

Chapter

THE ROLE OF UNSTABLE SHOE CONSTRUCTIONS FOR THE IMPROVEMENT OF POSTURAL CONTROL

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ABSTRACT

Postural control has been defined as the control of the body's position in space for the purposes of balance and orientation. Given the mechanical instability of the human body system, the neural process involved in stability organization and body orientation in space is necessary almost all motor actions. To manage movement variability, the postural control system presents a high adaptability in response to changing task and environment demands. The main sensory systems contribute to the development of an internal representation of body posture that is continuously updated based on multisensory feedback and is used to forward commands to control body position in space. For example, understanding the importance of proprioceptive information, and how ankle muscles can influence changes of support and stability that could improve postural control is of significant relevance. The purpose of this chapter is to review and discuss the short and long term influence of wearing an unstable shoe construction on postural control. The review provides instinctive knowledge that can be used during rehabilitation to improve motor performance. It also aims to provide a significant insight into areas that have been dedicated to the implementation of preventive measures, such as ergonomics.

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INTRODUCTION

Postural control is an essential function in daily activities, which varies as a result of the task-individual-environment interaction. [1, 2] Indeed, considering that the body centre of mass (CoM) is located at two-thirds of body height above the ground, the human body is an inherently unstable system that provides a particularly challenging balance task to the central nervous system (CNS). [3] In turn, the CNS has to manage the redundancy of degrees of freedom resulting from the large number of muscles and joints involved to create flexible synergies according to task specificities. [4-9] The neural process involved in postural control is necessary for all dynamic motor actions. [10] In fact, most voluntary movement induces a postural perturbation because of dynamic, inter-segmental forces, and also shifts of the CoM. Therefore, voluntary movements may be considered self-inflicted postural perturbations that may be predicted, to a certain degree, by the CNS, which adjusts the activity of postural muscles both prior to the actual perturbation and in response to it. [11]

Studies on balance and posture during quiet or perturbed standing have identified the dominance of ankle muscles in the anteroposterior direction (Figure 1) and hip abductor/adductor muscles in the mediolateral direction. [3, 12-15] During quiet standing, postural sway results from a combination of inherent fluctuations in the musculoskeletal system, cardiac and respiratory variations, and neural activity. However, it has also been suggested that postural sway serves as an exploratory behavior for the stimulation of somatosensory and vestibular pathways to provide sensory information for increased postural control. [16, 17] By reconciling these two points of view, it is likely that sway characteristics result from an interaction between physiological states, the environment, and the implicit and explicit goals of the current task. [1, 18]

Under normal conditions during standing on a rigid floor, the postural control system elaborates the reference position using information about the relative positions of body segments, muscular torques and interaction with the base of support, taking into account the energy cost of standing and demands for stability and orientation. [19-21] Body alignment can minimise the effect of gravitational forces that tend to pull-off the CoM from the base of support, and muscle tone, i.e., intrinsic stiffness of the muscles, background muscle tone and postural tone, keeps the body from collapsing due to gravity. [1] When postural conditions change, the CNS must identify and selectively focus the most reliable sensory inputs to provide optimal control. As a result of this weighting of afferent input, muscle forces can be produced to control the CoM efficiently to maintain a good equilibrium. [22] Much of the research has focused in quantifying the human response to balance system perturbation in a different number of ways, such as displacement of support surface, predictable and unpredictable external perturbations and internal perturbations. Several factors have been shown to influence postural control responses, but mainly at an immediate level. Taking into account the high adaptability of the CNS [23] in response to changing task and environment demands, [1] it is important to understand the long-term influence of these changes of afferent information that could be beneficial to postural control. Given the importance of the ankle

joint in upright postural control, [24] the influence of an unstable support base in postural control is of significant relevance.

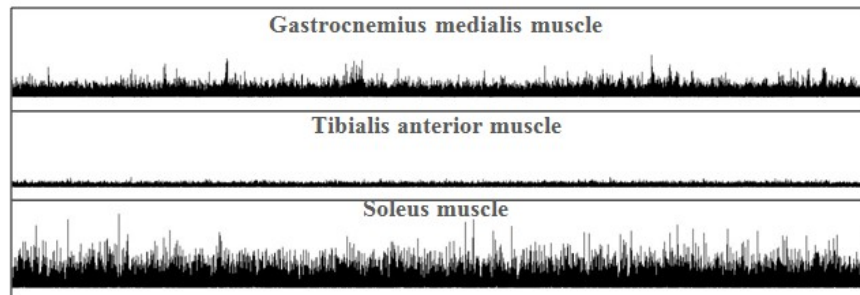


Figure 1. Muscle activity of ankle plantarflexors (soleus and gastrocnemius medialis muscles) and tibial anterior muscle during 60s of upright standing.

Neuromuscular Changes When Standing on an Unstable Support Base

When standing on an unstable support base the new postural requirements lead to postural control reorganisation through increased central drive [25, 26] associated with augmented gamma motoneuron activity leading to higher sensitivity of the muscle spindles [27] and higher muscle co-contraction. [28] However, anticipatory postural adjustments (APA) have been shown to decrease not only in very stable conditions, [29] but also in very unstable conditions. [30] Since the need for stabilising posture is diminished in stable conditions, the requirement for APA is also reduced. [29] Also, APA could themselves be a potential source of perturbation in case of unstable posture, and as such they are also reduced not to additionally destabilise posture. [30] Hence, it seems that the permanence in an unstable support base could, up to a certain level of instability, improve postural control.

Unstable Shoe Construction and Postural Control

Short-Term Postural Control Reorganisation in Response to an Unstable Shoe Construction

During quiet stance on a flat, stable platform individuals sway slightly, and the body oscillates around the ankle-joint axis like an inverted pendulum. [31] When standing on a see-saw (Figure 2), humans project the CoM onto the see-saw's point of contact with the floor. [32]

There is an increased postural sway when wearing rocking shoes, [33] Table 1, expressed by changes in most of the representative CoP displacement parameters, [34] reflecting a situation of high postural demand, which associated to a higher active control at the ankle level [33, 35] would lead to an increased proprioceptive acuity provided by ankle muscles [36] as a result of a higher fusimotor drive. [27, 37, 38] This aspect is supported by recent studies that demonstrated a decrease of onset timing of ankle plantar flexors in response to an external forward perturbation under the condition of higher support instability. [39, 40] The relation between an increase of proprioceptive acuity and the higher fusimotor drive of ankle

plantarflexors (gastrocnemius and soleus) during standing in an unstable support base is acceptable as length signals coming from the less adaptable spindles secondaries provide the CNS with an appropriate input for detecting low-frequency displacements occurring mainly about the ankle [21] and for assisting ankle muscle reflex responses. [41] This interpretation is valid if we consider the studies arguing that ankle plantarflexors are the main responsible for proprioceptive information signaling changes in body position. [42] Recently, based on the fact that during quiet standing reciprocal inhibition could be more important than autogenic stretch reflex, importance has been given to the role of un-modulated muscles crossing the joint in parallel with the active agonist. [43] Under this perspective, the use of unstable shoe construction (Figure 2), not affecting tibialis anterior muscle activity, [35, 39] would be also associated with maintenance of acuity of proprioceptive information provided by the un-modulated muscles, since no differences were observed in antagonist muscles activity in response to the unstable support base condition. In summary, it can be suggested that the higher performance of the postural system when using unstable shoes is associated with increased proprioceptive acuity related to higher motor drive of ankle plantarflexors spindles and to a maintenance of motor drive over muscle spindles of the antagonist.

Table 1. Representation of the variation of CoP displacement parameters obtained during standing with an unstable shoe construction in relation to a stable condition

Unstable shoe condition vs stable condition			
CoP displacement	CoP root mean square	CoP mean velocity	CoP area
↑	↑	↑	↑



Figure 2. Illustration of a kind of unstable shoe construction and a schematic representation of the see-saw adopted in various studies to induce an unstable support base.

Studies about postural control when standing on a see-saw have devaluated the role of the information provided by muscle spindles, arguing that the higher changes in orientation provided by this kind of support surfaces makes it difficult to use proprioceptive information about the relative positions of successive links of the kinematic chain for the reconstruction of a body's position internal representation. [32, 44] As a consequence, the authors gave more importance to the information provided by the Golgi organ tendon. [32] However, it should be noted that the format of the unstable shoes commercialized is different from the see-saw used in previous studies (Figure 2), leading to lower levels of changes in segment orientation at the ankle joint, justifying the maintenance of the role of muscle spindles in this condition.

The influence of the information provided by cutaneous afferents of the feet should be also questioned, considering its importance in standing postural control. [45, 46] However, to date, there is no evidence supporting this possibility.

In association with the previous paragraph, standing in an unstable support base is associated with increased reciprocal activation at the leg, thigh segments and muscle group levels, and lower co-activation levels. [39] Reciprocal activation of the agonist-antagonist set is present when the subject is uncertain of the task to be performed, when a quick compensatory force contraction is perceived to be required, [47] and in joints involving joint movement. [48] Studies using see-saws and continuous rotating platforms have indicated higher joint movement associated with the need of making see-saw rotation to place the support under the CoM. [32, 44] However, because the degree of perturbation induced by commercial unstable shoes is lower than that applied in the studies mentioned, it would be expected higher co-activation levels in the unstable support base condition, as co-activation has been described as the most robust strategy to counteract perturbations [49-52] by increasing joint stiffness. [53-57] However, the results obtained in recent studies [33, 39] indicate that wearing unstable shoes leads the postural control system to rely more on reflex feedback more than on stiffness increase to compensate for the decrease of stability, which has been demonstrated to be more efficient and accurate, but also more challenging for the postural control system. [58-64] This synergy pattern selection in association with the changes occurred in the magnitude of ankle muscles activity only [35] indicates that this kind of unstable shoe leads to instability levels that are perfectly managed by the CNS as a low perturbation. [65, 66] In fact, the postural performance is not modified when exposed to an external perturbation. [39, 40]

The higher demand over postural control in an unstable support base led to changes in the neuromusculoskeletal system, mainly at the ankle joint, leading also to positive effects over the venous return. [35] This could be related to the increased activity of the gastrocnemius muscle, to the kind of contraction imposed, as well as to the increased reciprocal activation.

Long-Term Postural Control Reorganisation in Response to an Unstable Shoe Construction

After prolonged standing in an unstable support base, the individual muscle activity, as well as the relation between agonist and antagonist, are close to the necessary for a stable support base condition. [33, 35, 40] However, exceptions were observed at the thigh level as reciprocal activation remained higher in the unstable condition [33, 40] associated to an increased biceps femoris activity in automatic and voluntary compensatory response and decreased gastrocnemius medialis activity. [40] These findings suggest a transfer of postural control synergy for the thigh which has been reported as more beneficial to optimise postural stability. [13, 19, 67-69] In fact, CoP parameters indicate higher performance by the postural control system in compensatory responses after prolonged wearing of unstable shoes, [40] and the relation between CoP and CoM [33] indicates a higher performance and efficiency [70, 71] of the supraspinal process, as well as of the action of spinal reflexes and/or of the intrinsic mechanical properties of muscles and joints. [72] Bearing in mind the important role of the information provided by group II fibers in postural control during standing, [41, 73-77] it can be hypothesised, based on the findings presented by Sousa et al., [40] that decreased gastrocnemius activity after prolonged wearing of unstable shoes could also be related to a possible decrease of medium latency responses. This hypothesis is based on the evidence that

medium latency responses mediated group II afferences are more influenced by the postural set and are the only that have a stabilising effect during perturbation of stance. [78, 79] The maintenance of decreased values of ankle muscle latency, even after prolonged unstable shoe wearing, [40] can be related to a remaining instability effect expressed by the higher activity of total agonist activity and higher values of CoP displacement in the unstable support base condition. [33]

From the findings and observations presented in this chapter, [33, 40] it is evident that prolonged wearing of unstable shoes leads to improved postural performance and efficiency. Also, even after adaptation by the postural control system, the venous return is higher in the unstable support base condition than in the control condition. [35] The results obtained by Sousa et al. [40] suggest that the main factor responsible for increased venous return is related to the kind of muscle contraction of plantarflexors, since dynamic muscle contractions favour venous circulation. This conjecture is sustained by higher CoP displacement values observed after prolonged wearing of unstable shoe [33] and by studies on see-saws. [32, 44]

The impact of postural control strategies on venous return is of significant relevance in healthy subjects that are in risk of developing venous insufficiency, but also in subjects with venous insufficiency. Chronic venous insufficiency explains those manifestations of venous disease resulting from ambulatory venous hypertension, which is associated with failure of the lower extremity muscle pumps due to outflow obstruction, musculo-fascial weakness, loss of joint motion or valvular failure. [80-83] Although the effect of an unstable support base has been explored only in healthy subjects, beneficial results would be expected in subjects with venous insufficiency, as balance training has been demonstrated to promote improved postural control performance both in healthy subjects [84-90] and in subjects with ankle muscles impairment. [87, 91] This is of significant relevance since it has been demonstrated that calf muscle strengthening exercises restore the pumping ability of the calf muscle and improve the haemodynamic performance in limbs with active ulceration subsequent to severe venous valvular and calf muscle pump impairment. [92-94]

CONCLUSION

This review chapter has discussed the role of instability imposed by rocking (unstable) shoes and how it may lead to positive effects over the postural control system. This effect appears to be related to higher acuity muscle spindles at the immediate level and after a long-term exposure. The changes occurred in terms of ankle muscle activity in response to an unstable support base favour venous circulation even after training adaptation by the neuromuscular system. Considering the review presented in this chapter, the use of unstable shoe constructions should be encouraged in rehabilitation as a strategy to improve postural control performance.

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REFERENCES

- [1] Shumway-Cook A, Woolacott M. Motor control: translating research into clinical practice. 3rd ed. Philadelphia: *Lippincott Williams & Wilkins*; 2007.
- [2] Allum JHJ, Bloem BR, Carpenter MG, Hulliger M, Hadders-Algra M. Proprioceptive control of posture: a review of new concepts. *Gait Posture*. 1998;8:214-42.
- [3] Winter DA. Human balance and posture control during standing and walking. *Gait Posture*. 1995;3:193-214.
- [4] Allum JHJ, Honegger F, Schicks H. Vestibular and proprioceptive modulation of postural synergies in normal subjects. *Journal of Vestibular Research*. 1993;3:59-85.
- [5] Allum JHJ, Honegger F, Schicks H. The influence of a bilateral peripheral vestibular deficit on postural synergies. *Journal of Vestibular Research*. 1994;4:49-70.
- [6] Diener HH, FB; Nashner, LM. Influence of stimulus parameters on human postural responses. *Journal of Neurophysiology*. 1988;59:1888-905.
- [7] Horak B, Nashner L. Central programming of postural movements: adaptation to altered support-surface configurations. *Journal of Neurophysiology*. 1986;55:1369-81.
- [8] Keshner EW, MH; Debu, B. Neck, trunk and limb muscle responses during postural perturbations in humans. *Experimental Brain Research*. 1988;71:455-66.
- [9] Macpherson J. Changes in postural strategy with inter-paw distance. *Journal of Neurophysiology*. 1994;71:931-40.
- [10] Massion J. Postural control systems in developmental perspective. *Neuroscience Biobehavioral Review*. 1998;22:465-72.
- [11] Arruin A. The organization of anticipatory postural adjustments. *Journal of Automatic Control*. 2002;12:31-7.
- [12] Fitzpatrick R, Taylor J, McCloskey D. Ankle stiffness of standing humans in response to imperceptible perturbation: reflex and task-dependent components. *Journal of Physiology*. 1992;454:533-47.
- [13] Kuo AZ, FE. Human standing posture: multi-joint movement strategies based on biomechanical constraints. *Progress in Brain Research*. 1993;97:349-58.
- [14] Johanson R. System modeling and identification. Englewood Cliffs: *Prentice Hall*; 1993.
- [15] Winter DA, Prince F, Frank J, Powell C, Zabjek K. Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology*. 1996;75:2334-43.
- [16] Riley MA, Balasubramaniam R, Turvey MT. Recurrence quantification analysis of postural fluctuations. *Gait & Amp; Posture*. 1999;9:65-78.
- [17] Riley MA, Wong S, Mitra S, Turvey MT. Common effects of touch and vision on postural parameters. *Experimental Brain Research*. 1997;117:165-70.
- [18] Rothwell J. Control of human voluntary movement. 2nd ed. London: *Chapman & Hall*; 1994.
- [19] Horak F, Nashner L, Diener H. Postural strategies associated with somatosensory and vestibular loss. *Experimental Brain Research*. 1990;82:167-77.

-
- [20] Dietz V. Human neuronal control of automatic functional movements: interaction between central programs and afferent input. *Physiological Reviews*. 1992;72:33-69.
- [21] Gurfinkel VS, Ivanenko YP, Levik YS, Babakova IA. Kinesthetic reference for human orthograde posture. *Neuroscience*. 1995;68:229-43.
- [22] Carver S, Kiemel T, Jeka J. Modeling the dynamics of sensory reweighting. *Biological Cybernetics*. 2006;95:123-34.
- [23] Winter DA. Kinematic and kinetic patterns in human gait: Variability and compensating effects. *Human Movement Science*. 1984;3:51-76.
- [24] Fitzpatrick R, Douglas K, McCloskey D. Stable human standing with lower-limb muscle afferents providing the only sensory input. *Journal of Physiology*. 1994;2536:395-403.
- [25] Ivanenko YP, Talis VL, Kazennikov OV. Support stability influences postural responses to muscle vibration in humans. *European Journal of Neuroscience*. 1999;11:647-54.
- [26] Gavrilenko T, Gatev N, Dimitrova D. Somatosensory evoked potentials during standing posture on different support conditions. *Homeostasis*. 1995;33:39-46.
- [27] Ribot-Ciscar E, Hospod V, Roll J-P, Aimonetti J-M. Fusimotor drive may adjust muscle spindle feedback to task requirements in humans. *Journal of Neurophysiology*. 2009 February 2009;101:633-40.
- [28] Dietz V, Mauritz K, Dichgans J. Body oscillations in balancing due to segmental stretch reflex activity. *Experimental Brain Research*. 1980;40:89-95.
- [29] Nardone A, Schieppati M. Postural adjustments associated with voluntary contraction of the leg muscles in standing man. *Experimental Brain Research*. 1988;69:469-80.
- [30] Arruin A, Forrest W, Latash M. Anticipatory postural adjustments in conditions of postural instability. *Electroencephalography and Clinical Neurophysiology*. 1998;109:350-9.
- [31] Winter DA, Patla A, Prince F, Ishac M, Gielo-Perczak K. Stiffness control of balance in quiet standing. *Journal of Neurophysiology*. 1998;80:1211-21.
- [32] Ivanenko Y, Levik Y, Talis V, Gurfinkel V. Human equilibrium on unstable support: the importance of feet-support interaction. *Neuroscience Letters*. 1997;235:109-12.
- [33] Sousa ASP, Macedo R, Santos R, Silva A, Tavares JMR. The influence of wearing unstable shoes on upright standing postural control. *Medical Engineering & Physics*. 2013;(submitted).
- [34] Rocchi L, Chiari L, Cappello A. Feature selection of stabilometric parameters based on principal component analysis. *Med Biol Eng Comput*. 2004;42:71-9.
- [35] Sousa ASP, Tavares JMRS, Macedo R, Rodrigues AM, Santos R. Influence of wearing an unstable shoe on thigh and leg muscle activity and venous response in upright standing. *Applied Ergonomics*. 2012;43:933-9.
- [36] Gandevia SC, McCloskey DI, Burke D. Kinaesthetic signals and muscle contraction. *Trends in Neurosciences*. 1992;15:62-5.
- [37] Gorassini M, Prochazka A, Taylor JL. Cerebellar ataxia and muscle spindle sensitivity. *Journal of Neurophysiology*. 1993 November 1, 1993;70:1853-62.
- [38] Gurfinkel VS, Popov KK, B.N. S. The support input as a reference for postural control. In: Woolacott M, Horak F, editors. *Posture and gait: Control mechanisms*. Oregon: *University of Oregon Books*; 1992. p. 182-6.

- [39] Sousa ASP, Macedo R, Santos R, Tavares JMR. The influence of wearing unstable shoes on compensatory control of posture. *Human Movement Science*. 2013; in press.
- [40] Sousa ASP, Macedo R, Silva A, Santos R, Tavares JMR. Influence of long-term wearing of unstable shoes on compensatory control of posture: An electromyography-based analysis. *Gait Posture*. 2014;39:98-104.
- [41] Schieppati M, Nardone A, Siliotto R, Grasso M. Early and late stretch responses of human foot muscles induced by perturbation of stance. *Experimental Brain Research*. 1995;105:411-22.
- [42] Loram I, Maganaris C, Lakie M. Active, non-spring-like muscle movements in human postural sway: how might paradoxical changes in muscle length be produced? *Journal of Physiology*. 2005;564:283-93.
- [43] Di Giulio I, Maganaris C, Baltzopoulos V, Loram I. The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. *Journal of Physiology*. 2009;587:2399-416.
- [44] Ivanenko Y, Talis V. Effect of surface support stability on the postural vibration reactions in man. *Human Physiology*. 1995;21:116-24.
- [45] Roll R, Kavounoudias A, Roll J-P. Cutaneous afferents from human plantar sole contribute to body posture awareness. *NeuroReport*. 2002;13:1957-61.
- [46] Wright W, Ivanenko Y, Gurfinkel V. Foot anatomy specialization for postural sensation and control. *Journal of Neurophysiology*. 2012;107:1513-21.
- [47] De Luca C, Mambrito B. Voluntary control of motor units in human antagonist muscles: coactivation and reciprocal activation. *Journal of Neurophysiology*. 1987 September 1, 1987;58:525-42.
- [48] Lavoie B, Devanne H, Capaday C. Differential control of reciprocal inhibition during walking versus postural and voluntary motor tasks in humans. *Journal of Neurophysiology*. 1997;78:429-38.
- [49] Milner T. Adaptation to destabilizing dynamics by means of muscle cocontraction. *Experimental Brain Research*. 2002;143:406-16.
- [50] Osu R, Gomi H. Multijoint muscle regulation mechanisms examined by measured human arm stiffness and EMG signals. *Journal of Neurophysiology*. 1999;81:1458-68.
- [51] Humphrey D, Reed D. Separate cortical systems for control of joint movement and joint stiffness: reciprocal activation and coactivation of antagonist muscles. *Advances in neurology*. 1983;39:347-72.
- [52] Damm L, McIntyre J. Physiological basis of limb-impedance modulation during free and constrained movements. *Journal of Neurophysiology*. 2008;100:2577-88.
- [53] Feldman A. Superposition of motor programs: 1. Rhythmic forearm flexion in man. *Neuroscience*. 1980;5:81-90.
- [54] Joyce GC, Rack PMH, Westbury DR. The mechanical properties of cat soleus muscle during controlled lengthening and shortening movements. *The Journal of Physiology*. 1969;204:461-74.
- [55] Nichols TR, Houk JC. Improvement in linearity and regulation of stiffness that results from actions of stretch reflex. *Journal of Neurophysiology*. 1976;39:119-42.
- [56] Serres SJ, Milner TE. Wrist muscle activation patterns and stiffness associated with stable and unstable mechanical loads. *Experimental Brain Research*. 1991;86:451-8.

-
- [57] Milner T, Cloutier C, Leger A, Franklin D. Inability to activate muscles maximally during cocontraction and the effect on joint stiffness. *Experimental Brain Research*. 1995;107:293-305.
- [58] Friedli WG, Hallett M, Simon S. Postural adjustments associated with rapid voluntary arm movements 1. Electromyographic data. *Journal of Neurology, Neurosurgery & Psychiatry*. 1984;47:611-22.
- [59] Hong D, Corcos D, Gottlieb G. Task dependent patterns of muscle activation at the shoulder and elbow for unconstrained arm movements. *Journal of Neurophysiology*. 1994;71:1261-5.
- [60] Latash M, Aruin A, Neyman I, Nicholas J. Anticipatory postural adjustments during self-inflicted and predictable perturbations in Parkinson's disease. *Journal of Neurology, Neurosurgery & Psychiatry*. 1995;58:326-34.
- [61] Hogan N. Adaptive control of mechanical impedance by coactivation of antagonist muscles. *IEEE Trans Autom Control*. 1984;29:681-90.
- [62] Aruin A, Almeida G. A coactivation strategy in anticipatory postural adjustment in persons with Down syndrome. *Motor Control*. 1997;2:178-97.
- [63] Garland SJ, Stevenson TJ, Ivanova T. Postural responses to unilateral arm perturbation in young, elderly, and hemiplegic subjects. *Archives of Physical Medicine and Rehabilitation*. 1997;78:1072-7.
- [64] Massion J, Ioffe M, Schmitz C, Viallet F, Gantcheva R. Acquisition of anticipatory postural adjustments in bimanual load-lifting task: normal and pathological aspects. *Experimental Brain Research*. 1999;128:229-35.
- [65] Santos M, Aruin A. Effects of lateral perturbations and changing stance conditions on anticipatory postural adjustment. *Journal of Electromyography and Kinesiology*. 2009;19:532-41.
- [66] Adkin A, Frank J, Carpenter M, Peysar G. Postural control is scaled to level of postural threat. *Gait Posture*. 2000;12:87-93.
- [67] Day BL, Steiger MJ, Thompson PD, Marsden CD. Effect of vision and stance width on human body motion when standing: implications for afferent control of lateral sway. *Journal of Physiology*. 1993;469:479-99.
- [68] Runge C, Shupert C, Horak F, Zajac F. Ankle and hip postural strategies defined by joint torques. *Gait Posture*. 1999;10:161-70.
- [69] Yang JF, Winter DA, Wells RP. Postural dynamics in standing human. *Biological Cybernetics*. 1990;62:309-20.
- [70] Prieto T, Myklebust J, Hoffmann R, Lovett E, Myklebust B. Measures of postural steadiness: differences between healthy young and elderly adults. *Biomedical Engineering, IEEE Transactions on*. 1996;43:956-66.
- [71] Bennell K, Goldie P. The differential effects of external ankle support on postural control. *Journal of Orthopaedics and Physical Therapy*. 1994;20:287-95.
- [72] Zatsiorsky VM, Duarte M. Instant equilibrium point and its migration in standing tasks: rambling and trembling components of the stabilogram. *Motor Control*. 1999;3:28.
- [73] Corna S, Galante M, Grasso M, Nardone A, Schieppati M. Unilateral displacement of lower limb evokes bilateral EMG responses in leg and foot muscles in standing humans. *Experimental Brain Research*. 1996;109:83-91.

- [74] Marchand-Pauvert V, Nicolas G, Marque P, Iglesias C, Pierrot-Deseilligny E. Increase in group II excitation from ankle muscles to thigh motoneurons during human standing. *The Journal of Physiology*. 2005;566:257-71.
- [75] Morasso PG, Schieppati M. Can muscle stiffness alone stabilize upright standing? *Journal of Neurophysiology*. 1999;82:1622-6.
- [76] Nardone A, Grasso M, Giordano A, Schieppati M. Different effect of height on latency of leg and foot short- and medium-latency EMG responses to perturbation of stance in humans. *Neuroscience Letters*. 1996;206:89-92.
- [77] Schieppati M, Nardone A. Medium-latency stretch reflexes of foot and leg muscles analysed by cooling the lower limb in standing humans. *The Journal of Physiology*. 1997;503:691-8.
- [78] Nardone A, Giordano A, Corrá T, Schieppati M. Responses of leg muscles in humans displaced while standing. Effects of types of perturbation and of postural set. *Brain*. 1990;113:65-84.
- [79] Jacobs JV, Horak FB. Cortical control of postural responses. *J Neural Transm*. 2007 2007/10/01;114:1339-48.
- [80] Araki C, Back T, Padberg F, Thompson P, Jamil Z, Lee B. The significance of calf muscle pump function in venous ulceration. *Journal of Vascular Surgery*. 1994;20:872-7.
- [81] Plate G, Brudin L, Eklof B, Jensen R, Ohlin P. Congenital vein valve aplasia. *World Journal of Surgery*. 1986;10:929-34.
- [82] Nicolaidis A, Hussein M, Szendro G, Christopoulos D, Vasdekis S, Clarke H. The relationship of venous ulceration with ambulatory venous pressure measurements. *Journal of Vascular Surgery*. 1993;17:414-9.
- [83] Stewart J, Medow M, Montgomery L, McLeod K. Decreased skeletal muscle pump activity in patients with postural tachycardia syndrome and low peripheral blood flow. *American Journal of Heart and Circulatory Physiology*. 2004;286:1216-22.
- [84] Balogun J, Adesinasi C, Marzouk D. The effects of a wobble board exercise training program on static balance performance and strength of lower extremity muscles. *Physiotherapy Canada*. 1992;44:23-30.
- [85] Heitkamp H, Horstmann T, Mayer F, Weller J, Dickhurth H. Gain in strength and muscular balance after balance training. *International Journal of Sports Medicine*. 2001;22:285-90.
- [86] Hoffman M, Payne V. The effect of proprioceptive ankle disk training on healthy subjects. *Journal of Orthopaedic Sports and Physical therapy*. 1995;21:90-3.
- [87] Rozzi S, Lephart S, Sterner R, Kuligowski L. Balance training for persons with functionally unstable ankles. *Journal of Orthopaedic Sports and Physical Therapy*. 1999;29:478-86.
- [88] Waddington G, Adams R. The effect of a 5-week wobble-board exercise intervention on ability to discriminate different degrees of ankle inversion, barefoot and wearing shoes: a study in healthy elderly. *Journals of the American Geriatrics Society*. 2004;52:573-6.
- [89] Waddington G, Seward H, Wrigley T, Lacey N, Adams R. Comparing wobble board and jump-landing training effects on knee and ankle movement discrimination. *Journal of Science and Medicine in Sport*. 2000;3:449-59.

- [90] Wester J, Jespersen S, Nielsen K, Neumann L. Wobble board training after partial sprains of the lateral ligaments of the ankle: a prospective randomized study. *Journal of Orthopaedics and Physical Therapy*. 1996;23:332-6.
- [91] Mattacola C, Lloyd J. Effects of a 6-week strength and proprioceptive training program on measures of dynamic balance: a single-case design. *Journal of Athletic Training*. 1997;32:127-35.
- [92] Yang D, Vandongen Y, Stacey M. Effect of exercise on calf muscle pump function in patients with chronic venous disease. *British Journal of Surgery*. 1999;86:338-41.
- [93] Kan Y, Delis K. Hemodynamic effects of supervised calf muscle exercise in patients with venous leg ulceration. A prospective controlled study. *Archives of Surgery*. 2001;136:1364-9.
- [94] Padberg F, Johnston M, Sisto S. Structured exercise improves calf muscle pump function in chronic venous insufficiency: a randomized trial. *Journal of Vascular Surgery*. 2004;39:79-87.

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