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The dynamics of standing balance

Ramesh Balasubramaniam and Alan M. Wing

The control of standing is a complicated task that involves the action of muscles distributed over the whole body. Forces arising from gravity, external events or our own actions all tend to disturb the unstable equilibrium that preserves posture. For the central nervous system the problem of standing can be cast in terms of finding appropriate relations among body segments to maintain the desired position of the body as a whole with respect to the environment. In this review we evaluate some recent discoveries on the effects of predictable and unpredictable perturbations, and the role of perceptual information, attention and cognitive processes in the control of upright stance.

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Standing straight is not as simple a task as one might think. It involves keeping several distributed joints and muscle groups in a geometric relationship with respect to the environment. Except for soldiers commanded to do so, most of us are always doing something else when we stand. When disturbed from an upright standing position we typically use certain strategies to recover balance and these strategies are almost always affected by what we are doing at that time (anything from walking the dog to singing in the shower). In this article we will review some recent developments in posture control studies that have shed some light on cognitive and perceptual factors that can affect balance in various contexts and environments.

Posture is defined as the geometric relation between two or more body segments (e.g. arm-trunk). The relation is expressed in terms of joint angle(s) between segments (e.g. ankle and knee angles describe the posture of the leg). A complete geometry defining the posture of the whole body should include the relation of the body to the environment (e.g. body relative to support surface) [1,2]. An issue for the central nervous system is that posture must be actively maintained because joints between body segments are free to move under external forces. The external force field might be constant (e.g. gravity), or variable (e.g. the pull of a boisterous dog on a leash). The effect of several simultaneous external forces acting around any given joint can be characterised in

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terms of a resultant torque (the product of force and distance from the joint). Maintaining posture thus depends on matching resultant external torque with torque developed by muscles acting around that joint. We define **balance** as the equilibrium resulting from the matching of torques, which can be organized in anticipation of (i.e. before), or as a reaction to (i.e. after), the effects of postural disturbance. In this article we focus on posture and balance subserving upright stance, or ‘standing balance’.

Studying balance

A common method of studying standing balance is to record body segment motions, reaction forces and torques between the feet and the ground when forces, acting externally to the joint(s) of interest, perturb balance [3]. Perhaps the most obvious means of perturbing balance is for the experimenter to apply forces in a predictable or unpredictable way [4]. A second paradigm involves perturbations to posture that result from the test subject’s own actions like displacing the arms in a forward extended position [5–7], as shown in Box 1. A third paradigm [8], which appears deceptively simple, is maintaining standing posture in the context of the steady force due to gravity. Although gravity is constant, equilibrium is unstable and small fluctuations are seen in balance measures that reflect continuous and intermittent muscle activity.

The effects of imposed perturbations on balance

Imagine standing on a platform that can be moved backwards or forwards (a situation akin to standing on a moving bus). Suppose, also, that initial posture is with body centre of mass (COM) slightly forward of the ankle joint. In this posture, gravity acting vertically down exerts a small net torque at the ankle. Keeping balanced involves the calf muscles exerting a steady counter torque. What happens if the platform is now displaced backwards? Assuming good frictional contact, the feet will travel with the platform, whereas inertia will tend to keep the body COM where it is. This imposes a rotation on the ankle and results in a forward lean. Gravity acting vertically down through COM now projects further forward of the ankle than before. This produces an increased torque around the ankle which is no longer balanced by the calf muscles and so acts to increase the lean. This can be prevented if the calf muscles increase their opposition of the external torque. If the increased muscle torque exceeds the increase in the external torque, the degree of lean will be reduced. In experiments with unpredictable perturbations of the support surface an action of this kind is followed by sequential activation of knee and hip muscles [9] (a ‘postural reflex’) with a latency of a tenth of a second, that is much shorter than voluntary reaction time (fifth of a second or longer). However, the time for the postural reflex is considerably longer than a spinal reflex (a thirtieth of a second or less). The additional time might involve supraspinal circuits, possibly the sensorimotor cortex.

The significance of the neural circuit involved in a feedback loop is that it affects the ways in which actions can be modified as a result of consequences. For example, past experience might have an influence on which corrective action is taken, or the context preceding a perturbing event might be used to fine tune direction of corrections when feedback indicates divergence between intention and performance. Additionally, postural reflexes are also more complex than spinal reflexes as they involve sequential organization over several muscle groups and they adapt to changes in context [42].

Under certain circumstances the use of ankle torque is replaced by hip flexion inducing shear forces at the ground [4]. The ankle strategy is found when the perturbation is small and the support surface is firm. The hip strategy is observed when the perturbations are rapid and larger and the support structure is compliant or smaller than the feet, like the balancing beam in Olympic gymnastics [10]. In addition it might be noted that there is a further strategy available in the balance repertoire. If the balance perturbation is too large to resist with the feet in place (the net force through the COM projects outside the support base provided by the feet), participants might elect to take a step to recover balance.

Self imposed perturbations and tracking tasks

It is interesting to note that switches between the ankle and hip modes of postural adjustments are not always strategic. Recent work on non-static self-perturbed stance has offered alternatives to the notion of the idea of discrete and modular synergies using pattern dynamics [11,12]. When subjects tracked sinusoidally moving targets with their heads [13,14] at various experimentally manipulated frequencies, two stable patterns of motion were observed between the ankle and hip joints. One involved an inphase relation (0 degree phase relation) between the ankle and hip and the other an antiphase (180 degree phase relation). When the movement tracking frequency was increased, a phase transition was observed from the antiphase to inphase pattern. The suggestion from this line of research is that postural synergies might not be discrete neural synergies, but functional synergies that are assembled in a task-specific way [15]. Other tracking tasks reported have shown the existence of a variety of frequency relationships between ankle and hip motions [16]. Whereas the ‘strategy’ approach deals mostly with muscular activation patterns, the pattern dynamics approach deals with macroscopic parameters like phase relations and their qualitative reorganisation.

Task specific assembly of postural synergies

If postural synergies are indeed functional, can they be independently modulated in the performance of spatial or cognitive tasks? Evidence from biomechanics shows that centre of pressure (COP) patterns (see Box 2), defined as the point location of

Box 1. Anticipatory postural adjustments

Rapid voluntary movements of the arms produce predictable (in the sense that the form and timing is directly related to the voluntary movement) perturbations to balance. Leg movements are often observed in advance of arm raising [a] and it is thought that these serve to stabilize the trunk against the effects of the arm raising action [b]. Anticipatory adjustments have also been demonstrated in a postural task involving the hand and arms [c]. Recently, links have been demonstrated between whole-body postural adjustments and upper-limb grip force in a grip task [d] (see Fig. I). The grip force increased before the load force produced by the arm, but importantly, early changes in grip force and ground-reaction forces and torques were positively correlated, suggesting a common predictive basis to the anticipatory adjustments in upper and lower limbs.

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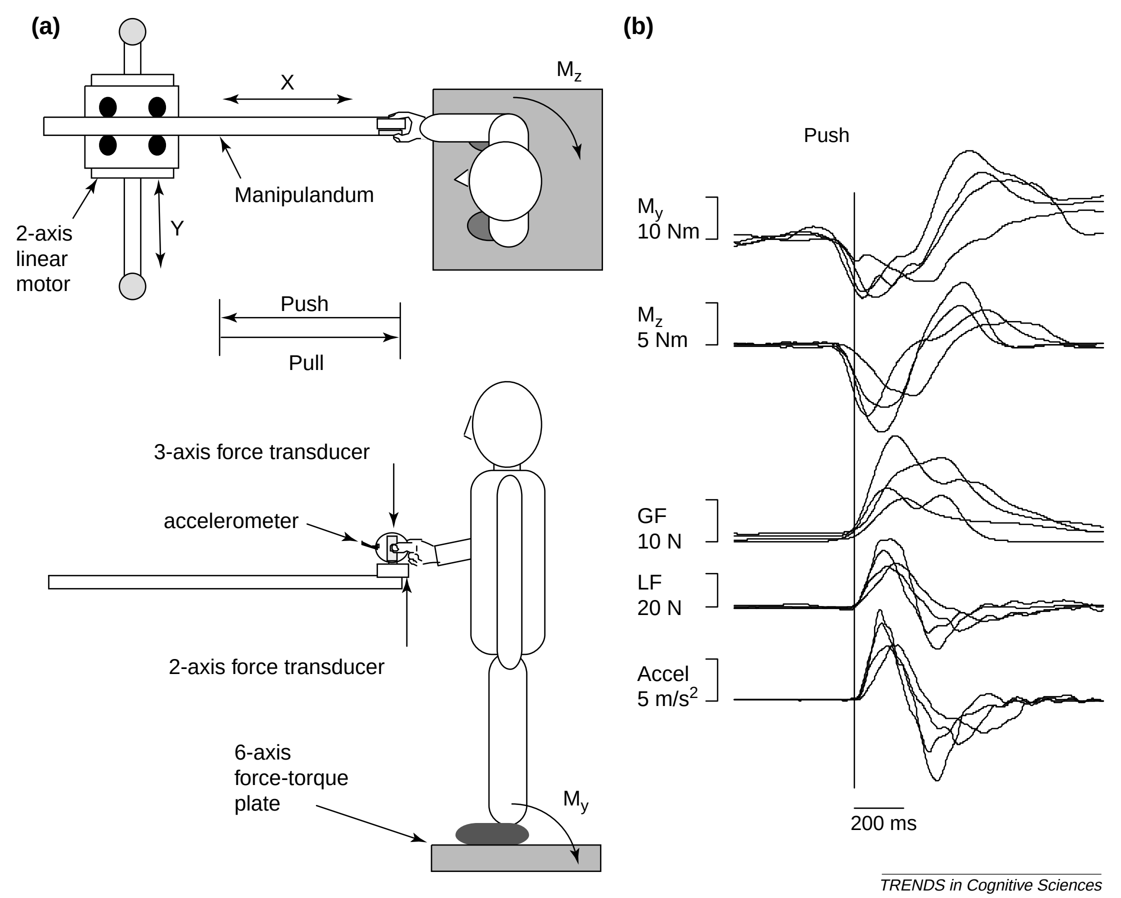
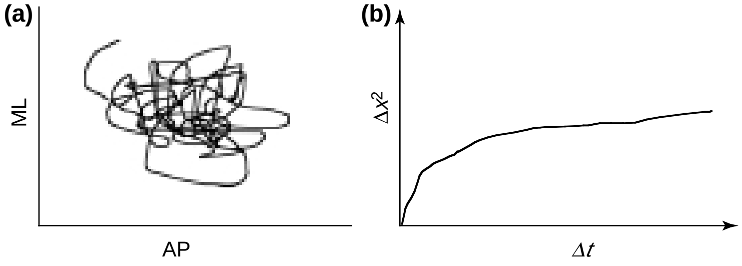


Fig. I. (a) Participants used precision grip (thumb opposing the fingers) to hold a manipulandum that they were instructed to push or pull. The manipulandum was instrumented to provide readings of grip force (GF), stabilizing the hand on the object, and load force (LF) produced by the arm movement on the object. The force plate under the participant recorded ground reaction forces and torques. (b) The forces (GF and LF) and torques (M_y and M_z) were observed as the arm developed load force, but were also present before arm action, shown by the acceleration trace.

weighted average of the sum of vertical reaction forces in the anteroposterior (AP) and mediolateral (ML) directions, can be independently organized [17] – by plantarflexion/dorsiflexion about the ankle joint, and abduction/adduction about the hip joint, respectively. Precision aiming tasks such as Olympic archery and rifle shooting require modulation of the sway on different axes. Research has shown that when aiming tasks were performed using a handheld laser pointer oriented parallel to the sagittal plane of the body, mediolateral sway was minimised with corresponding sway increase in anteroposterior sway. The converse was observed when the task was performed with the laser beam oriented perpendicular to the sagittal plane, to accommodate the different demands of the task [18,19]. The broad conclusion from this line of work is that postural synergies are flexible and can be activated or assembled by task parameters which are sensitive to biomechanical constraints [40] or attentional factors [41].

Box 2. Centre of pressure variability and its modelling

The variability seen in the time varying nature of the centre of pressure (COP) profile for the anteroposterior (AP) and mediolateral (ML) directions has been an interesting modelling problem that has drawn from methods in statistical mechanics and stochastic physics. It has led researchers to postulate [a–c] that postural sway is not skeleto-muscular noise, but has meaningful structure that can be modelled as a bounded correlated random walk, with the short positive slope at the beginning of the curve (t<1s) (see Fig. I) indicating positively correlated activity, in contrast with negatively correlated activity at longer timescales. The short timescale activity was interpreted as open loop control (where the CNS lets the system drift in the direction of change) and long-range activity as closed loop control (where the CNS performs corrective actions against the direction of change) [a]. Other interpretations have been that the short-term activity might refer to exploratory activity of the nervous system through which stability boundaries of the system are detected, and at longer timescales corrective activity is performed on the information obtained [b]. This dual-control model has been challenged on the basis of parsimony of explanation using a more generalised stochastic model [c], and on the basis of control theoretic interpretations [d–f]. One alternative model [e] proposes that similar results can be obtained from an inverted pendulum system considered to be driven by a proportional integrative and derivative (PID) neural controller. Such a system uses a control torque produced as a function of the deviation between the desired upright position and actual body position and has been shown to produce SDFs that mimic experimentally obtained SDFs.



TRENDS in Cognitive Sciences

Fig. I. (a) Variation in the centre of pressure (COP) in anteroposterior (AP) and mediolateral (ML) directions. (b) When the mean squared displacement (Δx^2) of the COP trajectories are plotted against the time interval of measurement (Δt), a diffusion curve known as a stabilogram diffusion plot (SDF) is obtained. The short positive slope at the beginning of the curve (t<1s) indicates positively correlated activity, in contrast with negatively correlated activity at longer timescales.

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Perception–action coupling in the control of stance

One view of standing balance is that the system seeks to maintain a target set-point using sensed deviations from that set point (or predictions of future deviations on the basis of sensed current state and known motor commands) to drive corrective actions [43] (Box 2). There are several distinct sensory inputs that might contribute to the detection and maintenance of such a target set-point.

Investigations of postural control mechanisms in the presence or absence of information from a certain modality have added to our basic understanding of the role of sensory information in stabilizing standing balance (Box 3). An alternative enterprise has also developed over the last two decades to perturb stance by dynamically varying aspects of the visual environment [20–22]. The main finding from most of these studies is that temporal coherence between postural sway and the optical drivers is controlled by aspects of the dynamic of the flow's geometry such as expansion and motion parallax [23,24] by matching in the intrinsic frequency of the postural control system to the frequency of the visual oscillations. Unpacking the relationship between flow geometry and how it informs the nervous system about the position of the centre of mass is much less understood and is likely to be a critical avenue of research in the future. Coupling relationships between a sinusoidally varying tactile stimulus and postural sway have also been reported [25]. Indubitably, a strong coupling exists between the postural control system and systematic changes in the environment.

Although reasonable progress has been made in the realm of postural adaptations to periodic variations in visual and tactile stimulation, much still needs to be understood about cognitive and attentional processes and their role in posture control. In the next section we discuss recent progress in that area.

Posture and cognition

Standing is a seemingly automatic motor task. We take for granted that we can carry on a conversation, think about the past, plan the future, see, or hear things around us without affecting standing balance. However, several studies indicate that there can be interactions between the control of balance and the performance of certain cognitive tasks [26]. This might seem surprising if posture and balance are thought of as spinal or subcortical processes and cognition is considered to be purely cortical. But neither of these views is tenable because the cerebellum has been implicated in sensory processing and cognition [37] and there is evidence of cortical involvement in postural reflexes [38].

An early demonstration of an interaction between cognition and balance [26] compared performance on two memory tasks, one with a strong visualization component, when standing in an unstable position with feet lined up heel to toe in tandem fashion and when sitting. When the memory tasks were performed in a sitting position, there was no overall difference in recall performance. However, when standing with feet in line, performance in the spatial condition was significantly worse whereas non-spatial performance was unaffected.

The selective effect on spatial memory of the more difficult balance task was attributed to competition for limited spatial processing resources, a problem of limited attentional capacity. However, the two memory tasks did not have a differential effect on

Box 3. Multisensory control of posture

Although vision has a powerful influence on standing balance we are clearly able to keep our balance in the dark or with eyes shut [a]. However, sway is noticeably increased. Interestingly, it has been found that with eyes closed, light active touch [b–d], which is insufficient to provide mechanical stabilization, reduces sway to levels comparable to those seen with vision. The same effect is also observed with passive touch [e]. In different environments, the different sensory systems provide postural information with varying degrees of accuracy. How does the brain select the appropriate source? One possibility is that rather than selecting one over the others, it uses all the various sources, but weights them according to their variability: the more variable (and thus less reliable), the less weight should be given [f]. Changes in reliability occur with ageing. Thus, muscle proprioception becomes relatively more important in older people as the acuity of the visual and vestibular systems decline. A heterodox view of perceptual systems, promoted by Gibson [g], suggests that instead of looking at sensory systems as separate entities, it might be more useful to define the sensory input on the basis of proprioceptive, expproprioceptive and exteroceptive information [h].

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standing stability [26,27]. This might imply balance has priority in terms of access to (spatial) processing resources. Thus, it is interesting to ask whether cognitive tasks can be shown to affect balance. Subsequent research has shown that measures of standing balance are indeed affected by concurrent cognitive tasks. However, in normal standing this tends to be truer of older participants or those with balance impairments than healthy young adults. For example, a recent study [28] evaluated the effect of a range of tasks, selected to contrast visuospatial and verbal components of working memory [29] on anteroposterior sway. Middle-aged (average 57 years) and older (average 77 years) groups of subjects were tested and an interaction was obtained between the effects of age and a digit recall task involving spatial memory. Compared with a condition without concurrent cognitive task, sway was elevated in the older group and reduced in the younger group. There was a similar interaction between the effects of age and a backwards digit recall task. Other tasks, including random digit generation, silent counting, and counting backwards in threes revealed no such interactions with age.

Questions for future research

- What influence does cognitive activity have on postural stability and how is this influence neurally transmitted?
- To what extent are quiet standing fluctuations exploratory rather than regulatory?
- Are the scaling regimes seen in short- and long-term activity of postural sway indicative of open- and closed-loop control, respectively?
- What are the limits on reducing postural sway?
- What role does attention play in the susceptibility of older people to balance problems?

A subsequent study was run to determine whether there might be differential effects on balance of encoding and retrieval in the memory tasks [30]. Changes in sway compared with a condition in which there was no concurrent task were seen in both spatial and non-spatial tasks. Reductions in sway were found during encoding whereas increases in sway were observed in both spatial and non-spatial memory in the retrieval phase. Other researchers have also found non-spatial tasks affect balance, when balance is tested in older people, sometimes under more difficult conditions such as reduced sensory feedback. It has been shown that sentence completion [31] and visual perceptual matching affect balance, both in older participants with identified balance difficulties, and in healthy older volunteers standing on an unstable support surface. Recovery from forward sway induced by backward movement of the support base (as discussed in an earlier section) has been used to look at the interaction between balance and a concurrent cognitive task also [32,33]. In this study the cognitive task involved counting (aloud) backwards from a two-digit number in threes. Compared with a young group of subjects, older subjects showed impaired responses to platform perturbation in that their muscle responses were reduced in amplitude in the counting condition. Moreover, in this condition, the older subjects were much more likely to take a step to control balance than young subjects. In another study [34] a vocal auditory reaction-time (RT) task was combined with the support base movement. Under conditions in which the sway was small enough to be resisted without taking a step, the time taken to stabilize centre of pressure was longer with the concurrent cognitive task in the balance impaired but not the healthy older population. Moreover, RTs were longer under dual task conditions, and particularly so in the case of the balance impaired subjects.

The above-mentioned studies all suggest that limited attentional capacity and perhaps sensory processing [35] cause interference between balance and the cognitive task. But the cognitive tasks in each case involved a spoken response. A recent study [36] contends that articulation is the primary cause of increased sway. Three tasks were examined: repeating a number aloud (articulation demand), counting backwards in sevens aloud (articulation and attention demand) or silently (attention demand). Sway was elevated in the two tasks requiring articulation compared with backward silent counting or a baseline condition without any concurrent cognitive task. This suggests that articulation demand is responsible for effects on balance. An important question still to be addressed is whether the effect of articulation is attributable to postural adjustments associated with breathing or whether it is due to a more central process, for example, associated with motor planning.

Another new technique [39] has been proposed for assessing the interference caused by balance perturbations (albeit in this study performed in a seated position with the feet used to balance an inverted pendulum). Subjects carried out a visuospatial tracking task using a hand-held manipulandum. Balance perturbations resulted in a pause in tracking at a delay of some 250 ms. It will be interesting to see this technique used in future studies to determine whether there is an effect of tracking difficulty on the postural response to induced sway. In that case it might suggest that the effect of articulation in previous studies reflects preparatory processes concurrent with motor action and not just breathing requirements.

Conclusions

Postural control is adaptive to changing mechanical contexts, visual or tactile environments. But the ability to recover balance or adapt to varying contexts largely depends on the tasks one is engaged in while maintaining balance. These tasks could be ones that give rise to interactions between biomechanical constraints [40], or place cognitive/attentional demands [41] on the subject. We have reviewed the nature of motor coordination for the control of balance, discussed sensory factors involved in maintenance of balance and considered the interactions between balance and cognitive function in several contexts. Unearthing the nature of postural reflexes and their neurophysiological underpinnings is an actively developing area which deserves the attention of cognitive psychologists.

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