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COMPREHENSIVE REVIEW

The sensory role of the sole of the foot: Review and update on clinical perspectives

Frederic J.F. Viseux [a,b,c,*]

[a] *UMR CNRS 8201, laboratoire d'automatique, de mécanique et d'informatique industrielle et humaine (LAMIH), université Polytechnique des Hauts-de-France, 59313 Valenciennes, France*
[b] *Centre d'évaluation et de traitement de la douleur (CETD), centre hospitalier de Valenciennes (CHV), 59322 Valenciennes, France*
[c] *Posture Lab, 75012 Paris, France*

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Summary The feet constitute an important sensory structure in the mechanisms of postural control. As a direct and often only interface between the body and the ground, the feet allow us to sense and interact with our environment. Sensory information provided by muscle and cutaneous afferents in the foot contribute to our ability to stand upright, and postural sway is necessary to detect both position and motion of the body in space. A decline in foot sole skin sensitivity occurs naturally with aging and as a result of neurological disorders, including different peripheral neuropathies, the commonest etiologies of which are diabetes mellitus or effects of chemotherapy. This decline in sensitivity is frequently associated with poorer postural control and increased risk of falls in these populations. The purpose of this comprehensive review is to summarize the evidence that supports a functional role of foot sole sensory tactile and muscular feedback in standing balance, and the postural consequences when this feedback is impaired with aging or disease. This brings new clinical perspectives on the development of intervention strategies to improve the quality of foot sole cutaneous feedback. It also seems to be a promising approach in the management of patients with balance disorders, with specific chronic pain syndromes, with neurologic diseases or those at risk of falling.

Introduction

Human postural control is a complex process involving sensory inputs from visual, vestibular, proprioceptors and tactile receptors. It may be defined as the act of achieving, maintaining or restoring a state of balance during any

* Correspondence at: Centre d'évaluation et de traitement de la douleur (CETD), centre hospitalier de Valenciennes (CHV), 59322 Valenciennes, France.
E-mail address: viseux-f@ch-valenciennes.fr

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posture or activity [132], and depends on a combination of both passive and active mechanical controls [191]. Passive control refers to the stiffness and kinematic proprieties of the joints, as well as the effect exerted on them by gravity. Active control is characterized by neural regulation of skeletal muscles responsible for sway detection and postural correction [9,140]. Postural instability seems to require a high hierarchical level of posture control and activation of different brain areas [144]. A facilitatory effect of postural instability on corticospinal pathways has been observed [154] and could depend on the existing level of background motor activity [81]. In addition, sensory transmission facilitation may occur depending on the motor task [14,109], and could play a critical role for feedforward mechanisms [109]. Automatic processes including sensory interaction (i.e., proprioceptive and tactile) and cutaneous reflexes contribute to control of posture [64,166]. Unavailable or disrupted signals from one or more sensors may result in a decrease in postural stability. When balance is disturbed, a postural adjustment by a series of cutaneous postural reflexes can be initiated by cutaneous mechanoreceptors [12,93,119].

It is clear that the feet constitute an important sensory structure in the mechanisms of postural control. As a direct and often unique interface between the body and the ground [63], the feet allow us to sense and interact with our environment. This ability results from the coordination between the motor system, which controls muscular activity and pressure exerted by the feet, and the somatosensory afferent system. Somatosensory feedback arises from a variety of sources, most notably the cutaneous mechanoreceptors in the skin, and muscle spindle endings found within most skeletal muscles that together provide tactile and proprioceptive feedback. Plantar cutaneous afferents transmit spatial and temporal feedback concerning the pressure variations and skin stretch exerted on the soles of the feet [58,63,179]. In response to this sensory feedback, corrective postural reactions are evoked by postural muscles [148,176,177]. The feet thus contribute to the upright stance in response to gravitational and ground reaction forces. The purpose of this comprehensive review is to summarize the evidence that supports a functional role of foot sole sensory tactile and muscular feedback in standing balance and the postural consequence when this feedback is impaired with aging or disease. Decline in foot sole skin sensitivity occurs naturally with aging [127,129] and as a result of neurological disorders, including different peripheral neuropathies (PN) [129,133,178]. This decline in sensitivity is associated with poorer postural control [94,153] and increased risk of falls in these populations [69,80,133,178]. Although PN may result from different etiologies such as traumatic injuries, infections, inflammatory and dysimmune processes, metabolic problems, inherited causes and exposure to toxins, PN related to diabetes mellitus and to chemotherapy are the most prevalent; as such, they will be particularly detailed later in this paper. The purpose of this review is first to describe the important relationship between the foot sole as a sensory structure and balance maintenance; secondly, to show how this sensory structure may be altered by aging or diseases. This review mostly concerns the peripheral processes of the foot sensory system, by highlighting the role of cutaneous and muscle receptors of the foot. neural mechanisms involved in the sensory processes to maintain balance are not described here. For additional reviews on cutaneous and muscle spindle feedback the author recommends the following works: Strzalkowski et al., [164], Proske and Gandevia [137] and Macefield and Knellwolf [89]. This review aims to provide scientific support for new clinical perspectives concerning the foot sole as a sensory structure and emphasizes how several intervention programs aimed at stimulating the foot sole can improve standing balance.

The foot sole as a sensory structure

Sensory information provided by muscle and cutaneous afferents in the foot [87] contribute to our ability to stand upright. The intrinsic muscles of the foot and the glabrous skin of the sole are supplied by the tibial nerve. The tibial nerve is a mixed nerve that extends from the arcade of the soleus muscle to the calcaneal canal as it travels along the posteromedial aspect of the ankle. Distally, it bifurcates into the lateral plantar nerve and medial plantar nerve which supply the majority of the cutaneous innervation of the plantar surface of the foot. Tibial nerve efferents also provide extensive motor innervation for the foot. This innervation contributes to movement of all toes, excluding extension, as well as assisting with maintenance of the longitudinal arches of the foot [73].

Muscular afferents

Muscle spindles are mechanosensory endings found within skeletal muscles. They are sensitive to muscle stretch as well as the rate of stretch and encode joint angular position and the velocity of movement [137]. Primary spindle fibers convey feedback about the velocity of muscle length changes using large diameter type Ia sensory neurons, whereas secondary fibers provide information about static muscle length using smaller type II neurons [89]. By providing proprioceptive feedback of muscle length, muscle spindles located in the intrinsic muscles of the foot contribute to control of upright stance [89]. The role of the medial arch has been suggested to be important for maintaining posture when performing standing balance [66]. EMG responses in tibialis anterior and gastrocnemius have been reported during manipulations of the digits and metatarsals, arguing that sensory input from the foot can trigger responses in muscles acting about the ankle [192]. This could relate to the function of the intrinsic muscles as toe-flexors [42], and muscle spindles within these muscles would be able to report the position of the body over the base of support. The majority of these spindle afferents are silent in the natural resting position [73] but during standing, spindles display a tonic discharge and respond to transient perturbations in position [73,150]. Recruitment of sensory afferents is a specific coding mechanism within the somatosensory nervous system; increase in the number of active muscle spindles endings seems to constitute an important source of sensory feedback from the foot [73]. In this context, muscle spindles in the intrinsic foot muscles provide useful proprioceptive feedback that play a role in the control of natural upright stance [74].

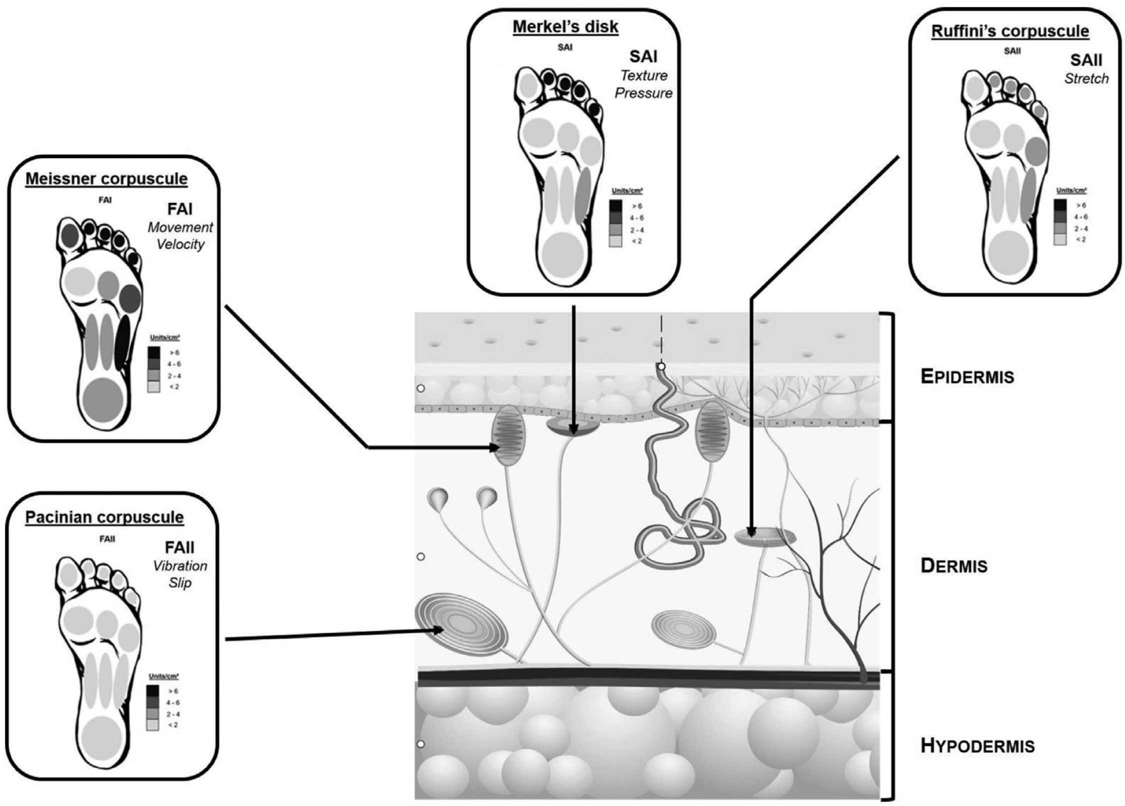

Figure 1 Organisation of cutaneous mechanoreceptors from the foot sole (Adapted with permission from Strzalkowski et al., 2018). Four classes of cutaneous mechanoreceptors are distributed in the depths of the glabrous skin of the foot sole. They inform the central nervous system via large diameter Aβ myelinated afferents. Representation of proximal-distal gradient and medial-lateral gradient in innervation density (Units/cm^2), of each afferent type across the foot. Greater innervation density are in Black and lower innervation density are in Light grey. FAI, fast-adapting type I; FAII, fast-adapting type II; SAI, Slowly adapting type I; SAII, Slowly adapting type II.

Cutaneous afferents

Cutaneous sensitivity characterizes a set of perceived sensations following tactile stimuli such as pressure, stretch, or vibration experience by the skin [58,62,63,180]. Specialized foot sole cutaneous mechanoreceptors [2,27,67,85], transduce these mechanical forces to the central nervous system (CNS) in the form of action potentials. The quality of this feedback depends on the biomechanical properties of the mechanoreceptors and tissue in which they reside. In the context of standing balance, tactile information arises from foot sole skin deformations induced by contact between the foot and the ground. The combination of cutaneous mechanoreceptors and sensory afferents constitute the fundamental functional unit for the transduction and transmission of tactile information to the CNS. The development of microneurography has allowed detailed analyses of the different mechanoreceptive afferents from the skin and muscles [73,88]. From a morphological point of view, cutaneous receptors consist of free or encapsulated nerve endings of first-order sensory neurons [98]. There are four subtypes of cutaneous mechanoreceptors (Fig. 1). Ruffini endings and Merkel discs maintain their firing for a longer duration during indentation; their afferents are classified as slowly adapting (SA). In contrast, Pacinian corpuscles and Meissner's corpuscles rapidly discontinue firing after the initial contact, and their afferents are classified as fast adapting (FA) [75,88,98]. Cutaneous afferents are further subdivided by receptive field characteristics. Type I afferents have small receptive fields with well demarcated borders. Type II afferents have large receptive fields with diffuse borders [67,139,179]. Afferents innervating Merkel discs and Meissner's corpuscles are classified as Type I, while afferents innervating Ruffini endings and Pacinian corpuscles are classified as Type II. Merkel discs (SA I) and Meissner's corpuscles (FA I) are the most superficial and are located at the level of the dermal-epidermal junction, while Pacinian corpuscles (FA II) and Ruffini endings (SA II) are located deeper within the skin [55,61] (Fig. 1). Each class of cutaneous afferent is sensitive and responds to specific mechanical deformations of the skin [161,163]. When vibration, pressure or stretch is applied to the skin, the skin receptors produce a generating potential by ion channel opening and membrane depolarization. If the generating potential reaches the excitation threshold, it triggers one or more action potentials or impulses that then propagate along the axon to the CNS [147]. FA afferents provide information about changes in the pressure distribution exerted on the foot skin [63]. FA type I afferents generally provide information about shear forces tangential to the skin or information about normal contact to the skin. They can also be activated by joint movements that induce skin stretch

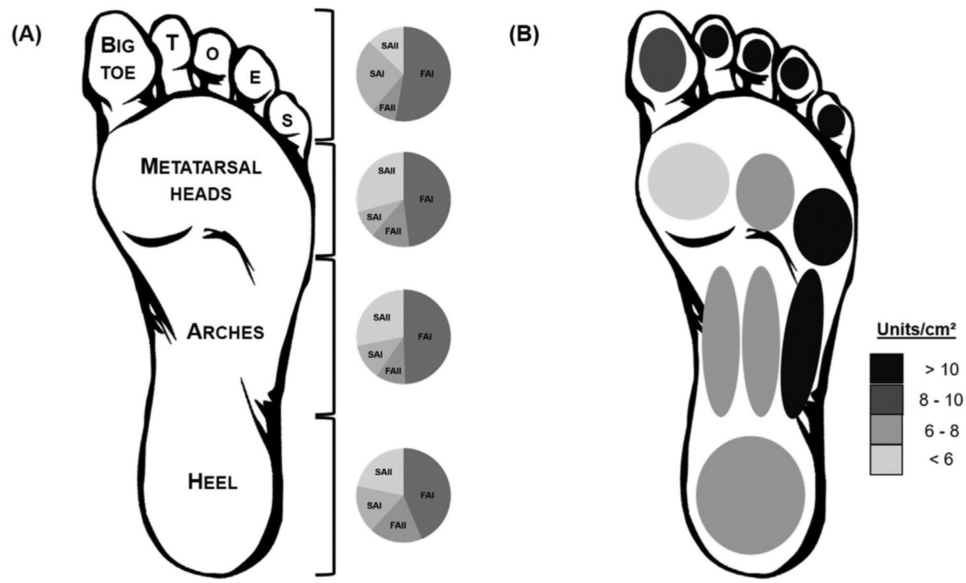

Figure 2 Distribution and Innervation density estimate of cutaneous afferents across the foot sole (Adapted with permission from Strzalkowski et al., 2018). According to Strzalkowski et al, [164], the distribution of foot sole cutaneous afferents increases from the heel to the toes, and from the medial to lateral aspects, driven primarily by type FAI afferents. (A) Pie chart illustrates the percentage distribution of each afferent type at the toes, metatarsal heads, arches, and heel. (B) Representation of proximal-distal gradient and medial-lateral gradient in innervation density, with greater innervation density (black) in the toes and in the lateral region, and lower innervation (Light grey) in the heel and in the medial region, FAI, fast-adapting type I; FAII, fast-adapting type II; SAI, Slowly adapting type I; SAII, Slowly adapting type II.

or compression when their receptive field is situated close to that joint [37,38] and FA type II afferents predominantly code skin stretch over compression [3,4]. Stretch and compression of skin seems to be important for kinanesthesia [85]. Since FA receptors are sensitive to dynamic deformation of the skin [60], they are thought to play a dynamic role in balance control and stability. By providing spatial information about the pressure distribution between the feet and the ground [62,116,126], SA afferents are therefore particularly sensitive to static mechanical pressure stimuli [54,61]. They are thought to provide a tonic response in relation to the position of the body over the feet. However, they also provide dynamic cues.

Foot sole innervation characteristics

Recently, Strzalkowski et al. [164] combined published [41,67,85,161] and unpublished microneurography tibial nerve recordings to investigate cutaneous afferent firing threshold and distribution across the foot sole. A total of 364 foot sole cutaneous mechanoreceptors were identified in this study. This sample consisted of 63 slow adapting type I (17%), 74 slow adapting type II (20%), 184 fast adapting type I (51%), and 43 fast adapting type II (12%). Across the foot sole, FA afferents consistently have lower firing thresholds than SA afferents (foot median: FAI 0.69 g, FA II 0.5 g, SA I 1.74 g, and SA II 10.0 g) [163]. Threshold afferents from the foot are higher than those in the hand (hand median: FAI 0.06 g, FA II 0.05 g, SAI 0.13 g, and SA II 0.76 g) [59,60] and may reflect their tuning to the high forces of standing balance. Strzalkowski et al. [164] found the distribution of foot sole cutaneous afferents to increases from the heel to the toes, and from the medial to lateral aspects, driven primarily by type I afferents (Fig. 2). The distribution of cutaneous afferents across the foot sole could indicate areas of relative tactile importance (Fig. 1). It may be that type I afferent feedback from the toes and lateral border play a particularly important role in the control of standing balance (Fig. 2). With high receptor populations, the toes are identified as important sensory locations with populations able to delineate the physical limits of the base of support, evoking appropriate postural responses [192]. The toes dictate the anterior limit of the base of support [164,192]. Through toe muscle activation, it is possible to control the movement of the centre of pressure (CoP) in the sagittal plane within the confines of the base of support [121,176]. In the same way, the lateral borders of both feet define the boundary of the base of support in the frontal plane. When the centre of mass (CoM) moves beyond the lateral limit of the base of support, a stepping reaction can occur to prevent a fall [99]. Since FAI afferents have strong synaptic coupling to lower [41] and to upper [10] limb motor neurons, their relatively large density in the toes and lateral foot sole border [164] (Fig. 2) may help facilitate reflexive loops important in balance control. In fact, increasing cutaneous feedback from the foot sole border [128] or from the toes [185,187] has been shown to change balance ability in different categories of people.

Cutaneous reflexes

Cutaneous reflexes in lower limb muscles play an important role in posture [30,48]. Several studies provide evidence of underlying reflexes arising from cutaneous afferents in humans from the sole of the foot. Afferents from mechanoreceptors in the foot sole have multi-synaptic reflex connections with the neuron pools innervating the muscles that act at the ankle [6,41]. Cutaneous afferents from different nerves enter spinal cord through dorsal horn, converge and synapse on a common spinal interneuron to modulate excitability and produce excitation and inhibition in functionally related groups of motoneurons [115]. Non-noxious electrical stimulation of cutaneous afferents from the foot, innervated by the sural or tibial nerve, evoked a sequence of waves with onset latencies as early as 40 ms and lasting up to 200 ms [6] that produced complex excitatory and inhibitory effects of muscles acting about the ankle [6,41,196]. For example, a short latency inhibitory pathway from plantar cutaneous afferents to ankle extensors following mild stimulation to the tibial nerve is enabled in subjects when the foot sole makes contact with a surface [1]. Excitation of cutaneous afferents arising from the foot sole induces long-lasting facilitation of the ipsilateral extensor motoneurons [41] and induces crossed inhibitory postsynaptic potentials in the knee and ankle extensors [36]. These effects may be related to:

- the action of plantar cutaneous afferents on the presynaptic inhibition acting on Ia afferent terminals [56];
- their interaction with the reciprocal innervation [146];
- their actions on Ib inhibitory pathways [130,131].

In addition, plantar foot reflexes innervating lower leg muscles appear to be organized in a highly location-specific manner in humans [41,113,194,195] and the magnitude of these cutaneous reflexes is strongly altered depending on the posture [1,21,77]. Gradual changes in the magnitude and reversal of the reflex sign occurred when the locus of the stimulation systematically moved from the toe to heel. For the soleus and the tibialis anterior, there appears to be a boundary at approximately the mid-lateral plantar region of the foot, in which the sign of the reflex is switched to the opposite direction [113]. Forefoot stimulation produced inhibitory responses in the soleus and medial gastrocnemius, but excitatory responses in tibialis anterior muscles. Following heel stimulation, an opposite effect was evoked [113]. Systemic stimulations from the fifth toe to the heel on the lateral margin of the plantar foot demonstrated that the border of this soleus and tibialis anterior reflex reversal occurred roughly around the middle of the foot sole, providing greater resolution in the fine sculpting of motor output than previously revealed by sural or tibial nerve stimulation. A functional organization of excitatory and inhibitory cutaneous reflexes in the tibialis anterior and soleus by non-painful electrical stimulation to the plantar foot was demonstrated during voluntary contraction [155]. In addition, the middle latency component of cutaneous reflexes in lower leg muscles was significantly larger when the reflex was recorded during voluntary contraction of the muscle rather than when the muscle was posturally active [47]. It was also observed that stimulation at the lateral forefoot and heel evoked excitatory responses in peroneus longus but following medial forefoot stimulation an inhibitory response was evoked [113,114]. It was suggested that tactile stimulation mimics a destabilization of posture and thus modulates peroneus longus responses to counteract uneven terrain through stabilization of the ankle joint [113,114]. Finally, when these muscles are active in standing, cutaneous feedback may play a role in modulating motoneuron output and thereby contribute to stabilization of stance [6].

Sensory contributions of the foot sole: a proprioceptive and tactile interaction

Sensory feedback from the foot sole is important for perceiving changes to body orientation [64], and to regulate postural sway [100,120,193,197]. The spatial coding of body verticality by plantar inputs results from the ever-changing contrast between the pressures exerted on different parts of one foot or between the two feet [63,145]. Cutaneous afferents from the foot are encoded in a pressure scale and decoded as spatially relevant cues about body orientation [145]. Change in skin pressure under the sole could inform how the foot is in contact with the ground and subsequently how far the body position has to be adjusted [145]. Cutaneous mechanoreceptors feedback supply information about surface contact pressure and help sense continuous changes of posture [105]. Cutaneous mechanoreceptors may be functionally involved in exteroceptive [97] and proprioceptive processing by informing the central nervous system (CNS) about body position and support state [145].

Ankle proprioceptive feedback also provides sensitive means for detecting postural sway while standing [43,44], and there is strong evidence supporting the contribution of both cutaneous [3,85,103] and spindle [5] cues to the awareness of ankle position and movement. Information from the skin surrounding the ankle is necessary for kinesthetic tasks at the ankle joint, in both dorsi- and plantarflexion angles [85]. Furthermore, a transient reduction in skin sensitivity on the foot dorsum and anterior lower leg in healthy young adults has been shown to impair passive joint position sense [85,86] and alter lower limb kinematics during gait [53]. In the same way, Mildren and Bent [103] showed that cutaneous input from the foot generated by both low and high frequency vibration could influence proprioception at the ankle joint, and that this influence was modulated by ankle joint angle. These results emphasized robust interactions between FA cutaneous input [103] from the foot sole and proprioceptive signals from the ankle [85,103]. Although the observed effects were small, they had functional significance, and it has been suggested that this similarity facilitates coprocessing [4], making it likely that muscle and skin information influence each other. Postural responses of both cutaneous and proprioceptive origin were found to be frequency dependent [64].

Finally, proprioceptive and tactile feedback might be differentially involved in human postural control according to body or environmental constraints [64] and could subserve complementary functions for postural purposes.

Changes with age and disease

Somatosensory information is important to the control of upright standing, and postural sway is necessary to detect both position and motion of the body in space. The relatively small body movements during quiet standing are sufficient to stimulate the various sensory receptors, especially plantar cutaneous mechanoreceptors, which constitute the direct interface between the body and the ground. Studies have found changes in receptor morphology (reduction in receptor density and elasticity) or physiology (slower nerve conduction) with age or disease. A decline in foot sole skin sensitivity occurs naturally with aging [128,129] and as a result of neurological disorders, including different peripheral neuropathy [129,133,178]. This decline in sensitivity is associated with poorer postural control [94,153] and an increased risk of falls in these populations [69,80,133,178].

Aging

Accurate detection and integration of somatosensory information from the feet is important for balance control [20], and degeneration of peripheral sensory receptors, can lead to a diminished capacity to detect information from the soles of the feet during interactions with the external environment [57,127]. Normal aging leads to changes in mechanical properties of the skin, as well as cutaneous receptor density, morphology and physiology. Age-related sensory deterioration of cutaneous afferents has been hypothesized as contributing to the increased risk of falling [57,142] as well as gait and balance disorders [32,84,101]. FA receptors exhibit structural modifications and are reduced in number with aging [13,23,46,151,157]. Several studies have compared sensory threshold testing in young and elderly groups of healthy subjects. Elderly feet were significantly less sensitive to mechanical stimuli (tactile and vibration) than the young [68,104]. Tactile thresholds in the elderly are significantly increased [174]. This is possibly due to a decrease in the density and distribution of Pacinian and Meissner corpuscles and Merkel's discs in the skin causing decreased spatial acuity [13,46,151,157]. This decrease in the density and distribution of cutaneous mechanoreceptors has been associated clinically with declines in vibration perception or touch thresholds [13,104], especially in the great toe [13]. Meissner's corpuscles of the plantar surface of the big toe of 30 persons were investigated histologically with respect to age [151]. The number of corpuscles decreases exponentially with increasing age. During the first decades of life the corpuscles exhibit a steady lateral and longitudinal growth, whereas at an advanced age an atrophy of Meissner's corpuscles occurs. In spite of considerable individual variations, a distinct dependency on age can be noticed. The deterioration of acuity in the great toe (averaging 400% between youth and advanced age) may adversely affect such diverse activities as maintaining balance [158]. This degradation of tactile acuity in the plantar aspect of the toe was significantly greater in fallers than in non-fallers [101].

Several studies have highlighted age-related changes in large fiber structure and decline in sensory nerve conduction velocity [16,182]. There is a decline in sensory nerve conduction velocity and in the amplitude of the sensory action potential with age [143]. Electrophysiological studies showed that sensory fibers are affected prior to motor fibers with aging [16]. Sensory nerve conduction velocities and response amplitudes peaked at age 40 years and subsequently declined [16]. Rivner et al. [143] found strong correlation of ageing with amplitude of the sensory action potential and a small but definite negative relation between age and sensory nerve conduction velocity. For example, the sensory response from the sural nerve was absent in 23% of subjects between the ages of 70 and 79 years and in 40% over the age of 80 years [143]. It has been speculated that age-related changes in myelination may cause decreased nerved conduction velocity. Thus, the longer conduction distances to the feet would induce greater vibrotactile sense dysfunction and higher thresholds [68].

There are well-documented age-related changes in postural stability as measured via quiet standing on a force plate, including increased sway amplitude, centre of pressure velocity, and whole-body acceleration [78,96]. Sensory impairment (i.e., vibration sense, discriminative touch, or sensory nerve conduction velocity) in older adults is associated with functional decline and fall risk [65]. Peripheral sensation seems to be the single most important factor in maintenance of static postural stability in an older adult population [84] and reduced foot tactile sense in the elderly contributes to postural instability along with deprivation of feedback [168,169]. Endo et al. [39], reported a strong correlation between force plate measures of toe plantar flexor strength and the anterior limit of the functional base of support. Toe muscle function may play a particularly important role in the maintenance of balance in older people. Tanaka et al. [168,169] have shown that when standing, older people exert greater pressure with their toes than younger people, possibly in an attempt to intensify sensory information to maintain balance in the setting of reduced muscle and cutaneous information [168].

In this context, vibratory perception threshold testing may provide a sensitive measure to detect the onset of age-related plantar insensitivity [127]. Discriminative touch (i.e., 2-point sensation) of the feet should be considered when screening for distal sensory impairments in older adults [127,183] and could have a clinically relevant role as an assessment measure in aging. Although peripheral sensory loss is generally irreversible, there is emerging evidence that augmenting tactile sensory information from the sole of the foot using insoles with raised projections [91] or vibrating pads [135] may improve balance in older people. Foot characteristics, particularly tactile sensitivity and toe strength [102], are important determinants of balance and functional ability in older people. Intervention studies to reduce risk of falling may possibly benefit from augmenting sensory information from the foot.

Peripheral neuropathy

Peripheral neuropathy (PN) is a complex disorder that arises from damage to peripheral nerves. PN can arise due to a variety of conditions, and the most common of which are diabetes mellitus [106] or effects of chemotherapy [25]. Peripheral nerve damage is characterized by abnormal conduction velocities and amplitudes [7] that typically progress in a distal to proximal manner [19]. Most cases of PN do involve pathology in the smaller sensory fibers such as Aβ, Aδ and unmyelinated C-fibers that transmit cutaneous sensations like touch, vibration and temperature [167]. Patients with PN describe several sensations such burning, tingling, hyperalgesia or allodynia, and loss of tactile sensation, proprioception, and thermal sensitivity [7]. In this context, PN frequently results in specific functional impairment, such as loss of balance and with marked increase in risk of falling [24,160].

Diabetes. Peripheral neuropathy is a pathology that affects sensory and/or motor nerves and degrades perception and action abilities [141]. The most common cause of these neuropathies is diabetes [184]. Diabetic peripheral neuropathy (DPN) is the result of a number of disturbances in the peripheral nervous system as a consequence of hyperglycemia [173]. Rapidly reversible abnormalities of nerve conduction may occur in patients with recent transiently poorly controlled diabetes and may be accompanied by uncomfortable distal sensory symptoms [18,173]. Duration and severity of exposure to hyperglycemia are related to the severity of neuropathy [124,156]. The most common clinical presentation of DPN is sensorimotor neuropathy [35,122]. DPN involves either or both small and large nerve fibers in limbs in a length-dependent pattern [184]. Small nerve fiber injuries classically occur earlier [92] than large ones [198]. Nevertheless, plantar vibration sense and/or distal tendon reflexes are also altered very early in the course of DPN [110,198], but these correspond to dysfunction in large diameter fibers. Although the pathophysiology of DPN remains unclear, peripheral mechanisms have been suggested, such as neural ion channels (Na+ and Ca2+), abnormal glycemic flux-related damage to the spinal cord, and central mechanisms, such as impaired central pain processing secondary to functional and structural brain remodeling [152].

Degradation of the somatosensory system occurs with DPN and can be determined by nerve conduction velocity and perception thresholds of different modalities such as pressure or vibration [19,141]. Typical symptoms of DPN are symmetric numbness, paresthesia, or pain in the distal lower limbs involving more than a single nerve distribution, which progresses in a centripetal direction [171]. Symmetrical sensory loss (''stocking or glove sensory loss'') in the feet above the ankles is evident on clinical examination. The ankle and Achilles reflexes are usually reduced or absent, which can result in foot abnormalities. These symptoms collectively result in disturbed proprioception and abnormal muscle sensory function. Increased vibration and thermal thresholds occur early during the course of the disease in both patients with type 1 and type 2 diabetes [198]. However, DPN symptoms may develop much earlier in the course of type 1 than in type 2 [124], suggesting a difference in the natural history or different mechanisms of nerve injury in DPN between diabetes types: predominant involvement of small nerve fibers in patients with type 2 versus large myelinated fibers in patients with type 1 diabetes, respectively, even in those with a similar severity of neuropathy [110]. Consequently, the degradation of the somatosensory system, including decrease in nerve conduction velocity and sensory threshold, patients with peripheral neuropathy have balance disorders [49]. The pathological findings of DPN are axonal loss, axonal regeneration, and demyelination in some patients [33]. The nerve conduction study is a reliable and objective diagnostic method to evaluate the DPN [40]. It is used to measure the speed of both motor and sensory conduction, amplitude, distal latency, distance, F wave latency, and other factors [34]. More precisely, several studies using electromyography [116—118] showed that decreased nerve conduction velocity associated with loss of sensory feedback may delay the onset of postural corrections in response to environmental disturbances [49,51]. In addition, Nardone and Schieppati [117] established correlation between postural oscillations and nerve conduction velocity in diabetic patients with both Ia and II fiber neuropathy. There was a significant relationship between postural instability and type II fiber involvement [118]. In the same way, a decrease in sensory thresholds [11] could induce postural instability [11,24]. It would appear that loss of information from the CoP position is the most important parameter for postural control [52]. From a clinical point of view, quantitative sensory testing (QST) represents a quantitative method usually graded using a continuous numerical scale to detect the threshold of thermal perception (cold or warm), vibration perception, current perception, pressure pain and sudomotor function [22,33]. Vibration thresholds are particularly sensitive to detect mild or subclinical neuropathy and correlate well with other QST measures [19]. The QST is probably effective for documenting sensory abnormalities and changes in sensory thresholds during longitudinal evaluation of patients with DPN. This should be complementary to thorough clinical assessment [34].

Chemotherapy. Chemotherapy, such as taxanes or oxaliplatin, is often used to treat different types of cancer [108]. One of the most important side effects of chemotherapy is painful peripheral neuropathy [25,31,188] with decreased sensory nerve action potential amplitudes on electrodiagnostic testing [25], increased vibration thresholds, dysesthesias and paresthesia in a glove and stocking distribution [25,45]. Peripheral neuropathy following chemotherapy correlates with a loss of proprioception and is associated with postural instability [52,118] and higher risk of falls [141,165,175], and can have a significant impact on physical function. Taxanes among other chemotherapeutic agents are well known to cause selective injuries to the peripheral nervous system, notably inflammation in the dorsal root ganglion and peripheral nerves involved in processing somatosensory information [95]. Large myelinated afferent fibers such as Ia fibers are injured by these neurotoxic agents [95] and may be responsible for balance disorders [188]. Neuropathy-induced loss of somatosensory information and processing leads to postural instability [15]. In this context, CoP parameters were significantly higher for patients with breast cancer compared with healthy controls [170,188]. These balance disorders tend to progress with cumulative chemotherapy and may be partially explained by somatosensory change, notably on the soles of the feet [76].

The effect of chemotherapy on patient balance appears to be clinically relevant when compared to balance impairments observed in diabetic patients [17] or in elderly adults [134]. The balance measures provide an objective approach to quantify changes in patient function by assessing postural control. These results support the clinical interest of implementing balance measures during routine oncology clinic flow to longitudinally quantify postural instability in breast cancer patients [107].

Clinical interest and interventions

Previous research has provided some evidence that experimental modulation cutaneous information can change postural sway. More precisely, artificially reducing somatosensory information by cooling [90], local anesthetics [51] or standing on a foam surface [125] can reduce the reliability of somatosensory information and increase postural sway.

In recent years, studies have demonstrated that additional somatosensory input has positive effects on postural control by using various stimulation methods [186]. These findings confirm that mechanical stimulation of the plantar sole have an impact on the mechanoreceptors of the feet, and this relevant tactile information helps in upright standing. Nevertheless, the effect of mechanical stimulation on postural control in patients with reduced cutaneous sensory acuity remains unclear.

Previous studies have used mechanical noise to improve standing balance [50,82,83,135,199], movement sensation [29] and tactile sensation [26,190] in elderly people [82,83,135], in people with peripheral diabetic neuropathy [50,83,136,199] or stroke [83,136]. Application of mechanical noise to the feet, administered as random vibrations from specific elements, induces stochastic resonance, which can transform previously unfelt subthreshold stimuli into suprathreshold stimuli that do produce action potentials [136,190]. Mechanical noise improves the vibration perception threshold of the plantar side of the foot in patients with diabetic neuropathy and may be helpful in preventing foot ulceration in patients with diabetic neuropathy [70,199].

Another potential aid to improve balance in patients with loss of sensation is application of low-level electrical stimulation [111,112] under the feet. These authors suggested that daily home use of plantar electrical stimulation was effective to enhance balance [172] and plantar sensation, as quantified by significant reduction in vibration perception threshold [111].

Considering the sensory deficits presented by subjects with Parkinson's disease, several studies have proposed automated mechanical peripheral stimulation applied under the foot, as a potential rehabilitation strategy [71,72,123,159]. Mechanical pressure applied, in sequence, under the feet has shown positive effects in terms of improving functional mobility and gait parameters [71,72,159], and postural control [138]. Low pressure-based stimulation (range of 0.3—0.9 N/mm^2) applied simultaneously in two target areas (head of the great toe and base of the first metatarsal bone) under both feet [138] could improve dynamic balance [71,159] and spatiotemporal parameters of gait [71,72,159]. In the same way, autonomic changes were observed following stimulation of the feet, either using low pressure (0.58 kg/mm^2) applied to the tip of the hallux and the lower great toe first metatarsal joint plantar surface [8], or vibration [162]. Autonomic changes resulting in diminished resting blood pressure values may help in controlling orthostatic hypertension, which often is present in patients with Parkinson's disease [8]. In addition, effective stimulation re-established the capacity to increase cardiac and vascular sympathetic modulation in response to the gravity stimulus and widened the functionality of the arterial baroreceptor mechanism [8].

Finally, stimulation of the plantar surface of the foot using vibration could represent an interesting and original way to assist the navigation of people with visual impairment [181]. Using vibrating motors, inexpensive and practicable devices have been proposed for stimulating the plantar surface and transmitting tactile information to people with visual impairment [181]. Results showed that people were capable of navigating environments using the directions provided by tactile interfaces for the foot [181].

Summary and conclusions

The sole of the foot is an important sensory structure in the control of standing balance. Specialized mechanoreceptors transmit tactile and proprioceptive feedback used by the CNS for reflexive and conscious adjustments to posture. This ability results from the coordination between a tactile system that permanently provides information about sway and weight distribution under the feet, and a motor system that initiates corrective postural reaction controlling muscular activity. Cutaneous receptors and associated afferents constitute the fundamental functional units that enables the transduction and transmission of tactile feedback to the CNS. Providing additional sensory information useful for postural control seems relevant to improve postural stability and balance. Plantar cutaneous inputs enhance the detection and transmission of weakened cutaneous signals and this region appears to be a good candidate for improving the postural stability in older adults or subjects with neurological disorders [189]. In this perspective, several interventions have been proposed and studied in the elderly [127] and patients with neurological diseases, such as peripheral neuropathy [94], Parkinson's disease [133] or multiple sclerosis [28].

The increased distribution of cutaneous afferents in the toes [164] may reflect the postural significance of feedback from the toes in the control of standing balance. In addition, the toe plantar flexion muscles contribute to controlling posture. Both amplitude and velocity of postural sway could be controlled by toe plantar flexion muscles [148]. In fact, the toes play a unique and important role in standing balance [121,168,169,176,185,187]. In order to maintain balance, the toes can be flexed and extended to apply pressure to the ground and correct for postural disturbance. During quiet standing, we can frequently feel that the movement of the toes helps in maintaining balance. Additionally, links were found between decreased toe sensitivity and increased body sway during quiet standing [168]. Tanaka et al. [169] proposed the idea that people with less toe sensitivity might use great toe pressure in order to intensify sensory input from the great toe as well as to maintain balance. In the same way, some authors [121,176] showed that the toe muscle stimulation was capable of regulating CoP displacement and this approach may be a good candidate for controlling balance. In these studies, forward movement of the CoP was induced by different intensity of electrical stimulation applied to the toe muscles. Furthermore, body acceleration could be controlled during quiet standing by regulating the intensity of stimulation applied to the toe muscles [176].

Finally, Viseux et al. [185,187] observed that small focal additional thickness placed under the toes has an effect on the CoP measures used to assess postural control during unperturbed stance. A significant change of balance was obtained with the lowest thickness (0.8 mm), even though the contact forces induced by the lowest thickness were probably too small to mechanically stabilize the body. In this context, it was believed that cutaneous mechanoreceptors of the toes were activated by a low focal additional thickness and seem to be consistent with tactile hypothesis of Tortolero et al. [176]. Since the foot is the only body part in contact with the surface during quiet standing, it is very likely that toe movements play an important role in balance control [148,192]. The toes provide a stable surface area that remains in contact with the ground and serve to relay relevant sensory information to the central nervous system [79]. It is clear that sensory information from the toes is used to perform postural corrections when balance disturbances occur [176] and their use can improve the feeling of stability [1,149,176]. These findings highlight the important functional role of the foot sole, where tactile feedback from the toes and plantar muscle activity may be more meaningful for the control of standing balance. This comprehensive review advances how the foot sole is viewed as a sensory structure that communicates with the CNS to help us balance and stand up. This brings new clinical perspectives for development of intervention strategies to improve the quality of foot sole cutaneous feedback (i.e. customized postural insoles) and seems to be an interesting and promising approach for the management of patients with balance disorders, with specific chronic pain syndromes, with neurologic diseases or those at risk of falling.

Disclosure of interest

The author declares that he has no competing interest.

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References

[1] Abbruzzese M, Rubino V, Schieppati M. Task-dependent effects evoked by foot muscle afferents on leg muscle activity in humans. Electroencephalogr Clin Neurophysiol 1996;101:339—48.
[2] Abraira VE, Ginty DD. The sensory neurons of touch. Neuron 2013;79:618—39.
[3] Aimonetti JM, Hospod V, Roll JP, Ribot-Ciscar E. Cutaneous afferents provide a neuronal population vector that encodes the orientation of human ankle movements. J Physiol 2007;580:649—58.
[4] Aimonetti JM, Roll JP, Hospod V, Ribot-Ciscar E. Ankle joint movements are encoded by both cutaneous and muscle afferents in humans. Exp Brain Res 2012;221:167—76.
[5] Albert F, Bergenheim M, Ribot-Ciscar E, Roll JP. The Ia afferent feedback of a given movement evokes the illusion of the same movement when returned to the subject via muscle tendon vibration. Exp Brain Res 2006;172:163—74.
[6] Aniss AM, Gandevia SC, Burke D. Reflex responses in active muscles elicited by stimulation of low-threshold afferents from the human foot. J Neurophysiol 1992;67:1375—84.
[7] Azhary H, Farooq MU, Bhanushali M, Majid A, Kassab MY. Peripheral neuropathy: differential diagnosis and management. Am Fam Physician 2010;81:887—92.
[8] Barbic F, Galli M, Dalla Vecchia L, Canesi M, Cimolin V, Porta A, et al. Effects of mechanical stimulation of the feet on gait and cardiovascular autonomic control in Parkinson's disease. J Appl Physiol 2014;116:495—503.
[9] Bauby CE, Kuo AD. Active control of lateral balance in human walking. J Biomech 2000;33:1433—40.
[10] Bent LR, Lowrey CR. Single low-threshold afferents innervating the skin of the human foot modulate ongoing muscle activity in the upper limbs. J Neurophysiol 2013;109: 1614—25.
[11] Bergin PS, Bronstein AM, Murray NM, Sancovic S, Zeppenfeld DK. Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. J Neurol Neurosurg Psychiatry 1995;58:335—40.
[12] Black FO, Wall C, 3rd, Nashner LM. Effects of visual and support surface orientation references upon postural control in vestibular deficient subjects. Acta Otolaryngo 1983;95:199—201.
[13] Bolton CF, Winkelmann RK, Dyck PJ. A quantitative study of Meissner's corpuscules in man. Neurology 1966;16:1—9.
[14] Bolton DAE, Patel R, Staines WR, McIlroy WE. Transient inhibition of primary motor cortex suppresses hand muscle responses during a reactive reach to grasp. Neurosci Lett 2011;504:83—7.
[15] Bonnet CT, Ray C. Peripheral neuropathy may not be the only fundamental reason explaining increased sway in diabetic individuals. Clin Biomech 2011;26:699—706.
[16] Bouche P, Cattelin F, Saint-Jean O, Leger JM, Queslati S, Guez D, et al. Clinical and electrophysiological study of the peripheral nervous system in the elderly. J Neurol 1993;240:263—8.
[17] Boucher P, Teasdale N, Courtemanche R, Bard C, Fleury M. Postural stability in diabetic polyneuropathy. Diabetes Care 1995;18:638—45.
[18] Boulton AJ, Malik RA. Diabetic neuropathy. Med Clin North Am 1998;82:909—29.
[19] Boulton AJ, Malik RA, Arezzo JC, Sosenko JM. Diabetic somatic neuropathies. Diabetes Care 2004;27:1458—86.
[20] Bronstein AM. Multiensory integration in balance control. Handb Clin Neurol 2016;137:57—66.
[21] Burke D, Dickson HG, Skuse NF. Task-dependent changes in the responses to low-threshold cutaneous afferent volleys in the human lower limb. J Physiol 1991;432:445—58.
[22] Casellini CM, Parson HK, Richardson MS, Nevoret ML, Vinik AL. Sudoscan, a noninvasive tool for detecting diabetic small fiber neuropathy and autonomic dysfunction. Diabetes Technol Ther 2013;15:948—53.
[23] Cauna N, Mannan G. The structure of human digital Pacinian corpuscles (corpus cula lamellose) and its functional significance. J Anat 1958;92:1—20.
[24] Cavanagh PR, Derr JA, Ulbrecht JS, Maser RE, Orchard TJ. Problems with gait and posture in neuropathic patients with insulin-dependent diabetes mellitus. Diabet Med 1992;5:469—74.
[25] Chaudhry V, Rowinsky EK, Sartorius SE, Donehower RC, Cornblath DR. Peripheral neuropathy from taxol and cisplatin combination chemotherapy: clinical and electrophysiological studies. Ann Neurol 1994;35:304—11.
[26] Collins JJ, Priplata AA, Gravelle DC, Niemi J, Harry J, Lipsitz LA. Noise-enhanced human sensorimotor function. IEEE Eng Med Biol Mag 2003;22:76—83.
[27] Collins DF, Refshauge KM, Todd G, Gandevia SC. Cutaneous receptors contribute to kinesthesia at the finger, elbow, and knee. J Neurophysiol 2005;94:1699—706.
[28] Compston A, Coles A. Multiple sclerosis. Lancet 2002;359:1221—31.
[29] Cordo P, Inglis JT, Verschueren S, Collins JJ, Merfeld DM, Rosenblum S, et al. Noise in human muscle spindles. Nature 1996;383:769—70.

[30] Day BL, Cole J. Vestibular evoked postural responses in the absence of somatosensory information. Brain 2002;125:2081—8.
[31] Dougherty PM, Cata JP, Cordella JV, Burton A, Weng HR. Taxol-induced sensory disturbance is characterized by preferential impairment of myelinated fiber function in cancer patients. Pain 2004;109:132—42.
[32] Duncan G, Wilson JA, MacLennan WJ, Lewis S. Clinical correlates of sway in elderly people living at home. Gerontology 1992;38:160—6.
[33] Dyck PJ, Karnes JL, O'Brien P, Okazaki H, Lais A, Engelstad J. The spatial distribution of fiber loss in diabetic polyneuropathy suggests ischemia. Ann Neurol 1986;19:440—9.
[34] Dyck PJ, Davies JL, Litchy WJ, O'Brien PC. Longitudinal assessment of diabetic polyneuropathy using a composite score in the Rochester Diabetic Neuropathy Study cohort. Neurology 1997;49:229—39.
[35] Dyck PJ, Dyck PJ, Larson TS, O'Brien PC, Velosa JA. Patterns of quantitative sensation testing of hypoesthesia and hyperalgesia are predictive of diabetic polyneuropathy: a study of three cohorts. Nerve growth factor study group. Diabetes Care 2000;23:510—7.
[36] Edgley SA, Aggelopoulos NC. Short latency crossed inhibitory reflex actions evoked from cutaneous afferents. Exp Brain res 2006;171:541—50.
[37] Edin BB, Abbs JH. Finger movement responses of cutaneous mechanoreceptors in the dorsal skin of the human hand. J Neurophysiol 1991;65:657—70.
[38] Edin B. Cutaneous afferents provide information about knee joint movements in humans. J Physiol 2001;531:289—97.
[39] Endo M, Ashton-Miller JA, Alexander NB. Effects of age and gender on toe flexor muscle strength. J Gerontol A Biol Sci Med Sci 2002;57:392—7.
[40] England JD, Gronseth GS, Franklin G, Miller RG, Asbury AK, Carter GT, et al. Distal symmetric polyneuropathy: a definition for clinical research: report of the American Academy of Neurology, the American Association of electrodiagnostic Medicine, and the American Academy of Physical Medicine and Rehabilitation. Neurology 2005;64:199—207.
[41] Fallon JB, Bent LR, McNulty PA, Macefield VG. Evidence for strong synaptic coupling between single tactile afferents from the sole of the foot and motoneurons supplying leg muscles. J Neurophysiol 2005;94:3795—804.
[42] Ferrari E, Cooper G, Reeves ND, Hodson-Tole EF. Surface electromyography can quantify temporal and spatial patterns of activation of intrinsic human foot muscles. J Electromyogr Kinesiol 2018;39:149—55.
[43] Fitzpatrick R, McCloskey DI. Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. J Physiol 1994;478:173—86.
[44] Fitzpatrick R, Rogers DK, McCloskey DI. Stable human standing with lower-limb muscle afferents providing the only sensory input. J Physiol 1994;480:395—403.
[45] Forsyth PA, Balmaceda C, Peterson K, Seidman AD, Brasher P, DeAngelis LM. Prospective study of paclitaxel-induced peripheral neuropathy with quantitative sensory testing. J Neurooncol 1997;35:47—53.
[46] Gescheider GA, Bolanowski SJ, Hall KL, Hoffman KE, Verrillo RT. The effects of aging on information-processing channels in the sense of touch: I. Absolute sensitivity. Somatosens Mot Res 1994;11:345—57.
[47] Gibbs J, Harrison LM, Stephens JA. Cutaneomuscular reflexes recorded from the lower limb in man during different tasks. J Physiol 1995;487:237—42.
[48] Grüneberg C, Duysens J, Honegger F, Allum JH. Spatio-temporal separation of roll and pitch balance correcting commands in humans. J Neurophysiol 2005;94:3143—58.
[49] Herrera-Rangel A, Aranda-Moreno C, Mantilla-Ochoa T, Zainos-Saucedo L, Jauregui-Renaud K. The influence of peripheral neuropathy, gender, and obesity on the postural stability of patients with type 2 diabets mellitus. J Diabetes Res 2014 [787202].
[50] Hijmans JM, Geertzen JH, Zijlstra W, Hof AL, Postema K. Effects of vibrating insoles on standing balance in diabetic neuropathy. J Rehabil Res Dev 2008;45:1441—9.
[51] Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. Exp Brain Res 1990;82:167—77.
[52] Horak FB, Dickstein R, Peterka RJ. Diabetic neuropathy and surface sway-referencing disrupt somatosensory information for postural stability in stance. Somatosens Mot Res 2002;19:316—26.
[53] Howe EE, Toth AJ, Vallis LA, Bent LR. Baseline skin information from the foot dorsum is used to control lower limb kinematics during level walking. Exp Brain Res 2015;233:2477—87.
[54] Iggo A, Muir AR. The structure and function of a slowly adapting touch corpuscle in hairy skin. J Physiol 1969;200:763—96.
[55] Iggo A, Ogawa H. Correlative physiological and morphological studies of rapidly adapting mechanoreceptors in cat's glabrous skin. J Physiol 1977;266:275—96.
[56] Iles JF. Evidence for cutaneous and corticospinal modulation of presynaptic inhibition of Ia afferents from the human lower limb. J Physiol 1996;491:197—207.
[57] Inglis JT, Horak FB, Shupert CL, Jones-Rycewicz C. The importance of somatosensory information in triggering and scaling automatic postural responses in humans. Exp Brain Res 1994;101:159—64.
[58] Inglis JT, Kennedy PM, Wells C, Chua R. The role of cutaneous receptors in the foot. Adv Exp Med Biol 2002;508:111—7.
[59] Johansson RS. Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptive units in the glabrous skin area. J Physiol 1978;281:101—25.
[60] Johansson RS, Vallbo AB. Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. J Physiol 1979;286:283—300.
[61] Johnson KO. The roles and functions of cutaneous mechanoreceptors. Curr Opin Neurobiol 2001;11:455—61.
[62] Kavounoudias A, Roll R, Roll JP. The plantar sole is a 'dynamometric map' for human balance control. Neuroreport 1998;9:3247—52.
[63] Kavounoudias A, Roll R, Roll JP. Specific whole-body shifts induced by frequency-modulated vibrations of human plantar soles. Neurosci Lett 1999;266:181—4.
[64] Kavounoudias A, Roll R, Roll JP. Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation. J Physiol 2001;532:869—78.
[65] Kaye JA, Oken BS, Howieson DB, Howieson J, Holm LA, Dennison K. Neurologic evaluation of the optimally healthy oldest old. Arch Neurol 1994;51:1205—11.
[66] Kelly LA, Kuitunen S, Racinais S, Cresswell AG. Recruitment of the plantar intrinsic foot muscles with increasing postural demand. Clin Biomech 2012;27:46—51.
[67] Kennedy PM, Inglis JT. Distribution and behaviour of glabrous cutaneous receptors in the human foot sole. J Physiol 2002;538:995—1002.
[68] Kenshalo DR. Somesthetic sensitivity in young and elderly humans. J Gerontol 1986;41:732—42.
[69] Kerr GK, Worringham CJ, Cole MH, Lacherez PF, Wood JM, Silburn PA. Predictors of future falls in Parkinson disease. Neurology 2010;75:116—24.
[70] Khaodhiar L, Niemi JB, Earnest R, Lima C, Harry JD, Veves A. Enhancing sensation in diabetic neuropathic foot with mechanical noise. Diabetes Care 2003;26:3280—3.
[71] Kleiner A, Galli M, Gaglione M, Hildebrand D, Sale P, Albertini G, et al. The Parkinsonian gait spatiotemporal

parameters quantified by a single inertial sensor before and after automated mechanical peripheral stimulation treatment. Parkinsons Dis 2015:390512.
[72] Kleiner AFR, Souza Pagnussat A, Pinto C, Redivo Marchese R, Salazar AP, Galli M. Automated mechanical peripheral stimulation effects on gait variability in individuals with Parkinson disease and freezing of gait: a double-blind, randomized controlled trial. Arch Phys Med Rehabil 2018;99:2420—9.
[73] Knellwolf TP, Burton AR, Hammam E, Macefield VG. Microneurography from the posterior tibial nerve: a novel method of recording activity from the foot in freely standing humans. J Neurophysiol 2018;120:953—9.
[74] Knellwolf TP, Burton AR, Hammam E, Macefield VG. Firing properties of muscle spindles supplying the intrinsic foot muscles of humans in unloaded and freestanding conditions. J Neurophysiol 2019;121:74—84.
[75] Knibestöl M, Vallbo AB. Single unit analysis of mechanoreceptor activity from the human glabrous skin. Acta Physiol Scand 1970;80:178—95.
[76] Komatsu H, Yagasaki K, Hirata K, Hamamoto Y. Unmet needs of cancer patients with chemotherapy-related hand-foot syndrome and targeted therapy-related hand-foot skin reaction: A qualitative study. Eur J Oncol Nurs 2019;38:65—9.
[77] Komiyama T, Zehr EP, Stein RB. Absence of nerve specificity in human cutaneous reflexes during standing. Exp Brain Res 2000;133:267—72.
[78] Kouzaki M, Shinohara M. Steadiness in plantar flexor muscles and its relation to postural sway in young and elderly adults. Muscle Nerve 2010;42:78—87.
[79] Ku PX, Abu Osman NA, Yusof A, Wan Abas WA. The effect on human balance of standing with toe-extension. Plos One 2012;7:e41539.
[80] Latt MD, Lord SR, Morris JG, Fung VS. Clinical and physiological assessments for elucidating falls risk in Parkinson's disease. Mov Disord 2009;24:1280—9.
[81] Lavoie BA, Cody FW, Capaday C. Cortical control of human soleus muscle during volitional and postural activities studied using focal magnetic stimulation. Exp Brain Res 1995;103:97—107.
[82] Lipsitz LA, Lough M, Niemi J, Travison T, Howlett H, Manor B. A shoe insole delivering subsensory vibratory noise improves balance and gait in healthy elderly people. Arch Phys Med Rehabil 2015;96:432—9.
[83] Liu W, Lipsitz LA, Montero-Odasso M, Bean J, Kerrigan DC, Collins JJ. Noise-enhanced vibrotactile sensitivity in older adults, patients with stroke, and patients with diabetic neuropathy. Arch Phys Med Rehabil 2002;83:171—6.
[84] Lord SR, Clark RD, Webster IW. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age Ageing 1991;20:175—81.
[85] Lowrey CR, Strzalkowki ND, Bent LR. Skin sensory information from the dorsum of the foot and ankle is necessary for kinesthesia at the ankle joint. Neurosci Lett 2010;485:6—10.
[86] Lowrey CR, Strzalkowski ND, Bent LR. Cooling reduces the cutaneous afferent firing response to vibratory stimuli in glabrous skin of the human foot sole. J Neurophysiol 2013;109:839—50.
[87] Macefield G, Burke D, Gandevia SC. The cortical distribution of muscle and cutaneous afferent projections from the human foot. Electroencephalogr Clin Neurophysiol 1989;72:518—28.
[88] Macefield VG. Physiological characteristics of low-threshold mechanoreceptors in joints, muscle and skin in human subjects. Clin Exp pharmacol Physiol 2005;32:135—44.
[89] Macefield VG, Knellwolf TP. Functional properties of human muscle spindles. J Neurophysiol 2018;120:452—67.
[90] Magnusson M, Enbom H, Johansson R, Wiklund J. Significance of pressor input from the human feet in lateral postural control. The effect of hypothermia on galvanically induced body-sway. Acta Otolaryngol 1990;110:321—7.
[91] Maki BE, Perry SD, Norrie RG, McIlroy WE. Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilization in young and older adults. J Gerontol A Biol Sci Med Sci 1999;54:281—7.
[92] Malik RA, Tesfaye S, Newrick PG, Walker D, Rajbhandari SM, Siddique I, et al. Sural nerve pathology in diabetic patients with minimal but progressive neuropathy. Diabetologia 2005;48:578—85.
[93] Manchester D, Woollacott M, Zederbauer-Hylton N, Marin O. Visual, vestibular and somatosensory contributions to balance control in the older adult. J Gerontol 1989;44:118—27.
[94] Manor B, Li L. Characteristics of functional gait among people with and without peripheral neuropathy. Gait Posture 2009;30:253—6.
[95] Mantyh PW. Cancer pain and its impact on diagnosis, survival and quality of life. Nat Rev Neurosci 2006;7:797—809.
[96] Masani K, Vette AH, Kouzaki M, Kanehisa H, Fukunaga T, Popovic MR. Larger center of pressure minus center of gravity in the elderly induces larger body acceleration during quiet standing. Neurosci Lett 2007;422:202—6.
[97] Maurer C, Mergner T, Bolha B, Hlavacka F. Human balance control during cutaneous stimulation of the plantar soles. Neurosci Lett 2001;302:45—8.
[98] McGlone F, Reilly D. The cutaneous sensory system. Neurosci Biobehav Rev 2010;34:148—59.
[99] McIlroy WE, Maki BE. Age-related changes in compensatory stepping in response to unpredictable perturbations. J Gerontol A Biol Sci Med Sci 1996;51:289—96.
[100] McKeon PO, Hertel J. Diminished plantar cutaneous sensation and postural control. Percept Mot Skills 2007;104:56—66.
[101] Melzer I, Benjuya N, Kaplanski J. Postural stability in the elderly: a comparison between fallers and non-fallers. Age Ageing 2004;33:602—7.
[102] Menz HB, Morris ME, Lord SR. Foot and ankle characteristics associated with impaired balance and functional ability in older people. J Gerontol A Biol Sci Med Sci 2005;60:1546—52.
[103] Mildren RL, Bent LR. Vibrotactile stimulation of fast-adapting cutaneous afferents from the foot modulates proprioception at the ankle joint. J Appl Physiol 2016;120:855—64.
[104] Mildren RL, Yip MC, Lowrey CR, Harpur C, Brown SHM, Bent LR. Ageing reduces light touch and vibrotactile sensitivity on the anterior lower leg and foot dorsum. Exp gerontol 2017;99:1—6.
[105] Mohapatra S, Kukkar KK, Aruin AS. Support surface related changes in feedforward and feedback control of standing posture. J Electromyogr Kinesiol 2014;24:144—52.
[106] Mold JW, Vesely SK, Keyl BA, Schenk JB, Roberts M. The prevalence, predictors, and consequences of peripheral sensory neuropathy in older patients. J Am Board Fam Pract 2004;17:309—18.
[107] Montfort SM, Pan X, Patrick R, Singaravelu J, Loprinzi CL, Lustberg MB, et al. Natural history of postural instability in breast cancer patients treated with taxane-based chemotherapy: a pilot study. Gait Posture 2016;48:237—42.
[108] Montfort SM, Pan X, Loprinzi CL, Lustberg MB, Chaudhari AMW. Impaired Postural Control and Altered Sensory Organization During Quiet Stance Following Neurotoxic Chemotherapy: A Preliminary Study. Integr Cancer Ther 2019;18 [1534735419828823].
[109] Mouchnino L, Fontan A, Tandonnet C, Perrier J, Saradjian AH, Blouin J, Simoneau M. Facilitation of cutaneous inputs during the planning phase of gait initiation. J Neurophysiol 2015;114:301—8.
[110] Myers MI, Peltier AC, Li J. Evaluating dermal myelinated nerve fibers in skin biopsy. Muscle nerve 2013;47:1—11.

[111] Najafi B, Crews RT, Wrobel JS. A novel plantar stimulation technology for improving protective sensation and postural control in patients with diabetic peripheral neuropathy: a double-blinded, randomized study. Gerontology 2013;59:473—80.
[112] Najafi B, Talal TK, Grewal GS, Menzies R, Armostrong DG, Lavery LA. Using plantar electrical stimulation to improve postural balance and plantar sensation among patients with diabetic peripheral neuropathy: a randomized double blinded study. J Diabetes Sci Technol 2017;11:693—701.
[113] Nakajima T, Sakamoto M, Tazoe T, Endoh T, Komiyama T. Location specificity of plantar cutaneous reflexes involving lower limb muscles in humans. Exp Brain Res 2006;175:514—25.
[114] Nakajima T, Sakamoto M, Tazoe T, Endoh T, Komiyama T. Location-specific modulations of plantar cutaneous reflexes in human (peroneus longus muscle) are dependent on co-activation of ankle muscles. Exp Brain res 2009;195: 403—12.
[115] Nakajima T, Mezzarane RA, Hundza SR, Komiyama T, Zehr EP. Convergence in reflex pathways from multiple cutaneous nerves innervating the foot depends upon the number of rhythmically active limbs during locomotion. Plos One 2014;9:e104910.
[116] Nardone A, Tarantola J, Miscio G, Pisano F, Schenone A, Schieppati M. Loss of large diameter spindle afferent fibres is not detrimental to the control of body sway during upright stance: evidence from neuropathy. Exp Brain Res 2000;135:155—62.
[117] Nardone A, Schieppati M. Group II spindle fibres and afferent control of stance. Clues from diabetic neuropathy. Clin Neurophysiol 2004;115:779—89.
[118] Nardone A, Grasso M, Schieppati M. Balance control in peripheral neuropathy: are patients equally unstable under static and dynamic conditions. Gait Posture 2006;23:364—73.
[119] Nashner LM, Woollacott M, Tuma G. Organization of rapid responses to postural and locomotor like perturbations of standing man. Exp Brain Res 1979;36:463—76.
[120] Nurse MA, Nigg BM. The effect of changes in foot sensation on plantar pressure and muscle activity. Clin Biomech 2001;16:719—27.
[121] Okay LA, Kohn AF. Quantifying the contributions of the flexor digitorum brevis muscle on postural stability. Motor Control 2015;19:161—72.
[122] Oyibo SO, Prasad YD, Jackson NJ, Jude EB, Boulton AJ. The relationship between blood glucose excursions and painful diabetic peripheral neuropathy: a pilot study. Diabet Med 2002;19:870—3.
[123] Pagnussat AS, Kleiner AFR, Rieder CRM, Frantz A, Ehlers J, Pinto C, et al. Plantar stimulation in parkinsonians: from biomarkers to mobility—randomized controlled trial. Restor Neurol Neurosci 2018;36:195—205.
[124] Partanen J, Niskanen L, Lehtinen J, Mervaala E, Siitonen O, Uusitupa M. Natural history of peripheral neuropathy in patients with non-insulin-dependent diabetes mellitus. N Engl J Med 1995;333:89—94.
[125] Patel M, Fransson PA, Johansson R, Magnusson M. Foam posturography: standing on foam is not equivalent to standing with decreased rapidly adapting mechanoreceptive sensation. Exp Brain Res 2011;208:519—27.
[126] Perry SD, McIlroy WE, Maki BE. The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation. Brain Res 2000;877:401—6.
[127] Perry SD. Evaluation of age-related plantar-surface insensitivity and onset age of advanced insensitivity in older adults using vibratory and touch sensation tests. Neurosci Lett 2006;392:62—7.
[128] Perry SD, Radtke A, McIlroy WE, Fernie GR, Maki BE. Efficacy and effectiveness of a balance-enhancing insole. J Gerontol A Biol Sci Med Sci 2008;63:595—602.
[129] Peters RM, McKeown MD, Carpenter MG, Inglis JT. Losing touch: age-related changes in plantar skin sensitivity, lower limb cutaneous reflex strength, and postural stability in older adults. J Neurophysiol 2016;116:1848—58.
[130] Pierrot-Deseiligny E, Bergego C, Katz R, Morin C. Cutaneous depression of Ib reflex pathways to motoneurones in man. Exp Brain Res 1981;42:351—61.
[131] Pierrot-Deseiligny E, bergego C, Katz R. Reversal in cutaneous of Ib pathways during human voluntary contraction. Brain res 1982;233:400—3.
[132] Pollock AS, Durward BR, Rowe PJ, Paul JP. What is balance? Clin Rehabil 2000;14:402—6.
[133] Prätorius B, Kimmeskamp S, Milani TL. The sensitivity of the sole of the foot in patients with Morbus Parkinson. Neurosci Lett 2003;34:173—6.
[134] Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Trans Biomed Eng 1996;43:956—66.
[135] Priplata AA, Niemi JB, Harry JD, Lipsitz LA, Collins JJ. Vibrating insoles and balance control in elderly people. Lancet 2003;362:1123—4.
[136] Priplata AA, Patritti BL, Niemi JB, Hughes R, Gravelle DC, Lipsitz LA, et al. Noise-enhanced balance control in patients with diabetes and patients with stroke. Ann Neurol 2006;59:4—12.
[137] Proske U, Gandevia SC. The proprioceptive senses: their roles in signalling body shape, body position and movement, and muscle force. Physiol Rev 2012;92:1651—97.
[138] Prusch JS, Kleiner AFR, Salazar AP, Pinto C, Marchese RR, Galli M, et al. Automated mechanical peripheral stimulation and postural control in subjects with Parkinson's disease and freezing of gait: a randomized controlled trial. Funct Neurol 2018;33:206—12.
[139] Pruszynski JA, Johansson RS. Edge orientation processing in first-order tactile neurons. Nat Neurosci 2014;17:1404—9.
[140] Qu X, Nussbaum MA. Evaluation of the roles of passive and active control of balance using a balance control model. J Biomech 2009;42:1850—5.
[141] Richardson JK, Hurvitz EA. Peripheral neuropathy: a true risk factor for falls. J Gerontol A Biol Sci Med Sci 1995;50:211—5.
[142] Richardson JK. The clinical identification of peripheral neuropathy among older persons. Arch Phys Med Rehabil 2002;83:1553—8.
[143] Rivner MH, Swift TR, Malik K. Influence of age and height on nerve conduction. Muscle Nerve 2001;24:1134—41.
[144] Rizzolatti G, Luppino G. The cortical motor system. Neuron 2001;31:889—901.
[145] Roll R, Kavounoudias A, Roll JP. Cutaneous afferents from human plantar sole contribute to body posture awareness. Neuroreport 2002;13:1957—61.
[146] Rossi A, Mazzocchio R. Cutaneous control of group I pathways from ankle flexors to extensors in man. Exp Brain Res 1988;73:8—14.
[147] Roudaut Y, Lonigro A, Coste B, Hao J, Delmas P, Crest M. Touch sense: functional organization and molecular determinants of mechanosensitive receptors. Channels 2012;6:234—45.
[148] Saeki J, Tojima M, Torii S. Clarification of functional differences between the hallux and lesser toes during the single leg stance: immediate effects of conditioning contraction of the toe plantar flexion muscles. J Phys Ther Sci 2015;27:2701—4.
[149] Schieppati M, Hugon M, Grasso M, Nardone A, Galante M. The limits of equilibrium in young and elderly normal subjects and in Parkinsonians. Electroencephalogr Clin Neurophysiol 1994;93:286—98.

[150] Schieppati M, Nardone A, Siliotto R, Grasso M. Early and late stretch responses of human foot muscles induced by perturbation of stance. Exp Brain Res 1995;105:411—22.
[151] Schimrigk K, Rüttinger H. The touch corpuscules of the plantar surface of the big toe. Histological and histometrical investigations with respect to age. Eur Neurol 1980;19:49—60.
[152] Selvarajah D, Wilkinson ID, Maxwell M, Davies J, Sankar A, Boland E, et al. Magnetic resonance neuroimaging study of brain structural differences in diabetic peripheral neuropathy. Diabetes Care 2014;37:1681—8.
[153] Siragy T, Nantel J. Quantifying dynamic balance in young, elderly and Parkinson's individuals: a systematic review. Front Aging Neurosci 2018;10:387.
[154] Solopova IA, Kazennikov OV, Deniskina NB, Levik YS, Ivanenko YP. Postural instability enhances motor responses to transcranial magnetic stimulation in humans. Neurosci Lett 2003;337:25—8.
[155] Sonnenborg FA, Andersen OK, Arendt-Nielsen L. Modular organization of excitatory and inhibitory reflex receptive fields elicited by electrical stimulation of the foot sole in man. Clin Neurophysiol 2000;111:2160—9.
[156] Sorensen L, Molyneaux L, Yue DK. Insensate versus painful diabetic neuropathy: the effects of height, gender, ethnicity and glycaemic control. Diabetes Res Clin Pract 2002;57:45—51.
[157] Stevens JC, Patterson MQ. Dimensions of spatial acuity in the touch sense: changes over the life span. Somatosens Mot Res 1995;12:29—47.
[158] Stevens JC, Choo KK. Spatial acuity of the body surface over the life span. Somatosens Mot Res 1996;13:153—66.
[159] Stocchi, Sale P, Kleiner AF, Casali M, Cimolin V, de Pandis F, et al. Long-term effects of automated mechanical peripheral stimulation on gait patterns of patients with Parkinson's disease. Int J Rehabil Res 2015;38:238—45.
[160] Stolze H, Klebe S, Zechlin C, Baecker C, Friege L, Deuschl G. Falls in frequent neurological diseases-prevalence, risk factors and aetiology. J Neurol 2004;1:79—84.
[161] Strzalkowski ND, Mildren RL, Bent LR. Thresholds of cutaneous afferents related to perceptual threshold across the human foot sole. J Neurophysiol 2015;114:2144—51.
[162] Strzalkowski ND, Incognito AV, Bent LR, Millar PJ. Cutaneous mechanoreceptor feedback from the hand and foot can modulate muscle sympathetic nerve activity. Front Neurosci 2016;10:568.
[163] Strzalkowski NDJ, Ali RA, Bent LR. The firing characteristics of foot sole cutaneous mechanoreceptor afferents in response to vibration stimuli. J Neurophysiol 2017;118:1931—42.
[164] Strzalkowski NDJ, Peters RM, Inglis JT, Bent LR. Cutaneous afferent innervation of the human foot sole: what can we learn from single-unit recordings? J Neurophysiol 2018;120:1233—46.
[165] Stubblefield MD, Burstein HJ, Burton AW, Custodio CM, Deng GE, Ho M, et al. NCCN task force report: management of neuropathy in cancer. J Natl Compr Cancer Netw 2009;7:1—26.
[166] Takakusaki K. Functional neuroanatomy for posture and gait control. J Mov Disord 2017;10:1—17.
[167] Talbot S, Couture R. emerging role of microglial kinin B1 receptor in diabetic pain neuropathy. Exp Neurol 2012;234:373—81.
[168] Tanaka T, Noriyasu S, Ino S, Ifukube T, Nakata M. Objective method to determine the contribution of the great toe to standing balance and preliminary observations of age-related effects. IEEE Trans Rehabil Eng 1996;4:84—90.
[169] Tanaka T, Hashimoto N, nakata M, Ito T, Ino S, Ifukube T. Analysis of toe pressures under the foot while dynamic standing on one foot in healthy subjects. J Orthop Sports Phys Ther 1996;23:188—93.
[170] Taube W, Gruber M, Gollhofer A. Spinal and supraspinal adaptations associated with balance training and their functional relevance. Acta Physiol Oxf Engl 2008;193:101—16.
[171] Tesfaye S, Boulton AJ, Dyck PJ, Freeman R, Horowitz M, Kempler P, et al. Diabetic neuropathies: update on definitions, diagnostic criteria, estimation of severity, and treatments. Diabetes Care 2010;33:2285—93.
[172] Thakral G, Kim PJ, LaFontaine J, Menzies R, Najafi B, Lavery LA. Electrical stimulation as an adjunctive treatment of painful and sensory diabetic neuropathy. J Diabetes Sci Technol 2013;7:1202—9.
[173] Thomas PK. Classification, differential diagnosis, and staging of diabetic peripheral neuropathy. Diabetes 1997;2:54—7.
[174] Thornbury JM, Mistretta CM. Tactile sensitivity as a function of age. J Gerontol 1981;36:34—9.
[175] Tofthagen C, Overcash J, Kip K. Falls in persons with chemotherapy-induced peripheral neuropathy. Support Care Cancer 2012;20:583—9.
[176] Tortolero X, Masani K, Maluly C, Popovic MR. Body movement induced by electrical stimulation of toe muscles during standing. Artif Organs 2008;32:5—12.
[177] Tosovic D, Ghebremedhin E, Glen C, Gorelick M, Mark Brown J. The architecture and contraction time of intrinsic foot muscles. J Electromyogr Kinesiol 2012;22:930—8.
[178] Uccioli L, Faglia E, Monticone G, Favales F, Durola L, Aldeghi A, et al. Manufactured shoes in the prevention of diabetic foot ulcers. Diabetes Care 1995;18:1376—8.
[179] Vallbo AB, Johansson RS. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. Hum Neurobiol 1984;3:3—14.
[180] Vedel JP, Roll JP. Response to pressure and vibration of slowly adapting cutaneous mechanoreceptors in the human foot. Neurosci Lett 1982;34:289—94.
[181] Velazquez R, Pissaloux E, Lay-Ekuakille A. tactile-foot stimulation can assist the navigation of people with visual impairment. Appl Bionics Biomech 2015;2015:798748.
[182] Verdu E, Ceballos D, Vilches JJ, Navarro X. Influence of aging on peripheral nerve function and regeneration. J Peripher Nerv Syst 2000;5:191—208.
[183] Verrillo RT, Bolanowski SJ, Gescheider GA. Effect of aging on the subjective magnitude of vibration. Somatosens Mot Res 2002;19:238—44.
[184] Vinik AL, Mehrabyan A. Diabetic neuropathies. Med Clin North Am 2004;88:947—99.
[185] Viseux F, Barbier F, Villeneuve P, Lemaire A, Charpentier P, Leteneur S. Low additional thickness under the toes could change upright balance of healthy subjects. Neurophysiol Clin 2018;48:397—400.
[186] Viseux F, Lemaire A, Barbier F, Charpentier P, Leteneur S, Villeneuve P. How can the stimulation of plantar cutaneous receptors improve postural control? Review and clinical commentary. Neurophysiol Clin 2019;49:263—8.
[187] Viseux F, Barbier F, Parreira R, Lemaire A, Villeneuve P, Leteneur S. Less than one millimeter under the great toe is enough to change balance ability in elite women handball players. J Hum Kinet 2019;69:7—20.
[188] Wampler MA, Miaskowski C, Hamel K, Byl NB, Rugo H, Topp KS. The Modified Total Neuropathy Score: a clinically feasible and valid measure of taxane-induced peripheral neuropathy in women with breast cancer. J Support Oncol 2006;4:397—402.
[189] Wang Y, Watanabe K, Chen L. Effect of plantar cutaneous inputs on center of pressure during quiet stance in older adults. J Exerc Sci Fit 2016;14:24—8.
[190] Wells C, Ward LM, Chua R, Timothy Inglis J. Touch noise increases vibrotactile sensitivity in old and young. Psychol Sci 2005;16:313—20.

[191] Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K. Stiffness control of balance in quiet standing. J Neurophysiol 1998;80:1211—21.
[192] Wright WG, Ivanenko YP, Gurfinkel VS. Foot anatomy specialization for postural sensation and control. J Neurophysiol 2012;107:1513—21.
[193] Wu G, Chiang JH. The significance of somatosensory stimulations to the human foot in the control of postural reflexes. Exp Brain Res 1997;114:163—9.
[194] Zehr EP, Komiyama T, Stein RB. Cutaneous reflexes during human gait: electromyographic and kinematic responses to electrical stimulation. J Neurophysiol 1997;77:3311—25.
[195] Zehr EP, Stein RB, Komiyama T. Function of sural nerve reflexes during human walking. J Physiol 1998;507:305—14.
[196] Zehr EP, Hesketh KL, Chua R. Differential regulation of cutaneous and H-reflexes during leg cycling in humans. J Neurophysiol 2001;85:1178—84.
[197] Zhang S, Li L. The differential effects of foot sole sensory on plantar pressure distribution between balance and gait. Gait Posture 2013;37:532—5.
[198] Ziegler D, Mayer P, Muhlen H, Gries FA. The natural history of somatosensory and autonomic nerve dysfunction in relation to glycaemic control during the first 5 years after diagnosis of type 1 (insulin-dependent) diabetes mellitus. Diabetologia 1991;34:822—9.
[199] Zwaferink JBJ, Hijmans JM, Schrijver CM, Schrijver LK, Postema K, van Netten JJ. Mechanical noise improves the vibration perception threshold of the foot in people with diabetic neuropathy. J Diabetes Sci Technol 2020 [1932296818804552].