

MECHANISTIC AND PHYSIOLOGICAL ASPECTS

Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls?

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Abstract

Postural control is no longer considered simply a summation of static reflexes but, rather, a complex skill based on the interaction of dynamic sensorimotor processes. The two main functional goals of postural behaviour are postural orientation and postural equilibrium. Postural orientation involves the active alignment of the trunk and head with respect to gravity, support surfaces, the visual surround and internal references. Sensory information from somatosensory, vestibular and visual systems is integrated, and the relative weights placed on each of these inputs are dependent on the goals of the movement task and the environmental context. Postural equilibrium involves the coordination of movement strategies to stabilise the centre of body mass during both self-initiated and externally triggered disturbances of stability. The specific response strategy selected depends not only on the characteristics of the external postural displacement but also on the individual's expectations, goals and prior experience. Anticipatory postural adjustments, prior to voluntary limb movement, serve to maintain postural stability by compensating for destabilising forces associated with moving a limb. The amount of cognitive processing required for postural control depends both on the complexity of the postural task and on the capability of the subject's postural control system. The control of posture involves many different underlying physiological systems that can be affected by pathology or sub-clinical constraints. Damage to any of the underlying systems will result in different, context-specific instabilities. The effective rehabilitation of balance to improve mobility and to prevent falls requires a better understanding of the multiple mechanisms underlying postural control.

Keywords: *posture, balance, falls, sensory*

Perspectives on postural control shape assessment and rehabilitation of balance

Our assumptions concerning how balance is controlled shape how we assess and treat balance disorders [1–3]. For example, balance control was once assumed to consist of a set of reflexes that triggered equilibrium responses based on visual, vestibular or somatosensory triggers [4]. Likewise, it was assumed that one, or a few, 'balance centres' in the central nervous system (CNS) were responsible for the control of balance. This simple view of a balance system is quite limiting and can partially account for our limited abilities to assess risks of falling accurately, to improve balance and to reduce falls [5–7].

The assumption of one balance system leads us to believe that one balance test can be used to measure balance efficacy. It leads to the assumption that tasks requiring 'good balance' can be ranked according to difficulty. And it leads to the assumption that generic 'balance exercises' can be used to improve the unitary 'balance system' in a group

of people with balance disorders and frequent falls. If the control of balance actually consisted of one neural system, such as the vestibulospinal system, it would be possible to evaluate and to treat this one system to prevent falls.

Alternatively, if the ability to stand, to walk and to go about daily activities in a safe manner depends on a complex interaction of physiological mechanisms, then many systems need to be evaluated to understand what is wrong with a person's balance. No one balance test could identify balance capability among a group of individuals, each of whom has a unique combination of constraints that affect their balance control. Treatment to improve balance—treatment aimed at practising just one or a few balance tasks—can never be optimal for every individual. For example, a person who falls due to ankle weakness would not benefit from practising sitting on a ball with eyes closed, but a person who is not adequately using their remaining vestibular function could find this practice useful to enhance their use of vestibular information.

Postural control is no longer considered one system or a set of righting and equilibrium reflexes. Rather, postural control is considered a complex motor skill derived from the interaction of multiple sensorimotor processes [8]. The two main functional goals of postural control are postural orientation and postural equilibrium. Postural orientation involves the active control of body alignment and tone with respect to gravity, support surface, visual environment and internal references. Spatial orientation in postural control is based on the interpretation of convergent sensory information from somatosensory, vestibular and visual systems. Postural equilibrium involves the coordination of sensorimotor strategies to stabilise the body's centre of mass (CoM) during both self-initiated and externally triggered disturbances in postural stability.

It is widely recognised that older people with balance disorders suffer from multiple impairments, such as multi-sensory loss, weakness, orthopaedic constraints and cognitive impairments [9, 10]. It is often assumed that these impairments lead directly to functional loss, such as the inability to walk safely, to climb stairs and to dress independently. Too often, we forget that impairments, alone, do not lead to functional deficits because some people with a particular impairment have much better function than others, depending on the type of impairment and the strategies each uses to compensate for the impairment. For example, an individual with sensory loss in the feet due to neuropathy may compensate by increasing dependence on visual information [11]—a strategy that results in instability in the dark. Another individual may compensate by using sensory substitution from light touch on a cane or walker [12], which is helpful in maintaining stability in the dark but may become an obstacle when the person needs to step quickly to the side to recover their equilibrium in response to a perturbation [13]. Thus, quantifying somatosensory loss in the feet, although helpful, cannot fully predict balance function because function also depends on strategies that individuals use to accomplish stability for a particular task given the impairments.

The postural system consists of many subcomponents

Just as it is important to consider the compensatory strategies that individuals use to function on a daily basis, despite their impairments, it is important to understand the normal strategies that the CNS uses to control balance. Another approach to understand postural control requires considering the many physiological systems underlying a person's ability to stand, to walk and to interact with the environment safely and efficiently. An understanding of these systems and their different contributions to postural control allows us to systematically analyse the particular balance disorders affecting each individual. This analysis also allows us to predict context-specific instability, in which each individual is at risk of falling in different contexts. For example, an individual who is incapable of using vestibular information will be at risk of falling in the dark on unstable surface, whereas an individual who requires a stepping strategy to control equilibrium will be unstable when they must balance with their feet in place [14].

Resources Required for Postural Stability and Orientation

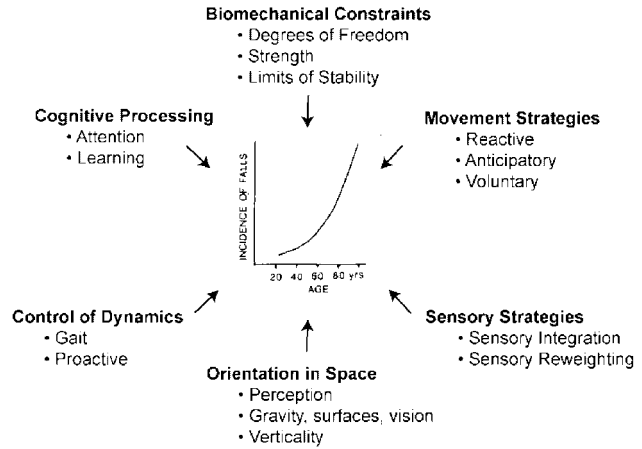


Figure 1. Important resources required for postural stability and orientation. Disorders in any of these resources may be the cause of balance disorders and the increased incidence of falls in the elderly, as shown by the graph. This framework suggests that each elderly individual is falling because of specific, unique constraints on their postural control system.

A summary of six important resources important for postural control is shown in Figure 1. A disorder in any one, or a combination, of these resources leads to postural instability. The graph in the centre of Figure 1 shows the well-known increased risk of balance disorders and falls as people age. This increase associated with ageing, however, is not due to ageing of ‘the balance system’ but to an increased likelihood of impairment or pathology in physiological sub-systems underlying the complex skill of balancing [5].

Biomechanical constraints

The most important biomechanical constraint on balance is the size and quality of the base of support: the feet. Any limitations in size, strength, range, pain or control of the feet will affect balance [15]. One of the most important biomechanical constraints on balance control involves controlling the body CoM with respect to its base of support. In stance, the limits of stability—that is, the area over which an individual can move their CoM and maintain equilibrium without changing the base of support—are shaped like a cone as shown in Figure 2 [2, 16]. Thus, equilibrium is not a particular position but a space determined by the size of the support base (the feet in stance) and the limitations on joint range, muscle strength and sensory information available to detect the limits. The CNS has an internal representation of this cone of stability that it uses to determine how to move to maintain equilibrium. In many elderly people with balance disorders, this cone of stability is often very small or their central neural representations of this cone of stability are distorted, both of which affect their selection of movement strategies to maintain equilibrium. Figure 2 shows a man demonstrating a normal forward limit of stability and a woman with multisensory problems demonstrating a severely reduced limit of stability. The man leans from his



Figure 2. Normal and abnormal limits of stability. **(A)** Healthy man leaning his body's centre of mass (CoM) (white dot) towards his forward limits of stability, represented as the area of a cone. **(B)** Woman with multisensory deficits attempts to lean forward without moving her body CoM forward. **(C)** Woman with multisensory deficits attempts to lean backwards but immediately takes a step to increase her base of support. The projection of the body CoM over the base of foot support is indicated schematically with a white arrow.

ankles to bring his CoM towards the front of his feet. In contrast, when the woman attempts to lean in the forward direction, she flexes at the hips to limit forward CoM motion, and when she attempts to lean in the backward direction, she immediately takes a step to move her base of support under her very small CoM displacement. Subjects prone to falls tend to have small limits of stability [17]. It is important for the CNS to have an accurate central representation of the stability limits of the body. Basal ganglia disorders, such as Parkinson's disease, may result in abnormal representation of limits of stability, leading to postural instability.

Movement strategies

Three main types of movement strategies can be used to return the body to equilibrium in a stance position: two strategies keep the feet in place and the other strategy changes the base of support through the individual stepping or reaching [18, 19]. The ankle strategy, in which the body moves at the ankle as a flexible inverted pendulum, is appropriate to maintain balance for small amounts of sway when standing on a firm surface. The hip strategy, in which the body exerts torque at the hips to quickly move the body CoM, is used when persons stand on narrow or compliant surfaces that do not allow adequate ankle torque or when CoM must be moved quickly [20].

Taking a step to recover equilibrium is common, especially during gait and when keeping the feet in place is not important. However, even when persons step in response to an external perturbation, they first attempt to return the CoM to the initial position by exerting angle torque. An elderly individual at risk of falling tends to use the stepping, reaching and hip strategies more than an individual with a low risk of falling and who uses the ankle strategy [21] to maintain postural stability. However, fear of falling can also lead to additional use of the hip strategy [22]. Although postural movement strategies have been triggered at 100 ms in

response to an external perturbation, individuals can influence which strategy is selected and the magnitude of their responses based on intention, experience and expectations [23–25]. Anticipatory postural strategies, before voluntary movement, also help maintain stability by compensating for anticipated destabilisation associated with moving a limb. Subjects with poorly coordinated automatic postural responses show postural instability in response to external perturbations whereas subjects with poorly coordinated anticipatory postural adjustments show postural instability during self-initiated movements [26].

Sensory strategies

Sensory information from somatosensory, visual and vestibular systems must be integrated to interpret complex sensory environments. As subjects change the sensory environment, they need to re-weight their relative dependence on each of the senses. In a well-lit environment with a firm base of support, healthy persons rely on somatosensory (70%), vision (10%) and vestibular (20%) information [27]. However, when they stand on an unstable surface, they increase sensory weighting to vestibular and vision information as they decrease their dependence on surface somatosensory inputs for postural orientation [27]. The ability to re-weight sensory information depending on the sensory context is important for maintaining stability when an individual moves from one sensory context to another, such as from a well-lit sidewalk to a dimly lit garden. Individuals with peripheral vestibular loss or somatosensory loss from neuropathy are limited in their ability to re-weight postural sensory dependence and, thus, are at risk of falling in particular sensory contexts. Some CNS disorders, such as Alzheimer's disease, may impair the ability of the CNS to quickly re-weight sensory dependence, even when the peripheral sensory system is intact.

Orientation in space

The ability to orient the body parts with respect to gravity, the support surface, visual surround and internal references is a critical component of postural control. Healthy nervous systems automatically alter how the body is orientated in space, depending on the context and the task. For example, a person may orient the body perpendicular to the support surface until the support surface tilts, and then they orient their posture to gravity. Healthy individuals can identify gravitational vertical in the dark to within 0.5° degrees. Studies have shown that perception of verticality, or upright, may have multiple neural representations [28]. In fact, the perception of visual verticality, or the ability to align a line to gravitational vertical in the dark, is independent of the perception of postural (or proprioceptive) verticality; for example the ability to align the body in space without vision [29]. Thus, the internal representation of visual, but not postural, verticality is tilted in persons with unilateral vestibular loss, whereas the internal representation of postural, but not visual, verticality is tilted in persons with hemi-neglect due to stroke [30]. A tilted or inaccurate internal representation of verticality will result in automatic

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postural alignment that is not aligned with gravity and, therefore, renders a person unstable.

Control of dynamics

The control of balance during gait and while changing from one posture to another requires complex control of a moving body CoM. Unlike quiet stance, a healthy person's body CoM is not within the base of foot support when walking or changing from one posture to another [31]. Forward postural stability during gait comes from placing the swing limb under the falling CoM. However, lateral stability comes from a combination of lateral trunk control and lateral placement of the feet [32]. Older people who are prone to falls tend to have larger-than-normal lateral excursions of the body CoM and more irregular lateral foot placements [33].

Cognitive processing

Many cognitive resources are required in postural control [34]. Even standing quietly requires cognitive processing, as can be seen by increased reaction times in persons standing compared with those in persons who are sitting with support. The more difficult the postural task, the more cognitive processing is required. Thus, reaction times and performance in a cognitive task decline as the difficulty of the postural task increases [34]. Because the control of posture and other cognitive processing share cognitive resources, performance of postural tasks is also impaired by a secondary cognitive task [35]. Individuals who have limited cognitive processing due to neurological impairments may use more of their available cognitive processing to control posture. Falls can result from insufficient cognitive processing to control posture while occupied with a secondary cognitive task.

Postural control and falls are context-dependent

Because each individual has a unique set of system constraints and resources available to control posture, the ability to maintain equilibrium and postural orientation will depend on the particular context. Thus, different persons will fall in different situations, depending on what systems are required to complete the task successfully. Table 1 provides examples of different contexts that determine successful postural performance.

Just as identifying risk factors of falling is multi-factorial, so too is identifying physiological risks for balance disorders. To predict risks of falling and to design an optimal intervention for persons with balance impairments, it is

Table 1. Postural performance depends on context

Biomechanical task constraints
Movement strategies
Sensory environment
Postural orientation
Dynamics of control
Cognitive resources
Experience and practice
Perception of goal and context

important to assess the integrity of underlying physiological systems and compensatory strategies available. Simple global measures of 'balance' are insufficient to provide the information needed to predict the particular environments and situations that will result in an individual's postural control system failing. Simple 'balance measures' cannot identify specific constraints on the sensorimotor processes underlying postural dyscontrol to customise balance rehabilitation for those constraints. Thus, comprehensive evaluation by a clinician skilled at systematically evaluating the impairments and strategies underlying functional performance in postural stability is necessary for optimal balance rehabilitation and fall prevention.

Key points

- Postural control is a complex motor skill based on interaction of dynamic sensorimotor processes.
- Balance function depends on strategies that individuals use to accomplish stability for a particular task given their impairments.
- Damage to different systems underlying postural control results in different, context-specific instabilities.
- Effective assessment and rehabilitation of balance disorders require an understanding of the many systems underlying postural control.

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Conflicts of interest

The author declares that there are no conflicts of interest.

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