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The role of plantar cutaneous mechanoreceptors on static stance and gait balance

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The role of plantar cutaneous mechanoreceptors on static stance and gait balance

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The role of plantar cutaneous mechanoreceptors (PCMR) and associated afferent input on static stance and steady-state gait in healthy adults and the elderly was evaluated. PCMR affect balance and motor task performance through activation of spinal reflexes and input to higher cortical centers to influence movement and motor planning. In older adults, PCMR insensitivity has a negative effect on balance and performance, whereas tactile and vibration stimuli improve balance and performance. PCMR play an important role in static stance and gait balance maintenance. This information can be utilized effectively in the screening of fall-risk patients. It also supports the use of textured insoles and plantar subthreshold vibration for improving balance and performance in static stance and gait in older adults.

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Abbreviations (in order of appearance):

CMR: Cutaneous mechanoreceptor

PCMR: Plantar cutaneous mechanoreceptor

SA: Slow acting

SAI: Slow acting type 1

SA2: Slow acting type 2

FA: Fast acting

FAI: Fast acting type 1

FA2: Fasting acting type 2

LLR: Late latency reflex

f-M: Medial forefoot

f-L: Lateral forefoot

HL: Heel

RF: Rectus femoris

BF: Bicep femoris

CNS: Central nervous system

PCML: Posterior column-medial lemniscus

CoG: Centre of Gravity

BoS: Base of Support

CoP: Centre of Pressure

CoM: Centre of Mass

A/P: Anterior/posterior

M/L: Medial/lateral

LA: Local anesthesia

SR: Stochastic Resonance

LRC: Long range correlation

Introduction

Glabrous skin on the sole of the foot contains a high density of cutaneous mechanoreceptors (CMR). Plantar cutaneous mechanoreceptors (PCMR) provide information on the tactile environment by processing surface texture and vibration. They are also integral to balance and stability. A high vibration perception threshold is an indicator of fall risk in the elderly.[1] The vibration perception threshold increases with age[23] and, to a lesser extent, there is an increase in monofilament threshold.[3] These age-related plantar sensitivity threshold elevations have been correlated with decreased balance and stability.[3] Therefore, interventions that target improving the sensitivity of PCMR's may improve balance and task performance in older adults. The purpose of this review is to summarize the literature on PCMR and their contribution to standing and gait balance and performance in healthy younger and older adults.

Mechanoreceptors

CMR are sensitive to mechanical deformation and skin motion. There are four types of CMR nerve-endings in glabrous skin: Merkel discs, Ruffini endings, Meissner corpuscles and Pacinian corpuscles. They are innervated by myelinated Aβ fibers and are categorized by their rate of adaption and receptive field characteristics.

SAI afferents are slow acting (SA), have small receptor fields (Type I) and have Merkel disc nerve-endings. SA2 afferents are SA, have large receptor fields (Type 2) and have a Ruffini corpuscle nerve-endings. FAI afferents are fast acting (FA), Type I and have Meissner corpuscles nerve-endings. Finally, FA2 afferents are FA, Type 2 and have a Pacinian corpuscle nerve-endings.[4] SA receptors respond through the duration of sustained stimuli. This is known as a sustained adaption.[5,6] FA receptors respond to the initiation and cessation of stimuli and code for velocity and acceleration of stimuli.[5] While each type of CMR encodes for a distinct stimulus, they collectively convey a wide spectrum of input to capture the tactile environment.

Cutaneous mechanoreceptor morphology

PCMR inhabit various depths in the skin. This influences receptor sensitivity. SAI receptors are located in the deepest epidermal ridges.[7] They have a semi-rigid structure and unlike the other mechanoreceptors, they are unencapsulated.[7] SA2 receptors are located deeper than SAI receptors and are connected to adjacent tissue by collagen fibers.[5] FAI receptors are located at the border of the epidermis and dermis[8]. This proximity to the surface may account for their high sensitivity to skin deformation. Finally, FA2 receptors are located within the dermis and subcutaneous tissue. They are the deepest CMRs.[5]

Type I (SAI and FAI) afferents bifurcate as they enter the skin and terminate in multiple CMR endings; whereas, Type 2 (SA2 and FA2) afferents do not bifurcate.[9,10] Type 2 receptors are innervated by a single neuron.[11] Therefore, Type I receptor fields have multiple regions of intense response to stimuli and Type 2 receptors do not.

Distribution & density

FAI receptors are the most densely populated[12] and are the most synaptically-coupled PCMR to the lower limb. [13] Strzalowski et al. sampled 364 cutaneous afferents and determined a percentage distribution of 48% FAI, 13% FAII, 18% SAI and 21% SAII.[12] This was supported by similar plantar microneurography research.[4]

There is a higher a density of PCMRs under the plantar toes, followed by the lateral arch and the lateral metatarsals. The lowest density is under the heel and medial arch boarder.[12] Type 2 receptors appear to be uniformly distributed.[12]

Firing characteristics & sensitivity

Each PCMR type is sensitive to unique stimuli. SAI receptors encode for pressure and texture and are sensitive to edges and curvatures.[5,9] SA2 receptors are insensitive skin to vibration indentation.[14] Connections to collagen fibers make them very sensitive to lateral skin stretch.[5,9] The primary stimuli for FA receptors is vibration. FAI receptors are sensitive to low frequency vibration (<10 Hz), edge discrimination, object recognition and shear forces.[5,9] FA2 receptors are sensitive to high-frequency vibration (80–300 Hz), acceleration of stimuli and skin deformation.[15]

SA receptors have higher tactile thresholds than FA receptors. Sustained static pressure is the primary stimuli detected by SA receptors. This may indicate an influence on postural control and static stance, however further research is required to confirm this. FA receptors have a higher VPT than SA receptors,[14] which is greatest under the heel and hallux and lowest under the medial arch.[16,17] Most studies in this field studies have been conducted with participants in non-weight bearing conditions; future studies are required to determine the activity of these afferents during functional weight-bearing tasks.

PCMR stimulation & mechanisms of balance control

Plantar stimulation influences muscle activation and motor task performance.[18–22] This relationship is facilitated by lower-order pathways to the spinal cord [middle-latency reflexes (80-120ms)] and higher-order pathways to supraspinal regions[late latency reflexes (LLR) (120-180ms)].[23–25] PCMR stimulation has been shown to generate ankle musculature LLRs during gait [26,27] and static stance.[2,28] Investigation using electroencephalography have found a positive correlation between PCMR stimulation with textured insoles and improved balance and decreased alpha power band cortical activity, which has been associated with information processing inhibition. .[29]

There is more research on PCMR stimulation and lower-order activation as compared to higher-order processing. Cutaneous spinal reflex pathways are active when standing and this suggests motor drive to lower limb muscles that help maintain postural balance.[18,30] Additionally, there are changes to discrete reflex patterns as an individual adopts different postures.[24] Researchers electrically stimulated the medial forefoot (f-M), lateral forefoot (f-L) and heel (HL) to test the effect of cutaneous spinal reflexes on lower limb muscle firing and static standing.[18] Reflexes were recorded with EMG during isometric contraction in weightbearing. The plantar flexor muscles, soleus (SOL) and medial gastrocnemius (MG), produced inhibitory MLR following forefoot stimulation and facilitatory MLR following HL stimulation. Conversely, the tibialis anterior (TA), the primary dorsiflexor, produced facilitatory MLR following forefoot stimulation and inhibitory MLR following HL stimulation. The peroneus longus (PL) produced inhibitory MLR's following f-M stimulation and facilitatory MLR's following both f-L and HL stimulation. Plantar cutaneous reflexes appear to be topographical organized. This is described as the "plantar tuning effect" and is suggested to influence postural balance by removing the foot from plantar obstacles. This theory was supported by research that found electrical stimulation of the medial arch promotes inversion via TA and SOL muscle activation, whereas stimulation of the lateral arch promotes eversion through PL muscle activation.[30,31] Therefore, plantar mechanical stimulation may modulate balance equilibrium via lower limb spinal reflexes as to keep the Centre of Gravity (CoG) within the base of support (BoS) and away from destabilizing obstacles. This is supported by extensive clinical research, which increased PCMR stimulation with improved postural balance.[32–35] Electrical stimulation bypasses PCMR and thus differs from naturally occurring mechanical stimulus. However, past research found that electrical stimulation can elicit a similar effect to mechanical stimuli and naturally occurring movements.[36,37] Additionally, plantar subthreshold mechanical noise has been shown to enhance electrically induced ankle musculature reflexes.[38] Further research on mechanical stimulus and spinal reflexes is required, however, current research on electrical stimulation suggests that cutaneous spinal reflexes are a viable mechanism explaining PCMR influence on postural balance.

The plantar tuning effect and topographical organization of plantar cutaneous reflexes also has a significant effect on the stance phase of gait. For example. electrical stimulation at the heel at touchdown evokes facilitatory plantarflexor MLR and inhibitory dorsiflexor MLR. During early stance, this results in increased forces under the forefoot and forward gait cycle progression.[19,39,40] During stance phase, electrical stimulation applied to the medial midfoot (m-M) causes inversion, except for when there is potential to generate an inversion ankle sprain. Lateral midfoot (m-L) and f-L electrical stimulation cause eversion.[40] This aligns with plantar cutaneous reflex and static stance research.[18] Therefore, plantar afferent input is believed to shift the Centre of Pressure (CoP) as to optimal load and stabilize the foot during gait. During propulsion, foot sole electrical stimulation results in inhibitory plantarflexor MLR and a decrease in force under the forefoot. This is accompanied by facilitatory PL MLR with f-L stimulation and facilitatory dorsiflexor MLR with f-M stimulation.[39–41] These location-specific responses aid gait by maintaining frontal plane stability during propulsion on uneven terrain. The CNS uses plantar cutaneous afferent information to move the foot away from the potentially destabilizing stimulus and facilitate forward gait progression.

Plantar cutaneous reflexes are task- and phase dependent. Task dependent modulation of plantar cutaneous reflexes has been demonstrated between standing and walking .[42] During locomotion, selective gating of inhibitory and facilitatory plantar cutaneous reflexes facilitate "phase-dependent reflex reversal".[19] This phenomenon helps maintain dynamic balance and forward gait progression. Tibial nerve (TIB) stimulation generates facilitatory TA MLR during the early swing phase and inhibitory TA MLR at the swing to stance transition. The summation effects of reflex amplitudes demonstrate that TIB stimulation and associated TA phase dependent MLR reversal is mediated by selective gating of forefoot and heel plantar cutaneous afferent pathways. TA MLR reversal results in dorsiflexion and foot withdrawal at terminal stance, as well as plantarflexion and optimal foot sole contact during the stance phase as to ensure stability.[19,25,37,43] Reflexes involved in foot-placing reactions dominate the swing-to-stance phase transition., Reflexes involved in weight support and stability dominate the stance and stance-to-swing phase transition.[33.] This is supported by clinical research on PCMR stimulation and gait balance.[34,35,44,45] Phase dependent reflex reversal helps improve gait performance by increasing efficiency and autonomy. This frees up information processing for other matters and allows for multitasking during gait.

The literature focuses on PCMR stimulation and ankle muscles; however, proximal muscles are imperative to upright balance. With participants in supine, researchers stimulated the foot sole and generated a MLR in the bicep femoris (BF) and rectus femoris (RF). These reflexes are "flexion dominant" and consistent across the foot sole.[34] A similar study tested participants in weightbearing and elicited a BF reflex. However, this was a short latency reflex (40ms), which indicates a monosynaptic spinal stretch reflex. A cutaneous reflex loop is indicated by a longer latency, either MLR (80-120ms) or LLR (120-180ms).[46] Researchers recorded reflexes from foot sole stimulation during gait and found a minimal response at the RF, BF, vastus lateralis (VL), gracilis (GR) and gluteus medius (GM).[40] In addition, tactile stimulation of the heel and electrical stimulation of the plantar lateral border influence erector spinae activity which can effect balance.[47] Future research should further investigate the effect of plantar cutaneous stimulation on the gluteus medius (GM). The GM muscle is proximal and has a significant role in static stance and gait frontal plane stability, which is important as M/L CoP sway is strong indicator of fall reoccurrence.[48]

Ageing

Ageing degenerates the somatosensory system.[49] This alters PCMR density, morphology and physiology. Resultant cutaneous afferent impairment is linked to increased falls risk.[1,21] Past research has recorded age-related reductions in FA receptors density[51] and FAI receptors cross-sectional area.[52] Additionally, there is a plantar sensitivity decline as we age.[49] For example, researchers examined VPT at 55 foot sole regions, at 4 different frequencies (25, 50, 250, and 400 Hz). They found a significant increase in VPT levels in older adults, particularly at frequencies mediated by FAII receptors (250 Hz and above).[54] Another study found that participants in their early 70’s (72–73yr) demonstrated a doubling of their VPT as compared to younger participants (65–71yr).[2] Older adults also exhibit significantly elevated monofilament threshold as compared to younger heath individuals.[3] In older adults, higher plantar VPT and monofilament measurements are correlated with a lower berg balance score and slower gait velocity, respectively.[55] Ageing negatively effects plantar cutaneous spinal reflexes. For examples, researchers found that 95% of young adults were able to generate a plantar cutaneous reflex in their TA but only 53% of elderly could. Additionally, reflex gain, coherence, and cumulant density at 30 Hz were lower in the elderly.[3] Perhaps, future elderly screening protocols could include a PCMR sensitivity and spinal reflex test. Researchers analyzed the relationship between ageing and plantar cutaneous afferent density, sensitivity, associated spinal reflexes, and postural balance using VPT and monofilament testing, EMG and posturography. The results showed a clear link between the older age group (mean 68yr) and reduced plantar sensitivity, reduced TA spinal reflexes strength and increase biplanar CoP sway as compared to the young group (mean 27,6yr).[3] Therefore, the literature clearly highlights significant plantar cutaneous afferent degeneration associated with ageing and the serious implications on falls risk.

Performance & Balance Control

The central nervous system (CNS) regulates balance equilibrium via interpretation and reaction to a continuous stream of sensory information.[56] This information is processed by the visual, vestibular and somatosensory systems. Interestingly, the somatosensory system is the most important system for regulating balance during activities of daily living.[21,57,58] It is comprised of proprioceptive and cutaneous structures. The literature often fails to distinguish their individual contributions and discriminate between the effects during motor tasks. Therefore, we elucidate the role of PCMR in both static and dynamic motor tasks of daily living.

Plantar afferent information may be co-processed with proprioceptive input for complementary effects on motor task balance and performance.[59] Therefore, it may have two roles, namely, to determine body orientation in space and to determine the details of the support surface.[60] CMR and muscle spindles aid proprioception and kinaesthesia in the index finger, upper limb and knee.[61] Additionally, plantar mechanical augmentation has been shown to improve whole body posture awareness and body representation in space.[62] FA afferents are believed to contribute more to proprioception than SA afferents. However, less is known of the FAI and FA2 contribution.[63] Vibration is received by both muscle spindles and FA PCMR. Transmission of signals from either source directed to the cortex can be altered via stimulus applied to either muscle or skin. Thus, we suggest that the two signals are not segregated and that they interact in the ascending posterior column-medial lemniscus (PCML) pathway.[64]

To investigate the relationship between plantar afferent feedback and motor skill performance researchers modify PCMR sensitivity and/or stimuli before and/or during the task. Posture is the orientation of one's body segments relative to the gravitational vector and balance is the dynamics of body posture to prevent falling. Postural balance is maintained when the CoG is confined within the BoS. The adjustments undertaken to achieve this are known as sway[56] and are correlated with fall risk in the elderly.[65,66] Gait is more complex and so we must consider more variables. These include kinematic, kinetic and spatial temporal variables such as, Centre of Mass (CoM) and CoP trajectory, as well as, velocity, stride width, stride to stride variability, cadence and more [56] These variables are correlated with falls risk in the elderly. [67,68] Additionally, researchers record muscle activation patterns so as to learn about the mechanisms behind the effect of plantar afferent input modification on motor skill performance.

Static stance

Static stance autonomy is achieved at an early age. However, for certain individuals, postural balance is jeopardized when plantar mechanical stimulus is reduced. For example, CoP sway excursion in the elderly (mean 74.6yr) with intact VPT is statistically similar to healthy adults (mean 37.5yr). However, elderly participants with a higher VPT have increased high frequency sway variance compared to healthy adults and the elderly with intact plantar sensation.[21] Therefore, aging, neurogenerative diseases and certain environmental impacts may affect PCMR activity and postural balance.

Plantar hypothermic anesthesia is the most common strategy to induce plantar insensitivity. Cooling below 10°C increases monofilament threshold [69,70] and VPT.[71] This review only includes studies that selectively cooled the plantar glabrous skin so as to best isolate PCMR. A meta-analysis concluded that plantar cooling did not have a significant effect on static stance in healthy adults.[72] This was explained by 'sensory reweighting', a strategy of input manipulation which compensates for the reductions in sensory information.[73] Nonetheless, some of the studies analyzed in Hoch et al's meta-analysis did find a significant effect. For example, researchers found a decrease in A/P CoP time-to-boundary post-plantar cooling with eyes closed.[74] Another found that PCMR desensitization caused changes in CoP excursion magnitude.[75] Therefore, we do not rule out a significant relationship between PCMR input and postural balance.

There exists little research on postural balance and induced plantar insensitivity in the elderly. Ageing is non-pathological, but it does lead to sensorimotor degeneration. For example, post-plantar cooling, M/L CoP excursion velocity and net body sway velocity are significantly higher in the elderly (mean 75yr) as compared to healthy adults (mean 35yr).[76] Increases in both of these variables have been correlated with higher falls risk in the elderly.[77] Therefore, augmentation of plantar sensitivity may not influence upright stability in healthy adults, but, it does in the elderly.

Intradermal LA injections are also used to induce plantar insensitivity. They are believed to best isolate the PCMR but are not often utilized. Research into their effect on static stance supports the "plantar tuning effect". For example, participants showed increased M/L CoP velocity post-forefoot injection and increased A/P CoP velocity post-entire foot-sole injection.[78] The CoP sway trajectory was directed away from the equilibrium point. This was indicative of an open-loop control model. The authors concluded that PCMR input is processed in higher-order structures to help select a motor program and set appropriate background muscle activity, but of little relevance to feedback control of static stance. This conflicts with the popular theory that PCMR input enhances closed-loop control of balance. We suggest further research to elucidate these conclusions.

There is a large body of research on the application of tactile stimulation, such as texture and vibration, on static stance. Tactile stimulation increases sensory afferent feedback[79] and has] wide clinical potential because it is inexpensive and non-invasive. Textures include pyramid elevations [80,81], nodules[82], and spikes.[83,84] Evenly spaced pyramid elevations are the most common type. They have a greater effect on posture as compared to concave texture[80]. Furthermore, insoles must be rigid with a high shore value because softer, thicker insoles may lead to sensory dampening. Textured insoles with medium and rigid hardness significantly reduce postural sway.[85–87] They are believed to provide more stimulation and are more effective than less rigid textured insoles. However, the optimal design for best balance outcomes remains unclear.

A meta-analysis concluded that tactile stimulation can improve static stance performance in healthy young participants, adult participants, and the elderly.[20] Textured insoles have been shown to decrease CoP sway[79,80,82,86,88,89] and CoP excursion velocity in healthy adults with eyes open.[79,82,88,90] These results were exaggerated in elderly participants. Furthermore, stimulation via an aluminum disc (diameter 26.5mm) caused smaller CoP oscillations around the equilibrium point which reflected improved error correction in healthy adults and the elderly.[91] Interestingly, this study showed that tactile stimuli enhanced closed-loop control, which contrasted the stabilography and intradermal LA research by Meyer et al. Performance improvements have even been noted in young healthy participants.[83,84,86] Researchers found that textured insole use improves ankle discrimination and dancing performance in young healthy dancers.[92]A follow up found improvements in M/L CoP sway and postural stability.[93] Therefore, textured insoles may have an application in sports performance.

There are opposite effects for subthreshold and suprathreshold vibration. The latter negatively affects one’s ability to detect mechanical input.[94] It has a destabilizing effect and does not have a clinical application. The former is believed to decrease PCMR sensitivity and increase spinal reflexes. Research has found that subthreshold tactile noise around 20% VPT can enhance cutaneous reflexes in the lower limb, particularly in the ankle musculature. The authors concluded that augmented plantar stimulation can improve postural balance via the modification of cutaneous reflexes.[38] Subthreshold vibration works via Stochastic Resonance (SR), a phenomenon described by enhancement of information transmission and stimuli detection when optimal noise is added to the system. Lowering VPT and increasing reflex response can combat nervous degeneration, however, it may have a lesser effect on static stance for those with an optimal sensorimotor system.[95] For example, up to 90% VPT plantar vibration resulted in decreased CoM and CoP separation distance and improved balance in the elderly.[96,97] Similarly, 70- 80% VPT vibration applied to lateral plantar border caused decreased M/L CoP sway [96] and 90% VPT vibration caused significant reductions in A/P CoP sway range and mean sway radius in both healthy adults and the elderly.[33] Furthermore, plantar subthreshold vibration results in reduced CoP sway excursion range in the elderly, from 20.7 to 18.9 mm in A/P direction and from 13.1 to 12.7 mm in M/L direction.[32] The chronic effects of subthreshold vibration have also been promising. For example, a 10week plantar subthreshold vibration intervention program resulted in significant decreases in A/P CoP velocity and CoP sway. However, retention was not tested.[98] The literature typically tests the orthotic effect and less is known about the therapeutic effects. Thus, further research is necessary to confirm successful long-term clinical application, as well as the effects on healthy adults. It is also important to investigate the effects against time. Perhaps they may dissipate through acclimatization after the initial period of effectiveness.

Recently, researchers explored the effect of plantar subthreshold vibration on healthy adults and single leg balance. Prior to data collection participants underwent foot sole cooling to induce PCMR insensitivity. Participants were divided into three groups; a control, ice no vibration, and an ice and vibration, groups.[22] They observed a greater CoP sway area in the ice no vibration group, as compared to the control and the ice and vibration group. For participants in the control, improved CoP sway was correlated with TA activation and the ice and vibration group had similar muscle activation patterns. Conversely, CoP sway area in the ice and no vibration group was correlated with activation in all extrinsic muscles. TA activation is significantly reduced in the elderly compared to healthy young individuals[99], however, PL and MG activity is not.[100] Therefore, plantar cutaneous sensitivity may affect motor programming. Furthermore, for those with somatosensory deficiencies, subthreshold vibration appears to be an effective method for returning plantar cutaneous sensitivity and a healthy balance strategy.

Gait

There exists a large body of research on the relationship between PCMR input and gait. Falls commonly occur during gait[68,67] and thus interventions that improve dynamic stability are vital.

The plantar tuning theory is supported by the plantar hypothermic anesthesia and gait research. Muscle activity and CoP movement are dependent on the specific region of cooling.

When the heel was cooled the amplitude of the MG increased, whereas the amplitude of the TA decreased. Forefoot cooling increased BF amplitude and reduced MG amplitude. Ice applied to the entirety of the sole caused a reduction in peak pressure at the heel , hallux and toes and an increase under the metatarsal heads.[70] A kinematic analysis showed decreased dorsiflexion at heel strike which led to a more “flat foot” touch down. At the propulsive phase, there was a less pronounced push-off and reduced plantar flexion, knee flexion, and hip flexion moment. Furthermore, there is a causative relationship between full sole desensitization and the adoption of cautious gait, characterized by a wide base of gait, reduced velocity and decrease moment at gait phase transition.[101–103] EMG analysis shows reduced overall muscle amplitude during gait, post-cooling. Decreased dorsiflexion at heel strike and decreased plantar flexion at push-off corresponds with decreased amplitude at the TA, GM and PL, respectively.[102] Furthermore, increased lateral pressure distribution during the stance phase results in a rigid foot type, which is unable to adapt to the support surface and prone to injury.[101] This may be due to increased co-contraction of ankle musculature as to increase ankle and subtalar joint stability. The influence of temperature and PCMR sensitivity on gait performance is clear. Interestingly, warming of the plantar foot increases sensitivity to mechanical stimuli[104]. This warrants further research.

Inducing plantar insensitivity via local anesthetics (LA) does not appear to affect balance during gait. LA injections administered to the plantar glabrous skin had no effect on CoP trajectory during gait in healthy adults.[105] This may be a result of successful sensory reweighting. The research on gait and induced hypothermic anesthesia [70,71,102] , as well as static stance and LA injections[78], leads use to expect that plantar intradermal LA injections would influence gait performance in the elderly and those with sensorimotor impairments.

Furthermore, when topical anesthetic cream was applied to the foot sole of healthy participants, gait velocity reduced by 6.06m.min-^{1} as compared to control group.[103] Some argue that non-invasive methods to induce plantar insensitivity fail to isolate PCMR.[78] A comparison of the different methods would be interesting to expand on their theory.

The microneurography literature would infer that textured insoles do not have a significant application for dynamic skills; but the clinical research is more positive. When a textured insole is worn, the stimulus does not separate from the skin, thus generating a sustained stimulation. Perhaps, plantar sensitivity is improved via increased mechanical noise. Acute application of textured insoles has been shown to enhance dynamic balance and decrease gait variability in the elderly.[90,106] Reductions in frontal plane variability have been recorded at heel strike and 200ms before and after heel strike when wearing textured insoles with a lateral wedge as compared to smooth insoles with a lateral wedge.[107] Chronic application of textured insoles in the elderly shows promise. For example, insoles with a raised perimeter ridge (2.5mm) have been shown to increase lateral stability in gait over a 12week program in elderly participants.[108] Similarly, 4weeks of textured insole use resulted in improved Time-Up and Go performance as compared to smooth insoles.[109]In healthy adults, textured insoles have been shown to induce kinematic changes in the sagittal plane and inhibition of the TA and SOL.[44] The authors of this study were uncertain of the implication and purpose of these changes; however, they do indicate a relationship between PCMR stimulation and gait. The effect of tactile stimulation on healthy adult gait is unclear. For example, researchers found an insignificant effect of tactile stimulation on steady-state gait in healthy adults, but found resultant reductions in velocity and stride length in the elderly and elderly fallers.[110,109]

Nevertheless, we believe that there is a clear application for tactile stimulation for the elderly and those with sensorimotor decline.

Plantar subthreshold vibration is an effective method for improving gait performance and balance. In the elderly, subthreshold vibratory insoles can decrease stride-to-stride variability, normalize gait phase time variability, and increase velocity.[34,111,45] These variables have been correlated with falls risk in the elderly.[58,68] Furthermore, plantar subthreshold vibration has been shown to increase gait velocity from 1.25 to 1.32 m/s and improve cadence.[112] It can reduce step variability and increase the coefficient of variation for step width and stride length.[45] A previous study applied 90% VPT vibration to the plantar first-fifth metatarsals, medial arch and heel. They found significant improvements in stride-to-stride variability and reduced spatial variability.[45]A similar study concluded that vibratory insoles reduced stride time variability as well as stance and swing phase time variability, in elderly fallers [34] and the healthy elderly with greater baseline variability.[45] This indicates that SR has a baseline-dependent effect and has a more pronounced effect for those with lower motor skill performance.

Vibration allows for considerable parameter modification and unique tuning for an individual For example, a reduction from 90% to 70% and 85% VPT has been shown to induce positive effects on gait, which were retained after vibration cessation.[35] Furthermore, manipulating frequency has been shown to alter long range correlation (LRC) in stride length and manipulation of amplitude can alter LRC's in stride interval timing without influencing gait variability. Thus, there may be independent neural mechanisms responsible for spatial and temporal coordination LRC's of gait parameters, which are influenced by separate vibration parameters.[113] We suggest further research focus the effects of parameter modification.

Limitations

Ageing degenerates the somatosensory system, but this degeneration is not linear. The "elderly' cohort is typically 65 or older. There is significant variation in PCMR sensitivity in this age range which may influence the accuracy elderly PCMR research. Therefore, we propose that it will be beneficial to subcategorize the "elderly" into multiple, smaller age ranges.

More research is needed into the mechanisms involved in PCMR stimulation and balance. While the effects of naturally occurring mechanical stimulation and electrical stimulation have been correlated,[36,37] we cannot confidently infer on mechanical stimulation mechanisms when using the results of electrical stimulation studies.

The literature shows variations in vibrating devices, as well as duration and magnitude of noise. In addition, there is great difficultly defining VPT, which may make subthreshold vibration inaccurate.[114–116] Studies typically utilize two or three vibrators at the metatarsal heads and heels. Future research could investigate the effect of additional vibrator location. This will improve our understanding of the effects of regional stimulation.

There is a lack of intervention variation, which reduces our ability to infer on clinical application. Subthreshold vibration appears to have a more significant effect on gait as compared to tactile stimuli. However, there is a lack of comparison research. Similarly, there is a lack of research on the combination of stimulation types. Most studies measure the acute effects of subthreshold vibration[32,35,113] and textured insoles.[20,107] Thus, more research on the chronic effect of subthreshold vibration and textured insoles on postural balance and gait in healthy participants is needed. This is important as they have been shown to have the greatest effect on CoP trajectory after a longer period of time.[117] Furthermore, the research on retention and the therapeutic effects of plantar cutaneous stimulation is limited. Finally, positive results have been found when stimulating during stance phase only[34,97] and during both swing and stance phase. We believe that selective phase stimulation may be advantageous for battery conservation and warrants further research.

Conclusion

We conclude that PCMR and associated afferent information have a significant influence on balance and performance of static stance and gait in the health of individuals, especially the elderly. Input appears to significantly contribute to exteroception and proprioception. The literature indicates that weight-bearing motor tasks can be compromised when PCMR sensitivity is increased and improved when stimuli is augmented. The findings of this report suggest that plantar afferent input and PCMR sensitivity should be more considered in falls risk evaluations of the elderly falls risk. Textured insoles and plantar subthreshold vibration may be used for improving standing and gait balance in the elderly; however, more research is needed to confirm an application for healthy adults. We suggest that the intervention be tested on healthy adults undergoing more difficult balance tasks, such a dynamic single leg task. Furthermore, future research is needed to explore the chronic and therapeutic effects of these interventions; however, the current literature is very promising and both interventions are safe. Therefore, we advocate their use in clinic for the elderly.

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