Cortical Changes as a Result of Sports Injuries: A Short Commentary*

Cambios corticales como resultado de lesiones deportivas: un comentario

[Artículos]

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Abstract

Currently, the treatment for the central nervous system (CNS) and neurocognitive fluctuations as a result of sports injuries is considered a relatively uncovered area under the sports neuroscience paradigm. For example, the compensatory neural changes (e.g., brain cortical changes) and the cognitive load can create a feedforward loop that affects recovery and relapse after a musculoskeletal injury. Although several methodologies have been promoted (e.g., brain mapping systems, inhibitory control, and cognitive flexibility), neuromuscular deficits are frequently non-assessed and non-intervened during rehabilitation practices. Here we present an up-to-date description of the most relevant CNS changes after injury, the concept of somatotopic maps, and their relationship with motor control, intracortical inhibition, and cortical facilitation processes. Neuroplasticity strategies beyond the traditional structural-based approaches on the injured tissue are also covered; however, further research is needed to establish evidence-based recommendations for sports professionals.

Keywords: cortical maps, proprioceptive distress, intracortical inhibition, motor control, pain, motor variability, neuroplasticity.

Resumen

En la actualidad, el tratamiento del sistema nervioso central (SNC) y las fluctuaciones neurocognitivas como consecuencia de las lesiones deportivas se considera un área relativamente poco abordada bajo el paradigma de la neurociencia del deporte. Por ejemplo, los cambios neuronales compensatorios (como los cambios corticales del cerebro) y la carga cognitiva pueden crear un bucle de alimentación que afecta a la recuperación y a la recaída después de una lesión musculoesquelética. Aunque se han promovido varias metodologías (por ejemplo, los sistemas de mapeo cerebral, el control inhibitorio y la flexibilidad cognitiva), los déficits neuromusculares no suelen ser evaluados ni intervenidos durante las prácticas de rehabilitación. En este artículo presentamos una descripción actualizada de los cambios más relevantes del SNC después de una lesión, el concepto de mapas somatotópicos y su relación con el control motor, la inhibición intracortical y los procesos de facilitación cortical. También se cubren las estrategias de neuroplasticidad más allá de los enfoques tradicionales basados en la estructura del tejido lesionado; sin embargo, se requiere más investigación para establecer recomendaciones basadas en la evidencia para los profesionales del deporte.

Palabras clave: mapas corticales, disfunción propioceptiva, inhibición intracortical, control motor, dolor, variabilidad motora, neuroplasticidad.

Introduction

The human body locomotion, as a dynamical system, is a complex network of interactions at different levels of functionality that contains both deterministic and stochastic elements (molecules, cells, tissues, and body systems) (Santuz *et al.*, 2020). Each time a muscle group contracts after neural activation it develops a force that triggers a work, so the latter is the expression of an energetic process that performs the transformation of chemical energy into mechanical work and heat. At this molecular level, the amount of chemical energy transformed into mechanical work in relation to the total energy used is called performance (Kraemer & Looney, 2012). In this sense, the human body can perform a given amount of work (e.g., physical effort) during a certain time using the energy supplied by several synchronized metabolic systems (mitochondrial and extra-mitochondrial pathways) (Chamari & Padulo, 2015). For instance, the energy consumption during an explosive effort (e.g., powerlifting or sprinting) is provided mostly by the extra-mitochondrial systems (i.e., phosphocreatine/creatine kinase system and glycolysis) (Hargreaves & Spriet, 2020). However, this energy is diminished through the exercise bout while central and peripheral fatigue progresses reduce intensity, which limits physical performance. The fatigue development will also affect motor control, quick decision-making, motor coordination, and reaction speed since it directly impacts the nervous system (Roschel *et al.*, 2021).

An external stimulus (e.g., exercise) is important to evoke systemic adaptations in a biological entity (e.g., the athlete). It is noteworthy mentioning that an efficient biological system is prepared in advance of possible energy needs (allostasis model) (Sterling, 2012). If the rate of neuromuscular activity is much higher than the intra-set recovery period (work-to-rest ratio as an external stimulus), there is a critical accumulation of several metabolites that might impair contractile function (e.g., H^+, Pi, and insensitivity to sarcoplasmic Ca^{2+}), demonstrating a causal role in central and peripheral fatigue (Sundberg & Fitts, 2019). However, suboptimal post-exercise recovery (including insufficient rest and energy/nutrient intake) might result in systemic disturbances that increase the risk of a musculoskeletal injury (Bonilla *et al.*, 2021a), which is represented by alterations in the myofibrillar structure and the decrease in force production (Grier *et al.*, 2020; Tidball, 2011). In sports, muscle injuries can be caused by mechanical impacts as well, such as bruising and spraining, which depending on the muscle trauma would generate a transient or permanent neurological deficit (due to denervation) and consequent muscle atrophy (Fernandes *et al.*, 2011).

Exercise and the brain

Under the sports neuroscience paradigm, we understand how the integration of neuromechanics allows for a better comprehension of human movement (Piskin *et al.*, 2021). This field seeks to understand how the muscular system interacts with the brain to produce coordinated movements in complex and unexpected situations (Nishikawa *et al.*, 2007; Seidel-Marzi & Ragert, 2020). Interestingly, the results of neuromechanical studies must be interpreted in the same context, in such a way that aspects of the body and the external environment are involved (Ting *et al.*, 2015). In fact, understanding the interactions between the components of a given biological system and their control mechanisms results in a 'BioLogic' interpretation that is systemic, evolutionary, and adaptive (Bonilla *et al.*, 2021b; Bonilla *et al.*, 2022).

It has been found that physical exercise of different intensity levels has numerous effects on the efficiency of neuromuscular transmission; hence, the adaptation to explosive musculoskeletal efforts produces hypertrophy in the neuromuscular junction (Nishimune *et al.*, 2014). This is independent of muscular hypertrophy although it is currently discussed whether these morphometric changes determine functional changes (Lepore *et al.*, 2019). In individual adults, motor neurons and, to a lesser extent, the muscle itself release neurotrophic factors (e.g., brain-derived neurotrophic factor [BDNF] or neurotrophin 4 [NT-4]) that enhance spontaneous neuromuscular transmission (Sakuma & Yamaguchi, 2011). BDNF and NT-4 stimulate the release of synaptic vesicles by increasing presynaptic Ca^{2+} reuptake, and these factors appear to induce the production of another neuregulin (Pinho *et al.*, 2019). BDNF can regulate neuronal plasticity in the central nervous system (CNS) through various actions on dendritic and axonal remodeling, synaptogenesis, and synaptic efficiency, contributing to cognitive and neuromuscular performance (García-Suárez *et al.*, 2021). In parallel, physical activity has been shown to increase cognitive function in animals and humans by the increased expression of BDNF in the hippocampus, probably via the muscle

FDNC5/irisin pathway (Islam *et al.*, 2017), which is an integral area for learning and memory. It has been stipulated that due to the metabotropic activity of BDNF (which influences critical aspects of energy metabolism) the effect on cognition can be justified by relating energy metabolism and synaptic plasticity. Thus, there is a complex relationship between the regulation by exercise and BDNF on the cognitive level (Gomez-Pinilla *et al.*, 2008). Complementary, it is important to clarify that muscle activity also increases NT-4 production by muscle fiber (Sakuma & Yamaguchi, 2011), among several other myokines with the potential to regulate exercise adaptations at the level of the nervous system (e.g., exerkines) (Vints *et al.*, 2022).

Injuries, cortical changes, and pain

Injuries in sports are commonly addressed in clinical detail because of their musculoskeletal involvement associated with known and highly studied elements (Ruddy *et al.*, 2019). The traditional view has been focused on the therapeutical treatment for recovery of the structure and the athlete's performance by assessing different physical capacities such as strength, speed, resistance, and flexibility. This approach is necessary to accomplish the return to the exercise at the professional and amateur level; however, changes in the strategies for assessment and intervention of sports injuries rehabilitation have been occurring due to the novel detected changes that are produced in the brain in response to the tissues' manifestations caused by the injury event (Piskin *et al.*, 2021). It is noteworthy that the fibrous connective tissues, which inform about positional state and joint kinesthesia to the CNS using mechanoreceptors, might present neurophysiological changes after an injury. The afferent information would have changes in the reception caused by the joint deafferentation (Kapreli & Athanasopoulos, 2006). The analyses from the pathomechanics, the type of training, the kinematics, and other constituent elements at the time of determining the cause are based on the evidence available in the scientific literature (Rosa *et al.*, 2014). Therefore, describing sports injuries should go beyond just categorizing and classifying them, in such a way that it is currently recommended to analyze these musculoskeletal dysfunctions with an orientation from both the posture alignment and biomechanics of the cranium-cervical region and their incidence in motor control (Ting *et al.*, 2015). For instance, it should also include the disturbances associated with anatomical pathways as a function of the fascial network and its distal dysfunctional components in anatomical areas (such as the shoulder and knee) (Ajimsha *et al.*, 2020).

In the brain, there are zones described and indexed, anatomical and functionally, as the primary motor cortex (M1) that are part of the somatotopic maps and overlap in relation to muscles and movement function, which are important for individualized control and movement coordination, respectively (Massé-Alarie *et al.*, 2017). The study of somatotopic maps is performed by transcranial magnetic stimulation (TMS), a non-invasive method to stimulate the cerebral cortex, which has been used given its potential effectiveness in neuropsychiatric treatments, management of chronic pain (Galhardoni *et al.*, 2015), intracortical inhibition and corticospinal excitability deficit (Piskin *et al.*, 2021; Vucic & Kiernan, 2016). Moreover, the analysis of muscle contraction (e.g., tensiomyography) allows us to see acute and chronic responses of the CNS to physical activity (Goodall *et al.*, 2012). The structural changes in the gray matter, in greater or lesser volume, are considered a consequence of the changes in axon outbreak, dendritic ramifications, synaptic density, glial volume, and regional angiogenesis, while the changes in the white matter involve adaptations to the activity that may be seen depending on the myelinated axons (Nordmark *et al.*, 2018).

Motor coordination changes, constantly in cases of chronic musculoskeletal pain, include lumbar pain (Arendt-Nielsen *et al.*, 1996). It is important to clear up that nociception does not necessarily mean pain. Due to noxious stimuli, like a muscle or joint injury, nociceptors are activated and produce pain; if this stimulus is repetitive, like in chronic lumbar pain or osteoarthritis, a sensitivity to the nociceptive system can be developed and this would increase the response to non-harmful stimuli (Courtney *et al.*, 2010). In fact, chronic pain is a widespread problem around the world, but Pain Neuroscience Education (PNE) is a novel approach to pain treatment. Influencing in a positive way brain maps associated to fear, or beliefs about exercise as a painful activity, may diminish menaces and strengthen safety. Thus, PNE as an intervention strategy might result in a reduction of kynophobia (Robins *et al.*, 2016).

Motor control and neuroplasticity

Among the frequent changes associated with motor control after an injury, one can find voluntary muscular activation deficit (Goodall *et al.*, 2012). Quadriceps weakness after knee surgery is a common situation, being pain and age a big part of the voluntary muscle activation variability. Quadriceps inhibition after surgery has several consequences in the recovery process (Berth *et al.*, 2002). Using change strategies for motor control, as a brain-level process to reduce the intracortical inhibition, may increase intracortical and cortical spinal excitability, and is one of the injury re-adaptation processes that are available today due to its proprioceptive de-afference (Kapreli & Athanasopoulos, 2006). Furthermore, some of the situations or aspects we need to pay attention to encompass injury chronicity are recurrence fear (Gokeler *et al.*, 2013), atherogenic muscular inhibition (Rice *et al.*, 2014), reduction of motor variability, and the cognitive load (Dhawale *et al.*, 2017).

According to Dhawale *et al.* (2017), “neuroplasticity is an inherent property (human evolution) that allows the nervous system to escape the restrictions of its own genome and, therefore, to adapt to environmental pressure, physiological changes, and experiences” (Dhawale *et al.*, 2017). Currently, it is being studied how to make changes in the motor cortex, using motor control exercises in specific training programs. Therefore, it is considered that the first step in the treatment of musculoskeletal disorders must begin with brain observation and includes exercises and tools to reinforce it. Recent evidence is proving that physiotherapy, which uses only therapeutic exercises, must change its focus from musculoskeletal structural and functional changes to looking for changes in the CNS since these cortical changes have shown to have an important role in clinical manifestations. Central alterations have proved to have a key role in physiopathology and the clinical manifestations of musculoskeletal disorders (Armijo-Olivo, 2018). For example, modifications have been found in the representation of motor areas for joint stability such as transverse abdominis in patients with low back pain, and at the knee level in patellofemoral pain in *vastus lateralis* and *vastus medialis* muscles (On Uludağ, Taskiran, & Ertekin, 2004; Tsao, Galea, & Hodges, 2008). For more information about External focus – Internal focus and the implications for motor control following anterior cruciate ligament reconstruction, please refer to Gokeler *et al.* (2013).

Practical Recommendations

It is becoming clear that injuries and other musculoskeletal disorders are associated with changes in the motor cortex (i.e., cortical reorganization) among several other brain regions (Figure 1). The following are practical take-home points for sports and performance practitioners and researchers:

- TMS is a non-invasive technique that might be used to study somatotopic maps. For example, the reorganization of the motor cortex has been demonstrated using TMS.

- Functional magnetic resonance imaging (fMRI) is useful to evidence alterations in brain function and structure in chronic pain patients (Baria *et al.*, 2011; Hall *et al.*, 2016). Studies that have been performed with fMRI have discovered pain processing activities and their relationship to musculoskeletal or neurological disease due to impaired functional connectivity in information between brain regions (Baliki *et al.*, 2011).
- Recent neurophysiological discoveries have led to the emergence of other treatment strategies to address cortical reorganization such as Action Observation Therapy (AOT), which consists of observing behavior or actions performed by an operator during the rehabilitation process (Cuenca-Martínez *et al.*, 2020). Unlike AOT, motor imagery is a mental simulation of a specific muscle action without any corresponding motor output. These motor simulation practice techniques have been proven to enhance recovery and muscle strength during the injury rehabilitation period (Paravlic, 2022).
- Local vibration increases muscle activity and, therefore, has been used for rehabilitation and performance enhancement. In fact, it also increases activity in the somatosensory cortex and motor cortex (decreased sensorimotor inhibition) possibly due to the influence of corticocortical connections between S1 and M1 regions (Lapole & Tindel, 2015). Vibration has been shown to reduce the intracortical inhibition of corticospinal outputs to the vibrated muscles (Rosenkranz & Rothwell, 2012).
- The influence on an untrained contralateral limb following a unilateral training program (also known as cross-education) has shown positive effects on the injury rehabilitation process (Hortobágyi *et al.*, 2011; Green & Gabriel, 2018; Manca *et al.*, 2021). Such positive changes in the absence of direct training on the injured region have raised the attention of practitioners as a countermeasure tool in certain unilateral injuries (e.g., hemiparesis caused by stroke, unilateral osteoarticular injuries, anterior cruciate ligament injury, etc.) (Colomer-Poveda *et al.*, 2021).
- Researchers might use brain stimulation techniques (e.g., TMS and direct current stimulation) to address the question of causality by inducing cortical changes and evaluating potential alterations in functional changes (Makin & Flor, 2020).

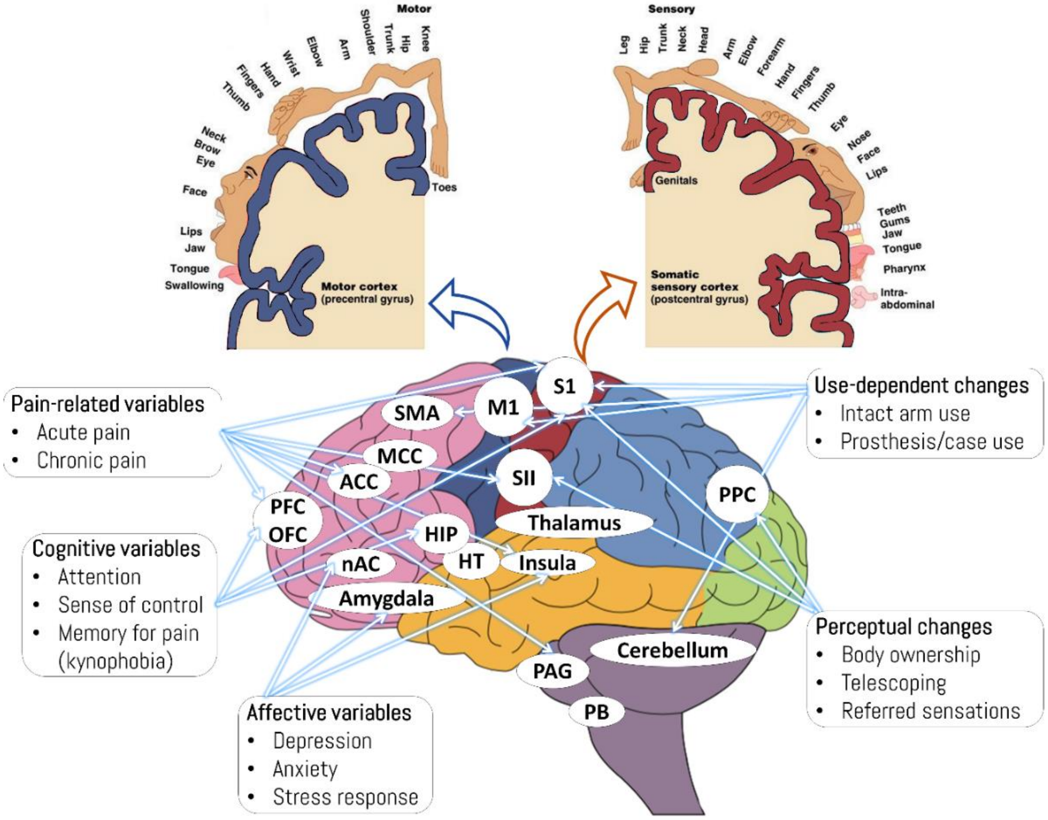

Figure 1. Characteristics of brain reorganization after injuries and musculoskeletal disorders. Source: designed by the authors (D.A.B.) based on Makin & Flor (2020)

ACC, anterior cingulate cortex; BG, basal ganglia; HIP, hippocampus; HT, hypothalamus; M1, primary motor cortex; MCC, midcingulate cortex; nAC, Nucleus accumbens; OFC, orbitofrontal cortex; PAG, periaqueductal grey; PB, parabrachial nucleus; PCC, posterior cingulate cortex; PFC, prefrontal cortex; PPC, posterior parietal cortex; S1, primary somatosensory cortex; SII, secondary somatosensory cortex; SMA, supplementary motor area.

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