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# Eccentric cycling involves greater mental demand and cortical activation of the frontoparietal network

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**Short title:** Cortical control of eccentric cycling

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**Abstract**

Eccentric, compared to concentric exercise, is proposed to involve different neuro-motor processing strategies and a higher level of mental demand. This study compared eccentric and concentric cycling at matched perceived effort and torque for the mental demand and related-cortical activation patterns. Nineteen men (30 ± 6 yrs) performed four different 5-min cycling conditions at 30 RPM on a semi-recumbent isokinetic cycle ergometer: 1) concentric at a moderate perceived effort (23 on the CR100® scale) without torque feedback; 2) concentric and 3) eccentric at the same average torque produced in the first condition; and 4) eccentric at the same moderate perceived effort than the first concentric condition. The conditions 2-4 were randomised. After each condition, mental demand was monitored using the NASA Task Load Index scale. Changes in oxy-($O_2Hb$) and deoxy-(HHb) haemoglobin during exercise were measured over both prefrontal cortices and the right parietal lobe from a 15-probe layout using a continuous-wave NIRS system. Mental demand was significantly higher during eccentric compared to concentric cycling (+52%, $p = .012$) and when the exercise intensity was fixed by the torque rather than the perceived effort (+70%, $p < .001$). For both torque- or perceived effort-matched exercises, $O_2Hb$ increased significantly ($p < .001$) in the left and right prefrontal cortices, and right parietal lobe, and HHb decreased in the left, and right, prefrontal cortices during eccentric compared to concentric cycling. This study supports that acute eccentric cycling, compared to concentric cycling, involves a higher mental demand and frontoparietal network activation.

**Keywords:** muscle contraction, bilateral motor task, perceived effort, optical imaging, brain, cognitive demand

## INTRODUCTION

Most human movements involve both eccentric and concentric muscle contractions (e.g., walking, running, jumping) and a large proportion of our daily living activities require accurate control of movements employing eccentric contractions (e.g., walking downstairs, sitting, lowering weight). During eccentric contractions, the external force on the muscle is greater than the force that the muscle can generate, producing a lengthening contraction; and vice versa for concentric contractions.[1] In the last decades, eccentric cycling at moderate intensity has been shown to promote functional (knee-extensor strength) and structural (hypertrophy) muscle adaptations in different populations due to its capability to achieve high loads on muscle tissue at low cardiorespiratory stress (athletic[2] and chronic diseases[3]).

Over the last 60 years, increasing research has been undertaken to understand mechanical, peripheral and neural features, as well as the metabolic cost of eccentric contractions. Eccentric cycling was initially introduced to investigate the physiology of concentric and eccentric muscle work[4]. Eccentric cycling requires substantially less oxygen uptake than concentric cycling to develop the same absolute external mechanical power output.[4,5] In addition, corticospinal excitability, electromyographic activity and rating of perceived effort are lower during eccentric compared to concentric cycling at the same absolute mechanical workload.[5-7] Notably, at a given metabolic workload, heart rate and rating of perceived effort were found higher in eccentric compared to concentric cycling.[5,6]

Eccentric cycling is associated with substantial effort perception and sustained attention when subjects are asked to match a given target mechanical power output.[8,9] However, little is known about cortical activity patterns of attentional resources involved

during eccentric cycling. Current literature contains several lines of evidence indicating that neurobehavioral relationships in eccentric contractions are associated with higher processing demands by various brain areas for controlling motor output.[10]

At the behavioural level, several studies have reported greater variability in the motor output during eccentric compared to concentric contractions.[11] This increased motor variability may indicate less practice and that eccentric contractions might be more cognitively demanding than concentric contractions.[10] This hypothesis is supported by the recent findings from Kan et al.[9] during submaximal eccentric and concentric cycling. First, an overall higher perception of the workload, evaluated by the NASA task load index (NASA-TLX) questionnaire, was reported during eccentric compared to concentric cycling. This difference is specifically related to two items of the questionnaire: mental demand and frustration. Second, the average dual-task reaction time in assessing cognitive load was 15% slower, and the accuracy score was 7% lower, during eccentric compared to concentric cycling. Altogether, these findings suggest that eccentric cycling is more taxing the brain than concentric cycling does.

A neuroimaging modality used in the study of Kan et al.[9] was functional near-infrared spectroscopy (fNIRS). Functional NIRS is an optical neuroimaging technique based on the theory of neurovascular coupling[12] and is relatively robust to motion artifacts.[13] Since the local supply of oxygen is greater than its consumption in activated brain regions, a higher concentration of oxy-haemoglobin ($O_2Hb$) and a decreased concentration of deoxy-haemoglobin (HHb) are to be observed.[13] Changes in $O_2Hb$ and HHb recorded with 2 channels over the prefrontal cortex in Kan et al.[9] were found to be smaller during two eccentric cycling exercises compared to a concentric cycling exercise, while there were higher scores for the two eccentric cycling exercise

108 regarding the mental demand subscale of NASA-TLX. These preliminary findings
109 suggest that a reduced supply of oxygen compared to relative mental demand occurs
110 during eccentric cycling. However, they seem not to be supported by previous studies
111 comparing the influence of the mode of muscle contractions from isolated and small
112 muscle groups on brain activity.[10] Using electroencephalography during elbow flexion
113 at matched torque, a greater amplitude of movement-related cortical potentials in
114 eccentric compared to concentric contractions was shown for electrodes located over
115 the motor areas, prefrontal cortex and parietal lobe.[14] Using functional magnetic
116 resonance imagery (fMRI), Yao et al.[15] observed an increased blood-oxygen-level
117 dependent signal in similar brain areas during an eccentric task of the first dorsal
118 interosseous muscle as compared to a concentric task. Yet, none of the neuroimaging
119 studies mentioned above directly investigated cortical activity over multiple brain areas
120 during whole-body eccentric and concentric exercise, such as cycling.

121 According to the aforementioned studies, the control of eccentric contraction
122 would require important activation of the prefrontal regions, the right parietal lobe as
123 well as the motor regions. These different areas are part of the central executive
124 network known to be involved in cognitive-motor tasks modulating attentional
125 demand[16] as well as in the modulation of mental demand during continuous cycling
126 exercise.[17] As attention-demanding tasks exhibit increased activity in the prefrontal
127 cortex and posterior parietal cortex, we hypothesized that the greater mental demand
128 of eccentric cycling compared to concentric cycling would be associated with cortical
129 activity increases in bilateral prefrontal cortices and right posterior parietal cortex.
130 Finally, most of the aforementioned studies investigating eccentric cycling used an
131 experimental design imposing an absolute mechanical power output. Using effort
132 perception for matching the exercise intensity between eccentric and concentric

133 cycling can be an alternative to circumvent the comparison of neurophysiological
134 responses, either at the same mechanical or at the same metabolic workload.[18] An
135 effort perception approach to prescribe eccentric cycling has been proposed for the
136 tailoring of rehabilitation programs in deconditioned populations, such as patients living
137 with cardio-respiratory chronic diseases leading to muscle weakness.[3] Considering the
138 gaps in the literature, the main objective of the present study was to quantify the acute
139 changes of attention-related cortical activity as well as those of relevant brain motor
140 areas from fNIRS during submaximal eccentric and concentric cycling exercise. As the
141 method to prescribe exercise is likely to influence cortical activity and mental demand,
142 eccentric and concentric cycling was performed at both matched perceived effort and
143 torque.

144

145 **METHODS**

146 **Participants**

147 Nineteen healthy male adults (mean age: 30 ± 6 years) volunteered in the study. All
148 participants reported no sign of neurological, respiratory and cardiovascular disease
149 or medication, which might affect brain and muscle functions. Participants provided
150 written informed consent prior to participation in the study. The study was approved by
151 the local ethics committee (ID: RCB_2016-A01722-49) and was conducted in accord-
152 ance with the ethical standards specified by the Declaration of Helsinki. This study is
153 belonging to the ExoMode project registered on ClinicalTrials.gov (NCT03280875).
154 The sample size required for the present study was calculated using G*Power
155 (3.1.9.6). The fNIRS results between the concentric and eccentric cycling conditions in
156 one previous study[9] were used as group parameters. The power analysis indicated

that a total of at least 17 participants was required for the brain activation (f = .85 – np2= ~.42 , corresponding to large effect – ; α = .05; 1-β = .90). Accordingly, a sample size of 17 participants was recruited. Two additional participants were included in case of experimental outliers.

## Experimental procedures

Participants were requested to visit the laboratory twice. The first visit consisted of a familiarization session and the second visit was the experimental session. Data collection occurred solely in the experimental session.

### *Familiarisation session*

The first visit to the laboratory was a familiarisation session with a double objective. First, participants were familiarised with the CR100® scale to evaluate their perception of effort and quadriceps pain, as well as to self-regulate the cycling exercise intensity based on a fixed perceived effort intensity. Second, the participants experimented with pedalling, driven by a motor either clockwise (concentric cycling) or anticlockwise (eccentric cycling), on an isokinetic semi-recumbent prototype cycle ergometer (Tech Med TMS, 89290 Champs-sur- Yonne, France). The seat of the semi-recumbent cycle ergometer allows for greater torso stabilization compared with a normal upright cycling position. This familiarisation cycling session consisted of participants understanding that they need to resist the pedals moving anticlockwise while they would have to accompany the pedals moving clockwise by exerting a suitable force to match a target line appearing on a screen in front of them. Participants were asked to perform eccentric and concentric cycling in a well-coordinated manner such that the knee extensors of each leg are activated at the right timing and intensity to ensure smooth pedal

182 rotation and torque production. This familiarization session was carried out with the
183 participant reaching submaximal torque values indicated by visual feedback on the
184 control screen. The visual feedback was adjusted to produce 75W. To ensure precise
185 execution of the concentric and eccentric isokinetic exercise, the researcher employed
186 manual palpation of the quadriceps as a mean of verification. Specifically, this involved
187 the researcher using manual palpation of the quadriceps to confirm that participants
188 were adequately familiarized with the task and successfully contracted their quadriceps
189 at the appropriate timing during pedal rotations. Finally, the participants performed four
190 submaximal cycling exercises at a moderate intensity for three minutes at 30 RPM.
191 The mode of muscle contraction (eccentric vs concentric) and the prescription of the
192 exercise (fixed perceived effort or torque) were manipulated as follow: 1) eccentric and
193 2) concentric cycling at a moderate effort intensity (corresponding to 23 on the CR100®
194 scale); 3) eccentric and 4) concentric cycling at a fixed torque value. The familiarization
195 session was carried out at least 48 hours before the experimental session.
196
197 ***Recording session***
198 In this second session, participants performed four cycling exercise conditions for 5
199 min at 30 RPM (see Figure 1), as experienced in the familiarisation session. The choice
200 of the exercise – rest ratio of 5 min – 5 min is based on pilot testing as well as the
201 literature. First, as the literature demonstrated that 5 min of concentric or eccentric
202 cycling is sufficient to obtain a steady state in physiological responses[4,5], we decided
203 to use this duration for the cycling bouts. Second, we tested this ratio during a pilot
204 experiment in 5 participants to ensure that completion of our experimental protocol did
205 not induce a marked decrease in maximal voluntary isometric contraction peak torque
206 (MVIC) of the knee extensor (i.e., neuromuscular fatigue), a confound factor known to

207 increase perception of effort.[19,20] This pilot experiment consisted of duplicating the
208 experimental session without measuring neurophysiological variables. Before the test
209 session, MVIC of the dominant knee extensors was assessed (under verbal
210 encouragement) as the best performance in three 5-s trials separated by a 30-s resting
211 period. Then, one MVIC was performed in less than 20-s after the completion of the
212 test. MVIC was performed on an isokinetic dynamometer (System Pro 4, Biodex
213 Medical System, New York, NY) at a knee angle of 90°. We observed no marked
214 decrease in knee extensor MVIC before starting the protocol (pre) vs after (post)
215 completion of the protocol [MVC pre = 318 ± 77 Nm; MVC post = 318 ± 80 Nm; p =
216 0.982. d (95%CI) = -0.011 (-0.887, 0.867). Finally, to control for potential muscle
217 damage at the onset of the experimental visit, we asked the participants at their arrival
218 to the laboratory for the presence of muscle pain in their lower leg at rest or while
219 walking, and no pain was reported.
220 In the first condition, participants performed concentric cycling at a fixed perception of
221 effort intensity corresponding to 23 on the CR100® scale (moderate intensity). No force
222 feedback was provided to the participants who were instructed to self-regulate their
223 force during each pedal revolution solely on their effort perception intensity, and to
224 keep it moderate during the 5-min of exercise. The maximal torque values produced
225 at each pedal revolution were extracted from the cycle ergometer every 15 s from
226 minutes 2 to 5 of the exercise. These values were then averaged over the last 3
227 minutes, excluding the last 15 s (i.e., when the participants were reporting their
228 perception), to individually determine the target torque used in the subsequent
229 conditions where exercise intensity was prescribed with a fixed torque. The same data
230 points were considered for analysis in all conditions. Then, the other three conditions
231 were performed in a randomised order: (i) concentric cycling at an intensity

corresponding to the average torque produced in the first condition, (ii) eccentric cycling at an intensity corresponding to the average torque produced in the first condition, (iii) eccentric cycling at a fixed perception of effort intensity corresponding to 23 on the CR100® scale (moderate, same perception of effort intensity than the first condition). Five minutes of rest were allowed between each exercise condition so that the physiological responses (heart rate and fNIRS signals) return to baseline levels. Heart rate was recorded with a chest belt and heart rate monitor (Polar V800, Finland) during rest and exercise periods for each condition. The average heart rate was obtained during the resting period before the onset of exercise and over the last minute of each exercise condition.

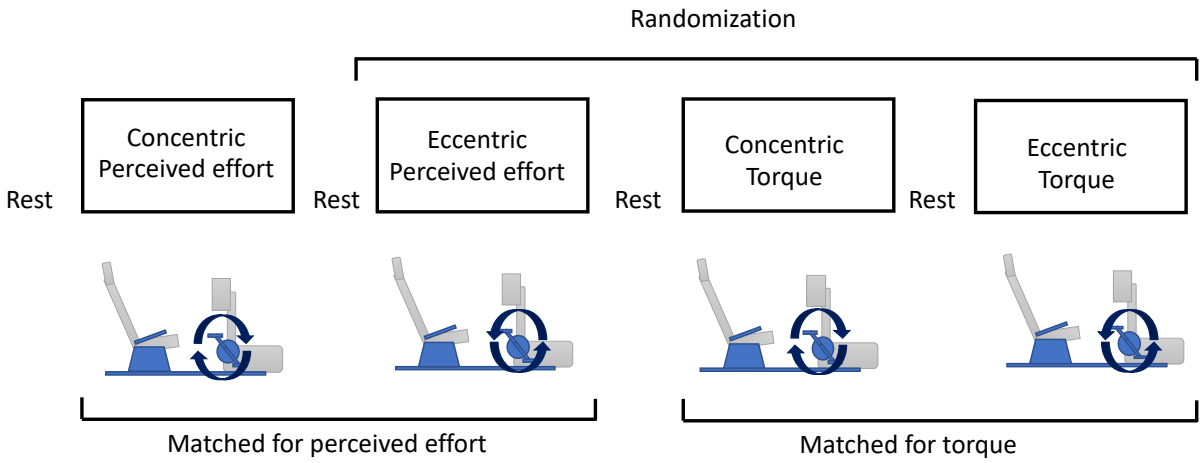
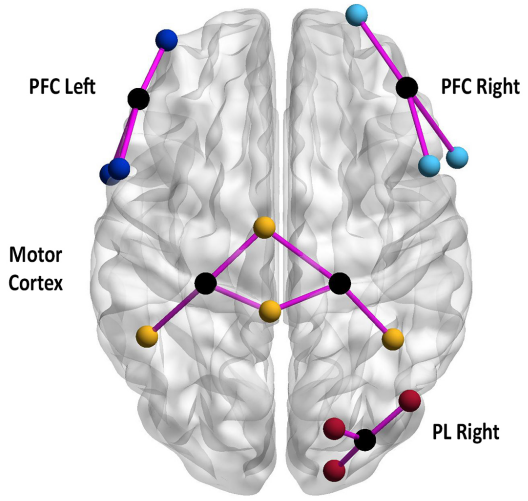



**Figure 1.** Overview of the experimental protocol. Four different 5-min cycling exercise conditions were realised in one session. In the first condition, participants performed concentric cycling at a fixed perception of effort (23 on the CR100® scale) without torque feedback. Then, the other three conditions were performed in a randomised order: eccentric cycling at a fixed perception of effort (23 on the CR100®), concentric or eccentric cycling at an intensity corresponding to the average torque produced in the first condition. Five minutes of rest were allowed between each exercise condition.

**Psychological variables**

252 Perception of effort, also known as perceived exertion or sense of effort, can be
253 described as a cognitive feeling of work associated with voluntary actions.[20]
254 Participants were asked to rate their perception of effort and quadriceps pain (CR100®
255 scale) and affective valence during the last 20 seconds of each condition. At the
256 beginning of the first sessions, participants were provided with validated instructions
257 to dissociate between perceptions of effort and muscle pain[21] and had the possibility
258 to ask questions to the researchers if clarification needed. In-task affective valence
259 (i.e., the pleasure/displeasure one feels) was measured using the Feeling scale, an
260 11-point bipolar scale ranging from -5 to +5. Seven anchors are provided ranging from
261 "very good" (+5) to ''very bad'' (-5). Finally, participants were asked to complete at the
262 end of each condition two subscales (mental demand and physical demand) of a
263 commonly used subjective workload level questionnaire, the NASA-TLX scale. For
264 each subscale, participants had to answer from 0 (very low or high) to 100 (very high
265 or low). The NASA TLX scale was provided to the participants immediately after
266 cessation of the 5-min cycling bouts. The NASA TLX scale was completed within 1 min
267 post cycling bout for all participants.
268
269 **Cortical activity**
270 ***Recording***
271 A two-wavelength (765 and 856 nm) continuous-wave 15-channels fNIRS system
272 (Oxymon MkIII, Artinis Medical Systems, The Netherlands) was utilised to measure the
273 changes in $O_2Hb$ and HHb over regions of interest (ROI): left and right dorsolateral
274 posterior parietal cortex, right parietal lobe and motor regions on both hemispheres as
275 a whole. The $O_2Hb$ and HHb data were acquired during rest and exercise periods at a
276 sampling rate of 10 Hz. $O_2Hb$ and HHb concentration changes (expressed in ΔμM)

obtained by using the modified Beer-Lambert law were displayed on a PC monitor in real time. The optodes (5 receivers and 13 transmitters resulting in a total of 15 channels, Figure 2) were placed on the participants using a fit neoprene fNIRS head cap to get a stable optical contact with the scalp by generating an equal amount of pressure. The pressure was adequate to induce a partial transient blockage of the skin circulation during the fNIRS study[22] as witnessed by the presence of well-defined circles over the skin that disappears about 15 min after the test session. In the 15 channels, the measurement points were defined as the midpoint of the corresponding illuminator-detector pairs interspaced by 3 cm. The Brodmann's areas covered by the different channels were extracted via the NFRI function[23] from the MNI (Montreal Neurological Institute) coordinates (Figure 2). Cartesian coordinates were obtained with a Fastrak® 3D Digitizer (Polhemus Inc., USA) allowing the localization of each optode and channel from four anatomical reference points: nasion, right and left mastoids and vertex.




| ROI | MNI | | | BA |
|---|---|---|---|---|
| | x | y | z | |
| PFC Left | -47 | 48 | 18 | 45-46 |
| | -40 | 47 | 30 | 45-46 |
| | -28 | 65 | 18 | 10-46 |
| PFC Right | 39 | 64 | 7 | 10-46 |
| | 54 | 44 | 7 | 45-46 |
| | 52 | 42 | 21 | 45-46 |
| Motor Cortex | -38 | -21 | 71 | 4-6 |
| | -14 | -2 | 75 | 6 |
| | -1 | -10 | 73 | 6 |
| | 12 | 0 | 75 | 6 |
| | 22 | -10 | 75 | 6 |
| | 36 | -20 | 73 | 4-6 |
| PL Right | 28 | -77 | 56 | 7 |
| | 30 | -85 | 44 | 7-19 |
| | 49 | -70 | 48 | 7-39 |

**Figure 2.** The functional near infrared spectroscopy (fNIRS) multichannel layout with 15 channels covering four regions of interest (ROI): motor cortex (yellow), left (dark blue) and right (light blue) prefrontal cortex (PFC) and parietal lobe (PL red). On the left, spatial organization of different optodes (BrainNet viewer toolbox[24]); in black the receivers, in colour the emitters, and pink edge the channels. On the right, MNI coordinates to each fNIRS channel (ROI) with corresponding Brodmann areas (BA).

***Data analysis***

Raw data (optical intensity) extracted from Oxysoft software (v3.0.75, Artinis Medical Systems) was converted in optical density (OD) using Matlab® (MATLAB 2014b, The MathWorks, USA). Then, to reduce possible head motion artifacts two methods implemented in the Homer2 toolbox[25] were used. First, the moving standard deviation and spline interpolation methods were applied using parameters: SDTresh = 20, AMPTresh = 0.5, tMotion = 0.5s, tMask = 2s and p = 0.99. Second, we used wavelet-based signal decomposition with the parameter: iqr = 0.1, as recommended.[9] Then OD time series were converted into relative concentrations of $O_2Hb$ and HHb using the modified Beer-Lambert law corrected by a differential pathlength factor depending on the age of the participant.[26] A low-pass Butterworth zero-phase digital filter (order 4) with a cut-off frequency of 0.08 Hz was applied to limit physiological artifacts (heart rate: ± 1 Hz, respiration: ± 0.4 Hz and Mayer wave: ± 0.1 Hz). For each participant, channels not having a sufficient signal-to-noise ratio were excluded from the analyses after observation of the power spectrum density of the $O_2Hb$ signals where the presence of a cardiac rhythm in the signal (peak around 1 Hz) indicates good contact between the optodes and the scalp.[27] After this preprocessing step, 14% of the channels were excluded.

319 Following a splitting of the fNIRS signals from events indicating the beginning of each
320 condition, the average between -30 seconds and -10 seconds of the minute of rest
321 preceding each condition was subtracted from the subsequent data during the exercise
322 period. The following dependent variables attesting to exercise-related cortical
323 activation magnitude were calculated per channel for the period (representative of the
324 steady-state level) between 2 minutes and 4 minutes 30 seconds of exercise for each
325 condition: area under the curve of $O_2Hb$ and HHb and average values. The average of
326 the channels positioned on 4 ROIs (the right and the left posterior parietal cortex and
327 primary motor, and right parietal lobe) was extracted for each participant and each
328 condition.
329
330 **Statistical analysis**
331 Statistical analyses were performed using Statistica (7.1, Statsoft Inc., France). Data
332 were examined for normality and sphericity using Shapiro-Wilk and Mauchly tests,
333 respectively. Where Mauchly's tests indicated violations of the sphericity assumption,
334 Greenhouse–Geisser corrections were applied. A one-way repeated-measure ANOVA
335 was used to assess the differences between the four exercise conditions for heart rate
336 recorded during the rest period. A fully repeated measures two-way ANOVA with the
337 factors *mode of muscle contraction* (eccentric vs. concentric) and *mode of exercise*
338 *prescription* (torque vs. perception of effort) were used to compare the NASA-TLX
339 scores and fNIRS responses. In case of significant effect, post hoc comparisons were
340 adjusted with the Bonferroni correction.
341 Wilcoxon signed-rank tests were performed for quadriceps pain and the Feeling scale
342 values when comparing the mode of muscle contraction and the mode of exercise
343 prescription. Student paired *t*-tests were carried out between the concentric and

344 eccentric torque conditions for the perceived effort. For the cycling torque data,
345 Wilcoxon signed-rank test was performed between the first condition (concentric at
346 fixed perceived effort) and the two conditions (eccentric and concentric) where the
347 intensity was fixed by a torque value.
348 Effect sizes were reported with the partial eta square ($\eta^2_p$) for the effects of the
349 ANOVAs[28] and with Cohen's *d* and rank-biserial correlation ($r_{rb}$) for pairwise
350 comparison. The significance level for all analyses was established at $p = .05$ (two-
351 tailed). All the fNIRS *p*-values were corrected using false discovery rate to control for
352 type 1 error due to the spatial dependency between brain areas.
353
354 **RESULTS**
355 **Torque and heart rate**
356 The average torque during concentric cycling at a moderate perceived effort was 41.1
357 ± 14.1 Nm. No difference was observed between the average torque produced when
358 performing concentric cycling at a moderate perceived effort, and the average torque
359 produced when performing concentric (42.7 ± 13.8 Nm; W (17) = 47.5; p = .17; rrb =
360 .33) or eccentric cycling at a fixed torque (40.3 ± 13.12 Nm; W (17) = 40; p = .08; rrb =
361 .42).
362 No difference in resting heart rate was observed before the start of each cycling exer-
363 cise condition ($F$ (3, 45) = 1.25; $p = .30$; $\eta^2_p = .08$). During the cycling exercises, the
364 main effect of the mode of muscle contraction revealed a higher heart rate during con-
365 centric cycling compared to eccentric cycling ($F$ (1, 18) = 40.3; $p < .001$; $\eta^2_p = .69$, 101
366 ± 13 vs. 87 ± 13 bpm). No main effect of the mode of exercise prescription ($F$ (1, 18) =
367 .09; $p = .77$; $\eta^2_p = .00$; perception of effort: 94 ± 14 bpm; torque: 94 ± 15 bpm) or mode

368 of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = .88; $p$ =
369 .36; $\eta^2_p$ = .05) was observed.
370
371 **Psychological variables**
372 When the exercise was prescribed with a fixed torque feedback, the *perception of effort*
373 *intensity* was higher ($t$ (17) = 3.39; $p$ < .01; $d$ = 1.07) during concentric cycling com-
374 pared to eccentric cycling (23.2 ± 3.9 and 17.4 ± 6.8).
375 No main effects of the mode of muscle contraction ($W$ (38) = 96.5; $p$ = .75; $r_{rb}$ = .05)
376 and prescription of intensity ($W$ (38) = 53; $p$ = .44; $r_{rb}$ = .13) were found for perceived
377 quadriceps pain during the exercise as well as for the affects (Feeling scale) ($W$ (38)
378 = 94; $p$ = .68; $r_{rb}$ = .07 and $W$ (38) = 79; $p$ = .12; $r_{rb}$ = .25, respectively).
379 For the perceived measures with the NASA-TLX subscales, one participant did not
380 complete the questionnaire at the end of the experimental session. Therefore, data are
381 available for 18 participants. For the *mental demand scores*, the main effect of the
382 mode of muscle contraction revealed a higher mental demand during eccentric cycling
383 compared to concentric cycling ($F$ (1, 17) = 7.86, $p$ = .01; $\eta^2_p$ = .32; Figure 3a). The
384 main effect of the mode of exercise prescription revealed a higher mental demand
385 when the exercise was prescribed with a fixed torque compared to a fixed perception
386 effort ($F$ (1, 17) = 26.22; $p$ < .001; $\eta^2_p$ = .61; Figure 3b). No mode of muscle contraction
387 × mode of exercise prescription interaction was observed ($F$ (1, 17) = .45; $p$ = .51; $\eta^2_p$
388 = .02). For the *physical demand scores*, the main effect of the mode of muscle
389 contraction revealed a higher physical demand during concentric cycling compared to
390 eccentric cycling ($F$ (1, 17) = 6.66; $p$ = .02; $\eta^2_p$ = .28; Figure 3c). No main effect of the
391 mode of exercise prescription was observed ($F$ (1, 17) = .54; $p$ = .47; $\eta^2_p$ = .03;
392 observed power = .11). Follow-up tests on the mode of muscle contraction × mode of

exercise prescription interaction ($F$ (1, 17) = 6.99; $p$ = .02, $\eta^2_p$ = .29) are presented in Figure 3d. The physical demand was greater for the torque condition in concentric cycling compared to eccentric cycling ($p$ = .005, $d$ = 0.315).

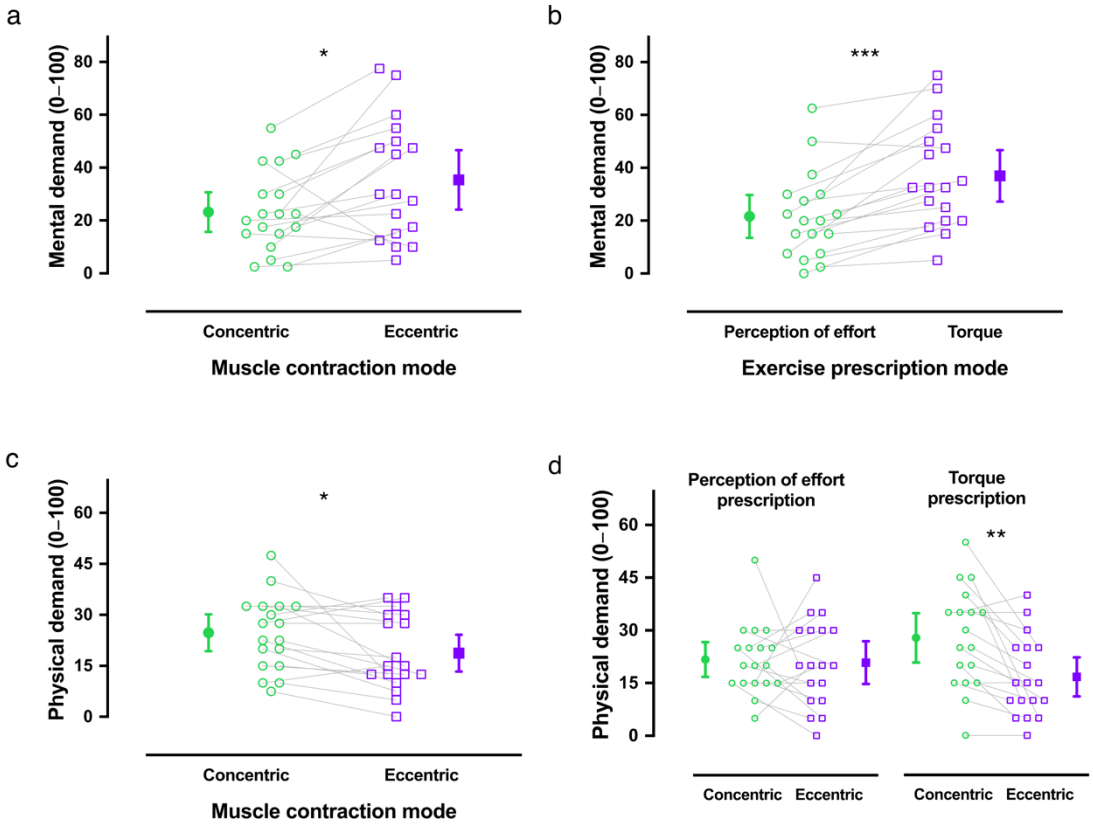



**Figure 3.** Perceived mental and physical demand scores measured with the NASA-TLX scale. The mental demand was perceived higher during eccentric cycling compared to concentric cycling (main effect of the muscle contraction mode, panel a), and during the exercise prescribed with the torque feedback compared to the perception of effort (main effect of the exercise prescription mode, panel b). The physical demand was perceived lower during eccentric cycling compared to concentric cycling (main effect the muscle contraction mode, panel c), and the interaction effect revealed a

specific lower perceived physical demand during the eccentric cycling compared to concentric cycling when exercise was prescribed with the torque feedback. Concentric cycling and eccentric cycling are represented with circle and square markers, respectively. Individual (n=18) data are represented with empty markers and mean (±95% CI) as filled markers. * $p < .05$, ** $p < .01$, *** $p < .001$.

**Cortical responses**

For the *left prefrontal cortex* (Figure 4A) and $O_2Hb$, the main effect of the mode of muscle contraction revealed a higher area under the curve during eccentric cycling compared to concentric cycling ($F$ (1, 18) = 16.35; $p < .01$, $\eta^2_p = .48$). Neither the main effect of the mode of exercise prescription method ($F$ (1, 18) = .1; $p = .75$; $\eta^2_p = .01$), nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = 1.48; $p = .24$; $\eta^2_p = .08$) was observed. Regarding HHb, the main effect of the mode of muscle contraction revealed a lower area under the curve during eccentric cycling compared to concentric cycling ($F$ (1, 18) = 35.77, $p < .001$, $\eta^2_p = .67$). Neither the main effect of the mode of exercise prescription ($F$ (1, 18) = .49, $p = .49$; $\eta^2_p = .03$) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = .07; $p = .80$; $\eta^2_p = .003$) was observed.

For the *right prefrontal cortex* (Figure 4B) and $O_2Hb$, the main effect of the mode of muscle contraction revealed a higher area under the curve during eccentric cycling compared to concentric cycling *(*$F$ (1, 18) = 6.96; $p < .05$; $\eta^2_p = .28$). Neither the main effect of the mode of exercise prescription ($F$ (1,18) = .30; $p = .59$; $\eta^2_p = .02$) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = 2.06; $p = .17$; $\eta^2_p = .10$) was observed. Regarding HHb, the main effect of the mode of muscle contraction revealed a lower area under the curve during eccentric cycling

compared to concentric cycling ($F$ (1, 18) = 22.26, $p$ < .001, $\eta^2_p$ = .55). Neither the main effect of the mode of exercise prescription ($F$ (1,18) = .63, $p$ = .44; $\eta^2_p$ = .03) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = 3.15, $p$ = .09; $\eta^2_p$ = .15) was observed. For bilateral *motor cortex* and $O_2Hb$ (Figure 4C), no main effect of the mode of muscle contraction was observed ($F$ (1,18) = 1.01, $p$ = .33; $\eta^2_p$ = .05). Neither the main effect of the mode of exercise prescription ($F$ (1,18) = .18, $p$ = .68; $\eta^2_p$ = .01) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 18) = .37, $p$ = .55; $\eta^2_p$ = .02) was observed. Regarding HHb, the main effect of the mode of muscle contraction revealed a lower area under the curve during eccentric cycling compared to concentric cycling ($F$ (1, 18) = 38.26, $p$ < .001, $\eta^2_p$ = .68). Neither the main effect of the mode of exercise prescription ($F$ (1, 18) = .73, $p$ = .40; $\eta^2_p$ = .04) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ = (1, 18) = 3.42, $p$ = .08; $\eta^2_p$ = .16) was observed.

For the *right parietal lobe* (Figure 4D) and $O_2Hb$, the main effect of the mode of muscle contraction revealed a higher area under the curve during eccentric cycling compared to concentric cycling ($F$ (1, 13) = 11.12, $p$ = .02, $\eta^2_p$ = .46). Neither the main effect of the mode of exercise prescription method ($F$ (1,13) = 1.09, $p$ = .32; $\eta^2_p$ = .08; Figure 4D) nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 13) = .20, $p$ = .66; $\eta^2_p$ = .01) was observed. Regarding HHb, no main effect of the mode of muscle contraction was observed ($F$ (1, 13) = .38, $p$ = .55; $\eta^2_p$ = .03). Neither the main effect of the mode of exercise prescription ($F$ (1, 13) = 2.2, $p$ = .16; $\eta^2_p$ = .14 nor a mode of muscle contraction × mode of exercise prescription interaction ($F$ (1, 13) = 1.33, $p$ = .27; $\eta^2_p$ = .09) was observed.

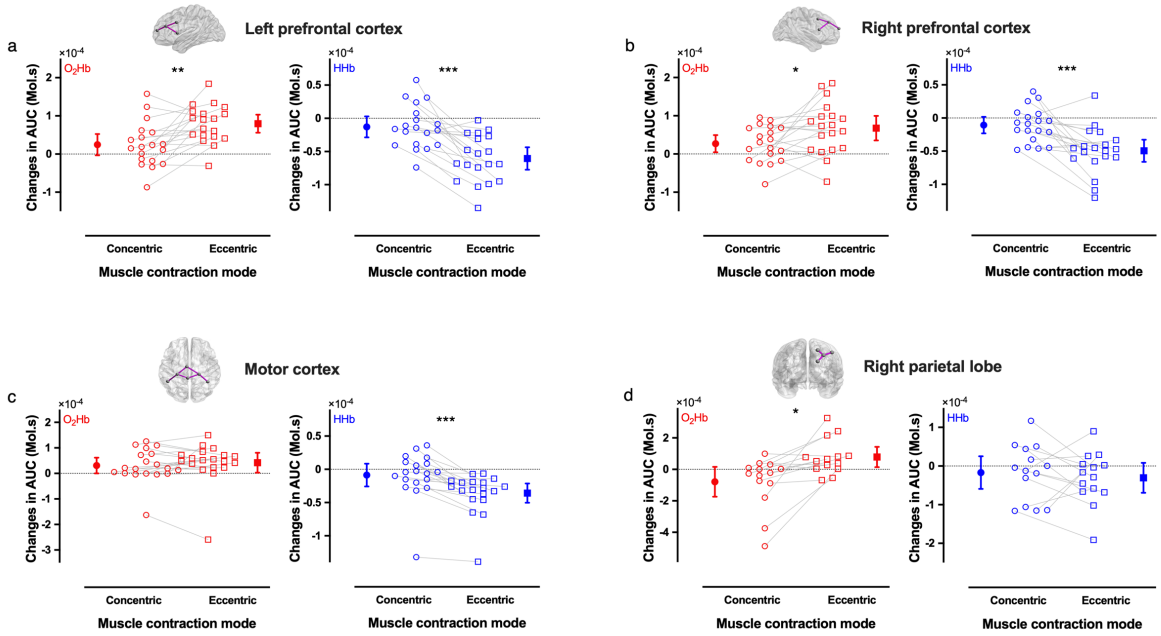



**Figure 4.** Changes in the area under the curve (AUC) for the oxyhaemoglobin (O2Hb, red) and deoxyhaemoglobin (HHb, blue). Data are presented for the main effect of the muscle contraction mode. The four regions of interest were the left prefrontal cortex (N=19, panel a), the right prefrontal cortex (N=19, panel b), the motor cortex (N=19, panel c) and the right parietal lobe (n=14, panel d). Data missing for the right parietal lobe is due to a damaged optical fiber occurring during one day of the data collection. Concentric cycling and eccentric cycling are represented with circle and square markers, respectively. Individual data are represented with empty markers and mean (±95% CI) as filled markers. * $p < .05$, ** $p < .01$, *** $p < .001$.

## DISCUSSION

The main objective of the present study was to quantify the acute changes in attention-related cortical activity as well as those relevant to brain motor areas from fNIRS during eccentric and concentric cycling exercises performed at both matched perceived effort (23 on CR100® scale) and torque. The main results showed a greater mental demand

472 and cortical activation in the right and left prefrontal cortices and right parietal lobe
473 during eccentric cycling compared to concentric cycling. These findings confirm
474 previous results suggesting that eccentric cycling is more cognitively demanding than
475 concentric cycling[9] and extend them by identifying specific brain activation patterns
476 underlying this greater mental demand.
477
478 **Mental demand during eccentric cycling**
479 Mental demand was subjectively measured with the NASA-TLX subscale. The mental
480 demand was reported to be 45% greater during eccentric cycling compared to
481 concentric cycling, while physical demand was 38% greater during concentric cycling.
482 These findings support the results of Kan et al.[9] Nevertheless, mental and physical
483 demand values were 2 to 3 times lower in the present study. The higher mental and
484 physical demand found in Kan et al.[9] is likely due to a greater exercise intensity
485 compared to the present study, as confirmed by the higher mean heart rate values
486 reported in their study as compared to ours (eccentric cycling: ~+29 bpm; concentric
487 cycling: +56 bpm). While mental demand refers to the mental and perceptual activity
488 imposed by a task and refers to related information processing, effort refers to the
489 voluntary engagement of mental and physical resources to perform, or attempt to
490 perform, in a task. [20,29] In the present study, coordinating the leg movements properly
491 during eccentric and concentric cycling required dedicated motor skills and so
492 adequate demand for attention. As described in the methods, participants were asked
493 to perform eccentric and concentric cycling in a well-coordinated manner to ensure
494 smooth pedal rotation and torque production. This was similar to the cycling exercises
495 proposed by Kan et al.[9], where the authors observed that attention and vigilance were
496 maintained after eccentric and concentric cycling. However, higher cognitive load

497 (based on both the NASA TLX score and choice reaction time) was found in the study
498 of Kan et al.[9] during eccentric cycling. Altogether, it appears that eccentric cycling is
499 more cognitively demanding than concentric cycling and that the less mental demand
500 of eccentric and concentric cycling in the present study did not likely change cognitive
501 functions post-exercise.

502 Regarding the mode of exercise prescription, the mental demand was
503 significantly higher when the intensity was set by a target torque value compared to an
504 exercise prescribed by a fixed perceived effort. To the best of our knowledge, this study
505 is the first to observe this difference in mental demand. A lower mental demand during
506 self-regulated exercise based on effort perception is not surprising as, in this specific
507 condition, participants did not have at each pedal revolution to visually focus on a
508 torque target to reach. Contrary to the mental demand, the mode of exercise
509 prescription did not alter the reported physical demand of the cycling exercise. This
510 observation is in line with no significant difference in heart rate between the two modes
511 of exercise prescription.

512

513 **Cortical activity during eccentric cycling**

514 Neuroimaging studies using various methods and exercise paradigms reveal
515 inconsistencies in the role of the primary motor cortex in the production of eccentric
516 muscle contractions.[10] Yao et al.[15] during unilateral movements of the first dorsal
517 interosseous muscle in an MRI scanner, as Fang et al.[14] in an EEG study for the elbow
518 flexors, showed a greater activation of the primary motor cortex contralateral to the
519 active muscles when performing eccentric compared to concentric contractions.
520 Conversely, a reduction was reported in the primary motor cortex blood-oxygen-level
521 dependent signal amplitude during eccentric compared to concentric contractions.[30]

522 The present study is the first to collect, during an eccentric cycling exercise (i.e., a
523 bilateral task), fNIRS data over the precentral gyrus (BA 4/6) and primary motor areas
524 (BA 4). The present study did not observe significant differences in motor cortices
525 activity between eccentric and concentric cycling. Our results can be explained
526 because the tasks performed are fundamentally different from the literature. First, the
527 different studies cited above performed unilateral distal movements of the upper limb,
528 unlike our study where the participants performed a bilateral task mobilizing larger
529 muscle masses of the lower limbs. In addition, in the present study, the cycling exercise
530 was performed at moderate intensity (23 on the CR100® scale or using an associated
531 torque). Studies showing a greater activity of the contralateral primary motor during
532 eccentric muscle contractions involved exercises performed either at maximum
533 intensity[14] or sub-maximum intensity fixed relative to maximal voluntary contraction
534 force or body weight.[14,15] Noteworthy, in the study of Olsson et al.[30] a continuous
535 imagery task paradigm was used by alternating concentric (lifting a weight) and
536 eccentric (slowing down a weight) muscle contractions. For other cortical areas
537 involved in the motor network (e.g. primary and secondary motor areas not recorded
538 here), a consensus seems to exist on the greater cortical activity observed during
539 eccentric contractions.[10]

540 The main results of the present study revealed a greater activity of the left and
541 right prefrontal cortices, as well as the right parietal lobe, when performing eccentric
542 cycling compared to concentric cycling, regardless of the mode of exercise prescrip-
543 tion. These observations likely unveil underlying neurophysiological mechanisms sus-
544 taining the increased mental demand reported by the participants during eccentric cy-
545 cling. The left and right prefrontal cortices as well as the right parietal lobe are known
546 for their roles in the modulation of mental demand during prolonged exercise[17] as well

547 as during sustained attentional cognitive tasks.[16] When focusing on a specific move-
548 ment to perform, several brain areas, constituting the central executive network, are
549 engaged. More specifically, these regions would be part of the fronto-parietal network
550 that consists mainly of the dorsolateral prefrontal cortex, the frontal cortex and the pa-
551 rietal lobe.[31] An increase in eccentric force variability has been proposed as a sign of
552 an increased motor control difficulty during eccentric contractions compared to con-
553 centric contractions.[11] Controlling the variability in motor output (not assessed in the
554 present study) during eccentric contractions would likely require greater attentional de-
555 mand, thus explaining the observed increase in the activity of the prefrontal cortices
556 and the right parietal lobe. Some authors have highlighted the complementarity of re-
557 gional brain activity magnitude measures and those linked to the dynamic activity of
558 brain networks.[32] On this basis, the fMRI study of Yao et al.[33] examined the strength of
559 functional connectivity between the primary motor cortex and other cortical regions in
560 the motor control network (e.g. supplementary motor area, cerebellum) involved in ec-
561 centric and concentric contractions. The authors observed a weaker functional con-
562 nectivity during eccentric compared to concentric contractions of the right first dorsal
563 interosseous muscle. A weaker statistical dependence between two-time series from
564 different brain areas may reflect more involvement of specialised regions (segregation)
565 and thus less functional integration.[34] This means that higher cortical activation may
566 be required during eccentric contraction to compensate for a weaker functional con-
567 nectivity. Yao et al.[33] hypothesized that the brain control of a concentric contraction will
568 be more efficient than an eccentric contraction. This first result needs to be supported
569 by more evidence, notably for a bilateral task mobilizing larger muscle masses of the
570 lower limbs. The analysis of functional connectivity could be a relevant and comple-
571 mentary approach to better understand the functional organisation of the brain when

performing eccentric cycling over time and its possible implications for rehabilitation and training.

**Methodological considerations**

In the present study, we controlled for the induction of muscle fatigue by providing a sufficient recovery period between cycling exercise conditions, thus allowing us to ensure that our results are not confounded by a decrease in force production capacity of the working muscles with changes in the corticospinal excitability.[35] Exercise-induced muscle fatigue plays an important role in the modulation of cortical activity during exercise. In an fMRI study involving a maximal-effort handgrip contraction, Liu et al.[36] observed an early increase followed by a decrease in brain activity in the primary motor cortex and in particular in the prefrontal cortex. The exercise intensity in our experimental design was low as indicated by perceived effort and heart rate values. In addition, our control experiment showed no significant decrease in the maximal force production capacity of the knee extensors after the whole exercise protocol.

The present study faces one limitation, which might be taken into account in follow-up studies. The fNIRS signal can be contaminated by the physiological responses to the task performed (e.g. heart rate, blood pressure). This signal contamination related to non-neural activity can lead to false positives or negatives in our analyses.[37] To overcome these issues, the use of short-distance channels (approximately 1 cm between the transmitters and the receivers) was proposed.[38] In this study, we did not use such short-distance channels for separating signals that stem from blood flow changes in the extracerebral layers (scalp blood flow) as well as the cerebral tissue layer (systemic blood flow). As indicated in the methods, we minimized this potential effect by inducing a partial transient blockade of the skin blood flow during the fNIRS data collection.[22]

Interestingly, heart rate was ~13% higher in concentric as reported before[39], whereas the greatest cortical activation was observed during eccentric cycling. These elements allow us to think that the results might not be influenced by systemic interference but future investigations are necessary to confirm this hypothesis.

Finally, it is important to note that 2-3 participants did not report a higher mental demand during eccentric cycling compared to concentric cycling. These interindividual variability responses may be due to the differences in the degree of expertise of our participants with eccentric cycling. Therefore, future studies should explore the link between the repeated and chronic use of eccentric cycling and a potential decrease in its mental demand. Regarding the variability in fNIRS responses, 3-5 participants presented results contradictory to the group. In line with this observed variability, we strongly encourage future researchers to increase their sample size beyond the one used in our present study to replicate and confirm our observations.

## CONCLUSION

In the present study we took advantage of using functional near infrared spectroscopy covering four regions of interest to investigate how mental demand induced by eccentric exercise modulated the central executive network. The present study showed that the higher mental demand observed during eccentric cycling compared to concentric cycling was associated with a greater activation of the left and right prefrontal cortices as well as the right parietal lobe. These findings provide evidence that heightened activation of the frontoparietal network may support eccentric movement control.

## PERSPECTIVES

A large proportion of our daily living activities require accurate control of movements employing eccentric contractions (e.g. walking downstairs, sitting). We encourage future studies to replicate and extend our results using different locomotion modalities such as uphill or downhill running, which are known to predominantly involve concentric and eccentric contractions of the knee extensors[40], respectively. As physiological responses to physical exercise are well known to be linked to the exercise intensity, it could also be of interest to explore the interaction between the exercise intensity and mental demand during various exercise modalities. Based on the findings of this study, future studies should investigate the potential use of wearable fNIRS for clinical and sports applications via an online neurofeedback approach to modulate the mental demand. Further investigations are also warranted to examine the impact of task familiarization on mental demand and the related brain activation during eccentric cycling. As learning is associated with increased automaticity and decreased resources engaged in a task, it is plausible that participants will experience lower mental demand when they become acquainted with the task. Another application is that self-regulated eccentric exercise based on perceived effort is less mentally demanding, suggesting that it may be more appropriate if one session needs to minimize the overall workload. Overall, eccentric cycling workload can be prescribed based on the individual's perceived rate of exertion, but also at a brain activation workload similar to that elicited by concentric cycling to improve both neuro-motor processing strategies and mental demand.

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## AUTHOR CONTRIBUTIONS

Lenaic Borot: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing –original draft; writing –review and editing. Benjamin Pageaux: Conceptualization; investigation; methodology; visualization; validation; writing –review and editing. Davy Laroche: Conceptualization; funding acquisition; methodology; resources; supervision; writing –review and editing. Gregoire Vergotte: methodology; formal analysis; writing –review and editing. Romuald Lepers and Stephane Perrey: Conceptualization; investigation; funding acquisition; methodology; project administration; resources; supervision; validation; writing –review and editing.

## CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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