A role for the prefrontal cortex in exercise tolerance and termination

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Involvement of the brain in endurance exercise regulation is not a particularly new concept. Whilst exercise termination has been proposed to occur when generation of the required power output is no longer possible due to failure at sites within the musculature (1), there is growing evidence that there is a neural component to our ability to tolerate sensations of fatigue and that exercise termination includes a psychological element (23). This involves afferent feedback of the disturbances in homeostasis at the musculature and cardiopulmonary systems to the brain (23), where these signals are interpreted. That the motor cortex (MC) is not activated maximally at exercise termination suggests that regions upstream of the MC provide such input into how we interpret these signals and when we terminate exercise.

Several authors have now addressed areas of the cortex that are activated during the control of voluntary movement and postulated how areas of the brain may be involved in exercise termination (21, 30, 31). There is strong evidence that our tolerance of physiological sensations can be modulated by a variety of psychological factors such as motivation (35) and presence of competitors (34), however, the neural pathways for volitional control of movement and their interaction with these factors has yet to be established (31). The aim of this viewpoint is to present potential cerebral pathways involved in the interpretation of physiological signals, which combine with internal and external factors present in exercise environments, to determine exercise tolerance (see figure 1.). We propose the prefrontal cortex (PFC) may have a role in the integration of such information providing a relevant response to the exercise situation, exerting a top down effect. Thus, allowing for motor unit de-recruitment, or in some situations, overriding of these signals and prolonging motor output (30) despite significant down regulation of motor control.
The PFC has previously been proposed to be involved in terminating incremental exhaustive exercise due to declines in prefrontal cerebral oxygenation (COxy) preceding exhaustion (6). The maintenance of prefrontal COxy during self-paced exercise, also suggests effective pacing involves COxy being at an appropriate level to avoid early exercise termination (7). Notably much of this research has been undertaken on the PFC due to accessibility of the site for NIRS rather than from a definitive hypothesis. As such, specifically how the PFC might be involved in exercise termination has rarely been proposed. Whilst there is not yet definitive evidence during exercise that a decline in COxy occurs in conjunction with a decrease in neural activity it has recently been shown that neural activity declines in the PFC at the respiratory compensation point (RCP) (25) where severe reductions in COxy are known to occur (6). Studies failing to show a decline in prefrontal COxy (16) or neural activity (2) prior to exhaustion during incremental exercise, have not utilised individual thresholds which might account for this discrepancy. There is some debate as to whether these changes in the PFC reflect part of the cerebral regulation of exercise due to the lack of importance of the PFC in motor control (16). Alterations in the PFC may reflect a redistribution of blood and oxygenation to more important and active parts of the brain (16) or to exercising musculature (27) to ensure metabolism is secure in these areas and subservient in quiescent regions less required for the generation of motor output.

The PFC is well known for its executive function, where cognitive control coordinates thought and actions related to the achievement of internally derived goals (20). Whilst the PFC is not directly connected with major motor control regions, it is indirectly linked via the pre motor area (PMA). It has been proposed to be able to supersede more direct regions of motor execution (12) which might be necessary in extending exercise tolerance, in the face of afferent feedback. Main cortical areas shown to receive afferent feedback include the
brainstem, lamina I spinothalamocortical system, somatosensory cortex (SSC) and insula cortex (IC) (9, 15). In contrast to the catastrophic model of exercise termination, whereby a specific system reaches failure (1, 28), an ability to tolerate homeostatic disturbances has been proposed to be dependent on the exercise model under consideration (18). In this latter situation, interpretation of afferent feedback in combination with the specific exercise environment and the cues involved in that environment are likely to help inform what response occurs (18): that is, whether to maintain intensity, moderate the pace or stop altogether.

Pathways for the interpretation of afferent signals could be via the anterior cingulate cortex (ACC), pre motor area (PMA) and regions of the PFC; such as the lateral PFC (LPFC) and orbitofrontal cortex (OFC). These regions of the brain have roles in motivation (14), reward (4), planning and execution (22, 26): cognitive and emotional functions that may be involved in the ability to increase exercise tolerance (5, 13, 34). As internal information is continuously updated during exercise, these regions may respond to this changing environment, as well as consolidate experiential learning required for optimal pacing (19).

Afferent feedback from the spinothalamic system reaches the OFC (8) and allows processing of signals to provide emotional relevance (affect) (8). Affect (pleasure-displeasure) is known to play a role in exercise tolerance and may play a role in the specific response chosen to accommodate uncomfortable sensations (32). Such responses have been shown to represent different physiological changes at the PFC (32).

The OFC is also able to integrate multiple sources of information regarding the outcome of a task response and in effect, calculate how rewarding an action is (11). In order to maintain exercise under intolerable conditions, external cues such as visual feedback of performance
(35), other competitors (34), or internal cues like self belief (13) may play a role in our interpretation of how rewarding tolerating disrupted physiological signals might be. The OFC processes both emotional and motivational responses to stimuli in an ongoing manner which would be required to make continuous decisions about motor output (30). This process is likely to be in conjunction with the ACC (4, 24) and other reward centres such as the amygdala, thus increasing the implication of dopamine and its role in exercise tolerance (33). The ACC is proposed to give motivational context to situations by providing incentive values from past events (14). This pathway may provide the experiential nature of exercise as previously reported (19) where interpretation of homeostatic signals is likely to play a role (19). During interpretation of afferent feedback there is co-activation of the ACC with the AIC suggesting that both these are involved in perception of bodily states (10, 24).

Processing task response selection is suggested to involve the LPFC in conjunction with information delivered by the ACC and OFC (3). Sustaining motor output under conditions of homeostatic perturbations is likely to trigger internal conflict (34) which is suggested to involve the ACC (3, 22). The LPFC integrates internal conflict about selecting a response in combination with the reward outcome, to guide selection of an appropriate response, which occurs in conjunction with PMA (17). Together these pathways are suggested to act in an integrated manner to choose a response which is likely then passed through the basal ganglia (BG) for motor execution (14) (see figure 1). The competitive nature of the brain means that expression of a certain behaviour will be achieved by the pathways with the strongest sources of support (20). An athlete’s ability to sustain exercise, despite severe deficiencies in motor control, may be implemented in situations where psychological drive ensures that the task relevant response chosen is to continue exercise (30). Attention paid to motivational and emotional cues from the environment and situation, rather than from the homeostatic signals,
would facilitate this, which has been shown to be relevant for both incremental tests to
exhaustion (35) and self paced exercise (5). Persistent choice of specific task responses
reinforces neural pathways (20), and may explain why athletes have a higher ability to
tolerate such sensations (29). Although the PFC may not be considered to be involved
directly in the execution of motor output (16) we posit it may be intimately involved in the
capacity to tolerate high levels of physical exertion and possibly in the determination of
exercise termination. As such, evaluating neurophysiological and psychological responses
when high levels of physiological demand are present, during externally controlled and self
paced exercise, will assist in our understanding of cerebral alterations in exercise tolerance
and how they impact our regulation of exercise performance.


Figure 1. During exercise such as self paced or exhaustive incremental exercise, decisions are made about when to stop or how to regulate pace such that exercise can be completed without catastrophic failure or a meaningful slow down before the finish line. The lateral prefrontal cortex (LPFC) allows for integration of afferent signals in combination with a motivational and emotional context provided by the anterior cingulate cortex (ACC) and the orbitofrontal cortex (OFC). Once these signals are integrated, a decision about the most relevant task response to the situation can be made. Depending on the mode of exercise, choices will vary from response 1 (R1) acting to modify the exercise pace by speeding up, slowing down or maintaining pace, to response 2 (R2) which will terminate exercise. The task response is carried out via the pre motor area (PMA) and the basal ganglia (BG).