BJMB
Brazilian Journal of Motor Behavior

Special issue:
Effects of aging on locomotor patterns

Walking speed does not affect age-differences in ankle muscle beta-band intermuscular coherence during treadmill walking

PAULO C. R. SANTOS[1,2] | INGE ZIJDEWIND[3] | CLAUDINE LAMOTH[4] | LILIAN T. B. GOBBI[5,#] | TIBOR HORTOBÁGYI[4,6,7,8]

[1] Department of Computer Science & Applied Mathematics, Weizmann Institute of Science, Rehovot, Israel.
[2] Center of Advanced Technologies in Rehabilitation, Sheba Medical Center, Ramat Gan, Israel.
[3] Department of Biomedical Sciences of Cells and Systems, University Medical Center Groningen, University of Groningen, Groningen, Netherlands.
[4] Department of Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, Netherlands.
[5] São Paulo State University (UNESP), Institute of Biosciences, Posture and Gait Studies Laboratory (LEPLO), Rio Claro, SP, Brazil.
[6] Institute of Sport Sciences and Physical Education, University of Pécs, Pécs, Hungary.
[7] Department of Kinesiology, Hungarian University of Sport Science, Budapest, Hungary.
[8] Somogy County Kaposi Mór Teaching Hospital, Kaposvár, Hungary.
[#] In memorium

Correspondence to: Paulo C. R. Santos, Department of Computer Science & Applied Mathematics, Weizmann Institute of Science, Rehovot, Israel
email: paulo-cezar.rocha-dos-santos@weizmann; paulocezarr@hotmail.com
https://doi.org/10.20338/bjmb.v16i5.323

HIGHLIGTHS

- Fast walking speed was ~9% slower in older vs. younger individuals.
- Aging affected ankle but not thigh muscle beta-band coherences.
- Older vs. younger individuals walked with ~53% lower ankle muscle beta-band coherence.
- Walking speed did not affect age-differences in ankle muscle beta-band coherence.

ABBREVIATIONS

BF	Biceps femoris
CoP	Center of pressure
CV	Coefficient of variation
d	Effect sizes
GL	Gastrocnemius lateralis
PL	Peroneus longus
RF	Rectus femoris
SL	Soleus
SPPB	Short Physical Performance Battery
ST	Semitendinosus
TA	Tibialis anterior
VL	Vastus lateralis
η^2_p	Partial eta squared

PUBLICATION DATA
Received 08 11 2022
Accepted 11 12 2022
Published 15 12 2022

BACKGROUND: By examining whether age and speed each differently affect beta coherence during walking, we can extend the limited evidence on age-related impairment in the neural control of walking.
AIM: We determined the effects of age and walking speed on intermuscular beta coherence between lower extremity muscle pairs and the association between stride characteristics and intermuscular beta coherence in these muscle pairs.
METHOD: Older (n=12) and younger (n=14) individuals walked on a treadmill at fixed (1.2 m/s) and fast (~1.3x preferred) speeds for 3min. For 100 dominant leg strides, we measured length, width, stance, swing time, cadence and intermuscular beta coherence (15-35Hz) for the synergistic thigh (biceps femoris (BF)-semitendinosus, rectus femoris (RF)-vastus lateralis (VL)) and ankle (Gastrocnemius lateralis (GL)-soleus (SL), Tibialis anterior (TA)-peroneus longus (PL)) and the antagonistic (RF-BF and TA-GL) muscle pairs in swing and stance phases.
RESULTS: Comparing fast vs. fixed speed, participants walked with longer strides (21%), faster cadence (12%), and greater coefficient of variation (CV) of stride length (14%), narrower stride width (-20%), and shorter stance (-5%) and swing times (-14%) and with stronger TA-GL beta coherence in early stance (69%, all $p<0.01$). Older vs. younger individuals walked with slower fast gait speed (~9%), higher CV of stride length (21%), weaker GL-SL (-47%) and TA-PL (-60%) beta coherences during the late swing and early stance phase, respectively (all $p<0.01$). No Group*Condition interactions occurred.
CONCLUSION: While old age seems to affect synergistic ankle but not thigh muscle beta coherence, based on a lack of speed effect on coherence and a lack of association between spatiotemporal gait variables and ankle muscle beta coherence, variables other than intermuscular beta coherence most likely underlie age-differences in the neural control of walking speed.

KEYWORDS: Aging | Gait | EMG | Oscillatory coupling | Neuromuscular control

INTRODUCTION

Healthy human aging modifies the biomechanics of walking [1], resulting in 16% per decade decreases in self-selected walking speed after age 60 [1–4]. A disproportionately slower walking speed for a given age and sex at mid-life predicts multiple health conditions

later in life, including cognitive decline and mental health, falls and risk of falls, fractures, adverse clinical events, hospitalization, mortality, and survival [4–7]. Although age-effects on walking speed have been thoroughly examined [8–11], the mechanisms underlying age-typical reductions in the capacity to modulate neuromuscular control with changes in walking speed have not yet been fully elucidated. Such information could be insightful because age can affect locomotor muscle activation in the amplitude but also in the frequency domain [12–14]. For instance, while aging was related to an increase in muscle coactivation during walking (accompanied by ~20% higher energy cost of transport in older individuals) [15], the rate of change in coactivation due to walking speed was substantially lower in older vs. younger individuals [12]. Specifically, coactivation between knee flexors and knee extensors increased by ~16% as walking speed increased to 1.8 from 1.2 $m \cdot s^{-1}$ in younger but not in older (~3.5%) [12]. Together, a lower capacity to modulate coactivation may indicate older individuals' impaired neural control of walking when speed is changing.

One way to determine if age affects the neural control of walking with respect to speed is to measure intermuscular coherence among the active muscles. Intermuscular coherence is a measure of the strength of synaptic inputs to the muscles activated while walking [16–19]. The frequency at which the intermuscular coherence arises may be related to the origin where the coherence is generated (spinal, cortical, subcortical) [20]. Based on lesion data in neurological patients, intermuscular beta coherence at 15–35 Hz emanates from cortical structures [19], which are known to contribute to gait control [16–19]. Intra/intermuscular beta coherence of synergistic lower extremity muscles measured during walking seems to decrease with age [13,14,18]. However, it is unknown if age and speed each differently affect beta coherence during walking. Therefore, the purpose of the present study was to determine the effects of age and walking speed on intermuscular beta coherence of lower extremity muscles and the association between stride characteristics and intermuscular beta coherence of these muscles. We hypothesized an interaction between age and walking speed in beta coherence so that older vs. younger individuals would have lower coherence without modulating it with walking speed. We based this expectation on a lack of age-related modulation in beta coherence during walking after muscle fatigue [14] and split-belt perturbations [13]. Our walking speed data would extend these previous data suggesting potentially a general age-related impairment in the neural control of walking.

METHODS

Participants

We recruited healthy younger (n=14, age = 23 [range 20–26] years, 7 Females) and older volunteers (n=12, age = 71 [range 66–77] years, 5 Females) to participate in the study. Inclusion criteria were: age 18 to 29 and > 65 years and either sex. Exclusion criteria were: inability to walk unassisted on a treadmill; musculoskeletal injury in the lower limb or surgery that could affect walking ability; self-reported pain in the lower extremities; and neurological or cardiac diseases. The procedures of this study were conducted following the Declaration of Helsinki [21], approved by the Ethical Committee of the Department of Human Movement Sciences, University Medical Center Groningen (#ECB2017.06.12_1), and participants consented to participate by signing the informed consent document before testing.

Experimental Procedures and data acquisition

Mobility was assessed by Short Physical Performance Battery [22]. Participants then walked on a treadmill to determine their 'comfortable' speed by progressively increasing belt speed by 0.1 m/s until the participant signaled 'comfortable'. This was considered the habitual walking speed. Subjects walked at a fixed (1.2 m/s) and at a "fast speed" (20-30% above comfortable walking speed) for 3 minutes, separated by 1-2 min of rest. We included a fixed speed at 1.2 to have a controlled speed walking condition (eliminating speed as a potential confounder), and we selected the range of 20-30% above comfortable walking speed to induce the individuals to walk fast but not run. During treadmill walking, volunteers wore a harness and were asked not to touch or hold onto the handrail and look at the wall in front of them.

The treadmill had two embedded force plates, and we used the vertical ground reaction forces as an event to align the data for analysis (data recorded at a sample frequency of 1 kHz, M-gait, Motekforce, Amsterdam, NL). During each treadmill walking condition, we recorded EMG activity using 8 wireless sensors (dimensions: 37×26×15 mm, electrode material: silver; Trigno Wireless System - Delsys, Natick, MA, USA). According to SENIAN (Surface Electromyography for the Non-Invasive Assessment of Muscles) [23], the electrodes were placed unilaterally on the dominant limb (determined by asking the participants and confirmed by asking the participants to kick a ball) on the following muscles: soleus (SL), gastrocnemius lateralis (GL), tibialis anterior (TA), peroneus longus (PL), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), and semitendinosus (ST). EMG signals were sampled at 2 kHz. The areas where the sensors were placed, body hair was removed, and the skin was cleaned with alcohol. Treadmill and EMG data acquisition were electronically synchronized with a custom-built timer and event generator.

Data analysis

Ground reaction and moment of forces, acquired from force plates, were 15 Hz low-pass second order zero-phase Butterworth filtered. Based on the minimum ground reaction forces, heel contact and toe-off were determined using a threshold of 50 N. Based on the ground reaction and moment of forces, we computed the center of pressure (CoP) [24] and detected heel strikes and toe-offs of 100 strides. From these strides, the mean and coefficient of variation (CV) of the stride length, step width, stance, swing time, and cadence were calculated (see for details [25]).

First, we visually inspected EMG data to minimize noise and artifacts. Then, the data were high-pass filtered (5 Hz) using a second-order Butterworth filter and full-wave rectified using the Hilbert transform. EMG data were then downsampled to 1 kHz to the same sample frequency as data from the force plate. We calculated, for each heel strike in both speed conditions, the coherence (frequency-domain coupling between two EMG signals) for the late swing phase: −400 to −50 ms before the heel strike, and early stance phase: 50 to 400 ms after the heel strike [14]. For each phase, intermuscular coherence was computed for six muscle pairs (four synergistic [BF-ST, RF-VL, GL-SL, TA-PL] and two antagonistic [RF-BF and TA-GL] muscle pairs).

To compute coherence, the auto-spectra (f_{xx} and f_{yy})) of each muscle and cross-spectrum of the muscle pairs (f_{xy}) via Welch's periodogram method was calculated [14,26]. For each of the 100 swing and stance phases, estimates were obtained using a 350 ms window with nonoverlapping data segments, resulting in a resolution frequency of 2.86 Hz. Spectral estimates of individual strides were then averaged across the 100 strides. Intermuscular

coherence was calculated by the squared modulus of the cross-spectrum divided by the product of the two auto-spectrum for each frequency (λ) [27]:

$$C(\lambda) = \frac{|f_{xy}(\lambda)|}{f_{xx}(\lambda).f_{yy}(\lambda)}$$

Coherence is usually reported in a frequency range of 0–55 Hz (but for the study proposal, we focused only on the range of 15-35 Hz – beta-band frequency), with values ranging from 0 (absent) to 1 (correlated). Significant coherence was considered if the value exceeded the confidence limit (at α = 0.05) for the number of segments (L) used to estimate the spectrum [27].

$$1 - (\alpha)^{\frac{1}{L-1}}$$

where α = 0.05 and L is the number of strides (100) used in the analysis. During the coherence calculation, for each subject and muscle pair, we verified the cumulant density plots and ensured that high coherences were accompanied by near zero-lag synchronization suggesting that cross-talk did not affect coherences [19,28]. To compare groups, intermuscular coherences of individual subjects were combined into pooled estimates for age groups for each walking phase for the fixed and fast walking conditions. Coherence estimates were Fisher transformed before pooling to stabilize variance [28,29]. Since our interest is in the beta-band, we computed the cumulative sum (area), in the range of 15-35 Hz, for each group (older and younger), phase (swing and stance), and walking speed condition (fixed and fast).

For statistical analysis, using SPSS for Windows (Version 25, IBM, Armonk, NY, USA), we, firstly, tested the data normality by Shapiro–Wilk. When data were non-normal distributed, data were log-transformed for further comparisons using T-tests or ANOVAs. T-tests were used to compare the effects of age on groups' characteristics (age, height, body mass, and SPPB) and fast walking speed. We compared stride outcomes (length, speed, velocity, swing and stance time) and intermuscular beta coherence by ANOVA with as between factor Group (younger vs. older) and within factor Condition (fixed vs. fast). ANOVA effect size was estimated using partial eta squared (η^2_p) [30]. In case of significant interactions, adjusted Bonferroni (post hoc) corrections for each factor were made. For post hoc level of comparisons, Cohen's d was calculated and considered as 0.21–0.50, 0.51 to 0.79, and > 0.79 to indicate small, medium, and large effect sizes (d), respectively [30]. To identify if speed was correlated with coherence, we computed a Spearman's correlation between change in walking speed (Δ = Fast – Fixed) of coherence with Δ walking speed as well Δ stride outcomes when Condition main effect indicates differences for such outcomes. For interpreting the strength of the association, we assumed that r-values ranging from 0–0.19, 0.2–0.39, 0.40–0.59, 0.6–0.79, and 0.8–1 as a very weak, weak, moderate, strong, and very strong correlation, respectively [31].

RESULTS

Participants

Younger and older groups were similar in height (1.75 ± 0.11 and 1.72 ± 0.77 m, p

= 0.61) and body mass (70.14 ± 13.51 and 73.9 ± 10.60 kg, p = 0.44). Each individual in both age groups reached the maximum score (12) on the Short Physical Performance Battery.

Stride outcomes

Table 1 shows T-tests and ANOVAs outcomes. A significant group difference in fast walking speed was observed, indicating that fast walking speed was ~9% slower in older (1.61 ± 0.18) vs. younger individuals (1.76 ± 0.06, d = 1.11). Regarding stride outcomes, a main effect of Group was found for CV of stride length and a main effect of Condition for stride length, width, stance, and swing time and CV of stride length. No Group by Condition interaction was observed (p<0.05). For Group, post hoc indicated that older vs. younger had a 21% higher CV of stride length (d = 0.90). For Condition, post hoc indicated for fast vs. fixed speed a significant increase in the mean of stride length (21%, d = 1.9), cadence (12%, d = 1.7), and CV of stride length (14%, d = 1.7) and a decrease in mean step width (20%, d = 0.51), swing (5%, d = 0.91), and stance time (14%, d = 1.94, Table 2).

Table 1. Statistical descriptors for the significant outcomes for Group and Condition comparisons.

Main Effect / Interaction	Outcome	T_{24} / $F_{1,24}$	p-value	(η^2_p)
Group	Fast walking speed	2.93	0.007	1.11*
	CV Length	8.94	0.006	0.27
	GL-SL coherence – Swing	9.20	0.006	0.28
	TA-PL coherence – Stance	8.26	0.008	0.26
Condition	Length	78.01	< 0.001	0.76
	Width	53.92	< 0.001	0.69
	Swing	24.66	< 0.001	0.51
	Stance	67.20	< 0.001	0.74
	Cadence	62.86	< 0.001	0.72
	CV Length	8.08	0.009	0.25
	TA-GL coherence – Stance	8.61	0.007	0.26

*Cohen d effects size for T-test

Coherence

ANOVA revealed a main effect of Group for GL-SL beta coherence during late swing and for TA-PL beta coherence during early stance, and of Condition for TA-GL beta coherence during early stance (Figure 1). ANOVA did not indicate Group by Condition interaction (p<0.05). For Group, post hoc indicated that, after the adjustment for walking speed, older vs. younger individuals had weaker beta coherences during the late swing and early stance phases for GL-SL (47%, d = 0.92, Figure 1a) and TA-PL (60%, d = 1.25, all p<0.01, Figure 1b). For Condition, individuals (from both older and younger combined) walked during fast vs. fixed walking speed with 69% stronger TA-GL beta coherence during early stance (d = 0.59, p<0.01, Figure 1c).

Table 2. Strides outcomes for younger and older individuals at fixed and fast walking speeds.

	Outcomes	Group	Fixed speed	Fast speed
Average	Stride Length (cm)	Younger	130.11 ± 10.02	161.94 ± 16.52
		Older	128.2 ± 14.29	150.19 ± 16.24
	Width (cm)	Younger	10.15 ± 4.33	7.97 ± 4.22
		Older	10.01 ± 3.52	8.21 ± 3.63
	Swing time (s)	Younger	0.38 ± 0.03	0.36 ± 0.02
		Older	0.37 ± 0.03	0.35 ± 0.02
	Stance time (s)	Younger	0.70 ± 0.06	0.59 ± 0.03
		Older	0.66 ± 0.05	0.59 ± 0.05
	Cadence (steps/min)	Younger	109.81 ± 8.6	125.45 ± 5.99
		Older	115.58 ± 8.15	126.31 ± 8.10
CV	Stride Length (%)	Younger	1.61 ± 0.30	1.38 ± 0.27
		Older	1.93 ± 0.44	1.68 ± 0.35
	Width (%)	Younger	13.73 ± 5.02	16.31 ± 6.39
		Older	12.86 ± 8.32	11.93 ± 3.55
	Swing time (%)	Younger	3.32 ± 0.74	3.21 ± 1.34
		Older	4.40 ± 1.47	3.57 ± 1.07
	Stance time (%)	Younger	3.08 ± 0.67	3.11 ± 0.90
		Older	3.84 ± 1.21	3.17 ± 0.87

Values are mean ± standard deviation

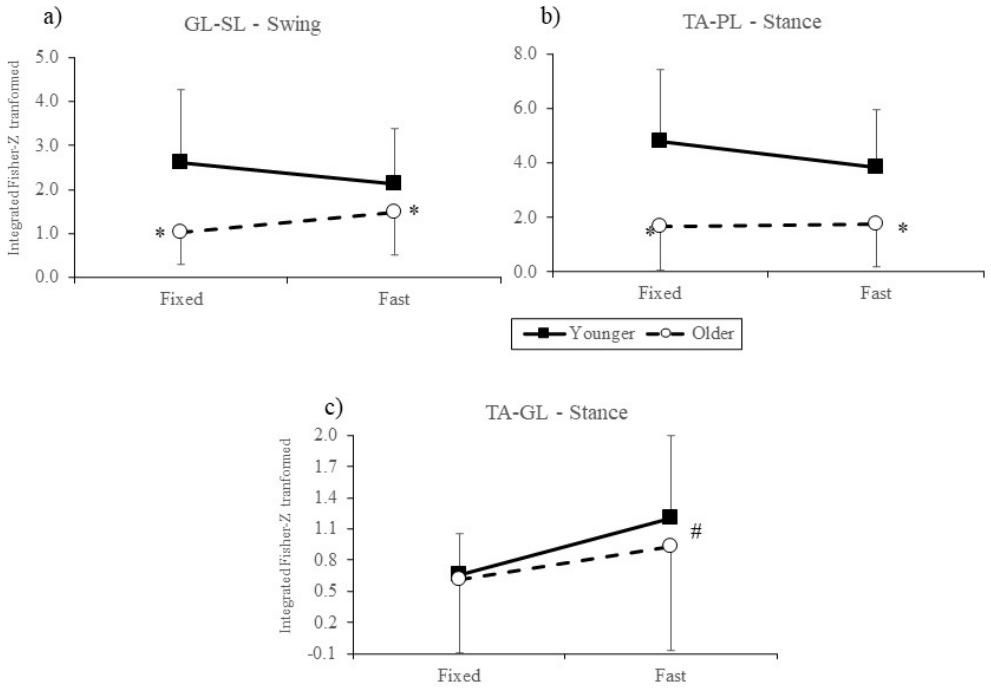

Figure 1. Significant intermuscular beta coherences between (a) GL-SL during stance; (b) TA-PL during swing; (c) TA-GL during stance. *Main effect of Age-indicating Older ≠ Younger individuals; # Main effect of Condition indicating that Fast ≠ Fixed walking speed. Data expressed in mean and standard deviation.

Correlation

Taking the difference between fixed and fast speed walking conditions, there was a positive correlation between ΔTA-PL beta coherence during swing and Δwalking speed (r = 0.48, p = 0.01, Figure 2). Also, higher ΔBF-ST beta coherence during swing was associated with Δcadence (r = 0.43, p = 0.03, Figure 2). Spearman's correlation also indicated that higher ΔGL-SL beta coherence during stance was associated with lower Δstance time and ΔCV of stride length during treadmill walking (r = -0.48 and -0.41, p = 0.02 and 0.04, respectively, Figure 2).

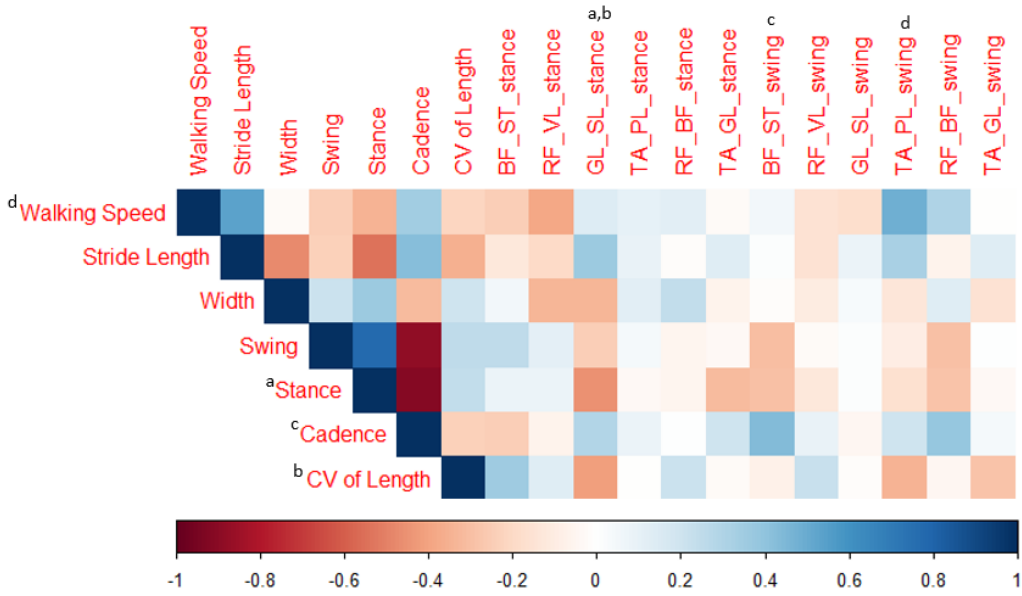

Figure 2. Correlogram indicating correlations between Δ walking speed and Δ strides outcomes (only the ones that ANOVA indicates Condition main effects) with Δ intermuscular coherence during late swing and early stance phases. Letters (a-d) indicate parameters that are significantly correlated.

DISCUSSION

We examined the effects of age and walking speed on lower extremity intermuscular beta coherence and the association between stride characteristics and ankle muscle intermuscular beta coherence (variables for which ANOVA indicated Group/Condition effects). As expected, intermuscular beta coherence between synergistic ankle muscle pairs was lower in older vs. younger individuals. Any age and walking speed effect occurred between thigh muscle pairs. However, because we observed only medium effects of walking speed on beta coherence between an antagonistic (TA-GL) ankle muscle pair during stance (d = 0.59) (one out of 6 coherence outcomes), we can interpret that this effect prevented us from observing the hypothesized age by speed interaction in ankle muscle intermuscular beta coherence.

In addition, although speed effects revealed moderate to no effects on the associations between stride characteristics and lower extremity muscle intermuscular beta coherence, any of the beta coherence outcomes involved in the main effect of age and speed correlate with Δ strides outcomes. While old age seems to affect synergistic ankle muscle beta coherence, based on a lack of speed effect and a lack of association between

spatiotemporal gait variables and ankle muscle beta coherence, we interpret our data to mean that variables other than intermuscular beta coherence most likely underlie age-differences in the neural control of walking speed. Thus, oscillatory coupling between the synergistic ankle muscle pairs during walking is lower in older vs. younger individuals, but this difference is independent of walking speed while walking on a treadmill.

Age-effects on beta coherence

As expected, we observed ~50% age-related reductions in beta coherence between synergistic ankle muscle pairs (Figure 1). Such reductions agree with previous data [13,14,18], suggesting that age affects the organization of synaptic input to the motoneuron pools. Weak intermuscular beta coherence for the ankle muscles may imply that output from the motor centers is sub-optimal. This inference is based on lesion data in individuals with a neurological condition [19,32], indicating that the origin of intermuscular beta coherence is cortical/supraspinal. Therefore, the observed reduction in beta coherence in older individuals might reflect an age-effect on the central set: the capacity to modulate central outputs during a motor task [33], including walking [34], but not necessarily in manipulating walking speed.

One element of the reduced ankle muscle intermuscular beta coherence during gait would be the age-related decline in inhibitory control. This reduction is speculated to interfere with the organization of the motor drive to muscles. This impairment is reflected in the summary measures of reduced intermuscular coherence in the frequency domain and increased muscle coactivation in the amplitude domain [12]. Thus, it is reasonable to expect an association between walking speed and coherence per se and between the ability to change walking speed and the accompanying change intermuscular coherence. Contrary to this expectation, we found no meaningful correlations between the absolute values of fast walking speed and coherence (data not shown). It is thus not possible to attribute individual differences in beta coherence to age-related differences in fast walking speed. We observed no age or speed effect on thigh muscle beta coherence, an observation that requires confirmation and further study.

Interaction between age and walking speed in ankle muscle intermuscular beta coherence

We found that fast walking speed was ~9% slower in older vs. younger individuals. This result agrees with prior data concerning the effects of age on walking speed [2,6,11]. As the fast speed was determined based on the comfortable speed, expectedly, comfortable walking speed was also affected even in highly mobile (based on Short Physical Performance Battery) older individuals (older: 1.30 vs. younger: 1.42 m/s, $p = 0.020$). Considering such results, it is reasonable to hypothesize that age-typical differences in walking speed would reflect the ability to adapt the neuromuscular control from fixed (slower than comfortable) to faster walking speed. This observation is also supported by previous evidence suggesting age-specific changes in neuromuscular control (amplitude of muscle activation) to changes in walking speed [12]. Thus, the lack of age groups and speed condition interaction on leg muscle intermuscular beta coherence was unexpected.

Although age-differences in fast walking speed were accompanied by differences in synergistic ankle muscle intermuscular beta coherence (GL-SL, TA-PL, Figure 1), we only observed a moderate effect of walking speed on increasing antagonistic (TA-GL) beta coherence during stance ($d = 0.59$). A strengthening of the oscillatory coupling between antagonistic muscles may be related to an increase in ankle joint stability needed as walking

speed increases. Unexpectedly, walking speed only affected TA-GL beta coherence but not any other coherence outcomes. As we hypothesized that modulation in intermuscular beta coherence with walking speed would occur in an age-specific manner (low to no modulation in coherence in older vs. younger), it is also unexpected that age and walking speed did not interact. However, while unexpected, previous evidence also suggested that changes in walking speed did not affect and did not interact with aging in inducing modulation in intermuscular coherence [13]. Different from frequency domain outcomes (as coherences), muscle activation as measured by EMG amplitude indicated a lack of modulation in coactivation in older vs. younger individuals as the walking speed increases [12]. Thus, it is likely that intermuscular beta coherence vs. muscle activation has less of a functional relevance in adjusting neural control to walking speed. Collectively, the higher task demand associated with faster walking speed seems to be regulated via increased muscle agonist and antagonist activation and coactivation towards ankle joint stability with less of a role assigned to modulating oscillatory coupling between ankle muscle pairs.

The significant speed-induced changes in TA-GL beta coherence (the only coherence outcome affected by walking speed) during stance did not correlate with the changes in stride characteristics and walking speed (Figure 2). Instead, ∆stance and CV of stride length were moderately negatively associated with ∆GL-SL beta coherence during stance (r = -0.48 and -0.41), and ∆cadence was associated with ∆BF-ST beta coherence during swing (r = 0.43, Figure 2). Since the coherence outcome affected by Speed (Figure 1c) did not associate with stride outcomes (Figure 2), it is difficult to assign a functional role to intermuscular beta coherence in walking control related to the speed of walking. This argument partially supports the idea that corticospinal drive is speed insensitive so that other neural mechanisms might be involved in the neural control of the speed effects on walking (e.g., heightened antagonistic coactivation [12]). Such an interpretation of our current data would explain a lack of age group by walking speed interaction compared with amplitude coactivation evidence [12].

Walking on a treadmill confines spatial-temporal characteristics of walking [35]. The uniform step pattern generated by the monotonic belt movement would require less cortical vs. central pattern generator control of walking [36]. If it were the case, the cortico-spinal drive shared by muscles would not be sensitive to changes in walking speed, as also suggested by our results here. Therefore, future studies should determine the effects of age and walking speed on intermuscular coherence during overground walking and treadmill walking at a fixed speed and also at a self-selected speed. Such data would provide a more complete understanding of the effects of age and walking speed on the neural control of walking.

Limitation

A lack of neurophysiological or imaging data complicates the interpretation of intermuscular coherence [18,19,37]. We rectified the EMG data in the process to compute intermuscular coherence even though there is no consensus concerning this step which could affect the results [38,39]. Notwithstanding the limitation of using the Fourier transform for non-stationary signals, as during walking, this has become standard in coherence analyses of EMG signals recorded during walking [14,16–18]. Still, using steps in data processing reported also by other studies facilitates interpretation and cross-study comparisons of our data [13,14,16–18].

CONCLUSION

We conclude that while old age seems to affect synergistic ankle but not thigh muscle beta coherence, based on a lack of speed effect on coherence and a lack of association between spatiotemporal gait variables and ankle muscle beta coherence, variables other than intermuscular beta coherence most likely underlie age-differences in the neural control of walking speed.

REFERENCES

1. Beijersbergen CMI, Granacher U, Vandervoort AA, DeVita P, Hortobágyi T. The biomechanical mechanism of how strength and power training improves walking speed in old adults remains unknown. *Ageing Res Rev*. 2013;12(2):618–627. doi: 10.1016/j.arr.2013.03.001
2. Bendall MJ, Bassey EJ, Pearson MB. Factors Affecting Walking Speed of Elderly People. *Age Ageing*. 1989;18(5):327-332. doi:10.1093/AGEING/18.5.327
3. Bohannon RW, Williams Andrews Normal walking speed: a descriptive meta-analysis. *Physiotherapy*. 2011;97(3):182-189. doi:10.1016/j.physio.2010.12.004.
4. Abellan Van Kan G, Rolland Y, Andrieu S, et al. Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force. *J Nutr Health Aging*. 2009;13(10):881-889. doi:10.1007/S12603-009-0246-Z
5. Kikkert LHJ, Vuillerme N, van Campen JP, Hortobágyi T, Lamoth CJ. Walking ability to predict future cognitive decline in old adults: A scoping review. *Ageing Res Rev*. 2016;27:1-14. doi:10.1016/j.arr.2016.02.001
6. Studenski S, Perera S, Patel K, et al. Gait speed and survival in older adults. *JAMA*. 2011;305(1):50-58. doi:10.1001/jama.2010.1923
7. Montero-Odasso M, Schapira M, Soriano ER, et al. Gait Velocity as a Single Predictor of Adverse Events in Healthy Seniors Aged 75 Years and Older. *Journals Gerontol Ser A*. 2005;60(10):1304-1309. doi:10.1093/GERONA/60.10.1304
8. Hagoort I, Vuillerme N, Hortobágyi T, Lamoth CJ. Outcome-dependent effects of walking speed and age on quantitative and qualitative gait measures. *Gait Posture*. 2022;93:39–46. doi:10.1016/J.GAITPOST.2022.01.001
9. Pimentel RE, Feldman JN, Lewek MD, Franz JR. Quantifying mechanical and metabolic interdependence between speed and propulsive force during walking. *Front Sport Act Living*. 2022;0:333. doi:10.3389/FSPOR.2022.942498
10. Lo O-Y, Halko MA, Zhou J, Harrison R, Lipsitz LA, Manor B. Gait Speed and Gait Variability Are Associated with Different Functional Brain Networks. *Front Aging Neurosci.* 2017;9:390. doi:10.3389/fnagi.2017.00390
11. Hortobágyi T, Lesinski M, Gäbler M, VanSwearingen JM, Malatesta D, Granacher U. Effects of Three Types of Exercise Interventions on Healthy Old Adults' Gait Speed: A

Systematic Review and Meta-Analysis. *Sport Med*. 2015;45(12):1627-1643. doi:10.1007/s40279-015-0371-2

12. Hortobágyi T, Solnik S, Gruber A, et al. Interaction between age and gait velocity in the amplitude and timing of antagonist muscle coactivation. *Gait Posture*. 2009;29(4):558-564. doi:10.1016/j.gaitpost.2008.12.007
13. Sato SD, Choi JT. Corticospinal drive is associated with temporal walking adaptation in both healthy young and older adults. *Front Aging Neurosci*. 2022;0:900. doi:10.3389/FNAGI.2022.920475
14. Santos PCR, Lamoth CJC, Barbieri FA, Zijdewind I, Gobbi LTB, Hortobágyi T. Age-specific modulation of intermuscular beta coherence during gait before and after experimentally induced fatigue. *Sci Rep.* 2020;10(1). doi:10.1038/s41598-020-72839-1
15. Hortobagyi T, Finch A, Solnik S, Rider P, DeVita P. Association Between Muscle Activation and Metabolic Cost of Walking in Young and Old Adults. *Journals Gerontol Ser A Biol Sci Med Sci*. 2011;66A(5):541-547. doi:10.1093/gerona/glr008
16. Halliday DM, Conway BA, Christensen LOD, Hansen NL, Petersen NP, Nielsen JB. Functional Coupling of Motor Units Is Modulated During Walking in Human Subjects. *J Neurophysiol.* 2003;89(2):960-968. doi:10.1152/jn.00844.2002
17. Jensen P, Frisk R, Spedden ME, et al. Using Corticomuscular and Intermuscular Coherence to Assess Cortical Contribution to Ankle Plantar Flexor Activity During Gait. *J Mot Behav*. 2019;51(6):668-680. doi:10.1080/00222895.2018.1563762
18. Spedden ME, Choi JT, Nielsen JB, Geertsen SS. Corticospinal control of normal and visually guided gait in healthy older and younger adults. *Neurobiol Aging*. 2019;78:29-41. doi:10.1016/j.neurobiolaging.2019.02.005
19. Norton JA, Gorassini MA. Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *J Neurophysiol*. 2006;95(4):2580-2589. doi:10.1152/jn.01289.2005
20. Grosse P, Cassidy MJ, Brown P. EEG-EMG, MEG-EMG and EMG-EMG frequency analysis: physiological principles and clinical applications. *Clin Neurophysiol*. 2002;113(10):1523-1531. doi:10.1016/s1388-2457(02)00223-7
21. World Medical Association Declaration of Helsinki. *JAMA. 2013;310(20):2191. doi:10.1001/jama.2013.281053*
22. Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, Wallace RB. Lower-Extremity Function in Persons over the Age of 70 Years as a Predictor of Subsequent Disability. *N Engl J Med*. 1995;332(9):556-562. doi:10.1056/NEJM199503023320902
23. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol*. 2000;10(5):361-374. doi:10.1016/S1050-6411(00)00027-4
24. Buurke TJW, Lamoth CJC, Vervoort D, Van Der Woude LHV, Otter R den. Buurke TJW, Lamoth CJC, Vervoort D, Van Der Woude LHV, Otter R den. Adaptive control of dynamic balance in human gait on a split-belt treadmill. *J Exp Biol*. 2018;221(13).

doi:10.1242/JEB.174896/262914/AM/ADAPTIVE-CONTROL-OF-DYNAMIC-BALANCE-IN-HUMAN-GAIT

25. Santos PCR, Hortobágyi T, Zijdewind I, Bucken Gobbi LT, Barbieri FA, Lamoth C. Minimal effects of age and prolonged physical and mental exercise on healthy adults' gait. *Gait Posture*. 2019;74:205-211. doi:10.1016/j.gaitpost.2019.09.017
26. Boonstra TW, Daffertshofer A, van Ditshuizen JC, et al. Fatigue-related changes in motor-unit synchronization of quadriceps muscles within and across legs. *J Electromyogr Kinesiol*. 2008;18(5):717-731. doi:10.1016/j.jelekin.2007.03.005
27. Halliday DM, Rosenberg JR, Amjad AM, Breeze P, Conway BA, Farmer SF. 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*. Published online 1995. doi:10.1016/S0079-6107(96)00009-0;
28. Halliday DM, Rosenberg JR. On the application, estimation and interpretation of coherence and pooled coherence. *J Neurosci Methods*. 2000;100(1-2):173-174. doi:10.1016/S0165-0270(00)00267-3
29. Amjad AM, Halliday DM, Rosenberg JR, Conway BA. An extended difference of coherence test for comparing and combining several independent coherence estimates: Theory and application to the study of motor units and physiological tremor. *J Neurosci Methods*. 1997;73(1):69-79. doi:10.1016/S0165-0270(96)02214-5
30. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988.
31. Akoglu H. User's guide to correlation coefficients. *Turkish J Emerg Med*. 2018;18(3):91-93. doi:10.1016/J.TJEM.2018.08.001
32. Thomas SL, Gorassini MA. Increases in corticospinal tract function by treadmill training after incomplete spinal cord injury. *J Neurophysiol*. 2005;94(4):2844-2855. doi:10.1152/jn.00532.2005
33. Beretta VS, Santos PCR, Orcioli-Silva D, et al. Cumulative additional information does not improve the neuromuscular control during postural responses to perturbations in postural instability/gait disorders subtype of Parkinson's disease. *Exp Gerontol*. 2022;166:111892. doi:10.1016/J.EXGER.2022.111892
34. Brown LA, Gage WH, Polych MA, Sleik RJ, Winder TR. Central set influences on gait. Exp Brain Res 2002 1453. 2002;145(3):286-296. doi:10.1007/S00221-002-1082-0
35. Lee SJ, Hidler J. Biomechanics of overground vs. treadmill walking in healthy individuals. *J Appl Physiol*. 2008;104:747-755. doi:10.1152/japplphysiol.01380.2006.-The
36. Roeder L, Boonstra TW, Smith SS, Kerr GK. Dynamics of corticospinal motor control during overground and treadmill walking in humans. *J Neurophysiol*. 2018;120(3):1017-1031. doi:10.1152/jn.00613.2017
37. Petersen TH, Willerslev-Olsen M, Conway BA, Nielsen JB. The motor cortex drives the muscles during walking in human subjects. *J Physiol*. 2012;590(10):2443-2452. doi:10.1113/jphysiol.2012.227397

38. Ward NJ, Farmer SF, Berthouze L, Halliday DM. Rectification of EMG in low force contractions improves detection of motor unit coherence in the beta-frequency band. *J Neurophysiol*. 2013;110(8):1744-1750. doi:10.1152/jn.00296.2013
39. Halliday DM, Farmer SF. On the Need for Rectification of Surface EMG. *J Neurophysiol*. 2010;103(6):3547-3547. doi:10.1152/jn.00222.2010

ACKNOWLEDGMENTS

We thank Nick Fennema and Inge Kenter for recruiting the participants and helping with testing. We are grateful for the expert technical assistance provided by Wim Kaan, Anniek Heerschop, Dirk van der Meer, and Emyl Smid and for the support of Dr. Tulika Nandi with the analysis.

Citation: Santos PCR, Barbieri FA, Zijdewind I, Lamoth C, Gobbi LTB, Hortobágyi T. (2022). Walking speed does not affect age-differences in ankle muscle beta-band intermuscular coherence during treadmill walking. *Brazilian Journal of Motor Behavior*, 16(5):372-384.

Funding: This work was partially supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES) [Finance Code 001], the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [LTBG-429549/2018-0; 309045/2017-7], and by Graduate School of Medical Science [PCRS]. Funding agencies did not influence the content of the manuscript.
Competing interests: The authors have declared that no competing interests exist.
DOI: https://doi.org/10.20338/bjmb.v16i5.323