Plantar cutaneous afferent responses to behaviourally relevant forces

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***Abstract*— Tactile feedback from the foot sole is important during balance and gait. Previous experimental research characterizing tactile afferent responses from the foot sole uses controlled vibratory stimuli with small amplitudes. However, forces experienced during natural behaviour are much greater and responses of tactile afferents to such stimuli are unknown. We present new experimental data using loads approximating those experienced by the foot sole during gait. We then compare these responses to model simulations to investigate afferent firing characteristics across a large range of tactile stimuli.**

I. Introduction

The foot sole is the primary interface between the body and environment, carrying information about the surface we are standing on and contributing to balance and gait. Current knowledge of tactile feedback from the foot sole stems from microneurography research, which typically employs stimuli with low amplitude. While such stimuli allow testing response thresholds and other important response characteristics, they do not reflect those experienced by the foot sole during everyday behaviour, limiting the generalisability of current experimental results to real-world behaviour.

II. Materials and methods

A. Natural loading microneurography data

We presented ramp-and-hold stimuli to the foot sole with forces up to 35 N/cm^2, reflective of those experienced during gait, via a contactor $1cm^2$ in size. Simultaneously, we used microneurography to record the response behaviour of individual tactile afferents to these stimuli. Ramp-and-hold stimuli were applied with a linear force ramp and a hold period of 3-4 seconds (Fig 1b).

B. Computational modelling

FootSim [3], a recently published computational model of tactile afferent response behaviour, was used to replicate the experimental ramp-and-hold protocol. For each experimental recording, a ramp-and-hold stimulus was applied to simulated afferents of the same class at the equivalent foot region. Firing rates during the 'ramp' and 'hold' phases were calculated. Responses to behaviourally relevant stimuli not possible to investigate experimentally were then simulated.

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III. Preliminary results

We first compared the force-derivative combinations that are used in traditional microneurography studies [1] to those experienced in everyday life [2]. Stimuli that are typically used to assess the response characteristics of afferent classes fail to capture the full range of stimuli experienced by the foot sole during everyday behaviour, while our additional stimuli greatly extend the range (Fig. 1a).

We identified that the greater forces and lower force derivatives in the natural dataset influenced afferent classes to different extents: slowly adapting afferents exhibited greater firing rates to higher force-low derivative stimuli, whereas fast adapting afferents responded more to low force-high derivative stimuli. Under higher forces, the force derivative contributes most strongly to firing rates during the ramp phase of the stimuli. These findings restrict the parameter space within which plausible computational models can be located. FootSim is capable of replicating the firing rates in response to high load stimuli observed during microneurography (Fig. 1c, d). The combined use of experimental and computational methods allows for new-found insight into tactile responses during natural behaviours, such as gait.

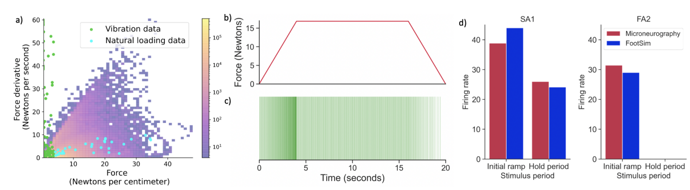

Fig. 1. a) Scatterplot of force and force-derivatives between two datasets overlaid onto a 2D distribution of force and force derivatives experienced during everyday behaviours. Green points relate to vibration data, blue points relate to natural loading ramp-and-hold stimuli. b) Example ramp-and-hold stimulus applied to the foot c) simulated response of a single SA1 afferent using FootSim, plotted as a raster plot. d) Firing rate of a single SA1 (left) and FA2 (right) afferent recorded using microneurography across the ramp phase and hold phase of the ramp-and-hold stimulus compared to simulated firing rates during the respective phases of the stimulus.

References

[1] N. Strzalkowski, R. Ali & L. Bent. The firing characteristics of foot sole cutaneous mechanoreceptor afferents in response to vibration stimuli, 2017, Journal of Neurophysiology

[2] L. Cleland, H. Rowland, C. Mazzà, & Saal, H. Complexity of spatiotemporal plantar pressure patterns during everyday behaviours, 2023, BioRxiv

[3] N. Katic, R. K. Siqueira, L. Cleland, N. Strzalkowski, L. Bent, Raspopovic, S. & Saal, H. Modeling foot sole cutaneous afferents: FootSim, 2023, iScience