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(Article begins on next page)

1 RESEARCH ARTICLE

2 RUNNING HEAD: Motor output intensifies cortical proprioceptive processing

3 Volitional muscle activation intensifies neuronal  
4 processing of proprioceptive afference in the primary  
5 sensorimotor cortex: an EEG study

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15 **ABSTRACT**

16 Proprioception refers to the ability to perceive the position and movement of body segments in  
17 space. The cortical aspects of the proprioceptive afference from the body can be investigated  
18 using corticokinematic coherence (CKC). CKC accurately quantifies the degree of coupling  
19 between cortical activity and limb kinematics, especially if precise proprioceptive stimulation of  
20 evoked movements are used. However, there is no evidence on how volitional muscle activation  
21 during the proprioceptive stimulation affects CKC strength. Twenty-five healthy volunteers (28.8  
22 ± 7 yr, 11 females) participated the experiment that included electroencephalographic (EEG),  
23 electromyographic (EMG) and kinematic recordings. 2-Hz ankle-joint rotations were elicited  
24 through a movement actuator in two conditions: *passive* condition with relaxed ankle and *active*  
25 condition with constant 5-Nm plantar flexion exerted during the stimulation. In total, 6-min of data  
26 were recorded per condition. CKC strength was defined as the maximum coherence value among  
27 all the EEG channels at the 2-Hz-movement frequency for each condition separately. Both  
28 conditions resulted in significant CKC peaking at the Cz electrode over the foot area of the primary  
29 sensorimotor (SM1) cortex. Stronger CKC was found for the *active* (0.13 ± 0.14) than *passive*  
30 (0.03 ± 0.04) condition ( $P < 0.01$ ). The results indicated that volitional activation of the muscles  
31 intensifies the neuronal proprioceptive processing in the SM1 cortex. This finding could be  
32 explained both by peripheral sensitization of the ankle joint proprioceptors and central modulation  
33 of the neuronal proprioceptive processing in the spinal and cortical levels.

34 **NEW & NOTEWORTHY**

35 The current study is the first to investigate the effect of volitional muscle activation on CKC-based  
36 assessment of cortical proprioception of the ankle joint. Results show that the motor efference  
37 intensifies the neuronal processing of proprioceptive afference of the ankle joint. This is a  
38 significant finding as it may extend the use of CKC method during active tasks to further evaluate  
39 the motor efference-proprioreceptive afference relationship, and the related adaptations to exercise,  
40 rehabilitation and disease.

1 **Keywords:** Corticokinematic coherence, Electroencephalography, Proprioception,  
2 Somatosensory

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3

## 4 INTRODUCTION

5 Motor control in humans relies on the combination of a multitude of senses regulated by sensory  
6 systems such as the visual, vestibular, and somatosensory system which are responsible of  
7 informing the central nervous system (CNS) about the environment and the body itself (1, 2).

8 Proprioception is part of the somatosensory system and it measures the internal state of the  
9 musculoskeletal system being responsible for providing information to the CNS about the position,  
10 movement and dynamics of the musculoskeletal system (3). Proprioception encompasses various  
11 senses related to changes in the internal state of the locomotor system and it is restricted to the  
12 ones that can be consciously perceived. These include, e.g., the sense of movement, the sense  
13 of balance, the sense of joint position, and the sense of force and heaviness (i.e. the sense of  
14 effort) (4). These sensations arise from peripheral signals generated by various types of receptors  
15 (i.e. proprioceptors) located in the muscles, joints, ligaments and soft tissues around the joints  
16 (5). Proprioceptors are mechanoreceptors which activity is modulated by bodily movements  
17 changing the muscle length (muscle spindles) or muscle tension (Golgi tendon organs).  
18 Proprioceptive signals can be further integrated with closely related information from cutaneous  
19 tactile mechanoreceptors sensitive to stretch of the skin during joint rotation (e.g., Pacinian  
20 corpuscles), thus providing specific “fingerprints” of certain movements to the CNS (4, 6).

21 Afferent proprioceptive pathways to the brain travel primarily along the afferent dorsal column-  
22 medial lemniscus first to the thalamus where the signals are further relayed to the cortex (7). Here  
23 the brain integrates the proprioceptive afference with inputs from other senses, such as vision or  
24 touch, carrying information from the external environment (4). Specifically, the primary  
25 sensorimotor cortex (SM1) is the site where the basic sensorimotor integration (i.e. the integration  
26 of sensory information from multiple sources aimed at producing task-specific motor output)  
27 occurs.

28 Proprioception has a crucial role in motor control as it provides essential rich regulatory feedback  
29 about the internal state of the locomotor system to the CNS (1). First, it is fundamental for joint  
30 stabilization in postural control and balance (8). Second, it is crucial to motor planning  
31 (feedforward strategy) rapidly signalling the brain allowing for anticipation, preparation, and  
32 response planning (9). Third, recent evidence supported the view that the proprioceptive  
33 afference is one of the key sensory modalities supporting motor learning (10, 11). Through  
34 proprioception it is also possible for the CNS to fine tune the ongoing motor command or action  
35 and thus produce smooth, appropriate motor actions, which is especially important for targeted  
36 movements of the limbs (feedback strategy) (12).

37 The relevance of proprioception in all human actions has encouraged researchers over decades  
38 to investigate the proprioceptive sense also at the cortical level (7, 8, 13–15). The majority of  
39 studies has utilized electroencephalography (EEG) or magnetoencephalography (MEG) in  
40 combination with stimulation of the proprioceptors using evoked joint rotations while the  
41 participant is at rest (14). The temporal and amplitude features of the neuronal cortical processing  
42 of the proprioceptive afference can then be examined by means of the averaged cortical activity  
43 time-locked with movements (i.e. evoked responses) (16, 17). In addition to the evoked  
44 responses, a recent approach proposed a robust quantification of the degree of cortical  
45 proprioceptive processing using corticokinematic coherence (CKC) (18, 19). Jerbi et al. (2007)

1 first demonstrated using MEG that hand movement velocity and SM1 cortex activity are correlated  
2 at the movement frequency (20). The CKC term was later introduced by Bourguignon et al., (2011)  
3 (21) and they proposed CKC as a tool for functional motor mapping of the hand region (i.e. locate  
4 the cortical origin for the coupling) using MEG and volitional continuous rhythmic movements.  
5 Later, it was demonstrated that CKC primarily reflects cortical proprioceptive processing by  
6 comparing CKC between active volitional and passive evoked movements. The contribution of  
7 corticospinal motor efference to CKC was negligible with respect to the somatosensory afference  
8 to the SM1 cortex (22–24). In addition, it was suggested that the strength of CKC can be used to  
9 quantify the degree of cortical proprioceptive processing. CKC strength ranges from 0 (no  
10 coupling) to 1 (perfect coupling) peaking at the frequency of the movement and its harmonics,  
11 following the somatotopy (25). CKC can be quantified using any peripheral signal (e.g.  
12 acceleration, force, electromyography, etc.) picking the rhythmicity of the movement (26).  
13 To date, several CKC studies have examined proprioception using movement actuators in  
14 passive (resting) conditions (27, 28). CKC strength has been shown to be influenced by factors  
15 such as the directed attention to the stimulus (29), the regularity of the stimulation (30), the  
16 movement range (18), the number of joints stimulated simultaneously (31), aging (32) or  
17 neurological disabilities (e.g. cerebral palsy) (33). Furthermore, reproducibility of CKC is high  
18 across experimental sessions both for MEG- and EEG- based measurements (28, 34) although  
19 MEG provides somewhat stronger CKC, because of the higher signal-to-noise-ratio (35).  
20 Despite the broad spectrum of studies attempting to understand the mechanisms behind CKC,  
21 there is no evidence how volitional muscle activation during the proprioceptive stimulation affects  
22 CKC strength. The motor efference is expected to alter the somatosensory afference to the brain  
23 via input to the muscles but also more generally to the spinal neuronal circuits (6). In addition,  
24 even light volitional muscle contraction can alter the muscle-tendon unit mechanics with respect  
25 to the relaxed passive condition. During volitional muscle contraction, the intrafusal fibers of the  
26 muscle spindles are also activated by the gamma motor neurons and thus the stretch-sensitivity  
27 of the spindle afferents are enhanced (6, 36, 37). Finally, the volitional muscle contraction also  
28 modifies the functional state of the SM1 cortex with respect to the passive condition that may  
29 likely alter the cortical processing of the proprioceptive afference.  
30 With the present study we aimed to examine the effect of volitional muscle activation on neuronal  
31 processing of proprioceptive afference in the human neocortex when quantified using CKC and  
32 EEG. We hypothesised that volitional plantarflexion during proprioceptive stimulation (i.e.  
33 continuous actuated ankle-joint rotations at 2 Hz) of the ankle joint would strengthen CKC when  
34 compared to a condition in which the ankle remains passive. The mechanisms are expected to  
35 be due to 1) motor efference-related sensitization of the peripheral proprioceptors through  
36 mechanical and neuronal factors and to 2) alterations in the neuronal proprioceptive processing  
37 in the spinal and cortical levels. Assessing the sensitivity of CKC to volitional muscle activation is  
38 relevant to better understand methodological aspects of CKC and to provide new insight into the  
39 neurophysiological processes underlying the complex interactions between the periphery and the  
40 brain.

## 41 **MATERIALS AND METHODS**

### 42 **Participants**

43 A total of 25 young, healthy adults (age  $28.8 \pm 7$  mean  $\pm$  SD, 11 females) were recruited for the  
44 study. The majority of the participants was right-footed (only 2 out of 25 were left-footed) based  
45 on Waterloo footedness inventory score that was on average  $42 \pm 32$  on a scale from  $-100$  to

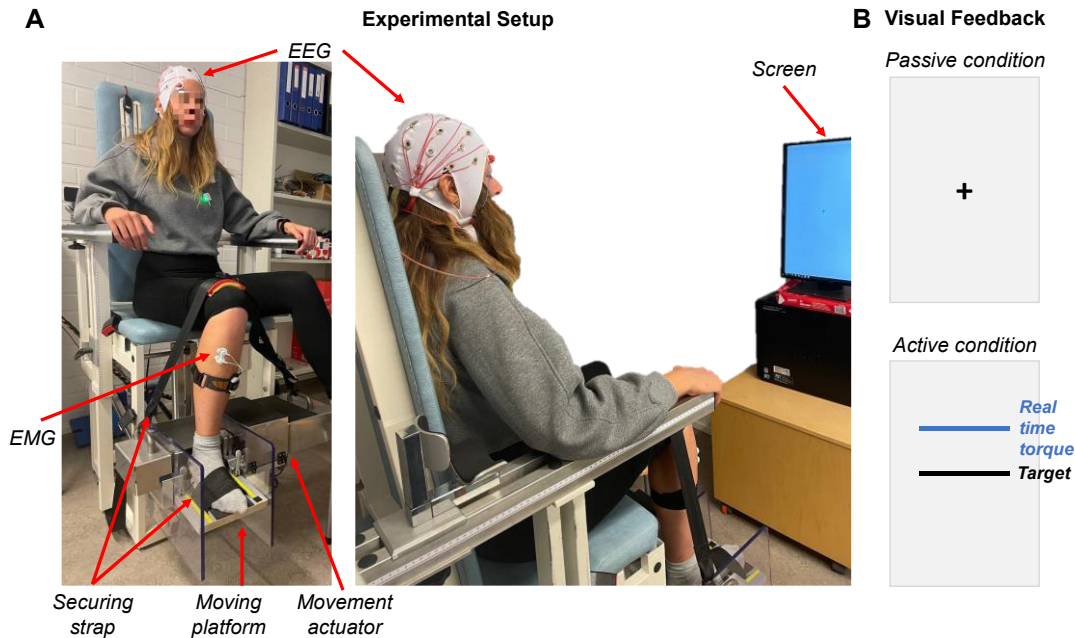
1 100. All participants reported their right hand as the writing hand. Participants were provided with  
2 a complete description of the study procedure after which they were asked to sign a written  
3 informed consent. The study was conducted in accordance with the Declaration of Helsinki and  
4 its approval was obtained by the Ethics Committee of the University of Jyväskylä before starting  
5 the measurements (approval number: 369/13.00.04.00/2020).

## 6 Experimental design and recordings

7 The measurements were conducted at the Faculty of Sports and Health Sciences of the University  
8 of Jyväskylä, Jyväskylä, Finland. Proprioceptive-perception ability of the ankle joint was tested  
9 first (38, 39). Then, a short (i.e. 30 s) resting state recording was performed and further taken as  
10 a baseline. Finally, CKC during ankle joint rotations was quantified for two conditions of the plantar  
11 flexor muscles: (1) active condition with steady 5-Nm plantar flexion and (2) passive condition  
12 with no plantar flexion torque exerted. The mechanical rotations (i.e. perturbations) were identical  
13 between the conditions. The two conditions were measured in four 3-min trials (two trials per  
14 condition) with a short brake in between in random order, to avoid effects from any systematic  
15 time dependent effects during the recording session.

## 16 Experimental Setup

17 Figure 1 shows the experimental setup adopted for the study. Participants were sitting in a chair  
18 with the forearms laying on the armrests and the left foot relaxed on a separate footstool. The  
19 right foot was placed on the rotating platform of a motorized ankle-movement actuator. The  
20 anatomical ankle-joint rotation axis was identified according to Isman et al., (1969) (40), and it  
21 was aligned with the axis of the rotating platform. Ankle and knee joint angles were set to 90°.  
22 During the experiment, EEG and electromyographic (EMG) signals were recorded synchronously  
23 with foot angular displacement and torque. Participants were instructed to completely relax their  
24 left leg throughout the recordings. Additionally, they wore shielded earplugs (ER-3C, 50 Ohm,  
25 Etymotic Research) playing 60 dB Brownian noise to ascertain masking of any, although minute,  
26 auditory noise caused by the ankle-movement actuator. No vibrations were generated either at  
27 rest or during the stimulations. Visual contact to the stimulated foot was blocked by using a brown  
28 cardboard panel while a screen was placed 1.5 m in front of the participants.



1  
 2 **Figure 1 – Experimental Setup.** A) Participant's right foot was placed on the rotating platform with knee and ankle joints  
 3 at 90°. 30 EEG, 2 EOG channels and EMG, electromyographic signals from right soleus and tibialis anterior were  
 4 recorded. B) Visual feedback varied between the conditions. A fixation cross was shown during the passive condition,  
 5 and the real-time torque with 5 Nm target level were shown during the active condition.

## 6 Movement actuator

7 Proprioceptive stimuli (i.e. ankle rotations) were produced using a custom-made silent ankle-  
 8 movement actuator. It was composed of a rotating platform driven by a servomotor controlling the  
 9 rotations according to the desired angular velocity (full operational range: 0–200 °/s) managed by  
 10 a control unit. The platform was equipped with torque and angular displacement sensors, that  
 11 were interfaced to a control unit generating analogue output signals in the range of 0–5 V. The  
 12 stimulation patterns were controlled using a custom-made Graphical User Interface (Matlab  
 13 R2022b, MathWorks Inc, Natick, MA, USA) that was configured to handle real-time visualization  
 14 and storage of the data. A data acquisition unit (USB-6216 AD-board, National Instrument Austin,  
 15 Texas, United States) was, indeed, configured as an I/O board communicating with the  
 16 proprioceptive stimulator and it was set through Matlab software to deliver the stimulation patterns  
 17 and to acquire analog torque and joint angle signals (sampling frequency of 1 kHz).

## 18 EEG recordings

19 A wireless light weight EEG amplifier (41–43) was used to record EEG signals with a 30 Ag/AgCl  
 20 electrodes cap (EasyCap GmbH, Gliching, Germany) following the international 10-20 system.  
 21 To ensure a good skin-electrode contact, each electrode site has been gently scrubbed through  
 22 a cotton swab with an abrasive paste (NuPrep, Weaver and Company, Aurora, USA) and then  
 23 filled with a conductive gel (NeurGel, SPES MEDICA, Genova, Italy). Additionally, electro-  
 24 oculogram (EOG) signals were acquired through two surface electrodes (30 mm x 22 mm Ambu  
 25 s.r.l., Denmark) placed in the up-left and down-right corners of the eye region. EEG and EOG  
 26 signals were acquired in a monopolar derivation, using the FCz electrode of the cap as the  
 27 reference with a sampling frequency of 2048 Hz, and a bandwidth of 0.1–500 Hz. EEG signals  
 28 were collected synchronously with EMG and they were offline synchronized with kinematic signals  
 29 according to a common external trigger by using the synchronization unit introduced in (41).

## 1 EMG recordings

2 EMG were recorded from the tibialis anterior muscle and right medial part of the soleus muscle  
3 using a pair of Ag/AgCl electrodes ( $\varnothing$  24 mm Kendall, Covidien, Dublin, Ireland) placed on each  
4 muscle according to the SENIAM recommendations (44) after a gentle skin abrasion of the  
5 interested area by using an abrasive paste (Nuprep, Weaver and Company, Aurora, USA) (45).  
6 EMG was acquired in a bipolar derivation through a wireless amplifier (DuePro, OT Bioelettronica,  
7 Turin, Italy) with a sampling frequency of 2048 Hz in the 10–500 Hz frequency band.

## 8 Proprioceptive-perception ability

9 To test the correlation between the neurophysiological and the behavioral measurements, the  
10 perceptual proprioceptive threshold was computed for each participant. Perceptual threshold of  
11 the evoked ankle joint rotation was defined for the right leg using the proprioceptive stimulator  
12 and an adaptive-test algorithm (38). The right ankle was passively dorsiflexed at a varying angular  
13 velocity from 0.3 to 1.5°/s (inter stimulus interval:  $4 \pm 0.25$  s). Participants were instructed to fixate  
14 a black cross on a grey background on the screen in front of them, and to press a response button  
15 with their right thumb as soon as they perceived the movement of the platform. The analogue  
16 output of the response button was sampled at 1 kHz through the I/O board and it was used as a  
17 marker of the rotation perception. The detection or missing of a stimulus was utilized to adapt the  
18 angular velocity (i.e. decrease or increase of 0.1°/s) of the subsequent stimulus allowing for the  
19 identification of the individual proprioceptive threshold. The proprioceptive-perception threshold  
20 was defined as the lowest angular velocity with >50% correctly perceived stimuli and it was  
21 automatically updated throughout the test after each stimulus. The experimenter manually  
22 stopped the test if two criteria were met: (1) a minimum of 5 stimuli at the threshold velocity were  
23 provided to the participant and (2) at least a total of 25 rotations were delivered during the test.

## 24 Corticokinematic coherence

25 To compare the degree of cortical proprioceptive processing during the *active* and *passive*  
26 conditions, CKC was computed. The right ankle joint was stimulated at 2-Hz with a continuous 4°  
27 ankle rotation in dorsi and plantarflexion direction (8° total range of motion) at 25°/s angular  
28 velocity 3 min per condition and trial (in total 6 min of data per condition). A screen was placed  
29 1.5 m in front of the participants to provide a visual feedback during the tested conditions. During  
30 the *passive* condition, participants were instructed to relax their lower limbs and to fixate at a black  
31 cross on the screen in front of them. During the *active* condition, participants were instructed to  
32 apply a constant plantarflexion torque of 5 Nm ( $\pm 2.5$  Nm) about the axis of the rotating platform,  
33 and they were provided with a visual real-time feedback displaying the applied torque and the  
34 desired target (Figure 1 B). The experimental design was planned to prevent visual contamination  
35 of CKC at the movement frequency. To this end, the torque feedback displayed on screen to the  
36 participants was computed by averaging the torque signal over a 600 ms moving epoch with 300  
37 ms overlap. This approach prevented continuous oscillation of the displayed torque signal at the  
38 2-Hz proprioceptive stimulation frequency that could have led to strong CKC in the occipital visual  
39 cortices and consequent bias in our SM1 cortex CKC strength. Finally, to prevent any vertical  
40 raise of the heel from the rotating platform, the sole of the right foot was secured to the platform  
41 using a strap around the knee and an elastic Velcro around the midfoot. EMG signals were real-  
42 time inspected by the experimenter to ascertain that the participant was relaxed during the  
43 *passive* condition. The experimental setup was the same in the two experimental conditions. The  
44 order of the *active* and *passive* conditions was randomized, with the starting condition balanced  
45 across participants. Each recording always started with 30-s rest period followed by 3 min  
46 stimulation.

## 1 Signal analysis

2 Signal processing was entirely performed offline in Matlab R2022b (Mathwork Inc, Natick, MA,  
3 USA). Angular displacement and torque signals were resampled at 2048 Hz to match with EEG  
4 and EMG signals. An offline synchronization was performed by aligning all the recorded signals  
5 according to the rising edge of a common external trigger sent at the beginning of each trial.

## 6 EEG and EMG signal preprocessing

7 FieldTrip Matlab toolbox was used for the EEG analysis (46). EEG data were first visually  
8 inspected to identify and mark the noisy channels. Then, EEG signals were bandpass filtered  
9 through a 4<sup>th</sup> order Butterworth filter at 0.1–95 Hz, and independent component analysis was used  
10 to extract 30 EEG independent components to identify those related to artifacts (e.g. due to eye  
11 movements or neck/temporalis muscular activity). Eye blinks or eye movements were identified  
12 based on the highest correlation with the EOG pattern and then they were removed. Only after  
13 the independent component analysis, noisy channels were interpolated by replacing them with  
14 the average of all the neighboring channels. Finally, a common average reference was applied to  
15 all EEG channels (47).

16 EMG signals were offline bandpass filtered at 20–400 Hz with 4<sup>th</sup> order Butterworth filter.

## 17 Corticokinematic coherence analysis

18 The formulation of Halliday et al., (1995) (48) was used to compute the coherence between EEG  
19 and the angular-displacement signal (i.e., the foot kinematics). EEG signals were split into 2-s  
20 epochs with 1.6 s overlap, yielding a frequency resolution of 0.5 Hz (49). EEG epochs exceeding  
21 200 mV were considered to be corrupted by artifacts and were rejected. Coherence computation  
22 yielded cross-, power- and coherence spectra between the foot kinematics and each EEG signal  
23 separately. The magnitude squared coherence was chosen as coupling measure as done in  
24 earlier CKC studies (19, 21, 28). CKC strength was defined as the coherence value at the 2-Hz  
25 movement frequency in the peak EEG channel among all the 30 EEG channels for each  
26 participant and condition. Then, averaged CKC value of the two trials for *active* or *passive*  
27 condition was used as final CKC strength estimate for each participant. For visualization  
28 purposes, CKC spectra from the two trials of the same condition were also averaged separately  
29 for each participant and topographic representations of CKC were further visualized at the group  
30 level.

## 31 Statistical analysis

32 All results are given as mean  $\pm$  SD. Statistical tests were performed in Matlab R2022b on the  
33 averaged data across the trials for both *active* and *passive* conditions (Mathwork Inc, Natick, MA,  
34 USA). We tested the normal distribution of the data through a Shapiro-Wilk test for each condition.  
35 All the variables were non-normally distributed ( $P < 0.05$ ), thus we used nonparametric statistical  
36 tests for the statistical analysis.

## 37 EMG activity during CKC testing

38 EMG root-mean square amplitude was computed to quantify the degree of muscular activation  
39 between conditions. The rest period (30 s) collected at the beginning of CKC recordings was  
40 considered as a baseline representative of a relaxed condition (i.e. without volitional muscular  
41 activation) and it was compared to the corresponding *active* and *passive* conditions to evaluate  
42 the presence and degree of the muscular activity of soleus and tibialis anterior. To this end, we  
43 conducted a Wilcoxon signed rank test (non-parametric statistical test) to search for statistically

1 significant differences between the muscular activity during rest, *active* and *passive* conditions.  
2 We considered merged trials for the abovementioned comparison.

### 3 Statistical significance of CKC

4 The hypothesis of linear independence of Fourier coefficients at each frequency between epochs  
5 was used to assess the statistical significance of individual coherence levels (21, 48). To correct  
6 for multiple comparisons, the significance  $\alpha$ -level was set to  $0.05/N_c$ , with  $N_c$  number of EEG  
7 electrodes, i.e., 30. Because of the non-normal distribution of the data, a Wilcoxon signed rank  
8 test (non-parametric test) was used to assess differences between the two trials, separately per  
9 each condition to investigate the possibility of pooling trials together to further inspect the effect  
10 of muscle activation on CKC.

### 11 Effect of volitional muscle activation on CKC

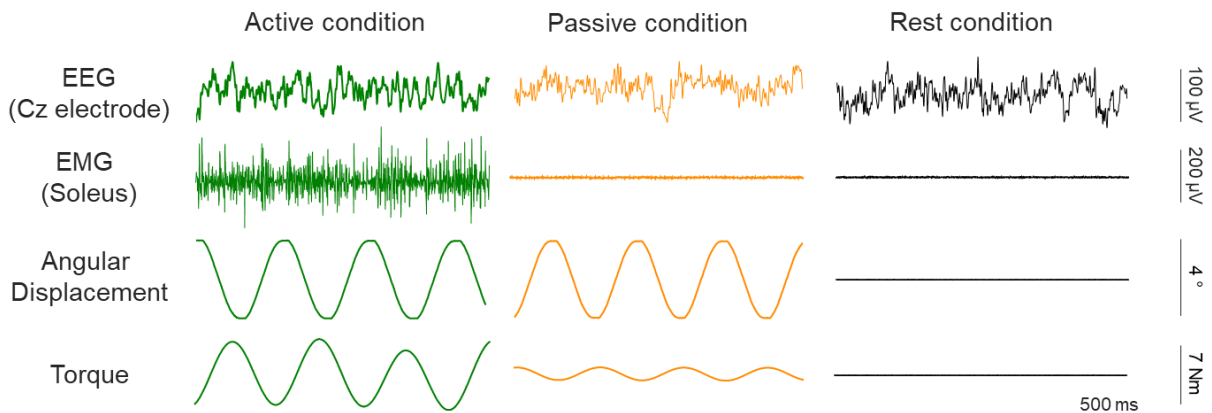
12 As a result of the non-normal distribution of the data, a non-parametric test (Wilcoxon signed rank  
13 test) was used to examine whether CKC strength differed between the *active* and *passive*  
14 conditions.

### 15 Correlation analysis

16 To evaluate the associations between CKC and proprioceptive-perception ability, the correlation  
17 of CKC strength to the proprioceptive-perception threshold was computed using Spearman rank  
18 correlation coefficient.

## 19 RESULTS

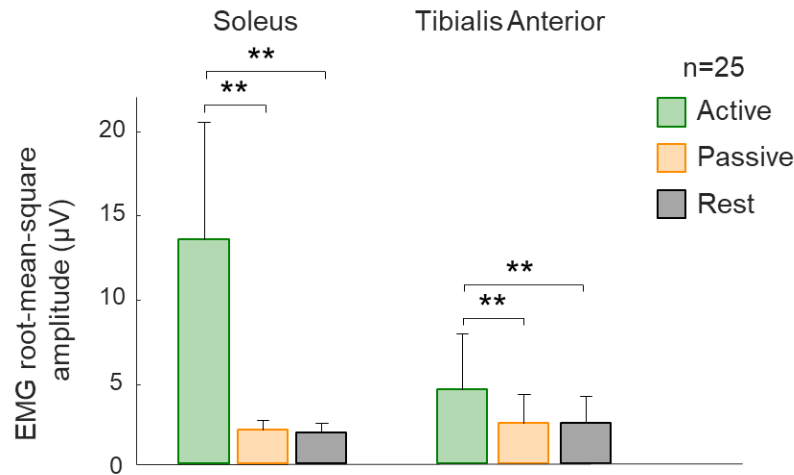
20 Figure 2 shows raw EEG, EMG and kinematic signals during rest, active and passive conditions.  
21 The overall signal quality was good, without any notable artifact rising from the ankle-movement  
22 actuator or the external environment. For both conditions we considered the same, fixed number  
23 of independent components (i.e. 30) explaining the  $99.28 \pm 0.43\%$  of the variation for *active*  
24 condition and the  $99.46 \pm 0.33\%$  for *passive* condition. On average,  $3 \pm 2$  independent  
25 components were rejected from EEG signals, while the average number of discarded epochs was  
26  $3 \pm 3$  across conditions and participants. Within the CKC analysis, the number of epochs was  
27 fixed at the minimum number of epochs across the four trials and participants, i.e., 468 epochs  
28 per trial.



29  
30 *Figure 2 – Example of preprocessed signals from a representative subject during 2 s from active, passive and rest*  
31 *conditions. From top to bottom: EEG from Cz electrode, EMG from soleus muscle, angular displacement and torque*  
32 *applied on the pedal are represented.*

## 1 EMG activity during proprioceptive stimulations

2 Figure 3 shows the muscular activation levels in terms of EMG root-mean-square values of *active*,  
3 *passive* and *rest* conditions (merged trials). As expected, activation levels were significantly  
4 higher during the active condition than both rest and passive conditions ( $P < 0.01$ ), both for soleus  
5 and tibialis anterior muscles without showing any statistically significant differences between  
6 *passive* and *rest* conditions. Although the task mainly required the activity of plantarflexor muscles  
7 (i.e. soleus) a slight co-contraction of the tibialis anterior muscle was also noticed.



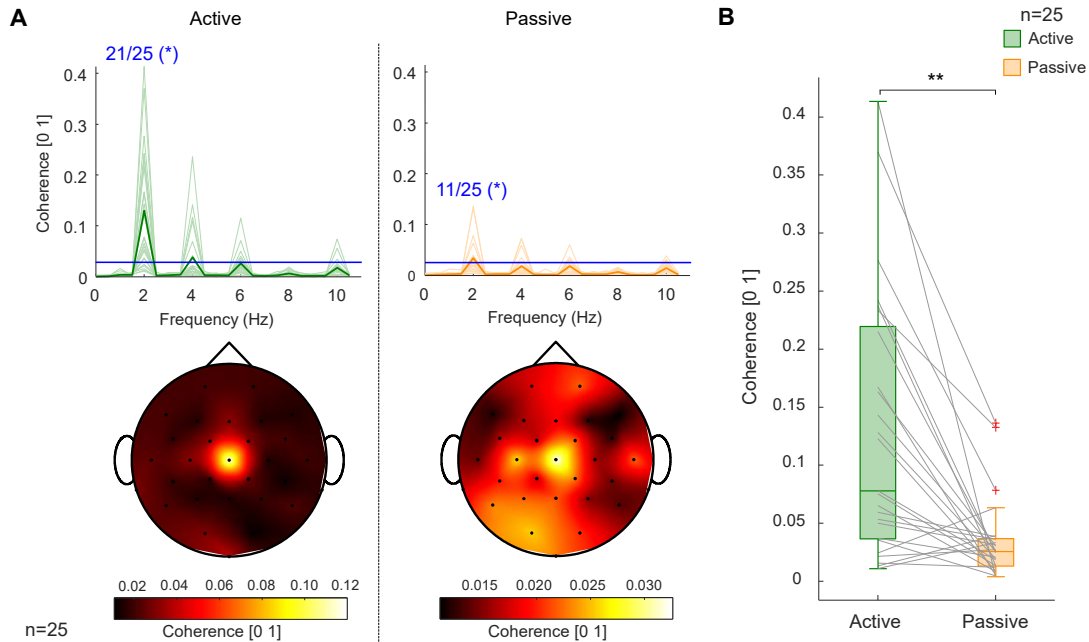
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9 Figure 3 – Bar diagrams showing the EMG root-mean-square amplitudes ( $\mu\text{V}$ ) of soleus and tibialis anterior muscles  
10 during active, passive and rest conditions averaged across participants. Error bars indicate the standard deviation of  
11 the muscular activation levels across participants. Statistical analysis by Wilcoxon signed-rank test, (\*\*  $P < 0.01$ ).

## 12 Corticokinematic coherence

13 Figure 4 shows the CKC results. At the group level, CKC was stronger during the *active* than  
14 *passive* condition ( $P < 0.01$ ). Figure 4 B shows the individual CKC strengths at 2-Hz peak for the  
15 Cz electrode for both conditions. Striking increase in CKC was observed in 22 out of 25  
16 participants from *passive* to *active* condition, while only 3 out of 25 participants showed an  
17 opposite tendency.

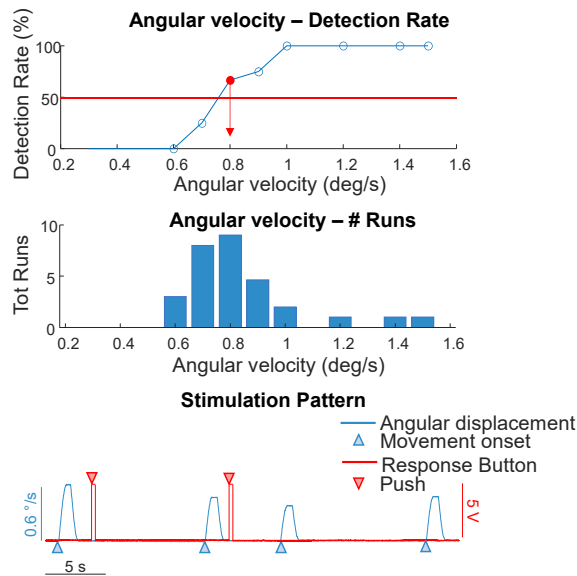
18 At the individual level, CKC was above the significance level in 21 out of 25 participants at the 2-  
19 Hz-movement frequency for the *active* condition and in 11 out of 25 participants for the *passive*  
20 one. For all the participants, when above the statistical significance level, CKC was peaking at  
21 the level of Cz electrode (i.e. above the midline central scalp region as expected for ankle-joint  
22 stimulation) in both conditions. Figure 4 A shows the coherence spectra for the *active* and *passive*  
23 conditions for the Cz electrode. The spectra show that the CKC strength was clearly stronger for  
24 the *active* than the *passive* condition at 2-Hz peak in the group level (*active* condition:  $0.13 \pm 0.14$ ,  
25 *passive* condition:  $0.03 \pm 0.04$ ), and peaked at the expected Cz electrode over the foot area of  
26 the SM1 cortex in both conditions. Although with weaker CKC values, results at the first harmonic  
27 (i.e. at 4 Hz) of the movement frequency confirmed what we found at the 2-Hz movement  
28 frequency in terms of spatial distribution and CKC strength trend between conditions (*active*:  $0.04$   
29  $\pm 0.17$ , *passive*:  $0.02 \pm 0.05$ ). Nevertheless, we found only 8/25 (*active* condition) and 4/25  
30 (*passive* condition) participants with CKC above the significance level at the first harmonic.



1  
 2 **Figure 4 – Corticokinematic coherence results (n=25).** A) CKC spectra of Cz electrode (top panel) and topographic  
 3 representation of CCK strength at the movement frequency averaged across subjects (bottom panel) for active and  
 4 passive conditions. The light colored lines indicate the individual spectra, whereas the marked lines indicate the grand-  
 5 average spectra. Horizontal blue line indicates the statistical significance level. Color bar scales of spatial topographies  
 6 are different for the two conditions to highlight the spatial distribution of CCK strength over the scalp for both conditions.  
 7 B) Boxplot representations of Cz-electrode-CKC strengths at the movement frequency for both conditions. Statistical  
 8 analysis by Wilcoxon signed-rank test, \* $P < 0.05$ , \*\* $P < 0.01$ .

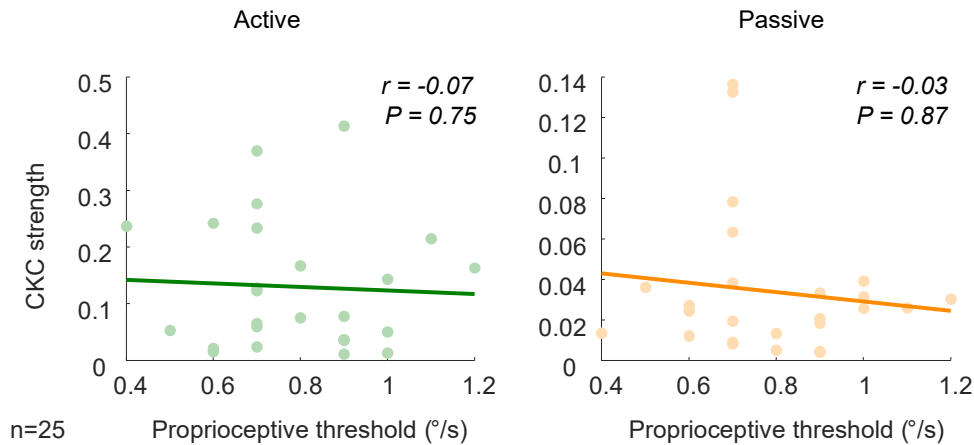
### 9 Correlation between CCK strength and proprioceptive-perception ability

10 Figure 5 shows the result of the proprioceptive perception ability test for a representative  
 11 participant (threshold at 0.8 °/s). The average proprioceptive threshold was  $0.79 \pm 0.19$  °/s across  
 12 the participants.



13  
 14 **Figure 5 – Evaluation of proprioceptive ability test performances of a representative subject.** From top to bottom,  
 15 representations of: angular velocity-detection rate, angular velocity-number of runs and evaluation of response time.

1 However, no statistically significant correlation was found between CKC strength and  
2 proprioceptive threshold (*active* condition:  $r = -0.07$ ,  $P = 0.75$ ; *passive* condition:  $r = -0.03$ ,  $P =$   
3  $0.87$ ; Figure 6).



4  
5 *Figure 6 – Correlation between CKC strength at the movement frequency and proprioceptive threshold for active and*  
6 *passive conditions. Pearson correlation coefficients are superimposed, (n=25 participants).*

## 7 DISCUSSION

8 Corticokinematic coherence was peaking at movement frequency and at the multiple harmonic  
9 frequencies as typically observed in EEG- or MEG-based studies (28, 30). However, as shown  
10 by Piitulainen et al., (2020) (34), CKC strength is slightly weaker in EEG than in MEG, also in  
11 harmonic frequencies. Therefore, because of the low number of participants with CKC above the  
12 significance level, we then performed the analysis focusing on the fundamental 2-Hz movement  
13 frequency only. The proprioceptive stimulation of the ankle joint evoked significant CKC in the  
14 EEG electrode above the foot region of the SM1 cortex. However, the CKC strength was weaker  
15 in the *passive* than *active* stimulation condition, supporting our hypothesis that volitional activation  
16 of the stimulated muscles would intensify the cortical proprioceptive processing because of (1)  
17 the neuronal and mechanical sensitization of the ankle joint proprioceptors and/or (2) the  
18 modulations of the neuronal proprioceptive processing in the spinal and cortical levels due to  
19 active motor control processes. This is a significant finding as it may extend the use of CKC  
20 method to further examine the cortical neuronal mechanisms related to interplay or closed loop  
21 between motor efference and proprioceptive afference during active tasks, and the related  
22 adaptations to exercise, rehabilitation and disease.

### 23 Effect of muscle activation on CKC

24 In line with our hypothesis, CKC was stronger during *active* than *passive* condition. From  
25 proprioceptors point of view, the main difference between these conditions is the functional state  
26 of the muscle spindles and mechanical condition of the ankle joint. The sensitivity of the muscle  
27 spindle to muscle-tendon length change is increased during active contractions (36, 37). This is  
28 because, the motor efference activating the muscles is accompanied with simultaneous activation  
29 of the intrafusal fibers within the muscle spindle by gamma motoneurons improving the detection  
30 of muscle length change (50). It is also noteworthy that the muscle spindle is the predominant  
31 proprioceptor providing the proprioceptive afference to the CNS occurring at the mid-region of the  
32 range of motion, as was the case for both *active* and *passive* ankle rotations in the present study.

1 The mechanical state of the ankle-joint also differed between the conditions. During the *active*  
2 condition, the constant 5-Nm torque increased the muscle-tendon unit tension and likely reduced  
3 the muscle-tendon unit slack, which may increase not only the muscle spindle sensitivity, but also  
4 the firing rate of Golgi tendon organs that are responsible for detecting the change in force  
5 produced by the muscle or directed to the muscle-tendon unit (6). Therefore, we suggest that the  
6 combination of the increased firing rate of the abovementioned proprioceptors results in the  
7 intensification of the somatosensory afference to the SM1 cortex. This would in turn intensify the  
8 cortical processing of the proprioceptive afference and thus resulting in stronger CKC during  
9 *active* than *passive* condition. In addition to the proprioceptors, also the cutaneous tactile  
10 receptors may contribute to the enhancement of CKC during the active versus passive condition.  
11 The plantar pressure under the sole of the foot is stronger during the active condition as seen in  
12 the torque signal in Figure 2. This might allow better activation of deep mechanoreceptors of the  
13 skin. To alleviate this difference, we used straps around the mid-foot to enhance the plantar  
14 pressure during the passive condition, and thus most of the plantar cutaneous receptors were  
15 likely activated in both conditions. The evoked movement inevitably also activates the tactile  
16 receptors in the skin around ankle joint as the skin is being rhythmically stretched. However, the  
17 kinematics of the evoked movements were identical between active and passive conditions, thus  
18 a similar tactile afference is expected to occur. Finally, we do not consider this tactile activation  
19 strictly as a confounding factor, but as one of the plausible mechanisms for the stronger CKC  
20 during the active condition. The brain utilizes the tactile and proprioceptive afference in integrated  
21 manner, and thus it is difficult or even unnecessary to separate them when examining naturalistic  
22 stimuli.

23 The brain can also modify its own somatosensory feedback both at spinal and cortical levels (51).  
24 Thus, the cortex may actively control its proprioceptive afference and spinal level sensorimotor  
25 processing. This mechanism is especially evident during the active maintenance of the isometric  
26 contraction in the *active* condition. Therefore, it is likely that the spinal, medullary and thalamic  
27 circuits influencing the afferent proprioceptive pathways to the SM1 cortex are modulated in a  
28 way that intensifies the associated cortical processing with respect to the *passive* condition. Such  
29 modulation can be also influenced by cortico-cortical connections. Thus, different cortical regions  
30 related to motor control and somatosensation can contribute to influence the SM1 cortex  
31 processing of proprioceptive afference during the *active* motor task. This interpretation is in line  
32 with earlier observation on rodents. It has been shown that focal enhancement of rat motor cortex  
33 activity facilitated sensory-evoked responses of topographically aligned neurons in the primary  
34 somatosensory cortex (52).

35 The state of the SM1 cortex may also affect the CKC strength. It is well established that the SM1  
36 cortex is activated just prior (i.e. motor preparation) and during (i.e. due to both volitional motor  
37 output and somatosensory input) volitional muscle contraction. The state of SM1 cortex is altered  
38 also during the passive rotations of the ankle due to the consequent strong proprioceptive  
39 afference to the SM1 cortex. Nevertheless, the volitional motor processes are not effective in  
40 similar manner in *active* versus *passive* condition. As an example, Piitulainen et al., (2013) (53)  
41 investigated CKC during active (i.e. self-performed) versus passive finger movements and they  
42 did not observe differences in CKC strength, spatial location or coherence directionality between  
43 the conditions. Although, this result might seem in contrast to ours (i.e. strengthened CKC during  
44 active versus passive condition), the active task fundamentally differed between these studies,  
45 and thus the results are not directly comparable. Piitulainen et al., (2013) (53) used self-paced  
46 (i.e. active) dynamic finger movements. On the contrary, the current task was to maintain steady  
47 plantarflexion torque despite externally evoked perturbations (i.e. rotations) to the ankle joint.

1 Thus, our active task did not include active movement, but active stabilisation of the ankle joint.  
2 In addition, different limbs were investigated (hand versus foot), thus we could not make any  
3 inferences between studies. Additionally, also the sensorimotor processes are partly different  
4 between *active* and *passive* condition. Indeed, CKC strength has been shown to be increased  
5 when attention is directed to the proprioceptive stimulation when compared to situation in which  
6 the attention was directed away from the stimulation to a visual task in passive conditions (29). In  
7 our *active* task, the attention was directed to the proprioceptive-motor task to stabilize the quasi-  
8 steady plantarflexion. The task was rather challenging since the ankle was being passively rotated  
9 simultaneously. Instead, during the *passive* condition, although attention was not expressively  
10 directed to the proprioceptive stimulation, participants followed the stimulations without being  
11 distracted by another visual or motor task. Consequently, these attentional differences may partly  
12 explain the enhanced CKC strength during *active* condition, but the attentional effects are  
13 expected only to minimally affect the dramatic difference in CKC strength between the conditions  
14 in the current study. Previous evidence demonstrated only a minor reduction in CKC strength  
15 (~9%) when attention was directed to the proprioceptive stimulation or away from it to a visual  
16 task (29). Indeed, given that there might have been more attention to the foot or to the stimulus  
17 during the *active* condition, this should have led to reduction in CKC, but we observed the  
18 opposite.

19 It is worth mentioning that less than 50% of our participants showed significant CKC at the  
20 movement frequency during the *passive* condition. This was somewhat surprising as strong CKC  
21 has been observed for ankle joint rotations in MEG (32). However, to the best of our knowledge,  
22 there are no EEG-based CKC studies involving passive stimulation for the lower limbs. Most of  
23 the CKC studies have focused on passive or self-performed upper limb movements in MEG (18,  
24 21–23). For the passive hand stimulation, CKC strength has shown to be weaker for EEG than  
25 MEG (34). Furthermore, the use of spatial filters (i.e. bipolar, Laplacian filters) and 58-electrode  
26 EEG cap enhanced CKC strength when compared to common reference filter (34). However, we  
27 recently showed that the improvement associated with spatial filtering when using a 30-electrode  
28 EEG cap is not systematically observed with less dense EEG electrode caps (35). Therefore, we  
29 did not use of a spatial filters (bipolar or Laplacian) in the current study. Nevertheless, the use of  
30 a more dense EEG cap could be suggested for future CKC studies using passive proprioceptive  
31 stimulation of the ankle joint and EEG recordings for the abovementioned reasons. The more  
32 spatially selective EEG derivations could enhance detection of CKC above the significance level  
33 also in the lower limbs.

34 Furthermore, the weak CKC may be specific to the lower limbs in comparison to the upper limbs,  
35 that are more widely investigated using CKC (19, 21, 34) with respect to the few MEG lower limbs  
36 studies (16, 32). Firstly, the cortical representation of the hand region in the SM1 cortex is more  
37 optimally located and oriented for EEG/MEG compared to the foot region that is located deeper  
38 and centrally in the posterior paracentral lobule, that is a U-shaped convolution that loops below  
39 the medial part of the central sulcus thus resulting in a deep localization of the source (54). The  
40 hand area is also wider with respect to the lower limb one. Consequently, non-invasive EEG  
41 recordings of cortical signals from the scalp surface will result in weaker signal-to-noise ratio  
42 negatively influencing CKC strength.

### 43 **Correlation between CKC and proprioceptive-perception ability**

44 The proprioceptive-perception ability of the tested population was in line with the result of our  
45 previous studies on young healthy adults (39). We did not detect a significant correlation between  
46 behavioral and cortical (i.e. CKC strength) proprioception. Thus, our hypothesis that lower

1 proprioceptive-perception threshold (i.e. better behavioral performance) would be associated with  
2 weaker CKC was not supported. Nevertheless, it is worth mentioning that our sample consisted  
3 of a rather homogeneous population of highly performing healthy young adults without  
4 proprioceptive deficits. Therefore, the variation in behavioral proprioceptive performance was  
5 small. This potential association should be further examined in samples with more variable  
6 proprioceptive performance, such as cerebral palsy, developmental coordination disorder or older  
7 adults (32, 38).

## 8 Perspectives and Significance

9 The present study is the first investigating the effect of volitional muscle activation on EEG-based  
10 CKC assessment of cortical proprioception of the ankle joint. We demonstrated that CKC was  
11 stronger when the muscles were active during proprioceptive ankle-joint stimulation when  
12 compared to *passive* stimulation condition. The intensified cortical proprioceptive processing may  
13 be related to neuronal and mechanical differences between *active* and *passive* conditions at  
14 muscle-tendon unit, receptor, spinal, medullar, thalamic and cortical levels. The proposed  
15 methods and technologies could be further adopted in future research to deepen the  
16 understanding and adaptation of the cortical proprioceptive processing during active motor tasks.  
17 As such these measures will become potential tools to evaluate also the effects of ageing or  
18 neurological diseases such as stroke, Parkinson's or developmental diseases to cortical  
19 proprioception.

## 20 DATA AVAILABILITY

21 The data are not publicly available due to privacy or ethical restrictions. However, data are  
22 available upon request from the corresponding author.

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30 Italy.

## 31 DISCLOSURES

32 The authors declare that the study was conducted in the absence of any commercial or financial  
33 relationships that could be construed as a potential conflict of interest.

## 34 AUTHOR CONTRIBUTIONS

35 H.P. conceived and designed the research; A.G. performed experiments, A.G., G.L.C., A.B. and  
36 H.P. analyzed data; A.G. prepared figures; A.G. and H.P. interpreted results of experiments, A.G.  
37 and H.P. drafted the manuscript, A.G., G.L.C., A.B. and H.P. edited and revised the manuscript;  
38 A.G., G.L.C., A.B. and H.P. approved the final version of manuscript.

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