Amplitude and stride-to-stride variability of muscle activity during Lokomat guided walking and treadmill walking in children with cerebral palsy

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Abstract
Background: The Lokomat is a commercially available exoskeleton for gait training in persons with cerebral palsy (CP). Because active contributions and variability over movement repetitions are determinants of training effectiveness, we studied muscle activity in children with CP, and determined (i) differences between treadmill and Lokomat walking, and (ii) the effects of Lokomat training parameters, on the amplitude and the stride-to-stride variability.

Methods: Ten children with CP (age 13.2 ± 2.9, GMFCS level II (n = 6)/III (n = 4)) walked on a treadmill (±1 km/h; 0% bodyweight support (BWS)), and in the Lokomat (50% and 100% guidance; ±1 km/h and ±2 km/h; 0% and 50% BWS). Activity was recorded from Gluteus Medius (GM), Vastus Lateralis (VL), Biceps Femoris (BF), Medial Gastrocnemius (MG) and Tibialis Anterior (TA) of the most affected side. The averaged amplitude per gait phase, and the second order coefficient of variation was used to determine the active contribution and stride-to-stride variability, respectively.

Results: Generally, the amplitude of activity was lower in the Lokomat than on the treadmill. During Lokomat walking, providing guidance and BWS resulted in slightly lower amplitudes whereas increased speed was associated with higher amplitudes. No significant differences in stride-to-stride variability were observed between Lokomat and treadmill walking, and in the Lokomat only speed (MG) and guidance (BF) affected variability.

Conclusions: Lokomat walking reduces muscle activity in children with CP, whereas altering guidance or BWS generally does not affect amplitude. This urges additional measures to encourage active patient contributions, e.g. by increasing speed or through instruction.

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1. Introduction

With a prevalence of two per thousand children [1], Cerebral Palsy (CP) is one of the leading causes of locomotor and postural impairments in children. CP is the result of non-progressive disturbances that occurred in the development of the fetal or infant brain [2]. These disturbances often lead to spasticity, muscle weakness, and impairments in selective motor control [3,4], resulting in an impaired ability to walk [5]. As walking ability is important for independence and participation [6], it represents a major rehabilitation goal for this group [7]. In recent years, robot assisted gait training (RAGT) has been proposed as a new training strategy for children with CP, that implements automated, repetitive and task-specific training [8]. To optimize the effectiveness of
The Lokomat is a commercially available robotic exoskeleton that is used for RAGT in neurological patients [9,10]. The availability of a paediatric model also allows training in children [11]. The actuated Lokomat exoskeleton moves the legs through a predefined pattern, and is combined with a treadmill and bodyweight support (BWS) system [10]. The training possibilities of the Lokomat are defined by three parameters: treadmill speed, BWS, and movement support. Although different algorithms can be used to provide robotic support (see Ref. [12] for a description), the most common approach applies impedance control to regulate guidance force. The approach applies impedance control to regulate guidance force. The guidance can be set by the therapist and determines with how much force the exoskeleton moves the legs. Voluntary drive has been shown to lead to better performance, and larger cortical reorganization than passive movements that lack these voluntary and autonomous contributions [13,14]. Second, the training environment needs to allow movement variability. Recent studies have shown that the presence of movement-to-motion variability is important for motor learning, as it provides the possibility to explore control solutions [15] and sense movement errors that provide feedback to the exoskeleton. The Lokomat Pro V6.0 (Hocoma AG, Volketswil, Switzerland) was used in this study. The Lokomat is a bilaterally driven exoskeleton, combined with a BWS system and a treadmill. The Lokomat can be fitted to the anthropometric characteristics of individual walkers by adjusting the geometry of the exoskeleton and variations in training parameters, affect active contributions of the patients and the level of displayed movement variability.

One approach to studying active contributions and variability is to look at the muscle activity that underlies the produced movements. Previous research has shown that neuromuscular control is different in the Lokomat compared to unsupported treadmill walking. The amplitude of activity is usually lower during Lokomat guided walking [17–19], increasing the amount of guidance generally lowers the activity [20], and modifies the effects of speed and BWS [20]. This indicates that the active contribution is generally lower during Lokomat guided walking, and that these can be tuned through adjustments of the available training parameters. Very little is known about the stride-to-stride variability of muscle activation patterns in the Lokomat and the related training parameters. In the present, exploratory study on a small group of children with CP, we compare the average amplitude of activity between treadmill and Lokomat walking when we systematically varied BWS and treadmill speed. In addition, we map the stride-to-stride variability of patterns by assessing the 2nd order coefficient of variation, CoV and compare it between the walking conditions.

2. Material and methods

2.1. Participants

Ten children with CP volunteered to participate in this study (6 males, age 13.2 ± 2.9 years, length 1.58 ± 0.2 m, weight 45.0 ± 9.7 kg). Participants had a Gross Motor Function Classification System (GMFCS) level of II (n = 6) or III (n = 4) [21], were diagnosed with spastic CP, and were either bilaterally (n = 8) or unilaterally (n = 2) affected. Participants were most severely affected on their right body side in 6 cases, and 4 participants were most affected on their left side. Six participants wore an ankle foot orthosis, and 2 wore adjusted shoes. Inclusion criteria for this study were (i) age 6 to 16; (ii) GMFCS [21] levels of II (‘Walks without assistive device; limitations walking outdoors and in the community’) to IV (‘Self-mobility with limitations; children are transported or use power mobility outdoors and in the community’); (iii) ability to walk independently with the aid of parallel bars; (iv) ability to signal fear, pain or discomfort; (v) ability to follow simple instructions; (vi) the participant had to meet the general requirements for training with the Lokomat (e.g. femur length between 0.21 and 0.47 m). Exclusion criteria were (i) co-morbidity that can affect study outcome (e.g. comorbid orthopedic or neurologic disorders, as judged by the physician of the candidate participant), (ii) treatment of leg muscles with botulinum toxin in the six months prior to inclusion, (iii) orthopedic or neurological surgery during the previous year, (iv) unstable epilepsy and (v) incapability to walk under the experimental conditions. Written informed consent was provided by the legal guardian (e.g. parents) of each participant, and by the participant if he/she was 12 years or older. Two of the ten participants had previous experience with Lokomat guided walking. Ethical approval for the protocol was obtained from The Central Committee on Research Involving Human Subjects (CCMO), the Netherlands, and procedures were in accordance with the Declaration of Helsinki [22] (project number: NL50598.000.14).

2.2. Apparatus

2.2.1. The Lokomat Pro

The Lokomat Pro V6.0 (Hocoma AG, Volketswil, Switzerland) was used in this study. The Lokomat is a bilaterally driven exoskeleton, combined with a BWS system and a treadmill. The Lokomat can be fitted to the anthropometric characteristics of individual walkers by adjusting the geometry of the exoskeleton (i.e. hip width, upper and lower leg length), and the size and position of the leg cuffs that are used to attach the exoskeleton to the legs of the walker. For participants with an upper leg length between 0.21 and 0.35 m, a specifically developed pediatric exoskeleton can be used [11]. The exoskeleton of the Lokomat is actuated by linear drives to provide ‘guidance’ to the legs, and follows a reference pattern based on the kinematics of healthy walkers [23]. The reference pattern can be fine-tuned by adjusting the hip- and knee angles to meet specific patient requirements. In the version of the Lokomat that was used...
in present study, movements are restricted to the sagittal plane and an impedance controller generates robotic guidance [10,12]. This type of controller monitors both the actual angles and the required angles, and only interferes when deviation of the predefined pattern occurs. The level of guidance can be set by the therapist, and determines the allowed deviation and magnitude of the corrective force. When guidance is maximal, the movements of the legs are guided in a rigid fashion, ‘forcing’ the legs to strictly follow the pattern. When guidance is minimal, free movement of legs is allowed [10,12].

2.2.2. Electromyography and detection of gait events

To assess muscle activity, surface electromyography (EMG) was recorded from the Gluteus Medius (GM), Vastus Lateralis (VL), Biceps Femoris (BF), Medial Gastrocnemius (MG) and Tibialis Anterior (TA) of the most affected side of participants. Self-adhesive, disposable Ag/AgCl electrodes were used (Kendall/Tyco ARBO; Warren, MI, USA) with a 10 mm diameter and a minimum electrode distance of 25 mm. Electrode sites were based on SENIAM guidelines [24], and were prepared before sensor placement by shaving, abrading and cleaning the skin with alcohol to improve skin conduction. Custom-made insoles equipped with pressure sensors (FSR402, diameter 18 mm, loading 10 g) were used to detect initial foot contact and swing onset for both legs. For participants with European shoe sizes below 35, three sensors were used (one under the heel and two under the forefoot), whereas for participants with European shoe size 36 and above four sensors were used (one under the heel and three under the forefoot).

Pressure sensor and EMG signals were simultaneously sampled at 2048 Hz and fed to a Porti7 portable recording system (Twente Medical Systems, Enschede, The Netherlands). The unit (common mode rejection of >90dB, a 2uVpp noise level and an input impedance >1 GV) pre-processed and A/D converted (22 bits) the signals before storage on a computer for offline analysis.

2.3. Procedure

The study was performed at the rehabilitation center ‘Revalidatie Friesland’ at Beetsitzerwaag, the Netherlands and consisted of two visits. During the first visit, the Lokomat geometry was adjusted to each participant’s characteristics, and participants practiced a selection of the experimental conditions to determine whether they could be included in the study. This also entailed evaluation of the ability to walk on the treadmill without BWS. The second visit was the test session during which measurements were conducted.

During the test session, the participants walked a total of 9 trials. First, participants walked a trial on the Lokomat treadmill without the exoskeleton attached (henceforth ‘treadmill walking’), at approximately 1 km/h (scaled to leg length, see below), and without BWS. Subsequently, participants walked eight trials in the Lokomat exoskeleton (henceforth ‘Lokomat walking’). During these trials, two levels of guidance (50 or 100%), two levels of BWS (0 or 50%) and two treadmill speeds were combined, resulting in eight unique conditions. Treadmill speeds were scaled to body height, as follows [25]:

\[ v^* = \frac{v}{g^{1/2}} \]

where \( v^* \) is the dimensionless speed, \( l_0 \) represents leg length, \( g \) is the gravitational acceleration (i.e. 9.81 m/s²), and \( v \) is the target velocity set by the experimenters, in this case 1 km/h (henceforth ‘low’ speed) and 2 km/h (henceforth ‘high’ speed). Treadmill walking was always conducted before Lokomat walking, to avoid possible after-effects of Lokomat walking. In order to limit effects of fatigue, the participants were allowed to rest between trials. The order of the trials of Lokomat walking was randomized between participants to prevent order effects. Participants were allowed to wear their own (adjusted) shoes and Ankle Foot Orthoses (AFO). The foot lifters of the exoskeleton were not used.

2.4. Data analysis

One participant was unable to complete all measurements due to fatigue and painful knees, so that a total of nine children were included for this exploratory study. In addition, EMG data of the GM muscle from one of the remaining participants were excluded due to equipment failure.

2.4.1. Signal analysis

Custom-made software routines were made in Matlab (version 2015b; The Mathworks Inc., Natick, MA) for offline analysis of pressure sensor and EMG data. To reduce movement artefacts, EMG data were first high-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 10 Hz. Subsequently, the data were full wave rectified, low-pass filtered (10 Hz 4th order Butterworth) and amplitude normalized with respect to the maximum amplitude over all conditions, for each muscle and participant. Based on the processed EMG data, for each muscle and each condition two parameters were calculated: (i) the amplitude of muscle activity per sub-phase of the gait cycle and (ii) the stride-to-stride variability.

To quantify the amplitude, the summed (rectified, low-pass filtered and amplitude normalized) EMG data was calculated and subsequently averaged over all strides for four sub-phases of the gait cycle based on pressure sensor data: the first double support (DS1), the single support (SS), the second double support (DS2) and the swing (SW) phase.

An often applied measure of EMG variability is the coefficient of variation (CoV) (e.g. Refs. [26–28]) which is defined as the ratio of the standard deviation to the mean [29]. Limitations of the traditional CoV are that there is no upper bound of the CoV, which makes it difficult to interpret, and that its magnitude is highly sensitive to outliers and the overall level of the mean. To resolve these issues, Kvålseth [30] recently proposed a second order alternative to the CoV that takes on values between 0 and 1, so that it allows a more straightforward interpretation. To compare the stride-to-stride variability between experimental conditions, here we calculated the average second order CoV over the time-normalized gait cycle, for each muscle. Over all \( m \) collected strides within a given condition, for each point \( n \) \((n = 1 \ldots 100)\) in the time-normalized gait cycle, the second order coefficient of variation (CoV₂) was calculated. Assuming approximately normally distributed data, the average CoV₂ for each condition \( c \) and each muscle \( m \) was calculated as:

\[ \text{CoV}^2(m,c) = \frac{\sum_{n=1}^{100} \sigma^2(n.m,c)}{100} \]

where \( \sigma \) and \( \sigma^2 \) are the local standard deviation and variance, respectively, and \( \mu \) represents the local mean. These averages were used as dependent variables in the statistical analysis, to determine whether stride-to-stride variability differed between walking conditions.

For visual presentation of the data only, the filtered EMG data of each individual step were time-normalized with respect to gait cycle time (i.e. 0 – 100%) for the stance phase (i.e. 0 – 65%) and swing phase (i.e. 65–100%) separately, to allow comparisons
between patterns despite possible differences in stance-swing distribution between experimental conditions (see e.g. Ref. [31]). Subsequently, the data were averaged over strides.

2.4.2. Statistical analysis

Differences in EMG amplitude were tested separately for each muscle (i.e. GM, BF, VL, MG and TA) and each gait phase (DS1, SS, DS2 and SW). To compare muscle activity during Lokomat guided walking with unrestrained treadmill walking, a series of univariate repeated measures ANOVA’s were performed to determine the main effects of the factor ‘Condition’. For this analysis, the treadmill walking trial (without BWS and at low speed) and a Lokomat trial with 100% Guidance (without BWS and at low speed) were used. To evaluate the effects of varying Lokomat training parameters on EMG amplitude, a series of three-way univariate repeated measures ANOVA’s were performed to determine the main and interaction effects of the factors ‘Guidance’ (50 vs 100%), ‘BWS’ (0 vs 50%) and ‘Speed’ (low vs high).

To analyze differences in pattern variability between Lokomat and treadmill walking (no BWS and low speed in both conditions), the CoV2 was compared using a set of paired samples t-tests. Tenability of the normality assumptions for the CoV data was tested as follows: Q-Q plots were inspected visually, and Shapiro-Wilk were performed on the difference scores (paired samples t-test) and the standardized residuals (repeated measurements ANOVA). In case the normality requirements were not met, a Wilcoxon Signed Rank Test was conducted.

The effects of Lokomat training parameters on pattern variability was tested using three-way univariate repeated measures ANOVA’s, with the within subjects factors Condition (treadmill vs. Lokomat), Speed (1 km/h vs. 2 km/h), and BWS (0% BWS vs. 50% BWS). All statistical analyses were performed using SPSS version 23 for Windows (SPSS, Chicago, IL, USA).

To account for multiple testing, the Holm-Bonferroni correction was used to maintain the family-wise alpha at 5%.

3. Results

Below the significant results of the statistical analysis will be discussed. For a full overview of all statistical results, please refer to Tables S1 and S2 in the supplementary material.

3.1. Differences in the amplitude of activity between treadmill walking and Lokomat guided walking

Fig. 1 shows the group-averaged EMG profiles, and the mean EMG values (+ standard deviation (SD)) for each of the four sub-phases, during treadmill and Lokomat guided walking at 1 km/h without BWS. The univariate Repeated Measures ANOVA’s revealed significant main effects of ‘Condition’ in the VL, MG and TA muscle (see also Fig. 1). More specifically, VL activity was reduced during Lokomat guided walking compared to unrestrained treadmill walking during the DS1 phase (average reduction of 22.8% of peak amplitude). Similar significant decreases of muscle activity were observed in the MG during DS2 (average reduction of 8.3% of peak amplitude) and SW (7.7%), and in the TA during DS2 (13.9%) and SW (22.7%).

Fig. 2 shows the average pattern variability for all tested conditions. Although the average pattern variability was higher during unrestrained treadmill walking in all muscles (see Fig. 2), statistical testing failed to show any differences in CoV2 between conditions, indicating that the overall level of pattern variability in muscle activity did not differ between treadmill walking and Lokomat walking.

3.2. Effects of training parameters on the amplitude of muscle activity during Lokomat guided walking

The average EMG profiles, and the mean EMG values (SD) for each of the four sub-phases, are presented in Fig. 3 (GM, VL and BF) and Fig. 4 (MG and TA).

3.2.1. Guidance

Varying the level of guidance significantly affected BF, VL and MG activity (see Figs. 3 and 4). For BFDS1 and BFSS, activity increased when guidance was reduced from 100% to 50% (average increase of 5% and 5.3% of peak amplitude, respectively). Similar increases in activity were observed in VLDS1 (7.5%) and in MGDS1SW (4.9% and 2.6% respectively).

A statistically significant effect of guidance on pattern variability was found only in BF (see Fig. 2), where lower guidance settings were associated with higher pattern variability. A similar trend (p = 0.068) was observed for GM.

3.2.2. Bodyweight support

Providing 50% BWS resulted in significant reductions of muscle activity in all muscles, except for the MG (see Figs. 3 and 4). When 50% BWS was provided, GMSS activity was reduced by 8.1% of peak amplitude, compared to full weight bearing. Similar reductions were observed in BgDS1, SS, SW (average reduction of 6%, 5.5% and 2.3%, respectively), in VLDSS2 (7.4% and 5.1%, respectively) and TA 50% (5.2%).

EMG pattern variability was not significantly affected by BWS (see Fig. 2), although statistical trends in BF (p = 0.74) and TA (p = 0.95) reflected slightly larger variability when BWS was provided.

3.2.3. Speed

Treadmill speed significantly affected muscle activity of GM, BF, VL and MG (see Figs. 3 and 4). GMDS1 activity increased with speed (average increase of 10.4% of peak amplitude). However, during the SS phase a paradoxical speed effect was observed, as GMSS activity decreased when speed was increased (average decrease of 4.3%). For the three other muscles, activity increased with increasing treadmill speed with average increases of 3.1% for BFSW, 15.5% for VLDSS2, 10.2% for MGDS1SW and 4.6% and 2.2% for MGDS1, DS2 SW respectively.

As Fig. 2 shows, lower pattern variability in MG was observed when speed was increased from 1 km/h to 2 km/h, and a similar trend was found in GM (p = 0.088).

3.2.4. Interactions between the training parameters

The univariate Repeated Measures ANOVA revealed that in BFSW BWS subtly attenuated speed effect, as indicated by a significant BWS by Speed interaction. More specifically, during full weight bearing, BFSW activity increased with 4.1% of peak amplitude when speed was increased, whereas the effect of speed was less pronounced when 50% BWS was provided (average increase of 2.3%; see Fig. 3).

For MDS2 a significant interaction between Guidance and BWS was found (see Fig. 4). During full weight bearing, the reduction of guidance level resulted in increased MDS2 activity (average increase of 4.0% of peak amplitude), whereas this effect of guidance was negligible when 50% BWS was provided (average increase of 0.4%). BWS attenuated Guidance effect. No other significant interactions between the parameters were found with regard to the amplitude of activity.

For pattern variability, no significant interactions were found between either of the training variables.
4. Discussion

4.1. General discussion

The present exploratory study assessed the amplitude and stride-to-stride variability of muscle activity patterns during unrestrained treadmill and Lokomat guided walking in a group of children with CP. The results indicate that Lokomat guided walking is associated with lower neuromuscular outputs, and that variations in training parameters result in modulation of the amplitude. High levels of robotic guidance and BWS were generally associated with lower muscle activity whereas increases in treadmill speed were associated with higher activity. The effects of guidance were notably small. No significant differences in stride-to-stride variability were observed when comparing Lokomat and treadmill walking, and the exoskeleton pattern variability decreased with speed (MG) and guidance (BF). Overall, these findings show that Lokomat guided walking reduces the amplitude but not the variability of muscle activity in children with CP in the (most) affected leg, and that higher treadmill speeds may be applied to promote more active contributions during training.

During fully guided Lokomat walking, walkers have to strictly follow the kinematic reference pattern and, in principle, allows passive walking. Consistent with earlier research, the current results show that for selected muscles and phases, children with CP showed less active participation in the Lokomat than during unrestrained treadmill walking [17–19]. In particular, the activity of TA (during DS2 and SW) that is normally associated with the control of foot clearance was greatly reduced. This may be related to the use of ankle-foot orthoses in the present setup, as restricting the range of motion through the use of an ankle-foot orthosis results in a substantial reduction in TA swing activity in CP [32]. Another substantial reduction in activity was observed in VL during the DS1 phase, suggesting that the stability that the Lokomat exoskeleton offers during full guidance reduces task demands associated with shock absorption. Despite these reductions in amplitude, the overall phasing of the activity, even during fully guided walking, appears to be intact, a finding that confirms earlier research in healthy walkers [19,33].

In the Lokomat, variations in robotic guidance further modulated the amplitude of BF, VL and MG activity. More specifically, activity increased when the guidance was lowered to 50%, although these effects were subtle (2.6–7.5% of the peak amplitude). These observations confirm recent findings in persons with post-stroke...
hemiparesis, showing that guidance was generally ineffective in modulating the amplitude of muscle activity [34]. Several explanations may account for the absence of dramatic effects of robotic guidance. First, with the current minimum settings of 50%, for important locomotor subtasks such as support and swing control, patients can still rely to a large extent on exoskeleton support. Second, the ability to exploit the available kinematic freedom at lower guidance settings may depend on the patient’s ability to autonomously generate activity, which potentially explains why larger effects of guidance were found in healthy walkers [20] than in neurological patients. Finally, although lowering guidance increases freedom of movement, an increase in kinematic freedom does not necessarily induce an increase in activity. Recently, Aurich-Schuler et al. [12] showed that in a group of adolescents with gait disorders, Lokomat guided walking in path control mode (which allows more room for trajectory deviations) did not result in more activity compared to a condition in which guidance force was set to 100% (i.e. when the Lokomat was in position control mode). Overall, the presently available literature suggests that reducing guidance may not be a reliable way to invoke larger contributions of patients [20,34].

In line with previous research on treadmill [35] and Lokomat walking [17,20] in healthy walkers, BWS reduced the activity in all muscles except MG. BWS was initially developed to aid leg support in neurological patients, which explains why effects mainly occurred during the stance phase. However, it must be noted that compared to the studies mentioned above, the magnitude of the effects was relatively small (2.5–8.1% of peak amplitude). Interestingly, a recent study of Lokomat walking in persons with hemiparetic stroke failed to find clear effects of BWS [34], which may indicate that patient groups with low voluntary activity may rely more on the support offered by the actuated exoskeleton than on the support provided by the BWS system. It is surprising that no effects were observed in the MG, as this muscle plays a prominent role in support, and previous studies have shown marked effects of BWS on the activity of this muscle [35]. The lack of effect of BWS on calf muscle activity may be partly related to the present use of ankle-foot orthoses that partly immobilize the ankle joint.

More pronounced changes in muscle activity could be elicited by altering treadmill speed. Higher walking speeds require a more active muscular contribution to increase propulsion and accommodate the larger accelerations and decelerations of the limb segments [31,36]. The present findings are in agreement with previous studies in both healthy and stroke patients, showing that during Lokomat guided walking, the speed of the treadmill can be effectively used to influence the active muscular contributions of the walker [20,34]. It is interesting to note that there was no statistical interaction between speed and guidance, implying that speed variations were also effective during fully guided walking where such increases are not strictly necessary.

We were unable to identify statistically significant differences in stride-to-stride variability between Lokomat and treadmill walking. This is an interesting finding because in position control mode (guidance set to 100%) the patient follows the reference pattern and no kinematic variability is allowed. However, it is important to recognize that the lack of kinematic freedom during fully-guided Lokomat walking does not necessarily imply that variation in muscle activity is no longer possible, as the normal

**Fig. 2.** Mean (±SD) second order coefficient of variation for Gluteus medius (GM), Tibialis anterior (TA), Biceps femoris (BF), Medial gastrocnemius, and Vastus lateralis (VL), for unrestrained treadmill walking at appr. 1 km/h (white bars), and Lokomat guided walking with 50% guidance (solid bars), and 100% guidance (dashed bars), and at appr. 1 km/h (black) and appr. 2 km/h (grey).
Fig. 3. Group-based EMG profiles and average EMG (n = 9) per gait phase of Gluteus Medius (n = 8), Biceps Femoris and Vastus lateralis. Upper panels: Time and amplitude normalized EMG profiles (% peak amplitude) during walking in the Lokomat under varying guidance levels (75% = dashed; 100% = solid), bodyweight support levels (0% = left panel; 50% = right panel) and speeds (appr. 1 km/h = black; appr. 2 km/h = grey). Lower panels: mean EMG (+SD) (% peak amplitude) for four gait phases, i.e. the first double support (DS1), single support (SS), second double support (DS2) and swing (SW), during walking in the Lokomat under varying guidance, bodyweight support and speed (see above for further explanation).
relationship between muscular drive and the resulting movement is absent in position control mode. Also, walking on a treadmill is known to result in a substantial decrease in the variability of the walking pattern relative to overground walking [37], which may further explain the here observed lack of differences. Indeed, the second order coefficients of variation in both walking conditions (approximately 0.4 in all muscles, see Fig. 4) can be considered ‘small’ (0.21–0.40) to ‘moderate’ (0.41–0.60) [30]. During Lokomat walking, only treadmill speed had a substantial effect on the pattern variability of the MG. Because the amplitude of this muscle also increased with speed, it cannot be excluded that the decreased variability at higher speed reflects the increased signal-to-noise ratio at higher speeds, and not primarily a less consistent neuromuscular control. Finally, it should be noted that despite the lack of statistically significant differences in pattern variability, the average variability was higher during treadmill walking for all five tested muscles. We cannot exclude that the lack of significant results may be partly due to the low statistical power associated with the small sample size.

4.2. Clinical implications

In general, the present study shows that Lokomat walking in children with CP reduces the amplitude of muscle activity, and results in subtle but statistically non-significant reductions in its stride-to-stride variability. The here observed reductions in active muscular contributions may limit clinical effectiveness of Lokomat therapy, as active contribution of patients represent a key aspect for motor learning [13–15]. Although it has been argued that repetitive production of externally imposed gait movements can trigger phased muscle activity [38], learning complex (loco-)motor skills requires active exploration of movement possibilities (van Asseldonk et al., 2009). The relatively low muscle activity during guided walking, urges the use of additional strategies to stimulate active contributions, such as verbal encouragement to actively follow the reference pattern [39] and combining Lokomat walking with less restrictive, e.g. overground gait training. The results also underline the findings of previous studies [20,34] that varying speed has the most prominent effect on muscle patterns during Lokomat guided walking. This can be applied during clinical practice, to increase active contribution during training. Arguably, this is an interesting training parameter in particular for children with CP with little muscle function, to induce phased activity of a reasonable amplitude even with full robotic support.

4.3. Limitations

In the current study, we included a small number of participants and, as a consequence, the statistical power was low. Although this should be taken into account when interpreting the lack of strong
effects of BWS and guidance, it should be noted that the average differences in amplitude and variability between conditions were generally small. This justifies the conclusion that the effectiveness of these parameters in modulating the active contributions of patients, is limited. It cannot be excluded that the effects of training parameters are different between children of different functional levels. Due to the relatively low number of participants in this study, meaningful stratification at GMFCS level was not possible and this issue may be addressed in future research. Another limitation is that the contrast between guidance was small (50% vs 100%), making the occurrence of outspoken effects on muscle activity less likely. However, these settings were chosen in consultation with therapists and are representative of the clinical training situation. It should also be noted that, for the majority of subjects, this was the first experience with Lokomat guided walking, and that unfamiliarity of the training environment may have affected the observed muscle activity. In addition, muscle activity was only measured unilaterally and future research should examine the bilateral effect of the Lokomat environment, e.g. to assess whether Lokomat environment affects the amplitudes of activity in these children with CP. Finally, the researchers have affected the observed muscle activity. In addition, muscle activity was only measured unilaterally and future research should examine the bilateral effect of the Lokomat environment, e.g. to assess whether Lokomat environment affects the amplitudes of activity in these children with CP.

5. Conclusions

The present study addressed the amplitude and stride-to-stride variability of muscle activation patterns in the most affected leg of children with CP, and compared these between Lokomat and regular treadmill walking, and between different training conditions in the Lokomat. The findings indicate that Lokomat walking reduces the amplitude of activity in these children with CP. Assessment of the effects of Lokomat training parameters showed that reductions in robotic guidance or BWS are generally ineffective in restoring amplitude. This urges additional measures to encourage active participation of patients, e.g. by increasing treadmill speed or through instruction.

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Declaration of competing interest

The authors declare that they have no conflicts of interests.

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Appendix A. Supplementary data

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