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INTEGRAÇÃO ENTRE OS FATORES BIOMECÂNICOS, SENSORIAIS E NEUROFISIOLÓGICOS DO CONTROLE POSTURAL: UMA REVISÃO NARRATIVA

INTEGRATION BETWEEN BIOMECHANICAL, SENSORIAL AND NEUROPHYSIOLOGICAL FACTORS OF POSTURAL CONTROL: A NARRATIVE REVIEW

INTEGRACIÓN ENTRE LOS FACTORES BIOMECÁNICOS, SENSORIALES Y NEUROFISIOLÓGICOS DEL CONTROL POSTURAL: UNA REVISIÓN NARRATIVA

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RESUMO: A literatura carece de trabalhos que abordem de forma mais ampla a interação de fatores extrínsecos e intrínsecos atuando em conjunto para o controle postural (CP), e dada a importância de se compreender as diferentes áreas que consideram o mesmo fenômeno do CP, o objetivo deste estudo é revisar os aspectos biomecânicos, sensoriais e achados neurofisiológicos que contribuem para o controle postural. O CP representa um aspecto básico na vida dos indivíduos e exige uma complexa interação entre diversos fatores que podem ser divididos em extrínsecos e intrínsecos. No caso do fator extrínseco, um exemplo é a força da gravidade, que atua sobre todos os corpos e, devido a distribuição desigual de massa e a forma dos corpos, podem interferir no centro de massa (CoM) de um corpo. Quando o CoM se distancia da base de suporte de um corpo, ocorre uma queda ou é acionada uma estratégia, sendo normalmente a estratégia do passo frente a uma grande perturbação. A regulação do CP é realizada pelos fatores intrínsecos e, o centro de pressão (CoP) é a resultante neuromuscular dessa regulação. Os fatores intrínsecos são aqueles relacionados aos componentes neurofisiológicos e sensoriais do indivíduo, por exemplo, os sistemas sensoriais e neurais. Os sistemas sensoriais que captam estímulos específicos e enviam esses ao SNC são os sistemas visual, vestibular e somatossensorial. O sistema visual capta informações do ambiente para auxiliar na orientação espacial. O sistema vestibular informa sobre as acelerações lineares e angulares da cabeça e, o sistema somatossensorial detecta estímulos de toque, posição do corpo, temperatura e dor. Entre os aspectos neurofisiológicos existem estruturas que atuam diretamente e indiretamente, sendo por exemplo, o cerebelo e o hipotálamo, respectivamente. Assim, conclui-se que o CP é uma habilidade complexa que envolve a integração de estruturas corticais, subcorticais e dos sistemas sensoriais que estão constantemente expostos a diversas forças que atuam sobre o corpo.

Palavras-chave: Equilíbrio estático; Integração sensorial; Neurobiologia; Neurociências.

ABSTRACT: The literature lacks work that address more broadly the interaction of extrinsic and intrinsic factors acting together for Postural control (PC) and given the importance of understanding the different areas that consider the same PC phenomenon, the objective of this study is to review the biomechanical, sensory, and neurophysiological findings that contribute to postural control. PC represents a basic aspect in the life of individuals and requires complex interaction between several factors that can be divided into extrinsic and intrinsic factors. In the case of the extrinsic factors, an example is the force of gravity, which acts on all bodies and, due to the unequal distribution of mass and the shape of the body, can interfere in the center of mass (CoM) of the body. When the CoM is distant from the base of support of a body, a fall occurs or a strategy is triggered, which is normally the step strategy in the face of a major disturbance. This regulation of PC is performed by intrinsic factors and the center of pressure (CoP) is the neuromuscular resultant of this regulation. Intrinsic factors are those related to the neurophysiological and sensory components of the individual, *e.g.*, the sensory and neural systems. The sensory systems that capture specific stimuli and send them to the CNS are the visual, vestibular, and somatosensory systems. The visual system captures information from the environment to aid in spatial orientation. The vestibular system informs about linear and angular accelerations of the head, and the somatosensory system detects touch stimuli, body position, temperature, and pain. The neurophysiological aspects include structures that act directly and indirectly, for example, the cerebellum and the hypothalamus, respectively. Thus, it is concluded that PC is a complex skill that involves the integration of cortical and subcortical structures, and sensory systems, which are constantly exposed to various forces acting on the body.

Keywords: Static balance; Sensory integration; Neurobiology; Neurosciences.

RESUMEN

La literatura carece de estudios que aborden de manera más amplia la interacción de factores extrínsecos e intrínsecos que actúan en conjunto para el control postural (CP), y dada la importancia de comprender las diferentes áreas que consideran un mismo fenómeno de CP, el objetivo de este estudio es revisar la Hallazgos biomecánicos, sensoriales y neurofisiológicos que contribuyen al CP. El CP representa un aspecto básico en la vida de los individuos y requiere una interacción compleja entre varios factores que pueden dividirse en extrínsecos e intrínsecos. En el caso del factor extrínseco, un ejemplo es la fuerza de gravedad, que actúa sobre todos los cuerpos y, debido a la distribución desigual de masa y la forma de los cuerpos, puede interferir con el centro de masa (CoM) de un cuerpo. Al igual que el CoM, el centro de presión (CoP) es preciso para detectar cambios en el CP. Cuando el CoM está demasiado lejos de la base de apoyo de un cuerpo, se produce una caída o se activa una estrategia, que suele ser la estrategia de paso ante una perturbación importante. Esta regulación del CP se lleva a cabo por factores intrínsecos y el centro de presión (CoP) es el resultado neuromuscular de esta regulación. Los factores intrínsecos son aquellos relacionados con los componentes neurofisiológicos y sensoriales del individuo, por ejemplo, los sistemas sensorial y neural. Los sistemas sensoriales que captan estímulos específicos y los envían al SNC son los sistemas visual, vestibular y somatosensorial. El sistema visual captura información del entorno para ayudar en la orientación espacial. El sistema vestibular informa sobre las aceleraciones lineales y angulares de la cabeza, y el sistema somatosensorial detecta los estímulos del tacto, la posición del cuerpo, la temperatura y el dolor. Entre los aspectos neurofisiológicos existen estructuras que actúan directa e indirectamente, por ejemplo, el cerebelo y el hipotálamo, respectivamente. Así, se concluye que la CP es una habilidad compleja que implica la integración de estructuras corticales, subcorticales y sistemas sensoriales que están constantemente expuestos a diversas fuerzas que actúan sobre el organismo.

Palabras clave: Equilibrio estático; Integración sensorial; Neurobiología; Neurociencias.

INTRODUCTION

Postural control (PC) is the ability to preserve or restore posture in any position, even during motor activity, and represents a basic aspect in the lives of individuals (PARREIRA; GRECCO; OLIVEIRA, 2017; CHIBA *et al.,* 2016). PC requires complex interactions between several extrinsic and intrinsic factors. One of the main extrinsic factors is the force of gravity, which acts directly on the body, influencing PC (IVANENKO; GURKINKEL, 2018). Since bodies can present different forms and sizes, their morphological characteristics influence the distribution of the body mass and, consequently, the positioning of the CoM (HO HOANG; MOMBAUR, 2015). The CoM is the point of action of the gravitational force on the body and its displacement refers to the oscillation of the body, through which the PC can be evaluated (WINTER, 1995). In addition to the CoM, the center of pressure (CoP) is the neuromuscular result of the regulation of PC and it is a measure widely used to investigate PC. This measure is obtained by posturography of force platform and is simpler, since it is not necessary to apply mechanical models (CRETUAL, 2015). However, even though it is important to understand the methods of prediction and measurement of PC, these should not be restricted to biomechanical bias, since biomechanics does not address the intrinsic factors of the individual that act simultaneously for PC to occur, this being an investigation which transcends the expertise in the area. In this sense, the importance of intrinsic factors related to

PC has been investigated (SAMUEL; SOLOMON; MOHAN, 2015; BRONSTEIN, 2016; CHIBA *et al.,* 2016).

Intrinsic factors are those related to the sensory and neural systems (SAMUEL; SOLOMON; MOHAN, 2015). Sensory systems are part of the nervous system; however, they are structures specialized in capturing internal and external stimuli to the body. This system captures stimuli specific each structure, and the dynamics that surround PC occur through multisensory integration between the visual, vestibular, and somatosensory systems (BRONSTEIN, 2016; CHIBA *et al.,* 2016). Each of these systems has specific functions for PC. The visual system captures information from the environment to aid in spatial orientation (orientation based on the interpretation of sensory information from somatosensory, vestibular, and visual systems; HORAK, 2006). The vestibular system is responsible for informing the central nervous system (CNS) about linear and angular accelerations of the head and how it is inclined in relation to gravity. The somatosensory system detects muscular stretches and contractions through the receptors of the muscle spindles and Golgi tendon organs, respectively (KANDEL *et al.,* 2014). In addition, the somatosensory system has mechanoreceptors, joint receptors, and nociceptors. Mechanoreceptors inform about the shape and strength characteristics of objects that come into contact with the skin (JOHNSON, 2001). The joint receptors are responsible for kinesthesia, which provides a reference of the positioning of the body parts in relation to an internal referential (TEIXEIRA, 2006). Nociceptors are selective receptors that respond to stimuli that can damage tissues (KANDEL *et al.,* 2014). After receiving the sensory stimuli, the afferent routes send the information to the CNS to be processed and contribute heavily to modulation of PC (BRONSTEIN, 2016).

The neural system contains important structures that act directly (*e.g.*, cerebellum) and indirectly (*e.g.*, hypothalamus) on PC (CEBOLLA*et al.*, 2016; SIBLEY *et al*., 2014). While the cerebellum contributes to the maintenance of equilibrium and is hyperactivated when the eyes are closed (CEBOLLA *et al.,* 2016), the hypothalamus is responsible for the homeostasis of the individual (*e.g.*, pH and temperature), without which, the action of the cerebellum and any other structures collaborating in PC would not be possible (SIBLEY *et al*., 2014). In PC, there is also the action of other subcortical structures and specific regions of the cerebral cortex (LORAM, 2015), which are noteworthy due to the complexity of the communication between them. However, regardless of all the neurophysiological components, it should be remembered that these PC modulations occur against a factor which is extrinsic to the body, *e.g.*, vertical gravity vector (modulations occur so that postural orientation occurs in relation to the vertical vector of gravity) (IVANENKO; GURKINKEL, 2018) and therefore, PC analysis should consider extrinsic and intrinsic factors.However, in spite of investigations that analyze the contribution of sensory information to PC and studies that attempt to understand the neural functions in motor control, few studies have tried to systematize the contributions provided by the sensory system and the neurophysiological aspects, together with the biomechanical factors of PC.

As the literature still lacks works that address more broadly the interaction of extrinsic and intrinsic factors acting together for PC and given the importance of understanding the different areas that consider the same PC phenomenon, the objective of this study is to review the biomechanical, sensory, and neurophysiological findings that contribute to postural control. The present study systematizes information that will aid in understanding the importance of biomechanical, sensorial, and neurophysiological information in PC regulation.

BIOMECHANICS OF POSTURAL CONTROL

Among the most commonly used methods to investigate PC are analysis of the CoP and CoM of an individual (CRETUAL, 2015). The CoP is a displacement measure, representing the central point of application of the vertical vector of the ground reaction force and is obtained by the opposite value of the weighted mean of the location of all internal and external forces acting on the body (WINTER, 1995). The CoM is the point of action of the gravitational force on the body and is obtained through the weighted mean of the CoM of all the body segments (WINTER, 1995).

The relationship between CoP and CoM in the anteroposterior direction can be observed in figure 1, which considers the inverted-pendulum model. In the transition from moment 1 to 2, it is possible to observe that CoM moves anteriorly while velocity and angular acceleration increases and, as CoP is a neuromuscular correction in relation to CoM (WINTER; PATLA; FRANK, 1990), also moves anteriorly (ApGRF), thus avoiding a possible fall. In the transition from moment 2 to moment 3, it is observed that the angular acceleration it is decreasing, passing through zero and subsequently presenting negative values (considering the previous direction as a positive vector). With the posterior displacement of the CoM, a new increase in speed starts to occur. CoP follows ApGRF until the previous wobble stops. To be counterbalanced, a new CoP shift in the opposite direction is necessary and this change continues to occur constantly (WINTER, 1995). The transition from moment 3 to 4 is similar to that from moment 2 to 3, considering only the change of direction, and the transition from moment 4 to 5 is similar to the transition from moment 1 to 2, also considering the reversal of direction. From moment 5 on, a new cycle starts.

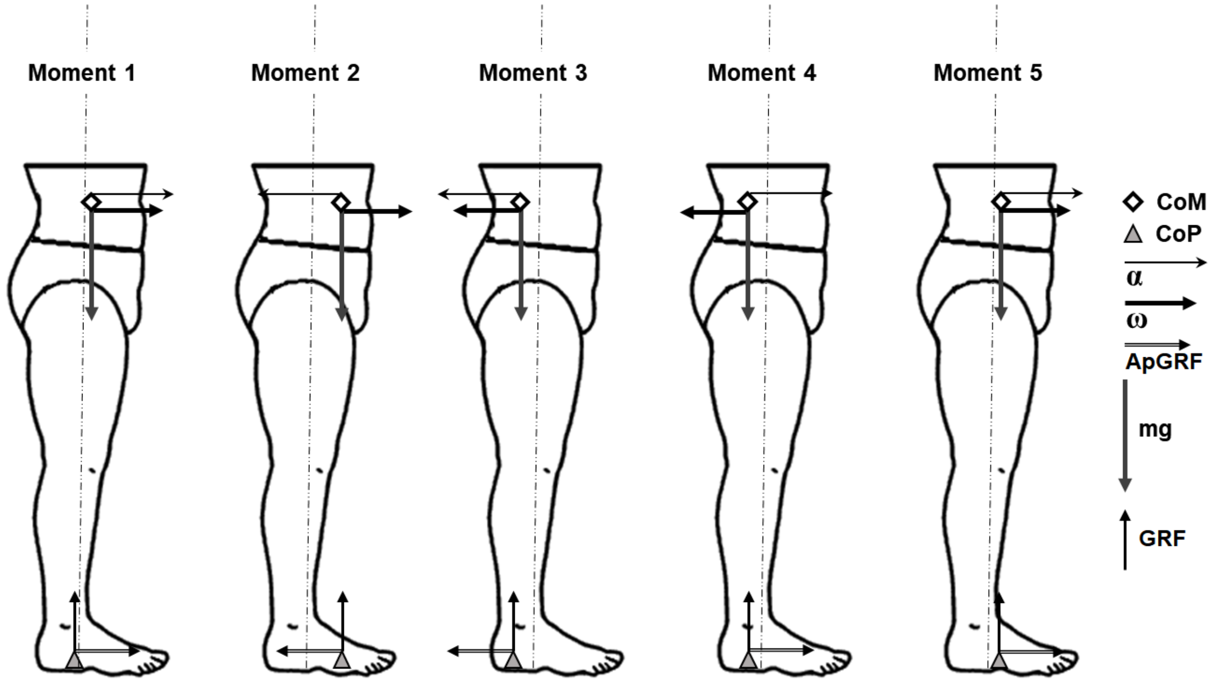

Figure 1. Subject swaying in the anteroposterior direction in a quasi-static upright posture. Five different moments are represented by the center of mass (CoM), center of pressure (CoP), angular acceleration (α), angular velocity (ω), anteroposterior component of the ground reaction force (ApGRF), weight force (mg), and ground reaction force (GRF). Modified from Winter (1995).

The CoM of the segments are obtained through models that, when applying the equations, allow the identification of these points. Assigning the concept of CoM (WINTER, 1995) to De Leva's model (1996) for example, there is a local system (LS) of the segments LS_j (x_j, y_j, z_j) so that according to the model, $1 \leq j \leq 13$ and moves from the origin of a global system (GS), this being GS_0 (x_0, y_0, z_0) (figure 2) (BARTON *et al.*, 2015). For this model, the length of the segment is used, based on the markers placed on anatomical accidents and, later, the value established by the author De Leva (1996) is considered to apply the value of proportion corresponding to the segment. Thus, creating a "virtual marker" by qualifying the CoM of the segment. To calculate the body's CoM, a weighted average is considered, considering the different contributions of each segment to the CoM of body, which is also presented by De Leva (1996). The CoM can be characterized as a midpoint, so that the distribution of mass in the body is considered for its identification. Thus, men and women, as well as young people, older adults, and children have different mass distributions, which should be considered for the projection of CoM(HO HOANG; MOMBAUR, 2015).

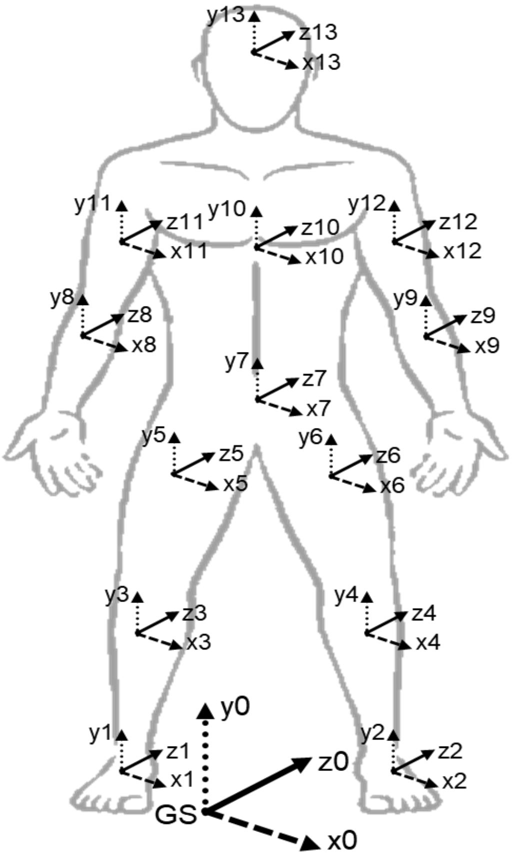

Figure 2. Biomechanical model for the calculation of CoM. In this model thirteen segments are considered for the calculation of the CoM, the mass of the hands being disregarded. These segments move from the origin of a global system (GS) which has a zero value for the components of the lateral (x), anteroposterior (z), and vertical (y) positions. Modified from Barton *et al.* (2015).

The PC skill aims to provide postural orientation, balance, and postural stability. According to Horak (2006), postural orientation encompasses the maintenance of body alignment and muscle tone in relation to internal and external references (*e.g.*, gravity and environment). Balance, in turn, comprises coordinating sensory and motor strategies that allow postural stability against external disturbances and; the postural stability of a body occurs through maintenance of the vertical projection point of the CoM on the ground (CoG, center of gravity) in the area of the base of support (BoS, area created from all contacts of a body with the support surface) (WINTER; PATLA; FRANK, 1990; POLLOCK, 2000), so that when the CoG moves away from the center of the BoS there is a decrease in stability and when it exceeds the limits of the BoS a movement is made (for an object, for example) or it results in a fall.

In addition to the possible fall, the subject usually performs the step strategy, in which the subject performs a step (front, side or back) to increase the base of support. In addition, there is also the hip strategy (in which there is an anticipatory activation of the proximal muscles of the trunk and hip) and ankle (in which the body acts as an inverted pendulum and moves in the anteroposterior direction, being used only with small oscillations) (CARNEIRO *et al*., 2013). There are three ways to improve the stability of an object or an individual, being: a) by verticality of the line of gravity (approximation of distance between CoM and CoG); b) the increase in BoS; and c) by a more centrally located CoG (POLLOCK, 2000). In this way, for example, when walking on a surface with less grip (such as on a wet floor) it is common to start from a position with the feet further apart (improves stability due to increased base support – POLLOCK, 2000), a slower movement (allows more time for compensatory postural adjustments - will be dealt with later - SANTOS; KANERKA; ARUIN, 2010), and perhaps opening of the arms (decreases the amplitude and speed of head movements - PATEL *et al*., 2014), as all these changes favor better stability.

Investigations which use CoP alone are usually performed due to the accessibility of direct measurements, since it is possible to acquire data with a single force/pressure platform (CRETUAL, 2015). However, this method restricts movement to an inverted pendulum model, based on the ankle joint (WINTER, 1995; IVANENKO; GURKINKEL, 2018), and it should be applied with caution to the elderly population, given that the aging process causes changes in stability parameters (KING; JUIZ; WOLFSON, 1994) and that this population seems to have greater dependence on the hip joint (AMIRIDIS; HATZITAKI; ARABATZI , 2003), limiting research to few dynamic conditions, *e.g.*, upper limb movements, flexion movements plantar (in the standing position) and beginning of a step.Besides these, would not be expected to obtain data (only for the force and pressure variables) from some other dynamic tasks, for example, running, since there is a period in which the foot totally loses contact with the ground. In these situations, dynamic analysis would be more difficult and/or unfeasible to perform through this method, since this instrument records information on forces and pressure (CRETUAL, 2015).

Postural analysis through the CoM presents the positive differential of enabling performance of multi-segmental analysis, which considers the innumerable degrees of freedom represented by the joints (KILBY; MOLENAAR; NEWELL, 2015; HSU *et al.*, 2007). However, this method requires kinematic analysis and the application of predictive mathematical models, which consequently demands greater time and processing to obtain the data (CRETUAL, 2015). Although these methods present limitations and/or points that hinder their use, both are precise enough to indicate changes in the PC of an individual with precision, when handled properly (Lafond; Duarte & Prince, 2004). Besides the contribution of biomechanics to PC, the sensorial systems also play an essential role in modulating balance (BRONSTEIN, 2016).

MULTISENSORY INTEGRATION AND POSTURAL CONTROL

The operation of PC involves multisensory integration (CHIBA *et al.*, 2016; BRONSTEIN, 2016). This integration refers to modulation of the visual, vestibular, and somatosensory systems, acting together with the force of gravity and controlled by the CNS to establish the regulation of the muscles involved in posture (BRONSTEIN, 2016). Each of these systems has a different function. The visual system captures information from the environment by means of light stimuli to aid in the orientation of the body in space (HORAK, 2006). The light stimulus enters the cornea, and sequentially traverses the anterior chamber, pupil, lens, and vitreous body until it reaches the retina, where the receptor cells are located, called cones and rods, which convert the light signal into electrical impulses (KELS *et al.*, 2015). This system participates in spatial orientation and can aid in reducing body oscillations under static conditions (WHITE; POST; LEIBOWITZ, 1980; THOMAS *et al.*, 2016).

The vestibular system makes use of five receptors (vertical anterior, vertical posterior, and horizontal semicircular canals, utricle, and saccule) located within the petrous portion of the temporal bone (KANDEL *et al.*, 2014). The semicircular canals are small circular tubes which contain hair cells that convert mechanical stimuli into neural signals, informing the CNS about the movements and angular accelerations of the head. The otolith organs detect linear accelerations (*e.g.*, gravity), thus indicating how much the body is inclined in relation to gravity (XU *et al.*, 2017; KANDEL *et al.*, 2014).

Vestibular signaling influences the direction of a postural response by means of the head orientation in relation to gravity, thus, when a slope occurs on the surface of the ground, this system causes a head inclination, usually followed by compensatory movement of the whole body, in the opposite direction, so that, in a compensatory way, the individual remains stable (KANDEL *et al.*, 2014).

The somatosensory system has receptors throughout the body that inform the CNS about touch stimuli, body position, temperature, and pain. This system has different groups and types of nerve fibers and receptors for its performance, these being muscle spindles, Golgi tendon organs, mechanoreceptors, joint receptors, and nociceptors. In muscle spindles and

Golgi tendon organs, somatosensory nerve fibers can be classified into groups I and II, and the fibers of group I are divided into fibers of type Ia and Ib. The Ia fibers are the afferents of the spindle receptors and the Ib of the Golgi tendon organs. The fibers of group II belong to muscle spindles and have postural functions; however, they are too slow to generate the beginning of a PC response (KANDEL *et al.,* 2014).

Spindles are bundles of fine muscle fibers (intrafusal fibers) that form a capsule and are parallel to muscle fibers. This capsule has sensory axons that detect the muscular extension through ion channels located in mechanoreceptors in the nerve endings, thus, these receptors can provide information about voluntary or passive movement, realized by external forces. The Golgi tendon organs (GTO) are an encapsulated complex of collagen and nerve fibers located at the musculotendinous junction and are responsible for detecting alterations in muscle tension, thus being more active in contractions (KANDEL *et al.*, 2014). In addition to reflex movements performed through excitation of the spindles and GTO, anticipatory posture adjustments (APAs) and compensatory adjustments (CPAs) are also performed. In APAs, the previous activation or inhibition of muscles of the trunk and legs is performed to reduce the postural consequences of the predicted postural disturbance (BOUSSET & ZATTARA, 1987; SANTOS; KANEKAR; ARUIN, 2010) and the amplitude and duration adjustments depend on the parameters of the disturbance (BOUISSET; RICHARDSON; ZATTARA, 2000). Still, recent studies indicate that transcranial magnetic stimulation, when performed in the supplementary motor area, has an inhibitory effect on APAs (TSURU *et al.,* 2020). CPAs are performed after the disturbance and are used with the objective of restoring the position of the CoM (BOUSSET & ZATTARA, 1987; SANTOS; KANEKAR; ARUIN, 2010).These adjustments start through feedbacks from the sensory systems (PARK; HORAK; KUO, 2004) and according to Claudino, Santos and Santos (2013), the CPAs are changed in the face of postural disturbances in the lateral direction, but this study was conducted only with seniors. Corroborating this finding, Mota*et al*. (2020) demonstrates that the aging process itself can be a factor that causes changes in the responses of CPAs.

Mechanoreceptors are non-myelinated afferent neurons divided into two types and each has a fast or slow adaptation receptor that provides distinct information on a touch stimulus. Among the type 1 receptors are the SA1 (slow adaptation type 1) and RA neurons (rapid adaptation type 1). The SA1 cells correspond to the cells of the Merkel disc and are sensitive to the deformation field, thus providing information about the edge and corner of the touch area. The rapid adaptation neurons (RA) or Meissner's corpuscles are cells sensitive to friction and sliding objects on the skin (JOHNSON, 2001). Type 2 mechanoreceptors are composed of cells of slow (AL2) and rapid adaptation (AR2). Ruffini's corpuscles or slow adaptation type 2 cells are much less widely distributed than SA1 or RA, have sensory fields which are about five times greater, and may be two to four times more sensitive to skin stretching than SA1 receptors (JOHNSON, 2001). In conjunction with SA1 receptors, AL2 receptors are primarily responsible for the detection of pressure points, and an example of almost exclusive use of these receptors is reading Braille (KANDEL *et al.*, 2014). The AR2 cells, or Paccini corpuscles, are located deep in the skin and yet are the most sensitive of the mechanoreceptors, for example, the vibration of a cell phone in a pocket can easily be perceived by these receptors, which capture frequencies from 30 to 150 Hz and skin movements of about 10 Hz. However, although the AR2 have high sensitivity, they have low spatial resolution capacity (JOHNSON, 2001). Through their combined action and the functional characteristics of all these receptors, PC can be improved with the gentle touch of only one finger on a rigid and stable surface during upright posture (BALDAN *et al.*, 2014), demonstrating the importance of this system to PC.

The joint receptors are responsible for kinesthesia. Although kinesthesia may be very important in dynamic situations, it is less important in PC in more static situations (TEIXEIRA, 2006). For example, although joint receptors may assist in identifying a joint angle, there are other receptors that collaborate with more accurate spatial and temporal information about the body. This is the case with muscle spindles and skin stretching receptors for finger positions, for example. However, it is possible that joint receptors also contribute to perception (KANDEL *et al.*, 2014) and, although the decrease in collaboration in static situations, are still sensitive enough to detect vibrations (CEYTE *et al.*, 2007) and temperature changes (SCHLEE; RECKMANN; MILANI, 2009), for example.

Nociceptors are selective receptors that respond to stimuli that can damage tissues. These should be considered in PC, since pain/injury can cause alterations in posture due to the adoption of a less painful posture or, by reducing the excitatory threshold of cells of a certain region affected by an injury (KANDEL *et al.*, 2014).

However, complex the multisensory integration is and its operation in the modulation of PC, there are several everyday situations that make these more explicit. Throughout the day, an individual is subject to various environmental and/or physiological alterations that disturb PC (*e.g.*, poorly lit environments and slippery floors) so that the individual performs PC while carrying out other tasks simultaneously (BONNET; BAUDRY, 2016).For this, the

CNS modulates the priority of each system in order to guarantee appropriate PC for the task to be performed (HORAK, 2006; FAQUIN *et al.*, 2018). An example of a task is PC in individuals on a moving bus. When the ground surface declines to the left, it causes the vehicle to decline to the same side (Figure 3). At that moment the hair cells present in the semicircular canals, the utricle and the saccule have already detected the accelerations present and inform the direction of the slope of the surface and how much the individual has tilted in relation to gravity (KANDEL *et al.*, 2014).

This inclination also causes the CoM to move and consequently there will be flexion and/or extension in one of the upper limbs which is supported (independent of the side) to minimize the CoM displacement and increase stability. Through the shortening/stretching of their muscles caused by flexion/extension of the upper limb (s), the individual may also notice the occurrence due to the muscle spindles. In the tendons, the Golgi tendon organs detect the tension generated by one of the muscles in the body. These two receptors together inform about the positioning of the body segments in space and the orientation of one against the other and transmit this information to the CNS (KANDEL *et al.*, 2014).

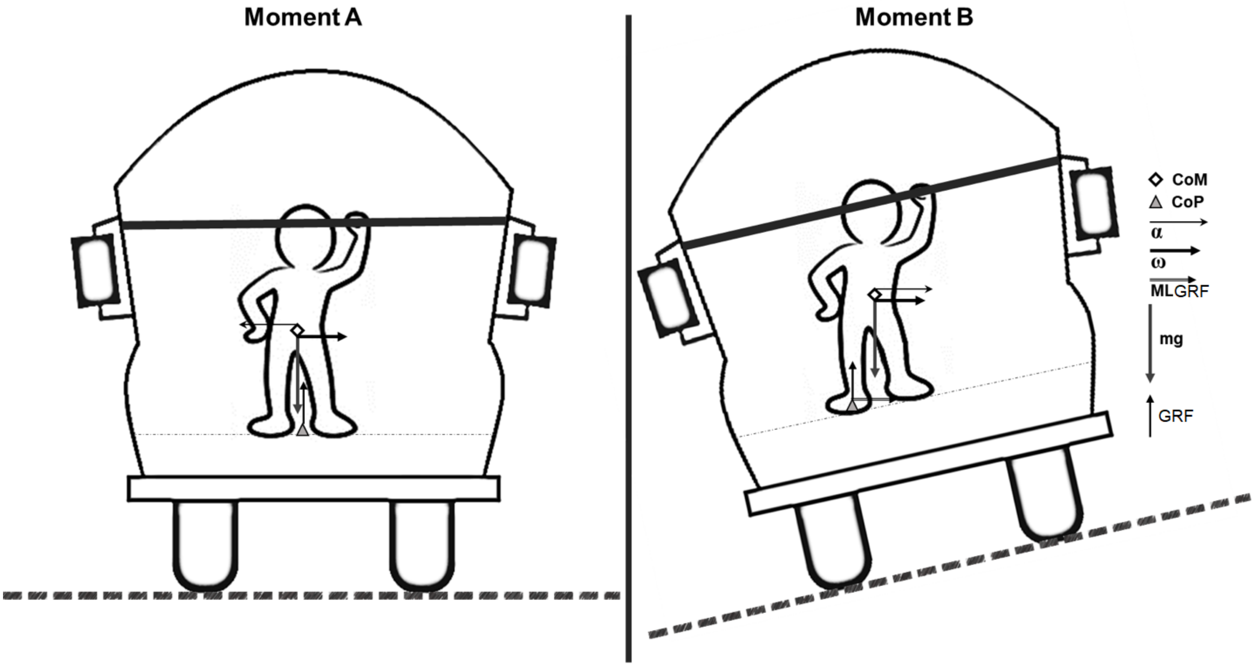

Figure 3. Subject swinging in the medio-lateral direction in a quasi-static upright posture. Two different moments are presented, consisting of the center of mass (CoM), center of pressure (CoP), angular acceleration (α), angular velocity (ω), medio-lateral component of the ground reaction force (MLGRF) (mg), and ground reaction force (GRF).

After milliseconds, this information has already been processed and the efferent signal begins its journey. The inclined/right hemibody musculature flexes until it reaches adequate values and receives innumerable action potentials that keep this musculature contracted almost as if it were in isometry (LIPPOLD, 1952; TOMKO *et al.*, 2018). Simultaneously, the declined/left hemibody extends and adopts the same behavior. These alterations in posture project the direction of the ground reaction force to the right side, while the CoP continues on the left side, remaining close to the location attained until the surface inclination alters again and this returns to being located centrally in relation to the BoS area of the body.

Among all the systems that influence body oscillation, the interactions between the visual and vestibular systems are the most commonly studied today, due to the importance of integrating these systems into PC (BRONSTEIN, 2016). For example, according to Parreira (2017), despite alterations in the organization of neurons due to neural plasticity as a way to compensate for the absence of visual information, congenital blind individuals present impaired PC when compared to subjects without visual impairment. In another study, it was observed that in individuals without visual impairment the signals are sent to the CNS and have a priority character in PC, since incorrect visual stimuli can suppress vestibular and proprioceptive signals, generating mistaken postural responses (BRONSTEIN, 2016). In contrast to these points Simoneau*et al.* (1995) and Peterka (2002) showed that, among all sensory systems, the somatosensory is the most relevant for PC. This is because its collaboration is much larger than the other systems, and alterations and/or disturbances in this system could increase the displacement of an individual's CoP by more than 60%.

Despite the numerous discussions about the relevance of each system, it is worth emphasizing that the idea of multisensory integration is to demonstrate that all sensory systems are of great importance and act simultaneously in PC. These systems act together, but with different proportions of contribution. The CNS ponders, or ranks, the relevance of each system (visual, vestibular, somatosensory) according to the situation to be faced and, during disturbance or suppression of a system, the CNS adapts and reorganizes the initial hierarchy (HORAK, 2006; BRONSTEIN, 2016; FAQUIN *et al.*, 2018). All ranking of sensory systems is performed by the CNS and its neurophysiological components, which are equally important for PC.

NEUROPHYSIOLOGICAL COMPONENTS OF POSTURAL CONTROL

The brain can act two ways on the PC. It is automatically defined when an action is performed but attention is not focused on the task/action being performed and, cognitively, when the action is perceived and, consequently, attention is focused on that task, thus controlling deliberate and conscious of the action (NORMAN & SHALLICE, 1986).

Recent studies have shown that the brain can act in the automatic regulation of PC (BOLTON, 2015; MURRAY *et al*., 2016) and, according to Degani*et al*. (2016), the brain actually plays an important role in PC, since individuals with brain trauma, even when mild, present deficits in PC when compared to non-injured individuals. According to Slobounov*et al*. (2005) and Bolton (2015), the motor cortex seems to be related to rapid balance reactions and also to anticipated reactions that aim to optimize balance recovery. In addition, Murray *et al*. (2016) pointed out that the primary visual cortex has multisensory participation in this regulation.

When cortical action is for the cognitive regulation of PC, the number of tracts and pathways that integrate for this ability is increased, that is, in addition to the sensory and efferent pathways corresponding to automatic regulation, the number of routes collaborating for control of posture increases due to cortical action. This does not mean that there will be less collaboration of subcortical structures (*e.g.*, cerebellum), but when "awareness" of this type of ability occurs (*e.g.*, in the performance of a new motor task), there is simultaneous transmission to the cerebral cortex via the cortico-cerebellar point and sensory feedback by the spinocerebellar tract, which may play an important role in PC (TAKAKUSAKI, 2017).

The CNS presents three levels of control for the PC. The first level refers to the spinal cord, that transfer of nerve impulses afferent (from the periphery to the CNS), interneurons, and motor/efferent impulses (from the CNS to the periphery). These neurons are responsible for responsible for performing basic reflex and/or locomotor patterns. Recent studies have identified that incomplete spinal cord injuries can cause changes in stability due to a decrease in afferent signals from the somatosensory system (NOEMANI *et al*., 2020; NOEMANI *et al*., 2021). The second level adds the performance of the vestibular nuclei and the reticular formation, and the final level involves the conjunction between cortical and subcortical structures (LORAM, 2015).

For PC to occur, the transmission of various stimuli and the processing of sensory signals in the CNS are necessary. Figure 4 shows the path covered by the visual stimulus and the possible associations with other structures during quasi-static upright posture. After being converted into an electrical signal, the stimulus is sent by the optic nerve to the primary visual cortex (V1), which has projections to the regions of the posterior parietal cortex (PPc). This information is sent via the supplemental motor area (SMA) to the dorsal region of the premotor cortex (dPM), then it is routed to the primary motor cortex (M1), and while the dPM receives prefrontal cortex (PF) projections, the M1 cortex has dual (afferent-efferent) pathways to the basal ganglia (BG) and cerebellum (C), as well as efferent pathways to the red nucleus (Rn) in the midbrain, which also receives projections from the cerebellum (LORAM, 2015). After all neural processing, the efferent signal can also be sent to the brainstem precisely in the pedunculopontine nucleus (PPn) in the ventrolateral tegmental portion of the reticular formation (RF). This region receives information from the cerebellum and enables the efferent signal to be conducted via the spinal cord through the vestibulospinal tract (TAKAKUSAKI, 2017).

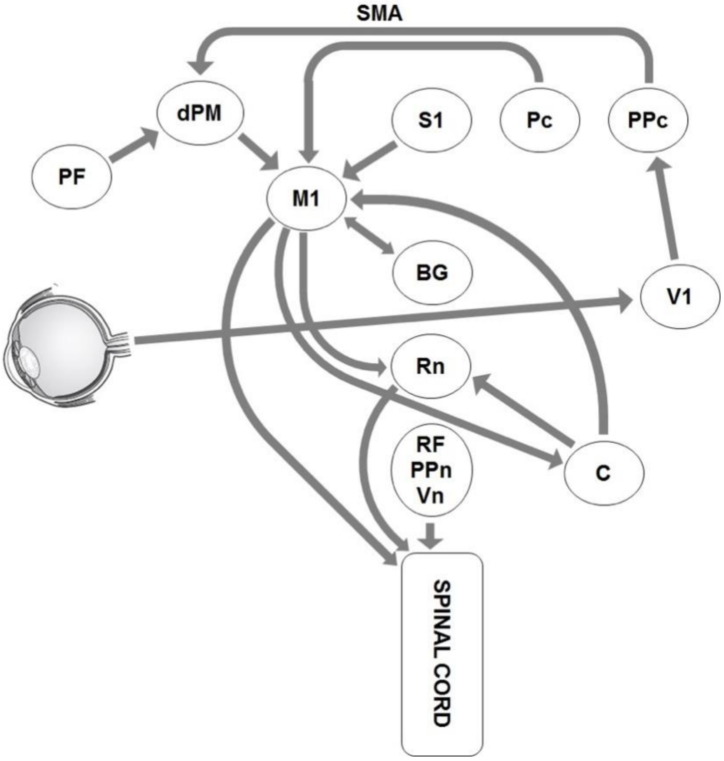

Figure 4. Schematic of the pathways and structures acting on postural control during quasi-static upright posture. During this task, complex integration is necessary and for each degree of control the addition of structures and their respective pathways are required, being: primary visual cortex (V1); regions of the posterior parietal cortex (PPc); supplementary motor area (SMA); dorsal region of the pre-motor cortex (dPM); primary motor cortex (M1); prefrontal cortex (PF); primary somatosensory cortex (S1); areas of the parietal cortex (Pc); basal ganglia (BG); red nucleus (Rn); reticular formation (RF); pedunculopontine nucleus (PPn); and vestibular nucleus (Vn). Modified from Loram (2015).

According to Drijkoningen*et al*. (2015), the smaller brainstem volume is associated with impairment in static and dynamic CP, in addition to being used as a predictor for greater deviations in CoP and greater chance of loss of balance, and, for Boisgontier*et al.* (2017), the brainstem is related to the ability to perform PC, so that the PPn nucleus is the brain subarea that has the greatest relation to PC. Corroborating this finding, Gallea*et al.* (2017) pointed out that the PPn nucleus and its connections with the supplemental motor area are really important for the total time of postural adjustments, since patients with Parkinson's disease take longer to make postural adjustments and are therefore more likely to suffer falls. BG are also present in the brainstem. These nodes are inversely related to better PC, that is, the larger the volume of these structures, the worse the PC (BOISGONTIER *et al.*, 2017). This could be justified by exaggerated postural adjustments (BOISGONTIER *et al.,* 2017). For example, if an individual needs to perform a small displacement (*i.e.*, 3 cm) to maintain stability, with an exaggerated adjustment this displacement would be greater than necessary and could cause a new imbalance. Nevertheless, the BG can also contribute to the modulation of PC through the performance of GABAergic neurons in the cortex and brain stem (TAKAKUSAKI, 2017). Besides the action of the brainstem there is also action of the cerebellum in PC (CEBOLLA*et al.,* 2016).The cerebellum is an organ located in the cerebellar fossa of the occipital bone that has projections to the brainstem, mesencephalon, cerebral cortex, nuclei, and vestibular apparatus, contributing to motor coordination and maintenance of muscle tone, and exerting a role in balance (KANDEL *et al*., 2014; BARLOW, 2005).

Through electroencephalography, it was observed that individuals in a waking state and with visual occlusion present an increase in the neural activity of the α-type waves (indicating cortical activity) in the parietal-occipital portion of the skull. Thus, when the eyes are closed the collaboration of the cerebellum in PC is increased (CEBOLLA *et al*., 2016). Studies show that the cerebellum can be stimulated for improvement of different motor actions (FOERSTER *et al.,* 2017; JAYARAM *et al.,* 2012). For example, Jayaram *et al*. (2012) found that in a walking activity with transcranial direct current stimulation, the anodic (negative) waves favored the cerebellar action, and the cathode (positive) waves interrupted this action, altering the spatial notions of the gait, but not the temporal notions. Thus, this finding indicates a possible future use of transcranial stimulation in motor rehabilitation, either with a modulatory role or to facilitate motor learning. In the study by Foerster *et al.* (2017) it was shown that when stimulation occurs in the right cerebellar hemisphere by positive waves, there is impairment in static unilateral balance. According to the authors, this may have occurred because stimulation of the positive waves diminished the responsiveness of the cerebellar neurons. PC is a complex task that does not only require participation of structures that act directly, since for these structures to act, homeostasis of the environment is necessary.

According to Sibley *et al*. (2014), part of the PC is due to autonomic contributions. Since the autonomic nervous system (ANS) coordinates the involuntary control of viscera and other soft tissues, with the exception of the muscular system (IAIZZO; FITZGERALD, 2015), it triggers a series of physiological responses due to alterations in posture (SIBLEY *et al.*, 2014). One example of physiological alterations due to changes in posture is orthostatic hypotension. This condition occurs during the transition from a horizontal to vertical (upright) position due to displacement of almost 500 ml of blood to the venous system below the diaphragm, resulting in a rapid decrease in blood volume and mean arterial pressure, systolic volume, and pre-ventricular load (RICCI; DE CATARINA; FEDOROWSKI, 2015). Although the hypothalamus is indirectly related to PC, its large importance is due to the control of homeostasis, since without the control of the internal variables of the body (e.g., pH and temperature), there would not be activation of all other systems that collaborate in PC (IAIZZO; FITZGERALD, 2015).

In addition to the CNS, the muscular system plays a role as important as the other PC systems (HORLINGS *et al*., 2008). The muscular system acts on PC mechanisms through non-linear joint oscillations, muscle activities with temporal delay, and closed *feedback* control. The non-linear articular oscillations refer to the insufficiency of the passive stiffness of muscles, tendons, and ligaments to resist the torque generated by the gravitational force acting on the inclination of the body. This movement begins with the muscular system with a time lag regarding the time for the stimulus to reach the CNS for neural processing and then the response returns via the efferent pathway to the effector muscles (TANABE; FUJII; KOUZAKI, 2017), however, it is not a rule that the activation of a particular efferent pathway presents a specific response. This is because the response generated is very dependent on the neurotransmitter used, since the RF is composed of different types of neurons, including monoaminergic, cholinergic, GABAergic, and glutamatergic (MENA-SEGOVIA, 2016; BROWNSTONE, CHOPEK, 2018). For example, during standing posture, the ventral neurons of the tegmental nucleus become active, whereas for suppression of muscle tone or for atony, neurons are activated starting from the pontomedullary nucleus of the RF and located in the dorsomedial portion of the spinal reticular tract. In addition, even in animals such as cats, it has been observed that the neurons of the PPn nucleus can suppress muscle tone via their cholinergic projections to the pontine nucleus of RF (TAKAKUSAKI, 2017).

The neurophysiological structures that act in PC are subject to several conditions and/or situations that alter their functioning. The study by Jacobi *et al*. (2015), for example, demonstrated that dual tasks (which required a task of static postural control and a cognitive task of verbal memory) in patients with cerebellar degenerative diseases (CDD) and healthy young people were able to restrict the movement of CoP in both groups, and this restriction may be related to cases of falls. Furthermore, the group of individuals with CDD presented a higher number of errors than the group of healthy young people and, when considering only the CDD, the double task increased the number of falls. The study by Zhou *et al*. (2015), demonstrates a similar pattern of CoP limitation in the double task compared to the simple task of PC in older adults. This study also demonstrates that transcranial electrical stimulation is able to improve performance in dual tasks, but little change in simple tasks. In addition to the conditions, Cameron and Lord (2010) argue that structural degradations (e.g., degradation of pathways due to multiple sclerosis) are also factors that influence PC, since, for example, they alter the response time to a stimulus in patients with multiple sclerosis due to slow conduction of somatosensory system afferents. Thus, this point can be applied to all other neurophysiological structures, demonstrating the importance of these for PC.

CONCLUSION

From this review we can conclude that PC is a complex and multivariate ability. The body is constantly exposed to various forces, and these are demonstrated in a cause-effect relationship with PC, so that at any moment postural adjustments are initiated, starting from an extrinsic or intrinsic factor; yet these adjustments can be cognitive or automatic. PC depends on the integration of cortical, subcortical, and sensory systems, and this association allows the action of the three levels of control.

We suggest future studies that address postural control during other tasks, such as walking, running, and jumping, as well as investigation of the alterations and different demands at the neurophysiological level. We also suggest the subject be approached by means of a systematized search method, which was not performed in the present study.

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Conflict of interest statement

We declare that we have no conflict of interest.

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