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Neuromuscular control of Lokomat guided gait

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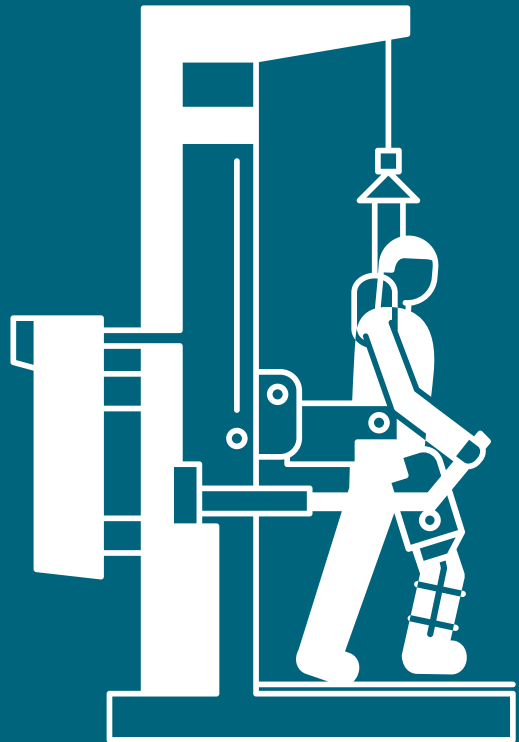
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Chapter 6

Summary and General Discussion



The aim of this thesis was to establish the effects of Lokomat walking and its training parameters (i.e. guidance, BWS and treadmill speed) on the neuromuscular control of gait, in both healthy and post-stroke hemiparetic walkers. This section of the thesis will start with a summary of the main results, after which the clinical implications and implications for future developments are discussed. Subsequently, a number of general considerations and ideas for future research are discussed, whereupon some concluding thoughts are given on the use of Lokomat guided therapy.

Main findings.

In **Chapter 2** it was shown that (1) the Lokomat exoskeleton, when not actuated (i.e. 0% guidance), alters the neuromuscular control of *healthy gait*, and (2) that the magnitude of the alterations depend on the level of BWS (0 or 50%) and selected treadmill speed (0.8, 1.8 or 2.8 km/h). It was found that muscular amplitudes (Erector Spinae, Biceps Femoris, Vastus Lateralis, Tibialis Anterior) were generally higher during Lokomat walking compared to treadmill walking, in particular at low walking speed (Erector Spinae, Gluteus Medius, Biceps Femoris, Tibialis Anterior). Speed effects on muscular amplitude were attenuated when BWS was provided (Erector Spinae, Vastus Lateralis, Medial Gastrocnemius). In addition, relative single support phase durations were prolonged during Lokomat walking, but also by the provision of BWS. The relative durations of double support phases were shorter during Lokomat walking, most prominently at low walking speed. Taken together, walking in the unactuated Lokomat exoskeleton differs from treadmill walking, with most deviations in both the muscular amplitude and the temporal structure of gait occurring during slow walking and with high levels of BWS.

Chapter 3 elaborates on these results, by zooming in on the effects of robotic movement guidance on the neuromuscular control of *healthy gait*. It was shown that increasing guidance (from 0% to 100%) generally reduced muscle amplitude, mainly in muscles responsible for stability and progression (i.e. Erector Spinae, Gluteus Medius, Biceps Femoris and Medial Gastrocnemius). However, even when fully guided, these muscles showed structurally phased activity. It is important to note that the magnitude of guidance effects did depend on interactions with the other two parameters. More specifically, the combination of low guidance levels and slow treadmill speed induced abnormally high amplitudes in a number of muscles (Gluteus Medius, Biceps Femoris, Tibialis Anterior). Also, both guidance and BWS caused strong reductions in muscular amplitude. As a result, some muscles (e.g. Erector Spinae) exhibited extremely low muscle activity under full guidance and 50% BWS conditions. With regard to the relative phase durations it was found that the provision of robotic movement guidance attenuated speed

related modulation of the temporal structure. This indicates that a fixed pattern in terms of relative phase durations is induced when walkers are robotically guided by the Lokomat exoskeleton.

Subsequently, **chapter 4** focused on the comparison of the neuromuscular control of *post-stroke hemiparetic gait* during treadmill and Lokomat guided walking, under controlled settings for the training parameters (i.e. 50% guidance, 0% BWS and 0.56 m/s). The results showed that, compared to treadmill walking, muscular amplitude was reduced during Lokomat guided walking in both stroke patients and healthy walkers (all muscles but the Biceps Femoris). As a result, in patients walking in the Lokomat, abnormally high muscle activity (affected Biceps Femoris, Vastus Lateralis and unaffected Gluteus Medius, Biceps Femoris, Vastus Lateralis) was reduced to levels comparable to healthy treadmill walking, whereas the already low activity of Medial Gastrocnemius muscle on the affected side was even further reduced. In addition, a reduction in temporal step asymmetry was observed in stroke patients during Lokomat guided walking, as the relative single support phase of the affected leg was prolonged towards durations similar to the unaffected leg.

Chapter 5 elaborates on *post-stroke hemiparetic gait* during Lokomat guided walking by evaluating whether the level of muscle activity and temporal symmetry is affected by the training parameters of Lokomat guided therapy. The results showed that when using a clinically relevant range of settings for guidance (50% vs 100%), BWS (0 vs 50%) and treadmill speed (0.28 m/s vs 0.56 m/s), only speed significantly influences muscular output (affected Biceps Femoris, Medial Gastrocnemius, Tibialis Anterior and all muscles of the unaffected leg). Temporal symmetry was not affected by the training parameters, and the effects of the parameters on both muscle activity and temporal symmetry did not interact.

Taken together it can be concluded that (1) walking in the Lokomat exoskeleton causes aberrations in muscular control, compared to unrestrained treadmill walking, in both healthy subjects and stroke patients, (2) the training parameters (i.e. guidance, BWS and speed) affect muscular amplitude in healthy subjects, but within the clinical range of settings only to a limited extent in post-stroke hemiparetic patients, (3) Lokomat guided walking is associated with abnormally long single support phase durations, which results in more symmetrical patterns among stroke patients and (4) Lokomat guided gait is characterized by a fixed temporal structure as the phase durations, and the associated symmetry ratios, are mainly unaffected by parameter settings.

Clinical implications.

It is important to consider how findings of the current thesis may impact clinical practice. Overall, the results show that guided walking in the Lokomat can be rather passive, as

muscular amplitude is generally reduced compared to treadmill walking, in both healthy and post-stroke hemiparetic walkers. And, although this reduction of activity in response to robotic guidance resulted in a normalization of abnormally high muscle activity in stroke patients, the already abnormally low activity of the calf muscles was even further reduced. This indicates that guidance by the Lokomat induces a-specific reductions of muscular output, which may negatively influence rehabilitation outcome. Research focusing on learning a novel hand or arm movement showed that task performance is not improved after practicing the movement with full robotic guidance [1-3], because the dynamics of the (novel) movement are changed when passively guided [4]. This indicates that learning requires active contribution to production of the task that needs to be learned [1-2,5]. As such, the reduced muscular contribution during Lokomat guided walking may limit gait (re)learning.

In addition, Lokomat guided walking modifies the temporal structure of the gait pattern in both healthy and post-stroke hemiparetic walkers. For stroke patients, the prolonged single support phase during Lokomat guided walking was mainly observed for the affected leg, resulting in a more symmetrical pattern compared to unrestrained treadmill walking. This seems to create favorable training conditions, as asymmetrical gait patterns may be related to negative consequences such as mechanical inefficiency, risk of musculoskeletal injury to the unaffected leg and loss of bone mass density in the affected leg [6-8]. In addition, sensory information induced by (normative) symmetrical patterns may inform neuroplasticity [9-11]. Nonetheless, the asymmetry observed in hemiparetic gait often represents a compensatory strategy for reduced balance control during single leg support on the affected side [12], or a limited ability to generate push-off power during the swing phase of the affected leg [13]. And, as the ability to develop compensatory strategies may be an important component of functional recovery [14], the question remains whether the symmetrical patterns practiced during Lokomat guided therapy can be generalized to overground walking.

Furthermore, based on the findings of the current thesis some recommendations for Lokomat therapy can be formulated. First, it is best to avoid extremely low levels of guidance. Therapists are likely to reduce the level of guidance in the course of Lokomat therapy as the walking ability of the patient increases [15]. However, the present results showed that very low levels of guidance may alter step regulation (e.g. abnormally prolonged single support phases) and induce abnormal neuromuscular control of walking (e.g. abnormally high muscle activity, see also [16]). These settings for guidance may then not be appropriate, as physiological patterns are often targeted during therapy to induce adequate task-specific afferent input that may guide motor learning [9-11].

Second, the level of BWS should be set as low as possible based on the abilities of the patient. BWS is applied during treadmill walking to reduce task demands related to weight and support. During Lokomat guided walking, these constraints are already secured, as the exoskeleton supports knee stabilization during weight acceptance and guarantees mediolateral stability by restricting movements to the sagittal plane [17-18]. Therefore, BWS may not be necessary to assist the walker. In addition, high levels of BWS may not be favorable during Lokomat guided walking as it can result in extremely low muscular amplitudes and abnormally prolonged single support phases, in particular in combination with high levels of guidance (see chapters 2-3).

Third, gait speed should be increased as soon as possible during Lokomat guided therapy and individual boundaries should be searched based on patient's capabilities. Increasing speed was effective in both healthy and post-stroke hemiparetic walkers to increase muscular amplitude and thus represents a useful tool to enhance active contribution during Lokomat guided walking. In addition, for healthy subjects it was shown that abnormalities during Lokomat walking, compared to treadmill walking, in both muscular output and the temporal structure of the gait pattern were most prominent during low walking speeds.

Fourth, it may be best to avoid the use of foot straps when possible, or at least limit them to the affected side, to increase muscular contributions of lower leg muscles during Lokomat guided gait. As foot support during swing will unload the dorsi-flexors, while the restriction of plantar flexion during stance will limit activity of plantar flexors, the use of foot lifters reduces the amplitude of these muscles (see also [19-20]). This is underlined by our results that healthy subjects still showed phased activity in the Medial Gastrocnemius and Tibialis Anterior during fully guided walking in the Lokomat without foot lifters (see Chapter 3, Figure 3), whereas both stroke patients and healthy controls showed significant decline of activity in these muscles when foot lifters were used (see Chapter 4, Figure 2).

To end, instructions and feedback may be useful tools and should be exploited to enhance the patient's participation and motivation during Lokomat therapy. Healthy subjects (chapters 2-3) were given motivational feedback and instructions to actively follow the pattern of the Lokomat. As instructions or feedback affect muscular amplitude [21-22], and the aim was to establish the 'pure' effects of the training parameters, it was chosen not to apply them during the stroke studies (chapters 4-5). This may have resulted in the relatively passive behavior of patients even when parameters were adjusted to induce active contribution (e.g. lowering the levels of guidance and BWS), underlining the importance of therapist instructions to increase patient participation.

Implications for future developments.

Besides the mentioned clinical implications, the results of current thesis also give insights on future developments for robot assisted gait training, to improve therapeutic outcome. Up till now, Lokomat therapy has not been proved superior to conventional therapy in terms of clinical effectiveness. Although a randomized control trial by Schwartz and coworkers [23] indicated beneficial effects of Lokomat therapy in stroke patients, others reported similar effects for both training strategies [24-25] or better results after conventional training compared to Lokomat therapy [26-28]. Despite the fact that Lokomat guided walking may provide the sensory information of successful stepping, which presumably induces spinal learning (i.e. the theoretical basis of Lokomat guided therapy), reduced active participation and low kinematic variability within the device may limit motor learning. Enhancing the therapeutic outcome of robot assisted gait training may rely on incorporating strategies that address these limitations.

One of the main findings of this thesis is that active (voluntary) control of leg muscles is reduced during Lokomat guided walking, especially in stroke patients, which can only be enhanced to a limited extent by varying the training parameters (i.e. level of guidance, BWS and selected treadmill speed). High levels of active participation, and also motivation, are believed to positively affect therapy outcome (e.g. [2]), which can be enhanced during Lokomat guided walking by instructions [21-22] and bio- or augmented feedback [29-30]. Incorporating advanced virtual reality technologies then seems promising, as it allows control and manipulation of feedback parameters and provides more motivating training environments [31-33]. Furthermore, as activity of the lower leg muscles may be particularly reduced by the use of foot lifters (see clinical implications) future devices may focus on alternative strategies to assist ankle movement. One option is to integrate actuated devices that are specifically developed to support ankle movements [see e.g. 34-35]. Another possibility is to apply functional electrical stimulation (FES) as a therapeutic tool, since this showed promising effect on post-stroke hemiparetic gait [36-38]. The therapeutic outcome of robotically guided therapy may be enhanced by incorporating FES to stimulate dorsi-flexor activity during swing, or any functional muscle contribution for that matter.

Kinematic variability represents an important mean to adjust to environmental changes, and both kinematic variability and movement errors are important components of motor learning [39-40]. However, by providing guidance with a fixed temporal pattern, the impedance controller of the Lokomat does not permit deviations in the timing of the movements [41]. This is reflected in the current results by limited speed modulations of phase durations in healthy walkers, and also by the fact that the temporal symmetry between the legs of post-stroke hemiparetic walkers is unaffected by variation in parameter

settings. Therefore the focus of developing new controllers has been on targeting freedom in movement timing. For example, a ‘path controller’ developed for the Lokomat assists the timing of movements by producing a supporting force that can be set separately from the guidance force [41-42], allowing more flexibility in the timing of leg trajectories and gait phases, and increasing patient participation [42-43]. Another approach is to assist certain sub-tasks of the gait rather than providing guidance throughout the whole gait cycle, as e.g. applied in the LOPES exoskeletons [44-46]. By only supporting the tasks of the gait where assistance is needed, e.g. foot clearance during swing, the remaining tasks have to be (actively) controlled by the walker, allowing kinematic variability and increasing active involvement [45-46]. However, with these types of controllers the level and timing of guidance still needs to be set by the therapist. Future developments may focus on interactive application of guidance, e.g. only assisting where the voluntary control of the patient is lacking and modulating speed based on the patients effort. Another interesting thought is whether robotic guidance should always be ‘assistive’. Motor learning may be driven to limit movement errors [47-48] and robotic controllers that exaggerate trajectory errors have shown to be effective to train novel arm [49-50] and leg movements [51]. Perhaps future controllers for robotic gait training may enable motor learning by permitting or even exaggerate errors that patients can try to correct [52].

Another important aspect to consider is that movements are restricted to the sagittal plane during Lokomat guided walking. This may not represent unrestrained walking, in particular when limiting mediolateral movements related to balance, possibly reducing generalization of learned skill to overground walking. Increasing the degrees of freedom by allowing free hip movements as incorporated in the FreeD module for the Lokomat [53] and also in the LOPES devices [44,46], may be promising developments. Another strategy to improve transfer to daily living is to incorporate additional tasks, e.g. by allowing practice of stair climbing [54], or using virtual reality to create environments similar to home settings. Nonetheless, even when using virtual reality, differences in visuospatial and optic flow signals between overground and treadmill walking remain [55-56]. As such, training with exoskeletons that are developed for overground walking, e.g. the ReWalk (Argo Medical Technologies Ltd., Haifa, Israel), may improve transfer to unrestrained walking and daily life.

Although the mentioned developments are promising, it is important to acknowledge that the choice for the type of controller, and the allowed kinematic variability (both in the timing of movements and the degrees of freedom) should be based on the skills of the walker. Patients with very limited voluntary neuromuscular control, for example, may require high levels of guidance and restricted degrees of freedom for successful

stepping. This is underlined by the fact that severely affected stroke patients benefit more from Lokomat therapy [57], whereas patients with more preserved walking skills showed greater progression after more challenging conventional overground training [26-27]. Successful development and implementation of robotics for gait rehabilitation requires multidisciplinary cooperation and knowledge sharing, e.g. between patients, engineers, clinicians, and human movement scientists.

General considerations and future research.

A strong point of the presented studies is that both healthy and post-stroke hemiparetic walkers are included. This allowed evaluation of the full range of parameter settings (i.e. in healthy walkers), as well as evaluation of the usability of a clinical range of settings (i.e. in stroke patients). In addition, it shows that the reduced muscle activity may be an a-specific response to Lokomat guidance, as it was observed in both groups. Nonetheless, it should be noted that there are more target groups for Lokomat therapy besides stroke patients, e.g. children with Cerebral Palsy or individuals with (in)complete Spinal Cord Injury. As the walking deficits in these target groups are very variable, and their neuromuscular control is affected in different ways, future research is needed to establish whether the currently found results and clinical implications apply for these patient groups.

The present thesis focused on short-term effects (i.e. a single Lokomat session) in novice Lokomat walkers. Arguably muscular response to the Lokomat training environment may change during the course of Lokomat therapy, due to habituation or learning effects. For example, usability of the training parameters may increase after a few sessions, as personal experience of our therapists indicates that some patients are able to walk with more advanced settings, e.g. guidance levels below 50%, at the end of a 10-week training program. Whether this is a result of improved walking ability, or caused by the fact that stroke patients get familiar with the gait pattern of the robot, needs yet to be determined. And future research needs to establish how the effects of training parameters on neuromuscular control evolve over multi-session therapy.

Furthermore, the study of surface EMG allowed interpretation of the muscular control underlying the production of gait, resulting in valuable information and clinical implications for Lokomat guided therapy. However, there may be other factors to include when optimizing training protocols. For example, a more complete insight on the control of robotically guided gait may be obtained when combining EMG measurements with information on cardiovascular or brain measures (see e.g. [15, 58-59]). Also, information on upper-body movements may be crucial to gain full understanding of Lokomat guided gait (see e.g. [60]). In addition, information is needed on optimal settings for the duration and frequency of

training, as well as the optimal time to start. This requires multicenter, long term research with a high number of participants and a large number of parameters. As such, it is advised that researchers should ‘stick together’ and cooperate to optimize Lokomat therapy.

Concluding remarks.

Although the current thesis did not conduct a clinical evaluation of Lokomat therapy, the presented results do give rise to the question whether we should continue using the Lokomat for gait therapy. The limited active muscular control and strict temporal patterns during Lokomat guided walking reported in this thesis may relate to the lacking evidence for the clinical effectiveness of Lokomat therapy. And although the presented results provide some implications to improve active participation (e.g. by increasing speed or using motivational instructions) and recent developments may improve kinematic freedom during Lokomat guided walking (e.g. the path controller and FreeD module), future developments are needed to enhance the motor learning potential of robotic gait trainers. The challenge for the next generation of robots is to incorporate approaches that are user driven and optimize therapeutic efficacy.

Still, the answer is a bit more complicated than a simple ‘no’. This generation of devices is developed especially to complement the existing treatment options. In such, the Lokomat has met its potential, as it supports the labor-intensive task of therapists. And as stated by Hilder and Wall [19]: *“simply because the Lokomat restricts movements and alters some muscle EMG patterns should not diminish the fact that the device allows patients to execute mass-practiced movements in a highly consistent manner”*(p.191). A clear advantage of the Lokomat is that it is strong enough to enable walking exercise in patients who are not (yet) capable of standing or moving their limbs by themselves. This also enables to start training as early as possible, possibly enhancing (spontaneous) recovery (see e.g. [57]). In addition, the experience of successful stepping, and the ability to move in upright position has a number of beneficial effects. For example, it may restore the confidence of patients in taking those first steps ‘in the hallway’. Practicing in such a high-tech and safe environment may then potentially induce the intrinsic motivation to practice, even outside of formal therapy hours. In addition, Lokomat guided walking may positively affect cardiovascular and musculoskeletal systems (reduced spastic or reflex symptoms [61]) and secondary complications (e.g. bladder or bowel problems). However, the majority of these benefits rely on personal and anecdotal information, and whether and how they may enhance therapy outcome is yet to be determined. It also does not imply that the Lokomat should replace standard or conventional gait training, but can be combined with overground walking, strength and condition training, and balance exercises as soon as possible.

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