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Time-dependent directional intermuscular coherence analysis reveals that forward and backward arm swing equally drive the upper leg muscles during gait initiation

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ABSTRACT

Background: Human bipedal gait benefits from arm swing, as it drives and shapes lower limb muscle activity in healthy participants as well as patients suffering from neurological impairment. Also during gait initiation, arm swing instructions were found to facilitate leg muscle recruitment.

Research question: The aim of the present study is to exploit the directional decomposition of coherence to examine to what extent forward and backward arm swing contribute to leg muscle recruitment during gait initiation.

Methods: Ambulant electromyography (EMG) from shoulder muscles (deltoideus anterior and posterior) and upper leg muscles (biceps femoris and rectus femoris) was analysed during gait initiation in nineteen healthy participants (median age of 67 ± 12 (IQR) years). To assess to what extent either deltoideus anterior or posterior muscles were able to drive upper leg muscle activity during distinct stages of the gait initiation process, time dependent intermuscular coherence was decomposed into directional components based on their time lag (i.e. forward, reverse and zero-lag).

Results: Coherence from the forward directed components, representing shoulder muscle signals leading leg muscle signals, revealed that deltoideus anterior (i.e. forward arm swing) and deltoideus posterior (i.e. backward arm swing) equally drive upper leg muscle activity during the gait initiation process.

Significance: The presently demonstrated time dependent directional intermuscular coherence analysis could be of use for future studies examining directional coupling between muscles or brain areas relative to certain gait (or other time) events. In the present study, this analysis provided neural underpinning that both forward and backward arm swing can provide neuronal support for leg muscle recruitment during gait initiation and can therefore both serve as an effective gait rehabilitation method in patients with gait initiation difficulties.

1. Introduction

Human bipedal gait exhibits a four-limb pattern that is comparable to that of quadrupeds, with arms swinging in anti-phase with the ipsilateral leg as if they are a remnant of neural connections used in quadrupedal gait. Although the role of stereotypical arm movements in human bipedal gait is not as obvious as in quadrupedal gait, arm swing has been found to influence gait stabilisation, energetic efficiency (for a review see [1]), and recruiting neuronal support for maintaining the cyclic gait pattern [2–4]. The latter is emphasised by numerous studies reporting that adding upper limb movements during rhythmic tasks indeed improved lower limb muscle recruitment in healthy participants and neurologically impaired patients (see [1] for an overview), whereas walking without arm swing in healthy participants vice versa resulted in less efficient gait control [3]. Besides its role in steady state gait, enhanced arm swing was also found to facilitate impaired gait initiation in Parkinson patients on a behavioural and cortico-muscular level [5]. Interestingly, all these studies were primarily based on the instruction of producing or enhancing forward arm swing (i.e. anteflexion of the shoulder), whereas the deltoideus posterior, which is responsible for retroflexion of the shoulder (i.e. backward arm swing), also exhibits active muscle activity during gait [6,7] and gait initiation [5]. This suggests that backward arm swing might similarly contribute to driving the lower limb muscles during gait. Unfortunately, traditional coherence

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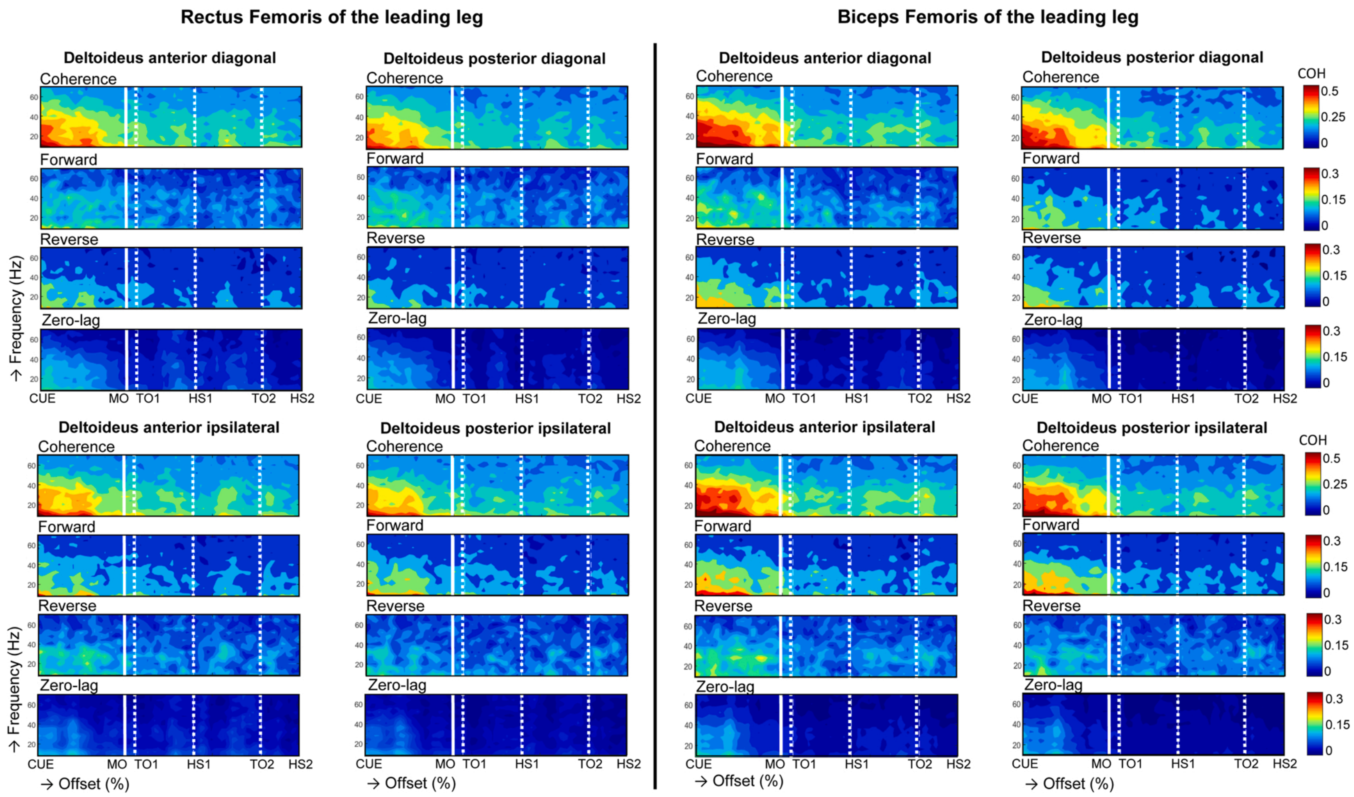

Fig. 1. Time-dependent intermuscular coherence between shoulder and upper leg muscles during gait initiation. Group averaged intermuscular coherence and the forward, reverse and zero-lag components of coherence between bilateral shoulder muscles and upper leg muscles of the leading leg across the frequency spectrum (y-axis, 8–70 Hz) during the gait initiation process (x-axis, offset 0–100%). Magnitude of coherence is colour coded and indicated using a colour bar on the right. Vertical lines mark the occurrence of movement onset (MO), toe-off (TO1 and TO2) and heel strike (HS1 and HS2), averaged across all participants. Colormaps were time warped to the individual time interval between auditory cue (CUE) and MO and between MO and HS2.

analysis cannot distinguish directionality between shoulder and leg muscles from shoulder and leg muscles receiving input from a common driver. Directional connectivity analysis, however, does enable such a distinction and allows us to make assumptions about directionality (e.g. shoulder muscles driving the leg muscles). Previous studies already demonstrated such directional connectivity analysis using a range of parametric approaches [8,9], whereas the current study demonstrates a non-parametric approach [10] that may be more suitable for time-series data. The aim of the present study is to exploit the directional decomposition of coherence to examine to what extent forward and backward arm swing contribute to driving the lower limb muscles during gait initiation.

2. Methods

Nineteen healthy participants (9 males, 10 females) with a median age of 67 ± 12 (interquartile range (IQR)) years started overground walking for six metres at a comfortable speed after an auditory cue without additional instructions (e.g. starting with a specific foot) to avoid blocking natural gait initiation. This was repeated 30 times. To keep the study population as homogeneous as possible, all participants were required to be right handed according to the Annett Handedness scale. The study was executed according to the Declaration of Helsinki (2013) and approved by the ethical committee of the University Medical Center Groningen.

Paired bipolar surface Ag-AgCl EMG electrodes were bilaterally placed on the rectus femoris, biceps femoris, soleus and tibialis anterior and deltoideus anterior and posterior muscles according to the SENIAM (http://www.seniam.org) guidelines. As in a previous study we found that neural coupling was most pronounced between shoulder muscles and upper leg muscles in healthy participants [4], we focused on analysing bilateral deltoideus muscles and the rectus femoris and biceps femoris muscles. Tri-axial accelerometers (Compumedic Neuroscan, Singen, Germany) were placed on the medial sides of both ankles and over the L3 lumbar spine segment. Data were recorded at a sampling rate of 512 using a portable amplifier (Siesta, Compumedics Neuroscan, Singen, Germany) and ‘Profusion EEG software’ (v. 5.0, Compumedics Neuroscan, Singen, Germany).

Time-points of movement onset (MO), heel strike (HS) and toe-off (TO) were determined using the accelerometers as described previously [5] and served as markers for EMG analysis. EMG data were analysed using custom scripts in MATLAB 2018a (The Mathworks, Inc., Natick, Massachusetts, United States) based on routines available at https://www.neurospec.org. All raw EMG data were first high pass (5 Hz) filtered using a finite impulse response filter and full-wave rectified. The time dependent intermuscular coherence analysis was undertaken as in [4,11]. Time dependent coherence estimates were constructed using a 200 ms sliding window with 50 ms increments using 40 offsets relative to the auditory cue, and 60 offsets relative to the MO trigger, giving overall analysis windows of 2000 ms and 3000 ms, respectively. Coherence and estimates of non-parametric directionality (NPD) [10] were constructed by averaging across steps for each time offset in the analysis windows. NPD provides a summative decomposition of coherence by time lag into reverse, zero-lag and forward components. This quantifies the directional dependence between shoulder and leg EMG signals, providing an indication of whether shoulder EMG leads or lags leg EMG. Using 40 and 60 time offsets gives individual time-frequency heat maps of directional dependence between EMGs at different time offsets and frequencies. Heat maps were time warped to the time intervals between each auditory cue and MO and between MO and second HS using linear interpolation, and subsequently pooled to produced group estimates. In locomotor data, the periodicity of the gait cycle

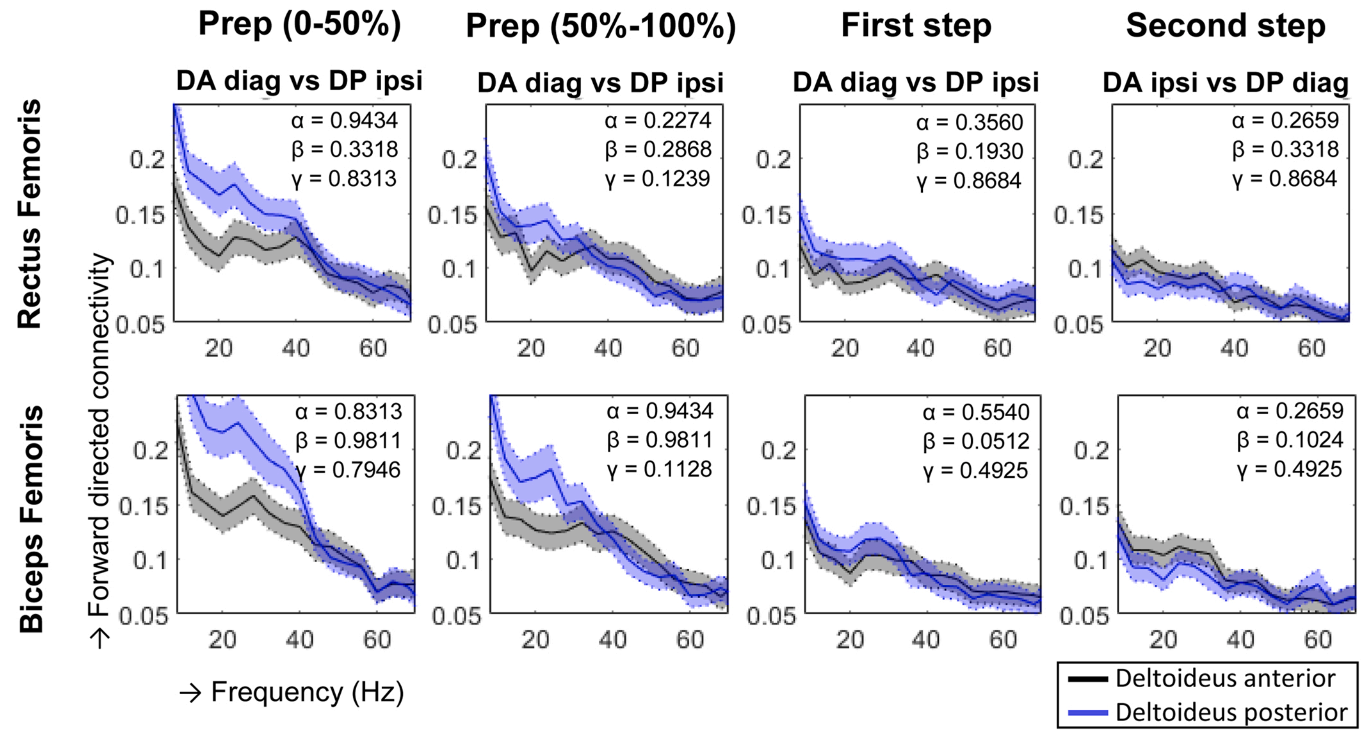

Fig. 2. Comparison between forward directed components from deltoideus anterior and posterior muscles. Group averaged forward directed components of coherence (y-axis) between shoulder and upper leg muscles during gait across the frequency spectrum (x-axis, 8–70 Hz) indicated by the solid thick line, where the shaded band depicts the 95% confidence interval. Blue colours indicate forward directed coherence between deltoideus posterior (i.e. backward arm swing) and upper leg muscles, whereas black colours indicate forward directed coherence between deltoideus anterior (i.e. forward arm swing) and upper leg muscles. Values in the right upper corner represent the p-values when statistically comparing (Wilcoxon signed rank test) forward directed connectivity from deltoideus anterior and posterior in the distinct frequency bands. Abbreviations: α = alpha, β = beta, γ = gamma.

dominates the low-frequency spectral components (<8 Hz) of EMG data, and therefore these frequencies were disregarded.

To determine whether forward or backward arm swing drives the legs more, forward directed connectivity (i.e. shoulder muscles driving the leg muscles) plots were generated from distinct periods of the gait cycle, which included the preparation phase (0–50% and 50–100% of CUE-MO interval), first step (MO-HS1 interval) and second step (HS1-TO2 interval). As the contralateral arm of the leading leg is first swinging forward and the ipsilateral arm is first swinging backward, deltoideus anterior of the contralateral arm was compared with deltoideus posterior of the ipsilateral arm during the preparation phase and first step. During the second step, deltoideus anterior of the ipsilateral arm (i.e. now swinging forwards) was compared with deltoideus posterior of the contralateral arm (i.e. now swinging backwards). For statistical comparison, Wilcoxon Signed Rank tests were applied to the area under the curve for the alpha (8–12 Hz), beta (12–30 Hz) and low-gamma (30–70 Hz) frequency bands, as these reflect subcortical [12–14] and transcortical pathways, respectively [12,15]. All p-values were corrected for multiple comparisons using the Benjamini Hochberg false discovery rate correction. An alpha level of 0.05 was assumed.

3. Results

Coherence between shoulder and upper leg muscles is most pronounced during the preparation phase before MO for all three directional components (Fig. 1). After MO, coherence became related to the gait cycle, with higher coherence during muscle specific stages of the gait cycle. When comparing forward directed connectivity between deltoideus anterior (i.e. forward arm swing) and upper leg muscles and between deltoideus posterior (i.e. backward arm swing) and upper leg muscles during distinct time intervals of the gait initiation process (i.e. preparation phase and first two steps), no significant differences were found (Fig. 2). Although the 95% confidence intervals within the alpha and beta frequencies during the preparation phase did not overlap, paired statistics did not reveal a significance difference in one direction.

4. Discussion

By decomposing time dependent intermuscular coherence into directional components (i.e. forward, reverse and zero-lag), we could establish directionality or causal effects between two EMG signals relative to certain gait events. Using this analysis, we found that the deltoideus anterior and posterior exhibit equal forward directed coherence with upper leg muscles during gait initiation. This suggests that forward and backward arm swing equally drive lower limb muscle activity. It is generally acknowledged that intermuscular alpha band coherence primarily reflects coupling via subcortical interconnections as these muscular alpha oscillations are generally not synchronised with cortical activity [12–14] while beta/gamma band coherence reflects the involvement of particularly transcortical pathways [12,15], suggesting that the currently observed neural coupling between shoulder and upper leg muscles derives from both subcortical and cortical origin. Which specific subcortical and cortical pathways are involved in this neural coupling between shoulder and leg muscles remains speculative, but some hypotheses are provided in [4]. The equal contribution of forward and (opposite) backward arm swing during gait initiation suggests that movements of the upper limbs have a common purpose. Overall, these results provide neural underpinning that both forward and backward arm swing can provide neuronal support for leg muscle recruitment during gait initiation and could be potentially useful for gait rehabilitation in patients with gait initiation difficulties. Time dependent non-parametric directional coherence analysis could be used as an alternative technique for future studies examining directional coupling between muscles or brain areas relative to certain gait (or other time) events.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] P. Meyns, S.M. Bruijn, J. Duysens, The how and why of arm swing during human walking, Gait Posture 38 (2013) 555–562, https://doi.org/10.1016/j.gaitpost.2013.02.006.
[2] F. Massaad, O. Levin, P. Meyns, D. Drijkoningen, S. Swinnen, J. Duysens, Arm sway holds sway: Locomotor-like modulation of leg reflexes when arms swing in alternation, Neuroscience 258 (2014) 34–46, https://doi.org/10.1016/j.neuroscience.2013.10.007.
[3] J.B. Weersink, N.M. Maurits, B.M. de Jong, EEG time-frequency analysis provides arguments for arm swing support in human gait control, Gait Posture 70 (2019) 71–78, https://doi.org/10.1016/j.gaitpost.2019.02.017.
[4] J.B. Weersink, B.M. de Jong, D.M. Halliday, N.M. Maurits, Intermuscular coherence analysis in older adults reveals that gait-related arm swing drives lower limb muscles via subcortical and cortical pathways, J. Physiol. 599 (2021) 2283–2298, https://doi.org/10.1113/JP281094.
[5] J.B. Weersink, S.R. Gefferie, T. van Laar, N.M. Maurits, B.M. de Jong, Pre-movement cortico-muscular dynamics underlying improved parkinson gait initiation after instructed arm swing, J. Park. Dis. 10 (2020) 1675–1693, https://doi.org/10.3233/JPD-202112.
[6] M. Goudriaan, I. Jonkers, J.H. van Dieen, S.M. Bruijn, Arm swing in human walking: What is their drive? Gait Posture 40 (2014) 321–326, https://doi.org/10.1016/j.gaitpost.2014.04.204.
[7] J.P. Kuhtz-Buschbeck, B. Jing, Activity of upper limb muscles during human walking, J. Electromyogr. Kinesiol. 22 (2012) 199–206, https://doi.org/10.1016/j.jelekin.2011.08.014.
[8] T.W. Boonstra, A. Danna-Dos-Santos, H.B. Xie, M. Roerdink, J.F. Stins, M. Breakspear, Muscle networks: Connectivity analysis of EMG activity during postural control, Sci. Rep. 5 (2015) 1–14, https://doi.org/10.1038/srep17830.
[9] C. De Marchis, G. Severini, A.M. Castronovo, M. Schmid, S. Conforto, Intermuscular coherence contributions in synergistic muscles during pedaling, Exp. Brain Res. 233 (2015) 1907–1919, https://doi.org/10.1007/s00221-015-4262-4.
[10] D. Halliday, Non-parametric directionality measures for time series and point process data, J. Integr. Neurosci. 14 (2015) 253–277, https://doi.org/10.1016/j.jneumeth.2016.05.008.
[11] D.M. Halliday, J.R. Rosenberg, A.M. Amjad, P. Breeze, B.A. Conway, S.F. Farmer, A framework for the analysis of mixed time series/point process data - theory and application to the study of physiological tremor, single motor unit discharges and electromyograms, Prog. Biophys. Mol. Biol. 64 (1995) 237–278, https://doi.org/10.1016/s0079-6107(96)00009-0.
[12] B.A. Conway, D.M. Halliday, S.F. Farmer, U. Shahani, P. Maas, A.I. Weir, J. R. Rosenberg, Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. J. Physiol. 489 (1995) 917–924, https://doi.org/10.1113/jphysiol.1995.sp021104.
[13] S. Salenius, K. Portin, M. Kajola, R. Salmelin, R. Hari, Cortical control of human motoneuron firing during isometric contraction, J. Neurophysiol. 77 (1997) 3401–3405, https://doi.org/10.1093/brain/122.2.351.
[14] M.R. Baker, S.N. Baker, The effect of diazepam on motor cortical oscillations and corticomuscular coherence studied in man, J. Physiol. 546 (2003) 931–942, https://doi.org/10.1113/jphysiol.2002.029553.
[15] K.M. Fisher, B. Zaaimi, T.L. Williams, S.N. Baker, M.R. Baker, Beta-band intermuscular coherence: A novel biomarker of upper motor neuron dysfunction in motor neuron disease, Brain 135 (2012) 2849–2864, https://doi.org/10.1093/brain/aws150.