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Review

Human Balance in Response to Continuous, Predictable Translations of the Support Base: Integration of Sensory Information, Adaptation to Perturbations, and the Effect of Age, Neuropathy and Parkinson's Disease

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Featured Application: A strong point of balance challenging experiments is that, in addition to representing a paradigm for understanding the control of dynamic equilibrium and the processes of sensory integration in a complex motor task, they are useful in quantifying sensory and motor impairments in patients with balance problems of central and peripheral origin. Moreover, these protocols can be easily and successfully adapted to balance training for rehabilitation purposes.

Abstract: This short narrative review article moves from early papers that described the behaviour of healthy subjects balancing on a motorized platform continuously translating in the antero-posterior direction. Research from the laboratories of two of the authors and related investigations on dynamic balancing behaviour are briefly summarized. More recent findings challenging time-honoured views are considered, such as the statement that vision plays a head-in-space stabilizing role. The time interval to integrate vision or its withdrawal in the balancing pattern is mentioned as well. Similarities and differences between ageing subjects and patients with peripheral or central disorders are concisely reported. The muscle activities recorded during the translation cycles suggest that vision and amplitude changes of the anticipatory postural activities play a predominant role in controlling dynamic balance during prolonged administration of the predictable perturbation. The potential of this paradigm for rehabilitation of balance problems is discussed.

Keywords: dynamic balance; motorized platform; antero-posterior translation; reflex responses; anticipatory adjustments; vision; ageing; neuropathy; Parkinson's disease

1. Introduction

Balance is one of the 4000 most commonly used words, according to the Collins dictionary [1] (admittedly, possibly boosted by its usage in economics). We would sustain here this trend by proposing a survey of the balancing behaviour when humans are forced to keep their equilibrium on a flat support base that continuously and predictably moves back and forth in the antero-posterior direction, i.e., along the sagittal axis of the standing subjects (Figure 1).

The antero-posterior (A-P) platform translation challenges body balance differently than the medio-lateral (M-L) translation. In the former case, both legs behave equally, in a symmetrical way: the feet act as a solid interface between body and platform because of their length and the efficacy of the action of the plantar- and dorsi-flexor foot muscles, and the distance between the feet may not be critical to the balancing task. Conversely, in the medio-lateral perturbations, the legs and pelvis configure a parallelepiped shape when standing on the platform [2], where both legs are equally displaced with respect to the vertical plane (in the same sense, both legs to the right or to the left). This compels reciprocal relaxation, contraction of the agonist neck, trunk, pelvis (mainly), and lower limb muscles of both sides of the body in order to minimize displacement in the frontal plane. Further, the medio-lateral perturbations imply a rotational torque component, albeit minimal, because the centre of mass (CoM) of the body lies somewhat ahead of the centre of the ankle joints during normal standing, and the inertia of the former and displacement of the latter would create an asymmetrical compensation.

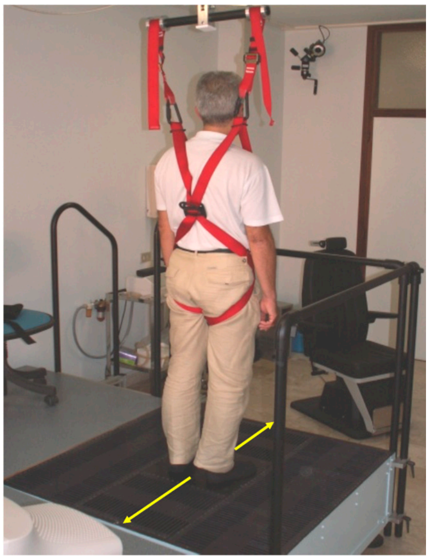

Figure 1. This shows a platform that can produce movements of the supporting base in various directions in the horizontal space according to different driving functions.

While many studies on balance control have addressed perturbations in the sagittal plane (such as A-P impulsive and continuous translations), less attention has been devoted to the balancing behaviour in response to M-L translations, and no prolonged perturbations have been administered, yet. Hence, this short review will not consider the findings obtained with perturbations in the frontal plane. This article will not address the mechanisms responsible for the maintenance of the erect stance under static conditions, either, even if during quiet stance, antero-posterior sway of the body occurs and can be easily detected [3]. Besides, this article will not deal with the automatic postural activities accompanying gait, be it simple walking along a linear path or more demanding walking as when we move along curved trajectories (e.g., [4,5]). As a further stipulation, we will not deal here with another type of perturbation, which has been popular in the past, consisting of the toe-up or toe-down tilt of the supporting platform. This perturbation challenges balance to a minor extent compared to the translations, because the platform is most often set to rotate (has the centre of rotation) around the ankle joint, thereby producing reflex responses in the stretched plantar- or dorsi-flexor muscles, but small displacements of the CoM with respect to the support base (see [6]). The main aim of that experimental condition has been indeed to study the stretch reflexes and their modulation under various sensory and environmental conditions [7] or in the case of neurological disorders [8]. A good review article on the broader issue of the control of perturbed balance is available [9].

2. The Continuous Predictable Balance Perturbations Administered by the Antero-Posterior Translation of the Platform

The peculiar challenge to our ability to remain upright, when we are standing in the critical situation represented by the continuous predictable back and forth displacement of the support base, prompts our balance capacities aimed at keeping the body's CoM over the moving support base. The brain controls our postural muscles accordingly, by activating short and long latency reflex responses, by preparing anticipatory activities once the features of the perturbation become known, and by putting in place corrective activities when the reactions are not perfectly calibrated. The sensory input from the periphery (proprioceptors, including the vestibular system, and exteroceptors, including vision) plays a crucial role [10]. The muscle spindles of the postural muscles (see [11]) and the vestibular system and vision would be paramount, since cutaneous receptors of the foot sole seem to contribute little to the control of stance [12,13], probably through modulation of the stretch reflex excitability [14]. The vestibular system would play a head stabilizing role [15,16] in keeping with [17], who showed that head displacement on the translating platform in chronic vestibular patients with eyes closed (EC) was larger than the 95th percentile of healthy subjects.

In addition, where the sequence of support-base perturbations goes on for any longer, the brain's computational effort and the muscle forces diminish over time, featuring a clear-cut adaptation phenomenon (see [18]). However, in many such experimental conditions, the analysis of the muscle activities and the body's mechanics have been limited to the epochs (the perturbation cycles) recorded in the period when the steady-state is reached (the term steady-state is reductive, owing to the high intra- and inter-subject variability of the balancing behaviour; see [19]). These limitations notwithstanding, though, this protocol has been rich with interesting conclusions about the strategies put in place for maintaining equilibrium and about the processes of the integration of proprioceptive and visual inputs.

Just before the turn of the century, two groups independently exploited this paradigm. Buchanan and Horak [20] observed the effects of the frequency of a sizable antero-posterior translation of the support platform on the movements of the body segments, with and without vision (eyes open (EO)). They found that at low translation frequencies (<0.3 Hz), subjects rode the platform showing no major joint motion, and the role of vision hardly affected this behaviour. At higher translation frequencies (<0.5 Hz), behaviour was characterized by large amplitude motions of the head and trunk when vision was not available, whereas vision strongly reduced these antero-posterior oscillations to the point that the head moved less than the platform (a "fixed-in-space" head behaviour). Corna et al. [21] observed the same behaviour, whereby subjects behaved as a non-rigid, noninverted pendulum and stabilised head in space with vision. Without vision, the head oscillated more than the platform, again at low translation frequencies. Therefore, the balancing strategy during this type of continuous perturbation shifts from a pendulum to an inverted pendulum type, passing from active head-and-trunk control with vision to maximal body compliance to the translation pattern with EC.

3. Muscle Activities

Muscle stretch (mainly of the postural muscles of the leg) certainly occurs during this condition. The feet are moved backwards with respect to the CoM of the body during the backward translation phase, producing ankle dorsiflexion and a stretch of the triceps surae. The forward translation produces an ankle plantarflexion and a stretch of the pretibial muscles. In passing, the intrinsic foot muscles are not unrelated to the reactions, and they play their own role, scarcely addressed so far [22,23]. Short and long latency leg reflexes are elicited in the leg muscles by the displacement of the body segments [24]. Trunk and neck muscles contribute prominent balance correcting effects [25–27] as they also do under similar perturbation conditions, seated [28].

Notably, the continuous, predictable translations of the support base elicit proactive strategies [29–31]. The related muscle activities are aimed at counteracting the balance perturbations elicited by the platform displacement reversal at the dead points of the platform translation cycles.

These activities are not connected to proprioceptive reflexes triggered by muscle stretch, but configure anticipatory postural adjustments. Figure 2 shows an example of a recording of the tibialis anterior activity during the first two cycles of a continuous perturbation at a 0.2 Hz frequency and the trace of the platform antero-posterior translation. The first cycle elicits a brisk EMG response due to the muscle stretch induced by the forward displacement of the platform. Before the turn-around point preceding the successive translation cycle, EMG activity not related to muscle stretch appears, to be followed by a stretch reflex response more modest than that occurring during the first cycle. The anticipatory activities appear when the leg muscles are not stretched and are appropriate for counteracting the inertia of the body at the time of the turning points of the platform. Anticipatory activities may not be optimally tuned to the complex combination of active and passive body movements from the beginning of the perturbation sequence and may be adjusted as the perturbation proceeds [32,33].

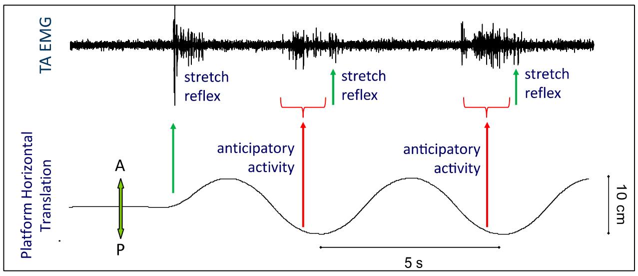

Figure 2. Top trace shows the tibialis anterior (TA) EMG at the beginning of a series of perturbations delivered with eyes open at a 0.2 Hz frequency. The bottom trace is the platform antero-posterior translation.

4. Vision

During quiet stance, unsteadiness in the dark is a sign of impaired proprioception (see [34] for a good review article, with historic hints). For instance, closing the eyes increased the body's sway in all the subjects, as detected by instrumented platforms [35]. The increase in sway can be inconspicuous in healthy subjects, whereas in patients with neuropathy or deficits of the vestibular system, the postural imbalance when standing or walking with EC can be remarkable [36–38]. An investigation based on continuous random platform tilts [39] suggested that vision modulates the vestibular noise, thereby reducing the threshold for position detection. When healthy subjects stand with EC on the antero-posterior translating platform, the balancing behaviour consisting of large head antero-posterior displacements (compared to those of the platform and head with EO) is obvious [40]. The large head displacements when balancing on that platform with EC occur therefore in the absence of any proprioceptive malfunction. This leads to two easy conclusions: (1) vision does increase stability when standing, both under quiet conditions and when balancing on the translating platform; (2) standing on the translating platform is quite different from a quiet stance in that, even with full somato-sensation, unsteadiness becomes an issue without vision. It is perhaps appropriate here to mention that healthy subjects never fall and rarely take a compensatory step during the trials, which commonly comprise numerous perturbation cycles [41].

The translating platform is not just a means for evaluating the role of vision in stance by enhancing the likelihood to detect clear-cut differences between eyes open/eyes closed conditions. It is an interesting protocol to address the role of vision and its disorders in the control of dynamic balance as well. It has been shown that the head antero-posterior oscillations, normally limited with EO, increase steadily with the severity of poor vision. When subjects balance on the mobile platform wearing test lenses to modify visual acuity from clear vision to blurred vision, head stabilization in space progressively worsens with the decrease in visual acuity and becomes similar to the EC behaviour when vision is severely blurred [42]. Thus, a simple light/dark dichotomy hypothesis for the visual control of dynamic stance is not supported, because the balancing pattern changes gradually from head-fixed-in-space to large head oscillation as a function of visual acuity. This suggests that the visual input is integrated as is the general somaesthetic feedback and that we have no capacity of extrapolating simple information from the fixed environment from an indistinct image of it. It is notable that, in this case, head stability gradually diminishes progressively with visual acuity deterioration even when all balancing trials are performed within a short period of time and within the same laboratory, i.e., when subjects are well accustomed to both the environment and the continuous perturbation protocol.

Hence, clear vision is a powerful player in the control of balance, particularly under critical dynamic conditions. However, what is the actual purpose of vision under these conditions? Is it necessary for minimizing body segments' oscillations? Two questions deserve an answer. (1) Are there conditions in which we can do without vision because other sensory receptors firing under unstable conditions come to the rescue? (2) Are supra-postural visual tasks able to modulate the stabilizing effect of vision? The former question receives an explicit answer: no. We have already mentioned that reduced vision is not enough to stabilize body oscillations on the platform. Moreover, blind people, including congenitally blind subjects (therefore, people used to moving in their environment and counteracting postural perturbations of various natures for years without vision), do not sway less than sighted people when administered the continuous perturbations of balance on the periodically moving platform. Their head oscillations are quite superimposed to those of the sighted people balancing with EC [43]. Hence, they have not learned to better exploit their somato-sensation or vestibular input in order to enhance stability, whereas they might have done so. On the contrary, normal subjects need not learn to exploit proprioception because it is so easy for them to open their eyes under critical conditions. Therefore, one is compelled to ask whether stability is an obligation for our body under the critical balancing condition and if vision is the means for achieving stability. The lesson from the blind subjects is that they can easily tolerate ample head and body oscillations, even if, in principle and if needed, they should be able to diminish their oscillations thanks to the proprioception and the vestibular input. The latter question receives an explicit answer: yes. As a matter of fact, under certain conditions, sighted subjects can tolerate ample head and body oscillations, when balancing on the translating platform, despite having normal vision, for instance while reading a text. In this case, as the text moves with the moving platform to which it is fixed as an integral whole, the head moves as much as the platform, and the distance between the eyes and the text is kept constant [44]. Therefore, these findings suggest that head stabilization in space can be revoked by the brain to enhance the performance of a non-postural task. Head stabilization is not necessarily produced by vision to obtain a dependable spatial reference. Not only that: if proprioception and the labyrinth do produce head stabilizing effects, their role would be anyway contingent and subject to the supra-postural task.

5. Playing with Vision

As said above, the differences in head oscillation eyes open/eyes closed are easily quantified. To summarize, oscillations are smaller than those of the platform with vision and larger without vision. One question had been raised some time ago. Given these clear-cut differences, it should be easy to investigate the phenomena occurring at the passage vision/no-vision (or vice versa) while subjects were balancing on the translating platform. Beyond curiosity, such an experiment can give hints as to the time necessary to integrate vision into the balance control [45]. As a matter of fact, closing the eyes in the middle of a series of perturbations soon produces a shift from small to large head oscillations, and the balancing pattern becomes definitely equal to that with EC. The same is true for the opposite change. The time period for integration of vision (the delay to reduction in head oscillation) is between 1.0 and 1.5 s, shorter than that for vision withdrawal (1.5–2.5 s). Of course, the periodic nature of the perturbations and the length of the translation cycles can affect the statistical estimate of the "true" delay. This time interval comprises the time to integrate the available sensory inputs, i.e., to change from an allocentric reference with EO to a proprioceptive reference with EC and vice versa and to adjust the calibration of the motor activity to reach the best motor control with the new sensory set. With a different technique, the delay in body sway on changing visual conditions has been calculated during quiet stance later on [46]. Interestingly, the delays observed during the platform continuous translations on addition or withdrawal of vision are broadly similar to those measured during quiet stance. This shows that the time to embodiment (or to disappearance) of the balance stabilizing effect of vision does not depend on the balancing condition at hand, is not at all negligible in duration, and may be critical in the prompt adaptation to changing conditions [47].

6. Aging

Gait perturbation paradigms are effective to improve reactive responses during walking in healthy elderly people [48]. Balance recovery is less prompt and effective in the oldest elderly people, in particular when sensory information is manipulated, and more so when more than one system is challenged [49,50]. However, the capacity to maintain quiet upright stance does not appear to be markedly altered in normal elderly subjects when estimated under static [51,52] and dynamic conditions by delivering isolated rotation tilt of the support basis triggering stretch responses [53]. This can be related on the one hand to the relatively easy task of standing quietly required by static force-platform measurements and on the other on the limited modifications with age in the latency and amplitude of the reflex responses [53–55].

It has been suggested, based on pseudorandom tilts of the support base, that older subjects rely more on proprioception rather than visual and vestibular cues for dynamic balance control [56]. When healthy elderly subjects are administered the periodic antero-posterior translations of the support base, they can perform even better than their young peers, provided vision is available and the frequency of oscillation is low (Figure 3, control). The smaller head oscillation is accompanied by higher flexibility of their body, as indicated by a low cross-correlation value between feet and head. With EC and high perturbation frequency, though, their oscillation is much larger than for the young subjects, and they assume a stiffer state [57]. Interestingly, when elderly persons rely on anticipatory adjustments during continuous perturbations, their behaviour is again similar to that of the young subjects, but they are more destabilized when perturbations are unanticipated (externally triggered) [58]. Van Ooteghem et al. [59] showed that older adults maintained the capacity to learn adaptive postural response minimization of instability similarly to young adults. However, despite practice, they still maintained a stiff attitude. Others have found, with continuous multidirectional perturbations, that elderly people do not behave in a strongly different way than the young subjects, but muscle weakness and postural asymmetries do represent a cause for enhanced risk of falling [49]. Anxiety is an additional problem in elderly, as seen by their increased sense of instability when balancing on a platform translating fore and aft in unpredictable mode [60].

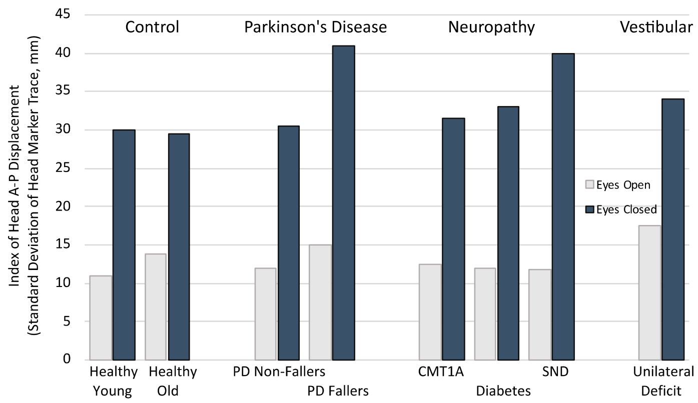

Figure 3. Mean indexes of head antero-posterior (A-P) displacement while standing on a platform moving continuously back and forth 6 cm in the A-P direction at a 0.2 Hz frequency with both eyes open and eyes closed. Despite data from small numbers of subjects per group contributing to the column values, overall, vision stabilizes the head compared to no-vision. CMT1A, Charcot-Marie-Tooth type 1A; SND, sensory neurone disease.

7. Neuropathy

How do neuropathic patients behave when they are exposed to such a critical balancing condition? These patients feature loss of sensation from the receptors innervated by the abnormal sensory fibres. The lesion can have several origins, from occupational exposure [61], metabolic, viral, toxic (chemotherapy), immune, and genetic nature, hypovitaminosis, and aging [62]. Diabetic neuropathy is a common example of sensory neuropathy. Small and large sensory fibres, or both, can be affected. The nerve fibres can show demyelination or axon degeneration [63]. Of course, in many cases including diabetes, neuropathies can affect both sensory and motor fibres [64], and in some cases, pure motor neuropathies can be observed.

It is known that body sway during quiet stance is increased in neuropathic patients [65,66] and that standing on foam with EC can detect subclinical neuropathies in older adults [67]. Therefore, neuropathic patients should experience severe instability when standing on the translating platform, all the more so when vision is not available. However, when neuropathic patients balance on the continuously back and forth translating platform, most of them show a surprisingly good performance (Figure 3, CMT1A, diabetes), in spite of a clear-cut unsteadiness during quiet stance [68]. This has been shown to occur in patients affected by diabetic sensorimotor neuropathy and Charcot–Marie–Tooth type 1A (CMT1A) neuropathy [69]. There are three reasons that can explain this behaviour. First, the proprioceptive input that drives the balancing behaviour originates not only in the more distal parts of the lower limbs (typically more affected by the fibre degeneration than other body parts), but likely from many different segments of the body as well, and the comprehensive afferent input would be more than enough for controlling balance. Second, at least as far as the Charcot–Marie–Tooth type 1A condition is concerned (the disease mainly affects the largest myelinated fibres; see [70]), the relatively good balancing capacity may depend on the integrity of the smaller (type II) afferent fibres originating from the muscle spindles. Third, the results are obtained under steady-state conditions, i.e., under conditions where subjects have learned to adapt optimally to the continuous perturbing stimulus by top-down control of the coordinated body movements in order not to stumble or fall as a consequence of the successive perturbations.

Conversely, patients affected by a rare form of pure sensory neuropathy with a lesion to both the peripheral and central axons of large nerve fibre tract (ganglionopathy or sensory neurone disease) ((Figure 3, SND) show severe unsteadiness under both static and dynamic conditions. When standing on the moving platform, the oscillation of their head is not larger than in healthy subjects with EO, but becomes abnormally large with EC. In a sense, the findings confirm the modest role of the large sensory afferent fibres in this task seen in Charcot–Marie–Tooth disease type 1A. However, removal of vision is more troublesome [71]. In these SND patients, the degeneration of the central branch of the afferent fibres would be responsible for the deterioration of equilibrium, possibly through abnormal reactivity of the brain cortices and circuits that elaborate and integrate the visual feedback for the control of balance [72].

Attempts have been made at understand the actual role of the somatosensory input in the balancing behaviour induced by the continuous perturbations of stance. A typical approach has been to vibrate postural muscles, since it is known that muscle-tendon vibration selectively activates the muscle spindle receptors, in particular those originating from the annulo-spiral endings of the spindle [73,74]. The vibration of either the Achilles tendon or the tendon of the tibialis anterior muscle in subjects standing on the translating platform produced only minor disequilibrium with EO [75]. On the one hand, these findings together with those from the pathological model mentioned above confirm that equilibrium under critical conditions is not severely affected by a continuous proprioceptive disturbance and that, more generally, the Ia muscle afferent input and the induced stretch reflex modulation are not essential in the control of stance under continuous perturbations. On the other hand, they suggest that anticipation rather than feedback would be the main mechanism by which the central nervous system manages this challenging situation. In the mentioned paper [75], however, abnormal head control did emerge with EC when the postural leg muscles were vibrated. This would be connected with abnormal cortical processing of the perturbation related sensory inflow because the unnatural discharge originating in the vibrated spindles would lead to gating of the proprioceptive volley reaching the somatosensory cortex [76].

8. Parkinson's Disease

If the balancing behaviour is affected not only by vision or by somato-sensation, but is also dependent on the supraspinal integration of these afferent inputs into a coherent motor response [8,77–79], balance performance should be considerably degraded in Parkinson's disease (PD) patients, particularly when the support base translates continuously. Quiet stance is affected in these patients, but in several of them, body sway is comprised within the normal values of age matched controls [52,65]. More than that, in partial attenuation of the statements about their proprioceptive deficits, the capacity of the patients to score their instability consciously is not affected, showing that they are able to collect and integrate the sensory inputs from the periphery and convert them into an explicit evaluation of their sway [65,80]. When patients with Parkinson´s disease are standing on the moving platform continuously delivering the cyclic perturbations, their trunk and head do not oscillate more than age matched healthy subjects, regardless of vision availability. Again, their preserved reflex responses and the capacity to anticipate the successive perturbation cycles [81] may help them to react properly to the postural challenge [82]. It should be considered that medicated patients maintain the capacity of improving automatic postural responses with practice [83]. However, patients characterized as fallers based on their medical history do show larger head oscillations compared to non-fallers when they close their eyes [84]. Further, these fallers show smaller cross-correlation and larger time delays between head and platform motion. Interestingly, in that cohort, head displacement increased with levodopa dose, suggesting the possibility for medication to worsen balancing capacity while improving the score of the Unified Parkinson's Disease Rating Scale.

As has been done in healthy young subjects, the translating platform has been exploited to answer the question of whether patients with PD are more sluggish in their ability to adapt promptly in the balancing behaviour to sudden changes in visual conditions [85]. Patients change body kinematics and EMG patterns to those appropriate for the new visual condition as normal subjects do when balancing on the moving platform. However, patients are slower in changing their behaviour (i.e., shifting from head-fixed-in-space with EO to body riding the platform with EC), in particular for the change EC to EO, as if adding a new important sensory inflow would represent an integration problem. These findings should be considered in the framework of the integration deficits in PD [86].

9. Adaptation to the Repeated Perturbation Cycles

The findings from the studies reported in the preceding sections were obtained mostly under steady-state conditions, i.e., when the initial uncontrolled reactions to the onset of the platform translation have vanished. Usually, the first few translation cycles are omitted from the analysis. Yet, these initial cycles and associated reactions and their changes as a function of the successive cycles can tell something about the way subjects comply with the condition and, in perspective, whether the problems in balancing behaviour affect more the transient phase or the steady-state behaviour or how pathologies affect these initial reactions. Adaptation implies a gradual shift from a reactive response to the abrupt onset of the perturbation series and from conscious control of the balancing behaviour to a more automatic processing, including modulation of the reflex responses triggered by the continuous stimulation (see [87] for the neck responses in seated subjects). Hence, understanding the adaptation phenomenon adds to our capacity of better exploiting this challenging perturbation procedure in order to understand the mechanisms and processes whereby the appropriate balancing behaviour is achieved and maintained in order to produce a more suitable behaviour.

The strength of the reflex response triggered by a certain ankle rotation during a series of horizontal translations is modulated appropriately by its repetition [88]. Even more so, the very same responses elicited by the translating platform itself should be liable to modulation by the continuous perturbation cycles. By using a sequence of discrete impulsive perturbations, Keshner et al. [89] had already suggested that adaptation was due to a generalized habituation in the postural control system. Others have shown that event related cortical potentials connected to the postural stimulus diminish over time with the successive cycles [90]. Of course, at the onset of the sequence of perturbations, a combined postural and startle response ensues [91,92].

Taken together, the studies show that adaptation occurs when a subject's balance is challenged by repeated perturbations. Under these circumstances, the sensorimotor processes underlying the adaptation to the repeated perturbations would require the collection of information about the amplitude velocity and frequency of the displacement of the support surface and of the instantaneous and continuously varying position of the body's CoM relative to the platform. This information would improve the performance by reducing redundant muscle activity (the initial co-contraction of the antagonist leg muscles) and enhancing the intersegmental coordination [33,41]. The reduction in the muscle activity concerns both the reflex responses and the anticipatory activities, a sign of coordinated modulation of responses occurring at different times of the perturbation cycle. Interestingly, the reduced muscle bursts of activity do not modify their time relationship with the perturbation cycle [93]. This indicates that the adaptation modulates so nicely with the neuronal excitability and muscle activity that it need not modify the time windows of their activation to comply with the changes in the body's mechanics. As a consequence, the head back-and-forth oscillation is diminished as well [41,94]. The speed of the adaptation process is susceptible to fatigue, even if the basic task of controlling the CoM of the body is substantially maintained [95–97].

10. Rehabilitation

Predictable balance perturbations have been successfully employed for rehabilitation of balance in selected patient groups [98] including vestibular patients [17], who may poorly behave on the platform when not compensated [99], and cerebellar patients, of both degenerative and vascular origin [100]. In all groups, such a training improved balance, allowing recommending the continuous translation as an effective and measurable way of rehabilitation. To our knowledge, clinical trials of balance rehabilitation in neuropathic patients based on this protocol have not been exploited, yet. However, these patients can improve balance control following multisensory training [101], strongly suggesting that continuous perturbations with and without vision could enhance their compensation capacities. Patients with Parkinson's disease show minor adaptation problems that can contribute to their balance dysfunction [8,85,102]. A balance training with a continuous, predictable translation of the support base has improved their balance and coordination capacities as much as training based on standardized exercises [103]. Interestingly, gait speed was also improved in both cases. Overall, the continuous and predictable translations of a support base onto which standing patients would be trained to enhance their reflex and balance correcting responses and to calibrate their anticipatory adjustments seem to be useful, yet still not exploited for all the potential advantages.

11. Conclusions and Perspectives

This short narrative review summarized some findings of studies on dynamic balance control. We briefly considered the potential of this protocol for both basic and translational research. It disclosed interesting features of balance control in healthy subjects and patients with balance problems. Much can still be done. Quantification of the variability of the balancing behaviour has not been addressed in depth. We are still missing normative values for the cross-correlation and time lag between moving body segments, which could likely be exploited as markers for initial balance problems. The effect of fatigue and adaptation while the training is administered needs further inquiry as well. Importantly, this protocol has proven helpful in rehabilitating balance in various cohorts of patients. Again, the rehabilitating potential can be further exploited, not only in patients with balance problems, but also in healthy older subjects, for which the risk of falling owing to stumbling or slipping is not uncommon.

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