Medial Gastrocnemius and Tibialis Anterior. Statistical effects were assessed using Statistical Parametric Mapping.
RESULTS: The provision of assymetrical guidance did not affect the level of lower limb muscle activity. In addition, no effect (except for Vastus Medialis in the affected leg during 1.5-2.4% of the gait cycle) of symmetrical guidance on muscle amplitude could be observed.
CONCLUSIONS: The results show no evidence that either symmetrical or asymmetrical guidance settings provided by the Lokomat can be used to manipulate activity of lower limb musculature in persons with post stroke hemiparesis.
CLINICAL REHABILITATION IMPACT: This study provides insights for the use of specific opportunities provided by the Lokomat for training purposes post stroke.

(*Cite this article as*: Minkes-Weiland S, Reinders-Messelink HA, Boonstra AM, van der Woude LH, den Otter R. Effects of asymmetrical support on lower limb muscle activity during Lokomat guided gait in persons with a chronic stroke: an explorative study. Eur J Phys Rehabil Med 2022;58:693-700. DOI: 10.23736/S1973-9087.22.07539-6)

KEY WORDS: Exoskeleton device; Electromyography; Locomotion; Rehabilitation.

In western countries, stroke is one of the most common causes of death[1-3] with more prolonged disability than any other condition.[2, 3] Stroke survivors frequently experience unilateral motor problems varying from a minor decrease in strength to complete paralysis.[2] Although the legs often recover sufficiently well to allow standing and walking, problems in coordination and balance during gait and ambulation often persist.[2] Therefore, training functional gait ability is an important goal in rehabilitation. During conventional treadmill training, two or three therapists are often required to support the trunk and the affected limb in stepping.[4] As an alternative, robot-assisted gait trainers (RAGT) have been developed to train the gait ability of persons suffering from stroke by maximizing the training intensity in a task-specific and safe way, while being less strenuous for therapists compared to manual gait training.[5, 6] Similar to manual gait training, specific RAGT can take the asymmetry of the gait pattern into account with its opportunity to provide more movement support to one leg compared to the other. However, there is a need to explore and understand these specific opportunities offered by RAGT more broadly before implementing them in training.

The Lokomat is a popular, commercially available treadmill-based robotic exoskeleton that consists of two leg orthoses,[7] and offers the possibility to set the level of movement support. This movement support, or 'guidance', can be provided based on an impedance control strategy that applies a corrective torque when the trajectory of the leg deviates from the reference trajectory.[8, 9] The magnitude of the torque that pushes the leg back to the reference trajectory increases with the amount of guidance provided.[9] Previous research on the neuromuscular control of Lokomat guided gait in able-bodied individuals showed that guidance levels can be used to manipulate the level of muscle activity, and that higher levels of guidance result in lower levels of muscle activity.[10, 11] The Lokomat offers the opportunity to set guidance levels for both legs separately or asymmetric. This possibility of setting guidance levels asymmetrically is incorporated into the Lokomat to specifically assist the walker when needed and to take the inherent asymmetries in the gait pattern of certain patients into account.

Asymmetrical movement support opens up opportunities for gait training post stroke. Firstly, an asymmetrical situation can be used to selectively unburden the limb with impaired voluntary control. More support can be provided to the affected leg compared to the unaffected leg to make a physiological gait pattern possible while at the same time allowing more active contributions from the unaffected leg. Secondly, asymmetrical guidance can be used to exploit the interlimb couplings for training purposes. In bipedal locomotion, bilateral leg control is subject to neuromuscular, kinematic, and kinetic couplings,[12] so that altered contributions of one leg potentially affect how much the contralateral leg contributes. It can be argued that in situations where asymmetric guidance requires more active contributions from one of the legs, these couplings can facilitate contributions from the contralateral leg. Findings of a previous study in healthy young participants showed that while maximal guidance was offered to the ipsilateral leg, the level of ipsilateral muscle activity could be increased when a higher contribution of the contralateral leg to the gait cycle was demanded by offering less guidance to the contralateral leg.[13] Arguably, by setting guidance asymmetrically during Lokomat training of participants with post stroke hemiparesis, the capacity of the unaffected leg may be utilized to evoke a higher muscle activity in the affected leg. In a training situation, this could be exploited to promote functional muscle activity of the affected leg in a task specific fashion.

Asymmetrical guidance settings can be a promising feature to use in the rehabilitation of hemiparetic patients. Therefore, there is a need to explore and understand these (a)symmetrical guidance settings of the Lokomat. As such, the aim of the present, explorative study was to assess whether (a)symmetrical guidance can influence lower limb muscle activity of the affected and unaffected leg. To the best of our knowledge, this study is the first to explore the potential of the specific asymmetrical training opportunities offered by RAGT in participants with post stroke hemiparesis. We will explore whether and how asymmetrical support can potentially contribute to training that takes the inherent asymmetries in the gait pattern of hemiparetic stroke patients into account. This is a first step in gaining fundamental knowledge about asymmetrical guidance settings in the Lokomat that can eventually contribute to the design of Lokomat training programs. Since previous studies on Lokomat guided gait showed that effects of guidance on muscle activity depend on treadmill speed,[10, 11] all effects were mapped on two speed levels separately.

Materials and methods

Participants

Ten participants with chronic hemiparetic stroke (7 male, 55.5±12.6 year, 1.73±0.11 meter, 85.6±15.2 kg, 24.4±35.4 months post stroke of which 2 walked with an AFO during the experiment) volunteered in this explorative study. All participants had a first ever unilateral stroke (4 persons had an infarction and 6 had a hemorrhage) that occurred at least three months prior to participation, suffered from a unilateral paresis of the leg (6 participants had a unilateral paresis of the left leg and 4 of the right leg) and had a Functional Ambulation Classification Score[14] of 3 (3 participants; is capable of walking when a safer environment with supervision or verbal guidance is provided), 4 (1 participant; can walk independently in and around the house (<200 m) with help of walking aids, on level ground, but requires help when walking >200 m, on stairs, slopes and uneven surfaces) or 5 (6 participants; is independently capable of walking on flat and non-flat surfaces, on slopes and is capable of walking the stairs). A total of 10 patients were included for this explorative study. This number of patients is similar to previous studies involving the Lokomat[10, 11, 15-18] and therefore seems sufficient for exploring the usefulness of asymmetrical Lokomat settings in rehabilitation after stroke. A rehabilitation physician from 'Revalidatie Friesland' (Beetsterzwaag, the Netherlands), where the research took place, recruited the participants. Participants were screened and excluded by a rehabilitation physician when they had severely impaired cognitive functions (Mini Mental State Exam Score ≤25), severe phatic disorders, communication problems in the Dutch language, visual problems or neglect, or comorbidities that are known to affect the gait pattern. Most of the participants had experience with walking in the Lokomat exoskeleton. The experimental procedures were approved by a Medical Ethical Committee (METc University Medical Center Groningen, the Netherlands; project code: 2017.453) and performed according to the declaration of Helsinki for medical research involving human subjects.[19] All subjects provided written informed consent prior to participation.

Materials

For this study, the Lokomat (LokomatPro version 6.0; Hocoma AG, Volkertswil, Switzerland) located at the rehabilitation center 'Revalidatie Friesland' (Beetsterzwaag, the Netherlands) was used. Besides the adjustable control over guidance levels, the Lokomat offers the opportunity to vary the speed level (0.14–0.89 m/s) and the extent to which body weight support (BWS; 0-100%) is provided.

To assess muscle activity, surface electromyography (EMG) was recorded from five muscles in both legs: Biceps Femoris (BF), Rectus Femoris (RF), Vastus Medialis (VM), Medial Gastrocnemius (MG) and Tibialis Anterior (TA). As previously employed,[10, 13, 15] signals were recorded using Ag/AgCl electrodes (Kendall/Tyco ARBO; Warren, MI, USA) with a 10 mm diameter and a minimum electrode distance of 25 mm. The sensors were used and placed according to the SENIAM guidelines.[20] To ensure good conduction, body hair and dead skin cells were removed and electrode sites were cleaned with alcohol. Custom-made insoles (Pedag international VIVA, Berlin, Germany), containing four pressure sensors (FSR402, diameter 18 mm, loading 10-1000 g), were used to detect gait events. EMG signals and the pressure sensor data were simultaneously sampled at 2048 Hz. A 32-channel Porti7 portable recording system (Twente Medical Systems, Enschede, the Netherlands) with a common mode rejection of 0.90 dB, a 2 mVpp noise level, and an input impedance of 0.10 GV was used to preamplify and A/D convert (22 bits) the signals before storage on a computer for offline processing.

Procedure

Similar to previous studies,[13, 16] speed levels of 0.28 m/s and 0.56 m/s were provided to the participants. Subjects walked first on the treadmill without the Lokomat exoskeleton during two conditions (0.28 m/s and 0.56 m/s). Then, subjects walked in 16 conditions in the Lokomat, during symmetrical and asymmetrical guidance settings, at both 0.28 m/s and 0.56 m/s. During the experiment, participants walked in the Lokomat with foot straps and without BWS. To ensure that an approximately equal number of steps was measured, conditions at 0.28 m/s lasted 120 seconds and conditions at 0.56 m/s lasted 60 seconds. In symmetrical conditions, both the affected leg and the unaffected leg received 30% guidance (30 affected leg [AL] / 30 unaffected leg [UL]) or 100% guidance (100AL/100UL). During asymmetrical conditions, the level of guidance offered to the unaffected leg was set higher (30AL/100UL) or lower (100AL/30UL) compared to the level of guidance offered to the affected leg. A randomized order of the two treadmill conditions (0.28 m/s and 0.56 m/s) was presented first. Next, the eight unique Lokomat conditions (30AL/30UL, 100AL/100UL, 30AL/100UL and 100AL/30UL, at both 0.28 and 0.56 m/s) were presented in a randomized order (block 1). Finally, the Lokomat conditions were repeated in the reversed order (block 2) to control for learning, order and fatigue effects resulting in a total of 16 Lokomat conditions. An acclimatization period of two minutes was provided to the participants before the start of each trial to get accustomed to the specific Lokomat settings. As body weight support is known to alter the muscle activation pattern in both amplitude and shape,[21] no body weight support was provided. Participants walked on their own shoes, without encouragement and instructions and under supervision of a physiotherapist during all conditions.

Data analysis

Offline analysis of the synchronized EMG and pressure sensor data was performed using custom-made software routines in Matlab (Matlab 2016a; MathWorks, Natick, MA). The EMG data were highpass filtered using a 10 Hz fourth order high-pass Butterworth filter to attenuate movement artefacts, full wave rectified, and low-pass filtered using a 20 Hz fourth order Butterworth filter. The EMG signals were time normalized from heelstrike to heelstrike based on the pressure sensor data and amplitude normalized with respect to the maximal amplitude observed during unrestrained treadmill walking at the same speed level, for each muscle and each participant separately. For the analysis, EMG data of the corresponding conditions performed in block 1 and 2 were averaged.

Statistical analysis

Repeated measures ANOVAs were performed using Statistical Parametric Mapping (SPM), which is a relative new approach for analysing continuous biomechanical data.[22] The SPM ANOVA calculates F-values (SPM{F}) separately for each data point in the time domain, meaning no time windows or specific regions of interest need to be defined a priori. Since muscle activity during Lokomat guided gait is observed within time windows that are atypical compared to unrestrained walking,[17] the continuous nature of SPM analysis avoids potential bias through specifically selected time windows.

SPM corrects for familywise error properly by dealing with the spatial correlation present in the continuous EMG signal.[23] Due to the spatial correlation in the signal, the number of independent tests does not equal the number of data points (t=1...100). Therefore, SPM estimates the actual number of independent tests based on temporal gradients and the number of data points to maintain the familywise error rate at the chosen 5%.[23] F-values that exceed the critical threshold are called ‘supra-threshold clusters’.

In order to answer the research question, SPM repeated measures ANOVAs with the factors Guidance (30% and 100%) and Symmetry (symmetrical and asymmetrical) were conducted for each leg, muscle and speed level separately. Following the aim, the Guidance by Symmetry interactions were interpreted to assess the effects of asymmetrical guidance. In addition, the main effect of the factor Guidance (30% and 100%) was assessed to map the effects of symmetrical levels of guidance on muscle activity. The direction of the effects was established by comparing the means within the supra-threshold clusters. All SPM analyses were conducted using open-source spm1d code (v.MO.1, www.spm1d.org) in Matlab (R2017b, The MathWorks Inc, Natick, MA, USA).

Data availability

The data reported in this paper are not publicly available but are available from the corresponding author on reasonable request.

Results

The level of lower limb muscle activity is not affected by setting asymmetrical levels of guidance.

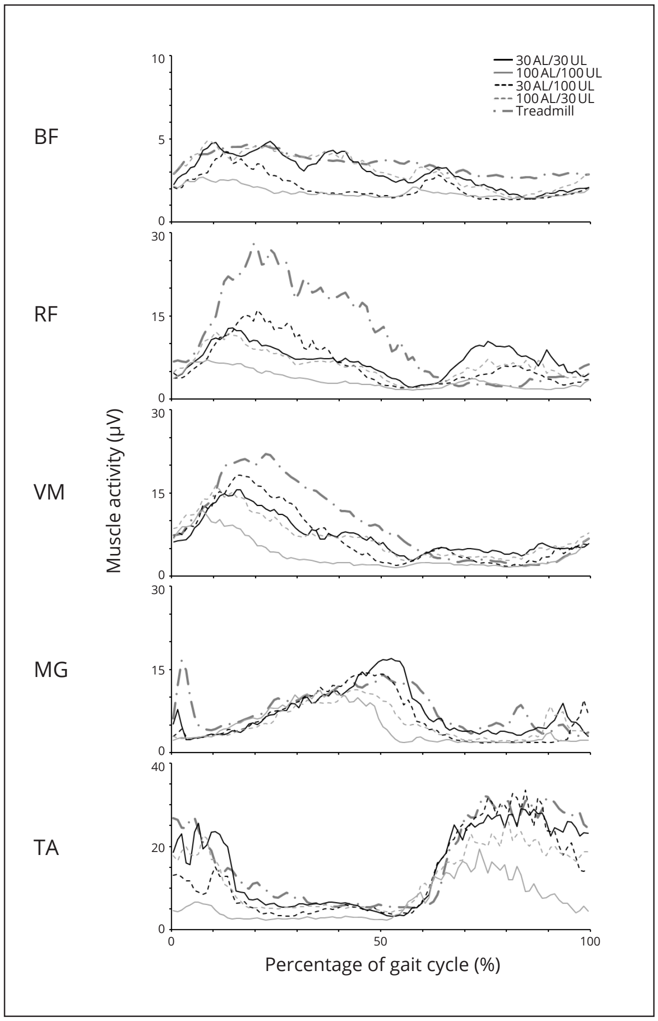

Figure 1.—EMG profiles during treadmill walking and Lokomat guided gait. Time normalized EMG profiles for Biceps Femoris (BF), Rectus Femoris (RF), Vastus Medialis (VM), Medial Gastrocnemius (MG) and Tibialis Anterior (TA) for a representative stroke patient at 0.28 m/s.

Figure 1 presents EMG profiles of the affected leg of a single representative participant at 0.28 m/s. As can be observed, muscle activity during Lokomat guided gait is lower compared to treadmill walking. However, the EMG amplitudes during the different guidance settings in the Lokomat do not seem to differ. Consistent with this, the SPM repeated measures ANOVAs showed no significant interaction effects of the factors Guidance and Symmetry (Figure 2, 3 for group averaged muscle profiles combined with the SPM{F} values). This indicates that the level of muscle activity in the different asymmetrical guidance conditions was not significantly altered for the both legs.

Symmetrical guidance levels do not have a profound effect on the level of muscle activity.

As presented in Figure 2, 3, no supra-threshold clusters for BF, RF, MG and TA for the main effect of Guidance were found. This indicates that a symmetrical change in the applied guidance levels had no effect on the level of muscle activity. One small supra-threshold cluster was found in VM of the affected leg at 0.56 m/s (1.5-2.4% of the gait cycle, P=0.0473; critical threshold =19.28; Figure 3), indicating that activity decreased during this small period of the gait cycle when guidance increased from 30% to 100%.

Discussion

To the best of our knowledge, this study is the first to explore the effects of asymmetrical guidance on lower limb muscle activity in persons with chronic hemiparetic stroke, during Lokomat guided gait. The possibility of setting guidance levels asymmetrically was incorporated into the Lokomat to take the inherent asymmetries in the gait pattern of certain patient populations into account. If (a) symmetrical guidance can be used to manipulate the level of muscle activity, this can open up opportunities for gait training post stroke. Asymmetrical guidance may than be used to selectively unburden limbs with impaired voluntary control and/or to exploit the interlimb couplings for training purposes. However, as the present results point

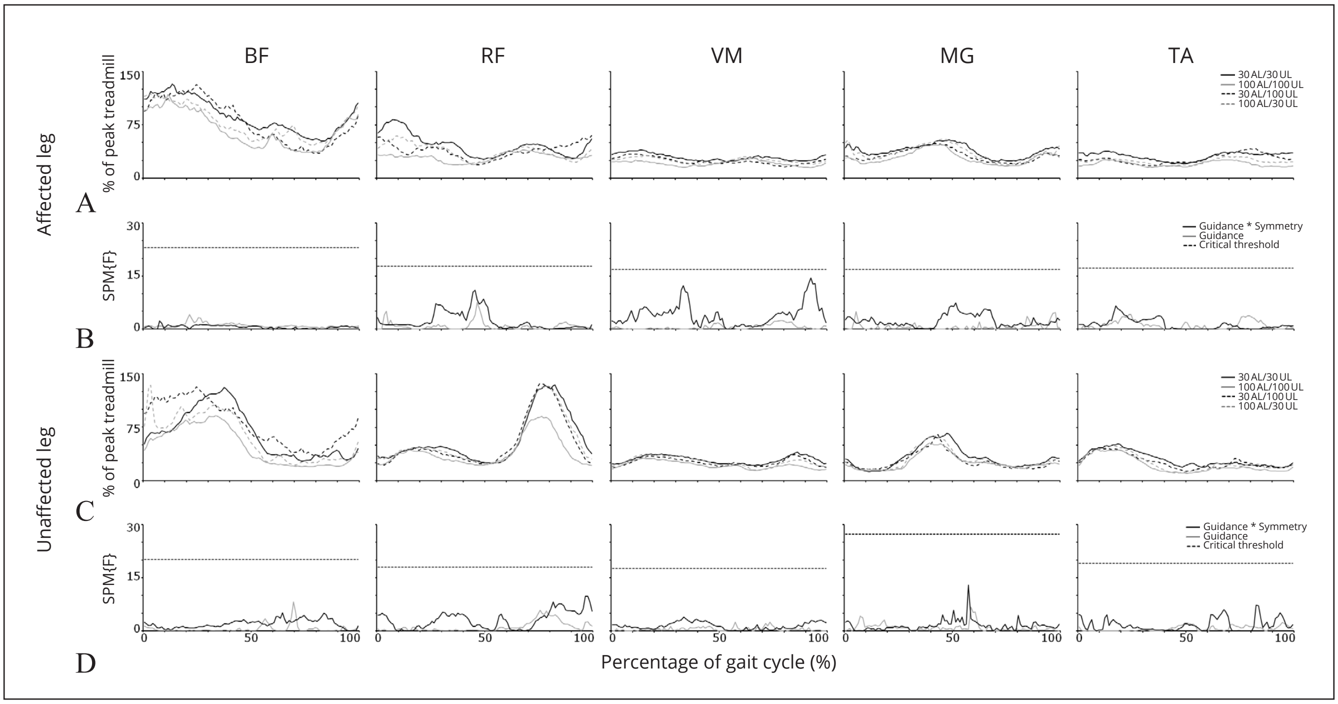

Figure 2.—Averaged EMG profiles during Lokomat walking at 0.28 m/s combined with the SPM results (N.=10 persons with a chronic hemiparetic stroke). Averaged EMG profiles for Biceps Femoris (BF), Rectus Femoris (RF), Vastus Medialis (VM), Medial Gastrocnemius (MG) and Tibialis Anterior (TA) are time and amplitude normalized for the affected leg (A) and the unaffected leg (C) for both symmetrical (solid lines) and asymmetrical (dashed lines) conditions when the affected leg receives 30% (black lines) or 100% (grey lines) guidance. EMG amplitude is expressed as a percentage of the peak amplitude during treadmill walking at the same speed level (0.28 m/s). The mean standard deviation for all conditions and all muscles is 14.2 for the affected leg and 15.3 for the unaffected leg. The SPM{F} values are displayed for the Guidance by Symmetry interaction (solid black lines) and the main effect of Guidance (grey lines) for the affected leg (B) and the unaffected leg (D). Threshold F values are indicated by dashed black lines.

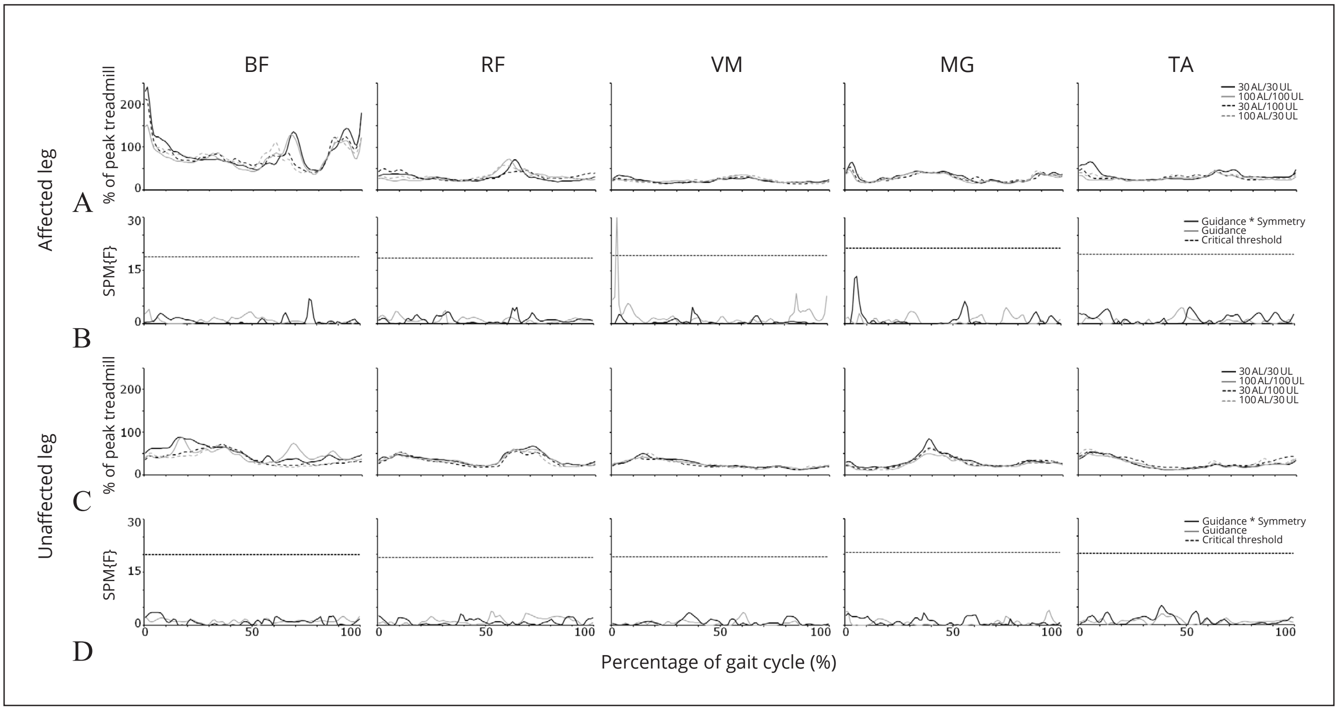

Figure 3.—Averaged EMG profiles during Lokomat walking at 0.56 m/s combined with the SPM results (N.=10 persons with a chronic hemiparetic stroke). Averaged EMG profiles for Biceps Femoris (BF), Rectus Femoris (RF), Vastus Medialis (VM), Medial Gastrocnemius (MG) and Tibialis Anterior (TA) are time and amplitude normalized for the affected leg (A) and the unaffected leg (C) for both symmetrical (solid lines) and asymmetrical (dashed lines) conditions when the affected leg receives 30% (black lines) or 100% (grey lines) guidance. EMG amplitude is expressed as a percentage of the peak amplitude during treadmill walking at the same speed level (0.56 m/s). The mean standard deviation for all conditions and all muscles is 14.9 for the affected leg and 16.4 for the unaffected leg. The SPM{F} values are displayed for the Guidance by Symmetry interaction (solid black lines) and the main effect of Guidance (grey lines) for the affected leg (B) and the unaffected leg (D). Threshold F values are indicated by dashed black lines.

out, alterations in either symmetrical or asymmetrical guidance settings were generally ineffective in modifying the level of lower limb muscle activity of persons suffering from hemiparetic chronic stroke.

Guidance may not be a reliable feature to use for training as guidance effects seem to be different for healthy able-bodied participants and persons post stroke. Research in healthy participants showed that (a)symmetrical levels of guidance can be used to tune the level of muscle activity.[10, 11, 13] However, recent research in persons suffering from stroke showed no effect of symmetrical guidance manipulations on the level of muscle activity.[23] In agreement with this, in the present study, no effect of (a)symmetrical guidance on muscle amplitudes in persons suffering from stroke could be observed (except for VM in the affected leg during only 0.9% of the gait cycle). In healthy participants, guidance effects are predominantly present at low speed levels in muscles related to progression of the leg through swing.[10, 13] It could be argued that the increase in muscle activity of these muscles with lower levels of guidance are an indirect result of altered leg dynamics due to uncompensated exoskeleton inertia at low speed levels. As the Lokomat does not fully eliminate torques of inertia, friction and gravity,[24] more active control may help progress the leg through swing, especially at low levels of guidance and speed. At higher speed levels, effects of guidance in healthy participants are also limited.[10, 13]

It is not self-evident that the presently used guidance force control mode can be used effectively to influence the level of muscle activity. In the presently used setup, guidance was provided by means of an impedance controller. With maximal guidance, no deviation from the reference trajectory is allowed by the robot,[9] meaning that in principle no activity is required for walking. With lower levels of guidance, small deviations from the reference trajectory are allowed[9] creating more movement freedom and allowing more active control from the walker to stimulate autonomous control.[25] However, manipulating the movement freedom with the level of guidance does not always go along with a change in muscular activity. For example, as can be observed in the muscle profiles (Figure 1-3), there is still a phased activity during maximally guided walking, despite the fact that kinematic trajectories in these conditions are fully restricted, and can be produced passively. On the other hand, increasing kinematic freedom, by reducing guidance levels to 30%, did not result in a structural increase in muscular activity. In this context, it is also important to mention that, muscle activity in all Lokomat conditions was remarkably low compared to unrestrained treadmill walking (Figure 1-3). This observation suggests that, irrespective of the level of guidance, the exoskeleton provides sufficient support to produce the required kinematic trajectories with relatively little active muscular involvement.

Other strategies may be more effective to promote a higher level of muscle activity during Lokomat guided gait. In this experiment, participants were not instructed to be more active with lower levels of guidance. As previously shown, children suffering from cerebral palsy increase their active participation when walking in the Lokomat under encouragement.[18] It can be argued that patients, more than healthy subjects, require more encouragement to utilize the additional movement freedom when walking in the Lokomat. The active participation in the Lokomat may also be promoted by using a different control mode. The Lokomat offers a path control mode in Lokomat Pro 6.0 versions[26] that has shown to increase the active participation[24, 26] and kinematic variability[26] during Lokomat guided gait compared to the guidance force control mode. Path control provides the walker temporal and spatial movement freedom inside a virtual tunnel while a supportive force assists in the movement.[26] Since muscle activity is higher when walking with encouragement or in the path control mode compared to the guidance force mode, this may allow for greater adjustments in the level of muscle activity when movement support is (a)symmetrically manipulated.

Generalization of the current results to therapy settings is not self-evident due to several limitations of the study. First, this study explored only the immediate effects of asymmetrical guidance. It is possible that chronic stroke patients need a longer time to adapt to the new situation because of compensation mechanisms that have already been strongly developed.[27] Second, the relative low number of participants is a limitation of this explorative study. However, a visual inspection of the individual data, averaged group data (Figure 2, 3) and the SPM{F} values (Figure 2, 3) indicated no trend of clinically relevant effects of asymmetrical guidance on muscle amplitudes. The visual inspection of the individual data also indicated participants responded divergently on guidance manipulations. Taken together, this means that (a)symmetrical guidance does not seem to be a reliable feature to use in training post stroke for each individual. Nevertheless, the use of the Lokomat for aims like improving blood circulation, lymph circulation and optimization of muscle tone is well established.[28] Lokomat training can thus be effective for patients with specific characteristics for specific training goals.

Conclusions

The present explorative study showed no evidence that (a)symmetrical guidance settings during Lokomat guided gait, evaluated at two different speeds, can be used to manipulate lower limb muscle activity in persons suffering from hemiparetic stroke. No clinically relevant effects in muscular output could be observed as a consequence of either asymmetrical or symmetrical guidance manipulations. Therefore, asymmetrical guidance force should not be used to selectively unburden the limbs with impaired voluntary control and to stimulate interlimb transfers for training purposes.

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Conflicts of interest.—The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Funding.—This research was funded by a grant from 'Het Revalidatiefonds' (projectnumber: R201705724).

Authors' contributions.—Sylvana Minkes-Weiland, Rob den Otter and Heleen A. Reinders-Messelink conceived the experiments; Sylvana Minkes-Weiland performed the experiments, analysed the data and wrote the manuscript. Rob den Otter, Heleen A. Reinders-Messelink, Anne M. Boonstra and Lucas H. van der Woude were involved in the design of the study, and the drafting and critical revision of the manuscript. All authors read and approved the final version of the manuscript.

Acknowledgements.— The authors wish to thank Emyl Smid for his technical support and the physiotherapists Steven Floor, Matthijs Dijkema and Geke van der Heide for their help with the recruitment and data collection.

History.—Article first published online: September 14, 2022. - Manuscript accepted: September 13, 2022. - Manuscript revised: July 29, 2022. - Manuscript received: March 30, 2022.