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ORIGINAL PAPER

Towards the Neuromotor Control Processes of Steady-State and Speed-Matched Treadmill and Overground Walking

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Abstract
The neuromotor control of walking relies on a network of subcortical and cortical structures. While kinematic differences between treadmill and overground walking are extensively studied, the neuromotor control processes are still relatively unknown. Hence, this study aims to investigate cortical activation during steady-state treadmill and overground walking using functional near-infrared spectroscopy, inertial measurement units and a heart rate monitor. We observed a higher concentration of oxygenated hemoglobin in prefrontal cortices, premotor cortices and supplementary motor areas during treadmill walking. Therefore, our results suggest that treadmill walking requires higher demands on cortical neuromotor control.

Keywords Steady state walking · fNIRS · Gait · Motor control

Introduction

Walking was generally considered a rhythmic and automatic motor task which does not rely on higher cognitive processes (Hausdorff et al. 2005). This traditional view is challenged by recent evidence pointing towards a complicated neuromotor control of walking via a wide network of cortical and subcortical structures (Hamacher et al. 2015). In particular, treadmill walking is, opposed to normal overground walking, thought to be mainly controlled by subcortical areas of the central nervous system like the central pattern generators because the repeating rhythmic afferents do stimulate those structures (Barbeau et al. 1987; Hamacher et al. 2016). If treadmill walking would be under automatic control and if it would merely rely on processes of subcortical areas, a secondary attention-demanding task, which especially targets higher cognitive processes, would presumably not influence the performance of the motor task or the performance of the secondary cognitive task. Interestingly, Regnaux et al. (2006) observed that treadmill walking has a negative impact on the performance of an additional cognitive task suggesting that there is some involvement of higher cognitive processes in motor control of treadmill walking (Regnaux et al. 2006). Especially the prefrontal cortex, whose functioning is crucial for higher cognitive processes (Miller 2000; Wood and Grafman 2003), is also involved in the control of movement automaticity (Clark 2015). Hence, it is likely that the activation of the prefrontal cortex could give insights into the motor control mode (automatic vs. controlled) of treadmill or overground walking. To our knowledge, only two studies compared the activation in prefrontal areas during treadmill and overground walking. However, the findings of those studies are controversial. While in one study, an increased prefrontal activity was noticed (Clark et al. 2014), the other study observed lower prefrontal activity during treadmill walking (Hausdorff et al. 2016). Thus, it still seems to be unclear which neuromotor control mode (automatic vs. controlled) is predominantly used during treadmill walking. Furthermore, the expression of an internal (overground walking) and external (treadmill walking) movement rhythm changes the activation of supplementary and premotor areas (Kuruma et al. 2007; Toyomura et al. 2012). Hence, further studies investigating the activation of prefrontal cortices, premotor cortices and supplementary motor areas are needed to understand the neuromotor control during treadmill and

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overground walking. The aim of the current study is to address those issues. Accordingly, we will investigate the activation in the prefrontal cortices, premotor cortices and supplementary motor area during treadmill and overground walking.

Methods

Thirteen healthy young adults with normal or corrected vision who had no self-reported history of orthopedic or neurological diseases participated in the study. In accordance with the Declaration of Helsinki (1964), all participants were informed about the study procedures and provide written informed consent.

To study the neuromotor control of walking, we applied the commonly used block design (Herold et al. 2017). In the two blocks (overground or treadmill walking), the participants were requested to absolve five walking trials. At the start of each trial, we asked our participants to stand as motionless as possible for 40 s to quantify baseline brain activation. After the baseline period, the participants walked forth and back along a 16 m track or on the treadmill for 40 s (see Fig. 1a). The treadmill speed was matched to the preferred overground walking speed. In addition, all participants were familiar with treadmill walking activities.

During walking, the cortical hemodynamics was recorded with a portable functional near-infrared system (NIRSport™, NIRx Medical Technologies, New York, NY, USA) which consists of eight detectors and eight sources. The sources emit wavelengths of 760 and 850 nm at a measurement frequency of 7.81 Hz. The placement of optodes was conducted with a standardized cap (EasyCap GmBH, Herrsching, Germany) and the optodes were positioned according to the 10–20 EEG system (see Fig. 1b). The sources and detectors were directly applied on the scalp with the recommended separation of 3 cm (Herold et al. 2017). As described in a previous publication (Lu et al. 2015) and as shown in Fig. 1b, the applied optode configuration covers the left (Channel 1) and right prefrontal cortex (Channel 2), the left (Channel 3–6) and right premotor cortex (Channel 11–14) and the supplementary motor area (Channel 7–10).

We preprocessed the fNIRS data with the software program "Homer 2" (Huppert et al. 2009). At the beginning, the raw intensity data were converted into optical density. Afterwards, the optical density signal was processed with a wavelet and a bandpass filter (Herold et al. 2017). For this, an IQR of 1.219 corresponding to the recommended α of 0.1 (Brigadoi et al. 2014; Wiggins and Hartley 2015) was used for the wavelet filter. The cut-off frequencies of 0.01 and 0.5 Hz were used for the bandpass filter (Brigadoi et al. 2014; Herold et al. 2017). The filtered optical density data were converted via the modified Beer–Lambert law into concentration changes of oxygenated and deoxygenated hemoglobin (Obrig and Villringer 2003). The differential path length factors were calculated for each individual participant using the formula provided byScholkmann and Wolf (2013).

After preprocessing with "Homer 2", the time series of oxygenated (oxyHb) and deoxygenated (deoxyHb) hemoglobin were exported and imported into Matlab (The Mathworks®, Natick, MA, USA). In Matlab, an in-house

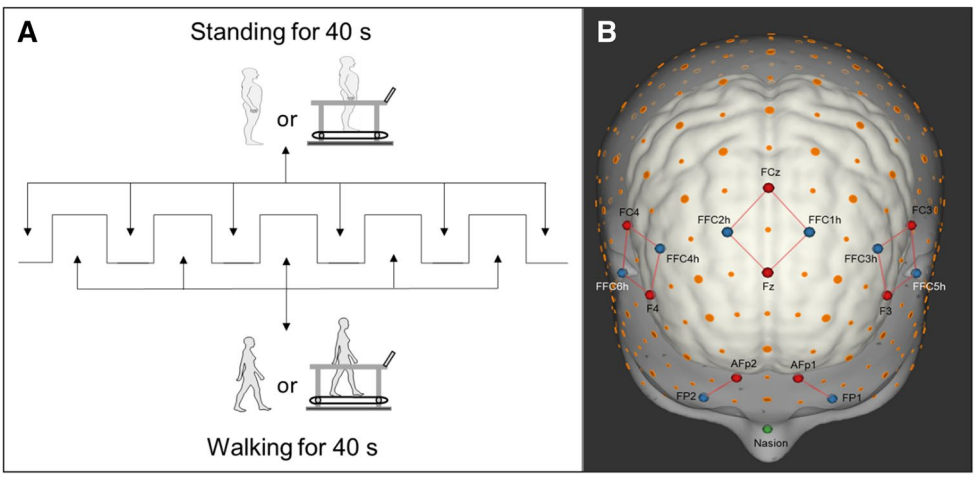

Fig. 1 Schematic illustration of the used block design (**a**) and of the channel positions (**b**). **a** A block consisted of six standing phases and 5 walking phases: at first, our participants stood still on the floor for 40 s (baseline) and then they walked for 40 s on a treadmill or over overground. **b** The "red dots" represents sources whereas the "blue dots" represents detectors. Following combinations of sources and detectors (EEG-positions) results in channels: Channel 1 (Afp1–FP1); Channel 2 (AFp2–FP2); Channel 3 (F3–FFC5h); Channel 4 (FC3–FFC5h); Channel 5 (F3–FFC3h); Channel 6 (FC3–FFC3h); Channel 7 (Fz–FFC1h); Channel 8 (FCz–FFC1h); Channel 9 (Fz–FFC2h); Channel 10 (FCz–FFC2h); Channel 11 (F4–FFC4h); Channel 12 (FC4–FCC4h); Channel 13 (F4–FFC6h); Channel 14 (FC4–FFC6h)

algorithm was used to extract the middle 20 s of the standing phases and walking phases for each trial. The middle 20 s of each phase were chosen to avoid confounding signals that could arise from the onset of walking and, more importantly, to cover the chromophore concentration during steady-state walking. Furthermore, we subtracted with our developed Matlab algorithm the values of each standing phase from the values of the corresponding walking phase to baseline correct the fNIRS data (Herold et al. 2017). The statistical analysis was conducted with the baseline-corrected oxyHb and deoxyHb concentrations.

The gait kinematics were quantified with an inertial-sensor-based measurement system which is described in detail in Hamacher et al. (2014). Furthermore, we recorded heart rate changes continuously with a portable heart rate monitor (RS800CX, Polar Electro Oy®, Kempele, Finnland). Heart rate signals were analyzed with "Kubios HRV" (Biosignal Analysis and Medical Imaging Group, Universität Kuopio, Finnland; Version 2.2) (Tarvainen et al. 2014). The mean heart rate over the entire task duration was used to assess systemic changes which could influence fNIRS signal (Tachtsidis and Scholkmann 2016; Herold et al. 2017).

To assess the participants' experiences in treadmill walking, we used a 5-point Likert scale ranging from (1) "no experience" to (5) "very strong experience".

The statistical analysis was performed with IBM SPSS (Statistical Package for social science, Version 22, Chicago, IL, USA). In the absence of normality, which was assessed with Shapiro–Wilk test, we compared the concentrations of oxygenated and deoxygenated hemoglobin, the mean heart rates and the mean LF/HF ratios of treadmill walking with those of overground walking using Wilcoxon tests. To account for systemic physiological changes, we calculated delta (Δ) values for oxyHb, deoxyHb (for each channel) and mean heart rates by subtracting the mean values obtained during treadmill walking from the mean values obtained during overground walking. Then, we calculated Spearmans Rho (r_s) correlations between ΔoxyHb as well as ΔdeoxyHb and Δheart rates to assess the influence of possible systemic changes (Harada et al. 2009).

The False discovery rate (FDR) was used to account for multiple comparisons. For this, the value of q, which defines the maximum FDR, was set to 0.05. This q-value ensures that not more than 5% would be false positives findings (Benjamini and Hochberg 1995; Glickman et al. 2014).

Results

The demographic characteristics of the investigated sample are shown in Table 1. The walking speed was not significantly different between the conditions. The mean heart rate was higher during treadmill walking when compared to overground walking (Z (N = 13) = − 3,18; p = 0,001; r = − 0,88), while LF /HF ratio did not change between conditions.

Table 1 The demographic characteristics of the investigated sample, mean heart rate and mean LF/HF ratio are shown

Parameters	Median (interquartile range)
Age (years)	25.00 (3.00)
Height (m)	1.83 (0.18)
Weight (kg)	80.00 (29.00)
Self-rated treadmill experience	4.00 (2.5)
Walking speed (m/s)	OW: 1.01 (0.21)/TW: 1.02 (0.25)
Mean heart rate (bpm)	OW: 94.15 (11.66)/TW: 101.10 (12.47)*
LF/HF ratio	OW: 3.37 (5.22)/TW: 3.60 (3.90)

OW overground walking, *TW* treadmill walking

*Indicates significant differences between conditions

During treadmill walking, a higher oxyHb concentration was observed regarding the left prefrontal cortex (Z (N = 13) = − 3,11; p = 0,002; r = − 0,86), the right prefrontal cortex (Z (N = 13) = − 3,04; p = 0,002; r = − 0,84), the left premotor cortex (Z (N = 13) = − 3,11; p = 0,002; r = − 0,86); the right premotor cortex (Z (N = 13) = − 3,18; p = 0,001; r = − 0,88) and the bilateral supplementary motor area (Z (N = 13) = − 3,18; p = 0,001; r = − 0,88) as compared to overground walking. The deoxyHb concentration did not significantly differ between conditions (see Table 2).

After FDR adjustment, we did not observe a significant correlation between ΔoxyHB as well as ΔdeoxyHb and Δheart rate.

Discussion

The aim of the current study was to investigate neuromotor control processes of treadmill walking and overground walking. Therefore, we quantified the hemodynamic responses in the prefrontal cortices, premotor cortices and supplementary motor area and we observed a higher concentration of oxyHb in those assessed cortical areas during treadmill walking.

It is generally assumed that both an increase in oxyHb and a decrease in deoxyHb mirrors neuronal activation (Obrig and Villringer 2003; Scholkmann and Wolf 2012). Furthermore, it is suggested that oxyHb is more sensitive to locomotion induced cortical changes (Hoshi et al. 2001; Miyai et al. 2001) while deoxyHb sometimes exhibits paradoxical signal changes (Hoshi et al. 2001). In addition, oxyHb shows stronger correlations with blood oxygenation level depend (BOLD) contrasts (Strangman et al. 2002; Toronov et al. 2007). Based on those assumptions, the observed increase in oxyHb is probably caused by a higher activation of the

Table 2 Median (interquartile range) of oxyHb and deoxyHb in the measured cortex areas during overground and treadmill walking

Cortex region	Overground walking		Treadmill walking	
	OxyHb (μM)	DeoxyHb (μM)	OxyHb (μM)	DeoxyHb (μM)
left PFC	0.14 (0.55)*	−0.13 (0.13)	0.61 (0.84)*	−0.09 (0.23)
right PFC	0.29 (0.47)*	−0.07 (0.11)	0.43 (1.01)*	−0.08 (0.19)
left PMC	0.06 (0.59)*	−0.09 (0.11)	0.56 (0.96)*	−0.13 (0.10)
right PMC	0.06 (0.51)*	−0.03 (0.12)	0.52 (0.73)*	−0.06 (0.17)
bilateral SMA	0.00 (0.56)*	−0.04 (0.13)	0.31 (1.05)*	−0.08 (0.18)

PFC prefrontal cortex, *PMC* premotor cortex, *SMA* supplementary motor area

*Indicates significant differences between conditions

neuronal tissue in the prefrontal cortices, the premotor cortices and the supplementary motor area.

There are two possible reasons explaining the differences in motor control between treadmill and overground walking. First, the increased prefrontal cortex activation may point towards a not fully automated neuromotor control of treadmill walking (Clark 2015) which relies, at least in parts, on attentional resources (Regnaux et al. 2006). Second, a pronounced activation of prefrontal structures goes also along with goal-directed control of movement which is associated with either not habitually conducted motor behavior (e.g. walking) or motor behavior of inexperienced motor tasks (Redgrave et al. 2010).

The self-ratings of our participants' treadmill experiences and the short time intervals (4 to 6 min) generally needed to familiarize with treadmill walking (Taylor et al. 1999; Matsas et al. 2000), points towards a more habitual control of treadmill walking in our cohort. Hence, we assume that the higher level of activation in prefrontal areas is not induced by differences in experience/habituation but rather evoked by the different walking modalities (treadmill vs. overground). However, to further elaborate on whether differences in cortical activation are evoked by different walking modalities (treadmill vs. overground walking) and/or different levels of habituation (habitual vs. goal-directed motor control), experienced treadmill walkers should be compared with non-experienced treadmill walkers in future studies.

The higher level of activation in premotor cortices during treadmill walking found in our study is in accordance with findings in the literature reporting a higher activity in these structures during externally triggered movements (Kuruma et al. 2007). Furthermore, the prefrontal cortices, the premotor cortices and supplementary motor area are parts of the indirect locomotor pathway exhibiting a pronounced activation during challenging walking conditions (Hamacher et al. 2015; Herold et al. 2017). The increased usage of the indirect locomotor pathway during treadmill walking may suggest that treadmill walking supposes higher demands on human neuromotor control and is, in turn, more challenging than overground walking (e.g. through the adaption of treadmill belt speed).

Since systemic changes (e.g. higher autonomous nervous system activity or increased heart rate during a condition) could cause false positive results, we used the correlations between ΔoxyHb as well as ΔdeoxyHb and Δheart rate to assess the influence of systemic physiological changes (Harada et al. 2009). Our correlation analyses did not show significant association between heart rate changes and concentration changes of oxyHb or deoxyHb. Furthermore, there is no change in the LF/HF ratio which is considered a marker of the activity of autonomous nervous system (Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology 1996; Xhyheri et al. 2012). Hence, it is assumable that the observed hemodynamic changes are (at least partly) evoked by cortical motor control processes.

In the current study, we did not quantify extracerebral systemic changes which possibly could have confounded our results, as well (Tachtsidis and Scholkmann 2016). Hence, further studies utilizing a higher sample size and using sophisticated methods to reduce the influence of extracerebral hemodynamic signals (e.g. short separation channels) should be conducted to verify or falsify our results.

In conclusion, treadmill walking at matched preferred overground speed leads to a higher concentration of oxygenated hemoglobin in prefrontal cortices, premotor cortices and supplementary motor area. This phenomenon is presumably caused by modality-dependent neuromotor control strategies (Wrightson and Smeeton 2017).

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