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The combined effects of guidance force, bodyweight support and gait speed on muscle activity during able-bodied walking in the Lokomat

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ABSTRACT

Background: The ability to provide automated movement guidance is unique for robot assisted gait trainers such as the Lokomat. For the design of training protocols for the Lokomat it is crucial to understand how movement guidance affects the patterning of muscle activity that underlies walking, and how these effects interact with settings for bodyweight support and gait speed.
Methods: Ten healthy participants walked in the Lokomat, with varying levels of guidance (0, 50 and 100%), bodyweight support (0 or 50% of participants' body weight) and gait speed (0.22, 0.5 or 0.78 m/s). Surface electromyography of Erector Spinae, Gluteus Medius, Vastus Lateralis, Biceps Femoris, Medial Gastrocnemius and Tibialis Anterior were recorded. Group averaged levels of muscle activity were compared between conditions, within specific phases of the gait cycle.
Findings: The provision of guidance reduced the amplitude of activity in muscles associated with stability and propulsion (i.e. Erector Spinae, Gluteus Medius, Biceps Femoris and Medial Gastrocnemius) and normalized abnormally high levels of activity observed in a number of muscles (i.e. Gluteus Medius, Biceps Femoris, and Tibialis anterior). The magnitude of guidance effects depended on both speed and bodyweight support, as reductions in activity were most prominent at low speeds and high levels of bodyweight support.
Interpretation: The Lokomat can be effective in eliciting normal patterns of muscle activity, but only under specific settings of its training parameters.

1. Introduction

There is ample evidence that intensive and task-specific gait training can optimize restoration of functional walking ability (Kwakkel et al., 1997, 2004; Teasell et al., 2003). Body-weight supported treadmill training (BWSTT) applies these principles, allowing repetitive execution of manually guided stepping movements with adjustable support of body-weight. However, BWSTT is strenuous and physically demanding for both the patient and the therapist (Duschau-Wicke et al., 2010a; Riener et al., 2010; Colombo et al., 2000), in particular in patients with low ambulatory status. The Lokomat was developed to automate BWSTT by replacing the manual guidance by automated guidance through a bilaterally motor driven exoskeleton (Colombo et al., 2000), allowing repetitive and task specific gait training in a therapist-friendly fashion. Three adjustable parameters define the Lokomat training environment: treadmill speed, the level of bodyweight support (BWS) and the amount of guidance provided by the exoskeleton. In order to purposefully exploit the learning potential of this device, it is crucial to understand muscle activity in the Lokomat, and how it can be altered using the available training parameters.

The Lokomat exoskeleton is designed to support limb movements throughout the stepping cycle. This so called '*guidance*' is a key feature of Lokomat training, making it possible to move along a predefined path derived from joint trajectories of healthy walkers (Duschau-Wicke et al., 2010a; Colombo et al., 2000). Initially, guidance was realized by a position control strategy, in which the limbs were moved passively through a predefined pattern, with minimal kinematic variability (Colombo et al., 2000). To promote active involvement, an impedance controller was implemented to adjust the level of guidance according to the patient's capacity (Riener et al., 2005). This type of control creates a virtual coupling between the actual and the predefined joint movement, by simulating a spring that 'pulls' the limb to the

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predefined path if deviations occur (Duschau-Wicke et al., 2010b). Guidance levels can be set by adjusting this pulling force, allowing free walking when guidance is set to nil, and forcing a predefined gait pattern at maximum guidance.

Offering guidance makes it possible to elicit a normal gait pattern in patients that are incapable of independent stepping (Duschau-Wicke et al., 2010a; Riener et al., 2010; Colombo et al., 2000). Although these conditions may limit the active contribution of patients, successful stepping induces task-specific sensory information that may inform plastic changes in the central nervous system, and stimulate unaided walking (Riener et al., 2010; Colombo et al., 2000; Riener et al., 2005; Dobkin et al., 1994; Hesse et al., 1999; Cramer and Riley, 2008). However, because active involvement and the production of variable movement patterns and movement errors are prerequisites for activity-dependent neuroplasticity (Duschau-Wicke et al., 2010a; Riener et al., 2010; Bernstein, 1967; Schmidt and Lee, 2005; Lewek et al., 2009; Krishnan et al., 2013), guidance levels should be progressively reduced according to the patient's capacity (Riener et al., 2010; Lewek et al., 2009; Krishnan et al., 2013; Knaepen et al., 2015). As such, the adjustment of guidance levels represents an important means for therapists to tailor Lokomat training to individual patients. Selective and well-dosed provision of guidance requires a good understanding of how this training parameter affects the amount of active involvement of walkers, and the respective contributions of muscles to the production of gait.

So far, studies on muscle activity during Lokomat walking have primarily focused on comparisons between unrestrained treadmill walking and fully guided (Schuler et al., 2013; Israel et al., 2006; Hidler and Wall, 2005; Moreno et al., 2013), partially guided (Moreno et al., 2013; Coenen et al., 2012), or unguided (Gizzi et al., 2012; Van Kammen et al., 2014) Lokomat walking, in patients (Schuler et al., 2013; Israel et al., 2006; Coenen et al., 2012) and healthy walkers (Hidler and Wall, 2005; Moreno et al., 2013; Gizzi et al., 2012; Van Kammen et al., 2014). Overall, the results suggest that patterns of muscle activity differ between Lokomat and treadmill walking, e.g. Lokomat walking requires less activity of the shank muscles, but more of the hamstrings and quadriceps. However, as these studies did not systematically vary guidance, they provide limited information on how these aberrations are related to the level of guidance. To the best of our knowledge, only two studies examined patterns of muscle activity under different guidance levels, showing that the modular output of synergistic muscle groups is invariant over guidance levels (Moreno et al., 2013) and that reductions in guidance force do not increase muscle activity (Duschau-Wicke et al., 2010b). Although these insights are relevant, for purposeful employment of guidance in training, it is also important to understand whether effects of guidance depend on gait speeds and BWS, because the contribution of individual muscles to key locomotor tasks (e.g. support and propulsion) depends on both the speed of progression (Den Otter et al., 2004) and the level of BWS (Finch et al., 1991). Recently, van Kammen et al. (2014) showed that the nature and magnitude of the differences between Lokomat and treadmill walking depend on complex interactions with BWS and gait speed. Therefore, to gain insight in how guidance affects muscle activity, and how the nature and magnitude of these effects depend on speed and BWS, healthy walkers were studied during Lokomat walking, while guidance, BWS and treadmill speed was varied systematically.

2. Method

2.1. Participants

Ten healthy young adults (6 females; age 20.9 +/− 2.2 years, body height 1.82 +/− 0.04 m and body weight 77.90 +/− 9.6 kg), without disorders that affect gait performance or muscle activity, and no previous experience with Lokomat walking, participated in this study. All participants provided their written informed consent. The protocol was in accordance with the Declaration of Helsinki (World Medical Association, 2013), and approved by the Medical Ethical Committee of the University Medical Center Groningen (METc UMCG, project number: NL42826.042.12), the Netherlands.

2.2. Experimental apparatus

2.2.1. The Lokomat pro

Participants walked in the Lokomat Pro version 6.0 (Hocoma AG, Volketswil, Switzerland) at the rehabilitation center 'Revalidatie Friesland' in Beetsterzwaag, the Netherlands, using the impedance control mode, allowing adjustments in guidance force (0–100%). The Lokomat exoskeleton exists of two actuated orthoses attached to the participant's limbs with cuffs and straps. The hip and knee joints of the Lokomat are actuated by linear drives that move the orthoses through the gait cycle, in the sagittal plane (Riener et al., 2010). Ankle dorsiflexion can be assisted by means of elastic foot lifters.

During this experiment, the level of guidance was varied systematically. In principle, when guidance is set to 0%, the exoskeleton only generates torques to compensate for the inertia of the exoskeleton, allowing unrestricted leg movements (Duschau-Wicke et al., 2010a; Van Kammen et al., 2014). With guidance set to 100%, participants are forced to closely track the predefined pattern of the exoskeleton (Duschau-Wicke et al., 2010a; Riener et al., 2010). At intermediate guidance levels, the actuated exoskeleton allows for small deviations, but redirects larger deviations towards the predefined trajectory. When deviations are too large to be re-directed, the Lokomat has a built-in safety mechanism that halts the apparatus immediately.

2.2.2. Electromyography and detection of gait events

Surface electromyography (EMG) was used to record activity from the Erector Spinae (ES), Gluteus Medius (GM), Vastus Lateralis (VL), Biceps Femoris (BF), Tibialis Anterior (TA) and Medial Gastrocnemius (MG), in the right leg. Signals were recorded using self-adhesive, disposable Ag/AgCl electrodes (Kendall/Tyco ARBO; Warren, MI, USA) with a 10 mm diameter and a minimum electrode distance of 25 mm, placed according to the SENIAM protocol (Freriks et al., 1999). The electrode sites were prepared by removing body hair, and by abrading and cleaning the skin with alcohol. Gait events were detected by means of customized insoles (Pedag, international VIVA) with four pressure sensors (FSR402, diameter 18 mm, loading 10–1000 g, one under the heel and three under the forefoot), placed in the footwear of the participants.

EMG signals and pressure sensor signals were sampled simultaneously at 2048 Hz and fed to a Porti7 portable recording system (Twente Medical Systems, Enschede, The Netherlands; common mode rejection >90 dB, 2 μVpp noise level, input impedance >1 GV)). Signals were pre-amplified and A/D converted (22 bits) before storage on a laptop for offline analysis.

2.3. Experimental procedures

Prior to testing, hip width, length of the upper and lower limbs of the exoskeleton, and size and position of leg cuffs were fitted to match the anatomy of the participant. Lokomat gait parameters (e.g. step length, patient coefficient, knee- and hip angles and their respective offsets) were set so that walking in the device was as natural and comfortable as possible. As the present group had full functional control of their ankle movements, foot lifters were not used. Settings were not adjusted during testing and participants were instructed to 'actively move along with the device' when guidance was provided.

Participants walked a total of 18 trials, divided in three blocks of six trials. Each block represented a fixed level of guidance (0, 50 or 100%) and each trial within a block provided a unique combination of BWS (0 or 50% of participants' body weight) and speed (0.22, 0.5 or 0.78 m/s). BWS was provided by means of a suspended harness and levels were