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Plantar sensation associates with gait instability in older adults

Jason R. Franz[1*], Andrew D. Shelton[1], Kota Z. Takahashi[2] and Jessica L. Allen[3]

Abstract

Background Advanced age brings a loss of plantar sensation, represented, for example, as higher sensation thresholds in standardized testing. This is thought to contribute to an increased risk of falls among older adults – an intuitive premise that has yet to be fully investigated, especially in the context of walking balance. The purpose of this study was to quantify the association between plantar sensation and the instability elicited by a suite of walking balance perturbations that differ in direction and context in a cohort of $n = 28$ older adults (73.0 ± 5.9 yrs).

Methods We measured plantar sensation using Semmes-Weinstein monofilaments and quantified margins of stability (MoS) and whole-body angular momentum (WBAM) during habitual walking and in response to optical flow perturbations, lateral waist-pull perturbations, and treadmill-induced slips.

Results Our two major results were that higher monofilament thresholds (i.e., worse plantar sensation) in older adults associated with: (1) larger anterior-posterior (AP) and mediolateral (ML) MoS and increased transverse plane WBAM ($p \leq 0.031$) during habitual walking, and (2) larger decreases in MoS_{AP}, MoS_{ML} and larger increases in transverse plane WBAM in response to lateral waist pull perturbations ($p \leq 0.018$). We found no associations between plantar sensation and responses to other perturbation contexts.

Conclusions We conclude that there is an association between worse plantar sensation and gait instability, both during habitual unperturbed walking and in response to some perturbation contexts. These results should build confidence that interventions designed to improve plantar sensation for older adults, possibly through insoles or footwear modifications, could be critical for reducing gait-related falls in at-risk populations.

Keywords Monofilaments, Margin of stability, Angular momentum, Balance, Falls

Introduction

Maintaining stability during walking requires a combination of vestibular, somatosensory, and visual feedback. Plantar somatosensation (which we refer to as "plantar sensation" from here on) provides critical afferent feedback to the body presumed necessary to regulate balance [1]. Advanced age brings a loss of plantar sensation, represented, for example, as higher sensation thresholds in standardized testing [2, 3]. This is intuitively thought to contribute to an increased risk of falls among older adults. Past research has hinted at this increased risk, using unperturbed standing or standing perturbation

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responses as proxies for increased fall risk or inducing loss of plantar sensation through anesthesia or hypothermia in younger adults [1, 4, 5]. However, no study to date has established an empirical relation between plantar sensation and vulnerability to perturbations applied during walking. This is important because walking is the task in which most falls occur among older adults [6]. This study is designed to address this clinically important gap in our understanding.

Preserving walking balance requires the deployment of neuromuscular corrections to a broad variety of challenges in the real-world. Balance perturbations are laboratory-based paradigms often used to emulate the instability elicited by these diverse balance challenges. These perturbations can take many forms, including surface translations [7], lateral pulls [8], sensory manipulations [9, 10], etc. We recently revealed that, despite some generalizations, the instability elicited by walking balance perturbations differs based on their context in both younger and older adults [11]. This implies that any study seeking to understand the association between a potentially modifiable factor – in our case, plantar sensation – and the gait instability elicited by balance perturbations would be encouraged to account for differences in the context of that instability. One way to account for those differences is to use of a suite of balance perturbations that emulates the diverse challenges capable of precipitating a fall in the real world.

Following the onset of a balance disturbance, somatosensory feedback is required to initiate a neuromuscular cascade that results in a balance correction to mitigate instability and prevent falls. As one primary example, compression of plantar cutaneous mechanoreceptors has the potential to provide rapid afferent signaling for balance corrections. The Semmes-Weinstein monofilament (SWM) test is a clinically-validated measure designed to quantify thresholds for plantar sensation [12–14]. Decreases in the integrity of that signaling pathway, for example via intradermal anesthetic solution injections to the plantar foot surface in younger adults, compromises recovery from unanticipated surface translations during standing [5]. These experimental findings bolster intuition regarding the effect of age-related declines in plantar sensation and those in balance integrity more broadly. Indeed, older adults have been reported to exhibit increased plantar sensation thresholds determined via the SWM test [2, 3]. Quantifying the extent to which those declines in planar sensation among older adults associate with an increased vulnerability to walking balance perturbations could build confidence in potentially modifiable factors to mitigate gait instability and therapeutic interventions to improve walking balance.

Thus, the purpose of this study was to address this gap and quantify the association between plantar sensation and the instability elicited by a suite of walking balance perturbations that differ in direction and context in a cohort of older adult participants. We tested the hypothesis that older adults with lesser plantar sensation, evidenced by higher average thresholds on a monofilament test, would also exhibit higher gait instability and vulnerability to walking balance perturbations.

Methods

Participants

28 older adults (73.0 ± 5.9 yrs, 15 Female/13 Male) participated in this study after providing written informed consent according to the UNC Biomedical Sciences Institutional Review Board. We excluded participants with recent leg injuries or fractures, lower-limb prostheses, use of an assistive device (e.g., cane or walker), or any self-reported neurological, musculoskeletal, or cardiopulmonary disease or disorder that would affect walking balance. We did not perform any medication review, and thus cannot speak to the extent to which medication usage influence our results.

Experimental protocol

The experimental protocol was part of a larger study conducted over two days separated by roughly one week (Fig. 1). For the purposes of this experiment, participants had plantar sensation measured on the first day using the Semmes-Weinstein monofilament test with a rigorous 4-2-1 design [14] as well as demographic data collected. Specifically, we recorded plantar sensation thresholds on the plantar surface of the heel and the first metatarsal head on participants' dominant foot and averaged these values for subsequent analysis. Dominant foot was determined via self-report of "what foot would you most likely use to kick a ball?" Demographic data used to describe the physical fitness and health of our cohort included preferred gait speed, timed up-and-go, five times sit-to-stand, dynamic gait index, and self-reported physical exercise. The monofilament test and physical function assessments were performed following training and best practices informed by a licensed physical therapist. On the second day, separated by approximately one week, participants completed four treadmill walking trials at their preferred overground walking speed in randomized order. In addition to a habitual, unperturbed walking trial, participants responded to: (i) treadmill-induced slip perturbations in which the treadmill belt decelerated at the instant of random heel-strikes at a rate of 6 m/s^2 for a duration of 200 ms before returning at the same rate to the nominal treadmill speed, (ii) lateral waist-pull perturbations via a custom, motor-driven system delivering a 6% body weight force applied toward the swing leg at random toe-offs, and (iii) continuous mediolateral optical flow perturbations in a custom and immersive virtual

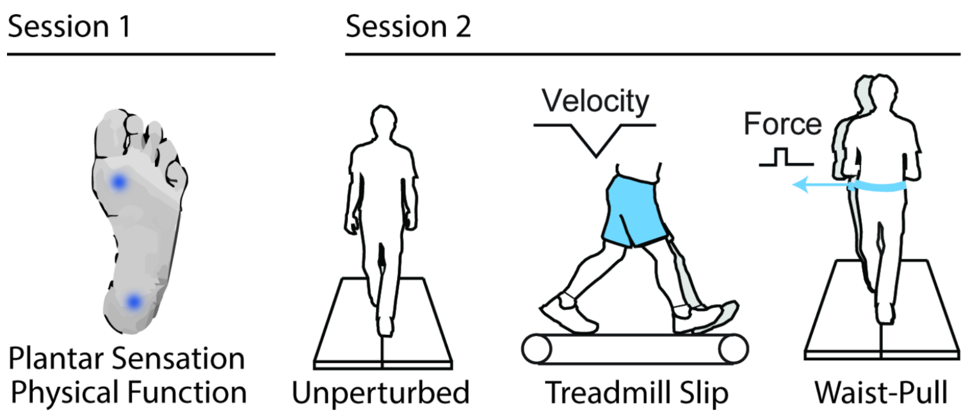

Fig. 1 Summary of our experimental protocol and methodological approach

reality system. All of the details of these perturbations have been described in detail in previous publications (e.g [11]). , .

Walking instability outcomes

A 10-camera motion analysis system (Motion Analysis Corp., Santa Rose, CA) captured the three-dimensional trajectories of markers placed on subjects' pelvis and right and left legs at 100 Hz. From these trajectories, we used published procedures and best practices to calculate two measures of gait instability. Specifically, we calculated margins of stability in the anteroposterior (MoS_{AP}) and mediolateral (MoS_{ML}) directions at the instant of heel strike (that directly following perturbation onset for slip and waist-pull perturbations) and whole-body angular momentum (WBAM).

For MoS, we first calculated the body's center of mass (CoM) velocity (v_{CoM}) from the first time derivative of CoM position and including the relative velocity of the treadmill using the methods described by Curtze et al. and adapted from Hof et al. [15, 16]. We estimated the body's instantaneous CoM as the centroid of a segment defined using two anterior and two posterior pelvis markers. We then calculated the extrapolated CoM (xCoM) using v_{CoM}, as shown in Eq. 1, with $\omega_0 = \sqrt{g/l}$, where g = 9.81 m/s^2 and l is the leg length.

$$xCoM = CoM + vCoM/\omega_0 \ \textit{Eq. 1.}$$

We defined the anterior and lateral as the position of the first metatarsal marker and the fifth metatarsal marker, respectively, and we defined leg length as the distance between the heel and sacral markers from standing trial. And lastly, we calculated anterior-posterior (MoS_{AP}) and mediolateral (MoS_{ML}) margins of stability at the instant of the heel-strike as the distance between xCoM and the respective BoS. (Eq. 2)

$$MoS = BoS - xCoM \ \textit{Eq. 2.}$$

For WBAM, we first performed 3D inverse kinematics in OpenSim using the gait2392 model [17]. Thereafter, we calculated WBAM about the body's CoM using marker locations and segmental velocities and centers of mass and standardized procedures. We scaled WBAM to body mass (kg), height (m), and walking speed (m/s) [18–21]. From these data, we calculated the range of WBAM in the sagittal (S), transverse (T), and frontal (F) planes within each analyzed stride.

We calculated the average of these values from all strides taken during the habitual, unperturbed walking trial and for response to optical flow perturbations, and from the immediate recovery steps for responses to lateral waist-pull perturbations and treadmill-induced slips. Finally, we calculated the vulnerability to each of our three perturbation paradigms as the change in MoS or WBAM from habitual walking.

Statistical analysis

The primary outcome measures in this study were average (heel, first metatarsal head) plantar sensation, gait instability during habitual walking, and the vulnerability to each of our three perturbation paradigms, the latter two measured herein both using MoS and WBAM. We used linear regressions with Pearson correlations to determine the association between plantar sensation and vulnerability to perturbations. We defined significance using an alpha level of 0.05.

Results

All participants completed the 2-session protocol. Table 1 summarizes the general demographics of our overall study cohort. Participants in this study averaged monofilament thresholds of 4.43 ± 0.48 and 4.49 ± 0.90 on the plantar surface of the heel and at the base of the first metatarsal head, respectively. Paired t-tests revealed that these values did not differ significantly ($p = 0.73$), and thus we used their subject-specific average (i.e., 4.46 ± 0.63) for correlating with gait instability outcomes. 5 participants

Table 1 Study cohort demographics

Outcome	Units	Mean ± SD
Walking Speed	m/s	1.19 ± 0.19
Timed Up & Go	s	9.14 ± 1.81
5 Times Sit-to-Stand	s	15.5 ± 4.2
Dynamic Gait Index	score	22.5 ± 2.37
Strenuous Exercise	counts/week	1.3 ± 1.5
Moderate Exercise	counts/week	3.2 ± 2.5
Easy Exercise	counts/week	2.7 ± 2.2

Table 2 Correlations between WBAM and SWM threshold

		r	p
Habitual	Sag	0.240	0.220
	Cor	0.311	0.108
	Tran	**0.461**	**0.014**
Pulls (Δ)	Sag	0.104	0.598
	Cor	0.325	0.091
	Tran	**0.590**	**< 0.001**
VR (Δ)	Sag	-0.062	0.755
	Cor	-0.029	0.882
	Tran	-0.185	0.345
Slips (Δ)	Sag	-0.265	0.172
	Cor	-0.113	0.568
	Tran	-0.141	0.473

WBAM: Whole-body angular momentum

SWM: Semmes-Weinstein monofilament

Sag: Sagittal. Cor: Coronal. Tran: Transverse

Table 3 Correlations between MoS and SWM threshold

		r	*p*
Habitual	ML	**0.488**	**0.008**
	AP	**0.409**	**0.031**
Pulls (Δ)	ML	-0.096	0.628
	AP	**-0.444**	**0.018**
VR (Δ)	ML	-0.033	0.867
	AP	0.027	0.891
Slips (Δ)	ML	-0.188	0.338
	AP	-0.084	0.67

MoS: Margin of stability

SWM: Semmes-Weinstein monofilament

AP: anterior-posterior. ML: mediolateral

surpassed the clinical cut-off for loss of protective sensation (i.e., ≥ 5.07), and an additional 7 participants were within 1 SD of this cut-off (i.e., ≥ 4.44) [22]. Of the measures of physical fitness collected, we found that worse plantar sensation correlated only with worse 5 repetition sit-to-stance performance ($r = 0.395$, $p = 0.037$).

We use tables to summarize the results of all correlations performed between monofilament thresholds and both whole-body angular momentum (Table 1) and margins of stability (Tables 2 and 3) during unperturbed (i.e., "habitual") walking and in response to each balance perturbation context. During habitual walking, we found that higher monofilament thresholds correlated with larger $WBAM_T$ ($p = 0.014$; Table 1; Fig. 2) and larger MoS_{AP} and MoS_{ML} ($p \leq 0.031$; Table 2; Fig. 3). We found no correlations between monofilament thresholds and balance outcomes in response to either optical flow or treadmill-induced slip perturbations. Conversely, we found that higher monofilament thresholds correlated with larger increases in $WBAM_T$ ($p < 0.001$; Table 1; Fig. 2) and larger decreases in MoS_{AP} ($p = 0.018$; Table 2; Fig. 3) in response to lateral waist-pull perturbations.

Discussion

Our purpose was to quantify the association between plantar sensation and the instability elicited by a suite of walking balance perturbations in a cohort of older adult participants. We specifically set out to test the hypothesis that older adults with lesser plantar sensation, evidenced by higher average thresholds on a monofilament test, would also exhibit higher gait instability and vulnerability to walking balance perturbations. As we elaborate in more detail below and consistent with this overarching hypothesis, this research study builds on previous working in standing to provide evidence in support of an important connection between plantar sensation and gait instability in older adults, impacting both habitual walking and vulnerability to certain contexts of walking balance perturbations. Ultimately, interventions to improve plantar sensation for older adults, possibly through insoles or footwear modifications, could be critical for reducing falls in at-risk populations.

The effects we report here on the association between plantar sensation and gait instability are consistent not only with our intuition and hypothesis, but also with prior evidence for similar associations in standing [2, 5]. Indeed, experimental paradigms that decrease plantar sensation (e.g., intradermal anesthetic solution injections) reduce the integrity of balance recoveries following unanticipated standing surface translations [5]. Moreover, declines in plantar sensation have associated with outcomes related to standing postural control, for example larger center of pressure RMS amplitudes in the mediolateral and anterior-posterior directions [2]. However, we cannot assume that associations found during standing will generalize to walking and any consistency between our findings and those of these past studies in standing was not guaranteed. Indeed, the neuromechanical interactions that underly standing and walking are fundamentally different. That associations between plantar sensation and instability generalize between these fundamentally different tasks (i.e., between standing and walking) is promising from the perspective of impactful intervention, alluding to a common determinant in plantar sensation to meet the needs of individuals at risk for falls.

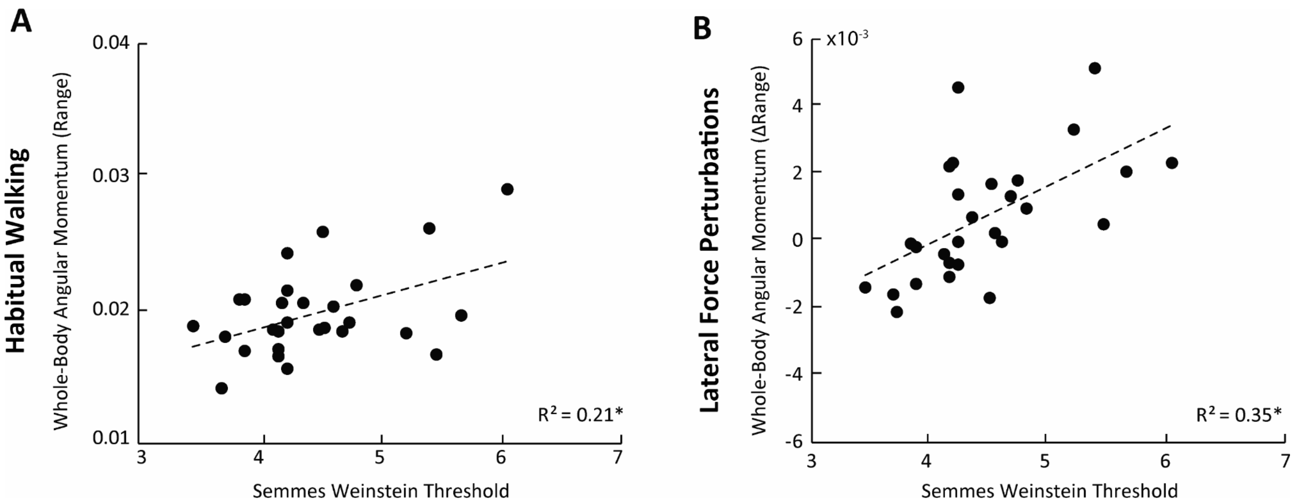

Fig. 2 Range of whole-body angular momentum during (**A**) habitual walking and (**B**) in response to lateral waist-pull perturbations (change from habitual walking). Values shown are normalized to body mass (kg), height (m), and walking speed (m/s)

As a requisite to discussing the associations between plantar sensation and vulnerability to perturbations, we found some important associations during habitual, unperturbed walking. We first found that higher monofilament thresholds in older adults associated with larger margins of stability, both in the AP and ML directions. One interpretation of these larger margins of stability is that those older adults who are less able to depend on plantar sensation to inform neuromuscular corrections may augment their habitual walking strategy proactively toward one that is more cautious and thereby more resilient to unanticipated threats to balance. We also suspect that these larger margins of stability are likely to explain the accompanying associations between higher monofilament thresholds and larger transverse plane WBAM. Indeed, Kim et al. (2022) found that walking with wider steps was also accompanied by higher WBAM $_T$ [23]. That said, we have also shown that the instability measured during habitual walking poorly associates with the vulnerability to balance perturbations [24], alluding to the pivotal role of deploying those perturbations to characterize the full repertoire and integrity of walking balance control in the context of instability and falls.

We have previously shown that the instability precipitated by balance perturbations is context dependent and can differ in magnitude and structure, for example, between emulated slips, lateral pulls, and sensory manipulations [11]. It is thus not entirely surprising that the associations between plantar sensation in older adults and their vulnerability to balance perturbations is also context dependent. We first discuss the perturbation responses we found that did not associate with plantar sensation and were thus inconsistent with our hypotheses. Specifically, we found no correlations between monofilament thresholds and balance outcomes in response to either optical flow or treadmill-induced slip perturbations. In prior work of ours and in other studies, we have shown that these perturbation contexts very effective elicit instability that can be objectively measured using biomechanical outcomes [10, 11] and neural correlates [25]. Optical flow perturbations capitalize on the increased reliance on visual feedback in aging to elicit disproportionate vulnerability, for example, in older versus younger adults [10]. This reliance has been thought to itself arise from a process of sensory reweighting prompted by a decrease in the integrity of plantar sensation [26]. Should this mechanism be revealed as sound, then our lack of a correlation between monofilament thresholds and vulnerability to optical flow perturbations is surprising and warrants further study. Though, there may be many highly inter-related explanations that would not exclude the potential for that mechanism; as one example, that sensory reweighting is precipitated by reduced integrity of muscle spindle receptors more than plantar sensation. In addition, we acknowledge the possibility that, given the broad options available for walking balance outcomes, we cannot be definitive in our assertion. It may at first also seem surprising, given the proximity of the perturbation to the plantar surface of the foot, that we found no association with vulnerability to treadmill-induced slip perturbations. However, those perturbations simultaneously elicit abrupt and rapid changes in ankle joint kinematics during early stance and thereby may trigger disproportionate neuromuscular corrections via muscle-mediated stretch reflexes rather than relying on plantar sensation. Indeed, this is bolstered by recent evidence that ankle angle changes differ between perceived and unperceived treadmill-induced slip perturbations [27].

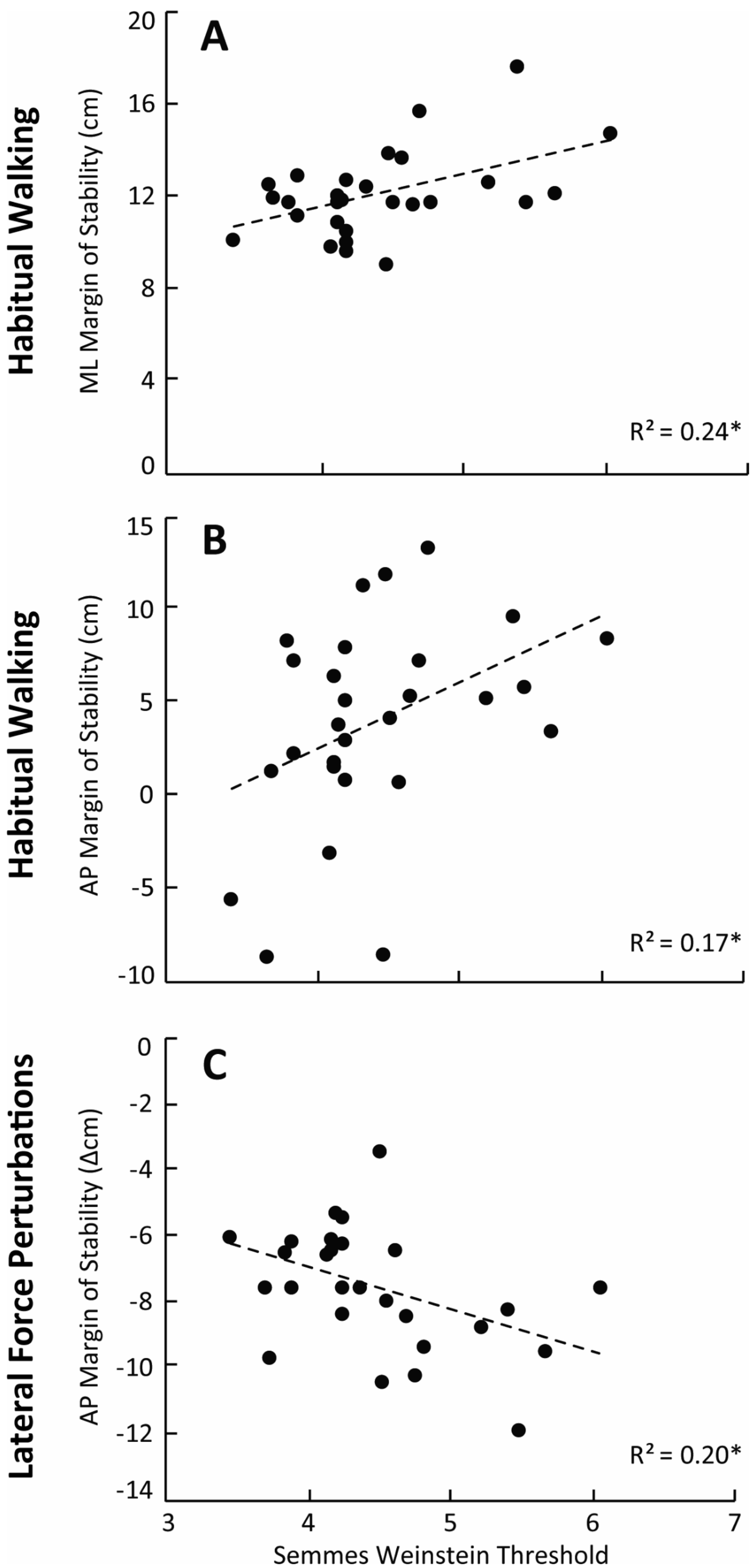

Fig. 3 Margins of stability during habitual walking in the (**A**) anterior-posterior and (**B**) mediolateral directions as well as (**C**) in response to lateral waist-pull perturbations (change from habitual walking) reported in cm

We found significant correlations between plantar sensation and vulnerability to a single context of balance perturbations – namely, impulsive lateral waist-pulls. These perturbations are designed to emulate characteristic environmental challenges in which the body's center of mass may be mechanically perturbed laterally and require rapid adjustments in swing leg kinematics and subsequent foot placement to restore balance. Despite the location of lateral force application being distant from the plantar surface of the foot, the timing and direction of this application may explain why vulnerability to these perturbations associates with monofilament thresholds. Specifically, lateral waist-pull perturbations were applied at the instant of toe-off toward the swing limb, leaving the contralateral foot in stance phase subject to non-sagittal dynamics that are less likely to trigger muscle reflex responses from local sensors embedded in larger lower leg muscles. Thus, neuromuscular corrections in response to lateral waist-pull perturbations may disproportionately rely on alternative sensory feedback modalities and, in this case, those via resultant plantar shear sensation. Accordingly, our results imply that older adults with higher monofilament thresholds (i.e., worse plantar sensation) exhibited larger changes in transverse plane WBAM and larger decreases in MoS_{AP} compared to older adults with lower monofilament thresholds (i.e., better plantar sensation). These findings further imply that older adults with worse plantar sensation would have a higher probability of being unable to successfully execute a corrective motor action in response to lateral balance perturbations and may thereby be more likely to experience a fall under similar circumstances in the community.

Plantar sensation may be a potentially modifiable factor that, based on our findings, could precipitate improved balance confident and/or improve stability during habitual walking and lessen vulnerability to certain contexts of walking balance perturbations. However, there appears not to be overwhelming consensus on the mechanism by which this should be achieved. We first contend that simple and plausible solutions for enhancing plantar sensation may point first to footwear modifications or insole prescription. As one example, insoles based on the theoretical premise of stochastic resonance with subsensory mechanical stimulation have been shown to improve some measures of habitual walking balance in older adults [28]. As an immediate call to action, there is a need for exploring the effects of these insoles not only on habitual walking instability but also on vulnerability to walking balance perturbations which, to our knowledge, have yet to be investigated. In addition, there are a variety of available medications prescribed to mitigate the effects of peripheral neuropathy and loss of plantar sensation. Most articles on the topic summarize a multidisciplinary approach that includes some combination of medication, exercise or physical therapy, removal of environmental hazards, podiatric care, and/or devices and wearable technology [29]. Certainly, more work is needed into the complex interaction between candidate interventions, neuropathological symptoms, walking balance control, and resilience to perturbations.

There are several limitations of this study. The first is that we opted to use a select combination of two walking balance outcomes (i.e., MoS, WBAM) which may not fully capture all the possible associations between plantar sensation and higher gait instability and vulnerability to walking balance perturbations. We also acknowledge that despite exploring a suite of balance perturbation contexts designed to emulate diverse balance challenges one may face in the community, our perturbation magnitudes were smaller than those that would precipitate an actual fall. Accordingly, first, any of our interpretations for actual falls risk arising from worse plantar sensation remain an extrapolation of our actual findings and are thus speculative. Second, larger amplitude perturbations would be presumed to elicit greater plantar surface disturbances (either via shear or normal forces directly or via changes in center of pressure) than those in this study. Third, conclusive public health data on fall circumstances – and the perturbations that induce them – are lacking, and most circumstances are often lumped together in a broad category of "fall events". Thus, it is unclear whether the two mechanical perturbations used in this study (i.e., lateral pulls and treadmill-induced slips) emulate the instability most commonly seen in the real world. We also note that our explanations for why plantar sensation associations were context dependent are likely incomplete and may also include, for example, differences in the timing of delivery (e.g., lateral waist pulls at toe-off vs. slips at initial contact) or direction (e.g., lateral vs. anterior). Future work should consider varying the timing and direction of each context to determine the extent to which these associations are context-dependent, timing-dependent, or direction-dependent. Finally, as with any laboratory-based examination of walking balance, the ecological validity of our responses is called into question compared to what we might anticipate in the real-world. Nevertheless, rigorously controlled experiments in laboratory settings continue to serve as the gold standard for studies such as this.

Conclusions

We conclude that there is an association between worse plantar sensation and gait instability, both during habitual unperturbed walking and as measured via vulnerability to lateral waist-pull perturbations applied at toe-off. These results should build confidence that interventions designed to improve plantar sensation for older adults, possibly through insoles or footwear modifications, could be critical to reducing falls in at-risk populations.

Abbreviations

SWM	Semmes-Weinstein Monofilament test
MoS	Margin of Stability
AP	Anterior-Posterior
ML	Mediolateral
CoM	Center of Mass
WBAM	Whole-body Angular Momentum

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Author contributions
JRF helped conceptualize the study, helped in data curation, analysis, and interpretation, and was the main contributor in writing the manuscript. ADS performed all human subjects data collections, helped in the data analysis and interpretation, and contributed to revising the manuscript. KZT and JLA both helped conceptualize the study, helped in data interpretation, and contributed to revising the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the UNC Biomedical Sciences Institutional Review board and written informed consent was provided by all participants (IRB# 20–0555).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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