Proprioception and Stability: Foot Position Awareness as a Function of Age and Footwear*

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Summary
We examined the hypothesis that awareness of foot position in terms of the slope of the weight-bearing surface declines with age. We further postulated that the decline would be due to a change in plantar tactile sensibility, and that footwear would further impair position judgements. We compared 15 men aged over 65 years (mean age 73) with 36 men aged under 40 (mean age 30) in terms of estimates of amplitude and direction of surface slopes. We employed a ratio scale of 0–10 representing actual slopes of 0°–25° in increments of 2.5°. In order to examine whether subjects overestimated high angles they were told that the scale ranged from 0 to 15.

We found significant differences between the two groups in terms of estimates and the effect of footwear. Psychophysical functions for estimate of slope were 0.95 for the young when barefoot and 0.71 when shod compared with 0.80 and 0.81 respectively for the older men.

We conclude that sensitivity to foot position declines with age, mainly owing to loss of plantar tactile sensitivity. Footwear impairs foot position awareness in both young and old. Loss of foot position awareness may contribute to the frequency of falls in later life.

Introduction
Health professionals face the task of reducing the incidence of falls by elderly people. Falls result from environmental destabilizing factors, acting upon an individual with declining sensory and motor performance, which reduces the individual's ability to anticipate hazards and compensate adequately for unstable equilibrium [1].

Environmental factors include poor lighting and conditions that influence foot-ground contact, such as low-friction surfaces causing slips, carpet edges, cracks in pavement causing trips, and footwear causing instability [1–3]. Slowing of behavioural response time also occurs with age [4]. Age-associated sensory decline has been well documented in the visual and auditory systems, but the effect of advancing years on proprioception has received scant attention, although this may partly explain falls by elderly people [5]. Gerontologists have postulated that impaired proprioception makes it difficult for older people to detect changes in body position caused by weight-bearing surface changes until it is too late for compensatory behaviours to prevent falls. Foot position awareness is of primary concern here because it is primarily affected by foot-surface influences [6].

Gerontologists have also suggested that footwear affects falls more than would be anticipated from motor and sensory involution alone, through footwear-induced impairment of proprioception. Tinetti and Speechley contended that 'The (unstable elderly) patient should be instructed to wear shoes with low heels and firm soles to maximize proprioceptive input', implying that shoes with thick soles and high heels impair an older individual's ability to judge and adjust to weight-bearing surface changes and detect obstacles [7]. Tideiksaar has suggested that 'Thick-soled shoes decrease proprioceptive feedback usually stimulated by striking the foot on the ground' thereby reducing stability of older individuals [8]. The influence of footwear on support surface judgements has never been examined.

The experiment that follows tests the hypotheses that foot position awareness declines with age, and footwear affects it. We do this by comparing how young and older men estimate weight-bearing surface slope when barefoot and when wearing shoes under quasi-static conditions.

Methods
Subjects: The elderly sample comprised 15 consecutive volunteers from an internal medicine clinic that met the following criteria: minimum age 65 years, male, good health, no condition affecting ability to walk, and no more than two falls
during past 12 months. The age range of the sample was 65–83 years (mean 73; SD 4.8); height: range 165–183 cm (mean 174; SD 3.6); weight: range 60–83 kg (mean 71; SD 7.2).

Thirty-six young male subjects were selected from the general population. Their ages ranged from 22 to 37 years (mean 30; SD 4.3); height: range 154–193 cm (mean 171; SD 10.5); weight: range 49–95 kg (mean 65.8; SD 11.5). Criteria for admission were age 18 to 40 years, good health and free of any disability affecting their capacity to walk.

Experimental footwear: Footwear were identical except for shoe size. Experimental shoes were similar to currently commercially available running shoes, with upper fabricated from suede leather and nylon fabric. The last was a standard one used by a major athletic footwear manufacturer that supplied the shoes. They were cement lasted, which is the current standard construction method for athletic footwear and had 20° heel flare. The outer sole was 5 mm thick carbon rubber, a full length fibre-board layer was under the insole, and the insole was composed of thin soft bonded-fibre fabric. The midsole was composed of a uniform expanded polymer foam of hardness A 33 (ASTM Standard D 240—Standard Test Method for Rubber Property—Durometer Hardness) [9]. The choice of 33 hardness was based on a pilot study which indicated this hardness to be typical of modern athletic and walking shoes, with no significant material compression under testing conditions. Thickness of the midsole was 27 mm at the heel and 16 mm under the metatarsal-phalangeal joint, typical of current footwear.

Apparatus: Eleven individual surface blocks were constructed of textured melamine-covered particle board, with centre point height of 20 cm and surface dimension of 30 x 30 cm.

Testing procedure: Testing was performed under quasi-static conditions; i.e. similar to locomotion in that the task required behavioural accommodation to foot support surface slope and maintenance of stable equilibrium when weight was transferred to the experimental surface, but differing from locomotion in that there was no forward movement. Blocks were placed on a rigid wall to ensure that subjects would stand vertically during testing, and to help in supporting subjects if they lost balance. Subjects were told that the purpose of the experiment was to examine how they judged support-surface angles. Their written consent was obtained for admission for both young and elderly subjects. Subjects were asked to estimate perceived direction and amplitude of surface slope once they applied full body weight to a series of blocks when barefoot and when wearing footwear. A wall was used for support. Legs were straight.

12.5° was designed to allow overestimation of surface slope. Subjects were told that any surface angle might be repeated more than once during the experiment, though this was not done. The order of presentation of surface blocks was counterbalanced across footwear condition first, and angle second. Subjects were given reference values of 0°, 12.5°, and 25° every 11 estimates. Subjects were asked to keep their legs straight (0° flexion at knee) during testing, and were monitored to ensure that they followed this instruction.

Data analysis: Estimates of surface slope and slope estimate error were examined according to a Group x Footwear x Angle design, in which the group factor included two levels (old, young), the footwear factor two levels (footwear, barefoot) and the angle factor 11 levels (0–25°, 2.5° increments). Data for old and young were pooled and analysed using multivariate analysis of variance for repeated measures, with post hoc analysis consisting of univariate tests. Mean slope estimate error was defined as the absolute value of the difference between slope estimate and actual surface slope. Power functions were fitted to magnitude estimation data for slope estimates for young and old groups separately, yielding values for barefoot and footwear conditions for each group. Since a previous report suggested that age and height were related to stability [3], and foot position sense is thought to be related to stability, we performed Pearson product-moment correlation coefficients to assess the relation between subjects' age, height, weight, estimates of support surface and estimate error. Statistical significance for all tests was defined as 0.05.

Results

Surface slope estimate as a function of slope orientation: Analysis of variance revealed no difference in slope estimates in relation to surface orientation; i.e., inversion, eversion, plantar and dorsiflexion, in young [F(30,476) = 1.90, p < 0.89] and elderly subjects [F(30,394) = 1.03, p < 0.42]. Accordingly, the average of the four surface orientations was used for statistical analysis.

Figure 1. Schematic representation of experimental set-up used for both young and elderly subjects. Subjects were asked to estimate perceived direction and amplitude of surface slope once they applied full body weight to a series of blocks when barefoot and when wearing footwear. A wall was used for support. Legs were straight.
Surface slope estimate as a function of testing condition: Multivariate analysis of variance revealed a significant main effect for group only \( F(1,49) = 55.94, \ p < 0.001 \). No significant difference was obtained in estimates between footwear and barefoot conditions for consecutive angles between the two age groups \( F(10,40) = 2.21, \ p < 0.18 \). All other two-way interactions and main effects were not significant. Figures 2 and 3 show that both young and elderly subjects underestimated surface slope regardless of testing condition or angle, with the elderly group having higher estimates of surface slope than the young cohort. This significant result is principally due to error in the high-angle range of the footwear–young-cohort condition, where there was no change in estimate with increasing slope (range 15–25).
Net mean estimate error as a function of testing condition: Multivariate analysis of variance of slope estimate error revealed a significant interaction between group and footwear \([F(1,49) = 14.28, p < 0.001]\), as well as main effects of group \([F(1,49) = 54.97, p < 0.001]\) and footwear \([F(1,49) = 57.45, p < 0.001]\), as shown in Figures 4 and 5. Net mean estimate error for the elderly was 3.86° when barefoot and 4.78° when shod. Mean estimate error for the young group was 3.40° when barefoot and 4.76° when shod. Shoes diminished foot position sense in both young and elderly subjects, with the elderly showing the largest error in estimates when shod. The three-way interaction of group \(\times\) footwear \(\times\) angle was not significant \([F(10,40) = 3.65, p < 0.199]\).

Absolute mean estimate error as a function of testing condition: Multivariate analysis of variance of slope estimate error revealed a significant interaction between group and footwear \([F(1,49) = 12.11, p < 0.002]\), as well as main effects of group \([F(1,49) = 27.66, p < 0.001]\) and footwear \([F(1,49) = 35.51, p < 0.001]\), as shown in Figures 6 and 7. Age influences foot position awareness most when shod, but also significantly when barefoot. Therefore, the relative effect of age was greater in the shod than in the barefoot condition. Absolute mean estimate error for the elderly group was 6.59° when barefoot and 7.35° when shod. Mean estimate error for the young group was 3.41° when barefoot and 3.97° when shod. The three-way interaction of group \(\times\) footwear \(\times\) angle was not found to be significant \([F(10,40) = 1.11, p < 0.326]\).

Fitting magnitude estimation data to a power function: Power functions were fitted to group data for surface slope estimates, yielding exponents between 0.71 and 0.95, indicating a downsloping function (curves cave downward) for both age groups and testing conditions.

Elderly—Exponents were 0.80 \((r = 0.73)\), and 0.81 \((r = 0.75)\), for barefoot and shod conditions, respectively.

Young—Exponents were 0.95 \((r = 0.95)\), and 0.71 \((r = 0.88)\), for barefoot and shod conditions, respectively.

Discussion

The current meaning of proprioceptive sense is ascribed to Sherrington, who considered it the sense of body position in space, which at the sensory level includes perceived static and dynamic joint position sensibility, vestibular sense, and, as McCloskey noted, 'inputs from muscles and joints that are not necessarily perceived' [10, 11]. The present experiment deals with a territory within proprioceptive sensibility, kinaesthetic sense at the ankle, which accounts for static and dynamic foot position awareness, essential to understanding the effect of foot–ground interactions and footwear on stability.

Early investigators attributed kinaesthetic sense to joint capsular receptors, but contemporary research shows that these receptors only respond at extremes of the joint range and therefore cannot give precise position awareness [12]. Appreciation of joint position in the upper extremity derives from muscle spindles and local skin mechanoreceptors [13]. The importance of plantar tactile sensibility to foot position awareness has never been examined, although a recent report implies its relevance [14].

Somatosensory sensibility declines with age but in
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varies depending on sensory modality and body location; tactile sensitivity in the hand hardly declines at all but plantar tactile sensitivity may be profoundly affected. In subjects free of disease and neuropathies, plantar vibrotactile threshold (tested at 250 Hz) remains constant until age 40, but rises by 20% by age 50, and 75% by age 80 [15]. Most authors attribute this decline to receptor degeneration. Meissner corpuscle density has been shown to be 69, 27 and 8 per mm² for ages 3, 32 and 83, respectively [16]. Other glabrous skin mechanoreceptors probably decline as well, although morphological documentation is not possible owing to in vitro receptor degeneration, inadequate staining methods, or both [17].

The plantar tactile receptor responsible for precise kinaesthetic sense is probably the slowly adapting mechanoreceptor with myelinated afferent (SAII mechanoreceptor), since it alone is capable of transducing plantar shear and stimulus direction, information essential to relating tactile information to position sense. Further support of its role is provided by psychophysical arguments given later. Fitness of SAII mechanoreceptors with advancing years is unknown. Differences between upper and lower extremity in the rate of decline in tactile sensitivity with age may be attributable to the trauma inseparable from use; locomotion causes repeated plantar skin damage resulting in measurable plantar insensitivity [18].

It is uncertain whether muscle-spindle mediated kinaesthesia declines with advancing years. Kokmen et al. [19] found no age-associated decline in threshold of perceived passive movement at the metacarpophalangeal and metatarsophalangeal joints. This used a method in which clamps were placed on digits to reduce (though not completely eliminate) cutaneous tactile cues of induced movement [19]. Skinner et al. examined proprioception at the knee in relation to age in subjects whose skin was anaesthetized by pressure cuffs [6]. They found minimal decline in reproduction of passive position and movement threshold until the seventh decade, and more rapid decline thereafter. Their means of anaesthetizing skin probably produced muscle ischaemia, and their results may reflect impaired motor function.

An incline of 5° is a moderately steep hill and 15° approaches the greatest paved incline pedestrians can ascend safely when wet. Our experiment indicates that age influences foot position awareness most when the subject is barefoot, but also when shod. Mean error in support surface estimate in the young subjects was 1.96° when barefoot, similar to the position estimate error obtained at the wrist and digits of young volunteers [21]. Mean estimate error by the older group was 5.13°, 162% greater than by the young. Shoes diminished foot position awareness; mean estimate error in the young increased by 103% to 3.97°, and added 28% to 6.58° in older subjects.

Decline in foot position awareness with age is statistically significant, but is it clinically significant? Our experiment cannot answer this directly because it does not relate a clinical condition, such as falls, with foot position sense, but it suggests a relation. For example, in older people, falls during locomotion are the result of trips as they attempt to negotiate easily observable obstacles and cracks in pavement, because inadequate ‘toe clearance’ causes the shoe to catch obstacles [22]. Our data suggest that these trips are probably due to perceptual error, because underestimation of actual position implies that older people will avoid obstacles with less toe clearance than they realize, thereby often tripping [23].

Stevens advanced his ‘power law’, as an inherent relation between stimulus amplitude and its perceived magnitude [24]. He claimed his ‘psychophysical function’, the exponent of best-fit power function to estimates of perceived sensory magnitudes, to be basic to all sensory modalities and testing conditions. The power function has been used for many purposes, including deducing how sensory information is transmitted through the nervous system and processed centrally. We fitted support surface estimates to a power function and obtained values of 0.95 for the young when barefoot and 0.80 for unshod elderly subjects. We previously found the psychophysical function relating how young volunteers perceive load applied to plantar skin to be close to unity, which further resembles perception of indentation of glabrous skin in young subjects, a sensation known to be transduced by SAII mechanoreceptors [25]. The psychophysical function of support surface estimates by the young subjects when wearing footwear was 0.71, therefore, as Figures 2 and 3 show, any slope above 15° was essentially perceived as 19°. The psychophysical function for the elderly subject with shoes was 0.81, identical to barefoot.

Psychophysical functions obtained for two forms of plantar mechanical stimulation (skin indentation and skin pressure against flat surface) and perceived support surface angle in barefoot young were all near unity, which suggests that barefoot young individuals rely heavily upon plantar tactile information for foot position judgements. Conversely, psychophysical functions in the older group under both conditions and in the shod young diverged from unity, which suggests that these groups relied less on plantar tactile sense for foot position judgements and muscle receptor information was probably used. Decline in foot position sense in the elderly subject when shod or barefoot and in the young wearing shoes can be explained by decline in plantar tactile sense, and attenuation of tactile information caused by footwear, respectively. Furthermore, these psychophysical arguments are consistent with an analysis which attributes poorer foot position sense at later ages to senescence of some part of the SAII mechanoreceptor system (receptor, afferents, or central processing).

One limitation of our experiment was that foot position sense testing was performed in quasi-static conditions, which calls for caution in applying results to actual locomotion. However, some of our data can be safely applied to the stability of the elderly people.
There is support for the notion that decline in foot position awareness at least in part may explain age-associated deterioration in stability. Increased softness and thickness of sole material probably worsens foot position awareness and impairs stability. It therefore seems prudent to recommend footwear with thin hard soles for use by unstable elderly people [3]. Finally, it may be possible to design footwear that can improve foot position awareness in all age groups through augmented plantar tactile sensory feedback, a concept we are pursuing.

In conclusion, foot position awareness declines with advancing years and footwear can significantly impair this sense. Age and footwear influence foot position awareness mainly through their effect on plantar tactile sensibility. This report should direct attention to correcting environmental hazards by interventions that consider somatosensory decline with age.

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