Thresholds of cutaneous afferents related to perceptual threshold across the human foot sole

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Abstract

Perceptual thresholds are known to vary across the foot sole, despite a reported even distribution in cutaneous afferents. Skin mechanical properties have been proposed to account for these differences, however, a direct relationship between foot sole afferent firing, perceptual threshold and skin mechanical properties has not been previously investigated. Using the technique of microneurography, we recorded the monofilament firing thresholds of cutaneous afferents and associated perceptual thresholds across the foot sole. In addition, receptive field hardness measurements were taken to investigate the influence of skin hardness on these threshold measures. Afferents were identified as Fast Adapting; FAI (n=48), FAII (n=13), or Slowly Adapting; SAI (n=21) or SAII (n=20), and were grouped based on receptive field location (Heel, Arch, Metatarsals, Toes). Overall, perceptual thresholds were found to most closely align with firing thresholds of FA afferents. In contrast, SAI and SAII afferent firing thresholds were found to be significantly higher than perceptual thresholds and are not thought to mediate monofilament perceptual threshold across the foot sole. Perceptual thresholds and FAI afferent firing thresholds were significantly lower in the Arch compared to other regions, and skin hardness was found to positively correlate with both FAI and FAII afferent firing and perceptual thresholds. These data support a perceptual influence of skin hardness, which is likely the result of elevated FA afferent firing threshold at harder foot sole sites. The close coupling between FA afferent firing and perceptual threshold across foot sole indicates that small changes in FA afferent firing can influence perceptual thresholds.

Introduction

It is well established that cutaneous feedback from the soles of the feet is fundamental in the control of upright stance. Previous work has shown foot sole cutaneous feedback to play a role in standing balance (Roll et al., 2002), gait (Perry et al., 2001; Eils et al., 2004), automatic postural adjustments (Inglis et al., 1994; Perry et al., 2000), as well as in the modulation of lower (Fallon et al., 2005) and upper limb (Bent and Lowrey, 2013) muscle activity and vestibular reflexes (Muise et al., 2012). What remains unclear is the capacity of individual types of foot sole cutaneous afferent classes to transmit distinct tactile cues to the central nervous system (CNS) and what impact this feedback has on balance control.

Tactile sensibility from the glabrous skin of the foot sole and hand arises from four classes of low threshold cutaneous mechanoreceptors located in the dermal and epidermal layers of the skin. Each class is sensitive to unique features of tactile stimuli and demonstrate distinctive firing characteristics in response to indentation forces, skin stretches, textures, and vibrations (Johansson et al., 1982; Johnson and Hsiao, 1992; Aimonetti et al., 2007). Cutaneous afferent firing characteristics as well as receptive field properties establish the classification of each subtype as fast adapting (FA) or slowly adapting (SA), and type I (small, distinct borders) or type II (large, undefined borders). The development of microneurography by Vallbo and Hagbarth in the 1960's, allowed for the direct comparison between primary afferent activity and perceptual experience (Hagbarth and Vallbo, 1967). Pioneering work in the hand found light touch perceptual threshold to most closely resemble the firing thresholds of FA afferents (Johansson and Vallbo, 1979). In the most sensitive hand regions (fingers and lateral border), a small amount of activity from FAI afferents, even single spikes, were capable of evoking a percept. Further support for a one-to-one relationship between afferent firing has been demonstrated through the electrical micro-stimulation of individual cutaneous afferents. Using this technique, researchers have demonstrated that specific tactile sensations can be evoked from the activity of single cutaneous afferents; e.g., flutter (FAI), vibration (FAII), and pressure (SAI) (Ochoa and Torebjörk, 1983; Macefield et al., 1990). These findings are in line with the lower envelope principle, in that perception can be set by minimal activity in the most sensitive afferents (Parker and Newsome, 1998).

Previous work that has investigated tactile perception has focused almost exclusively on cutaneous feedback from the hand. The fingers have been shown to have lower perceptual thresholds compared to the palm, despite similar afferent firing thresholds between these regions (Johansson and Vallbo, 1979). This led the authors to postulate that cutaneous feedback is not weighted equally across the body, and that central mechanisms may integrate input from the fingertips with more fidelity than the palm of the hand. The higher density of afferents in the finger tips may increase the probability of activating highly sensitive afferents leading to the disparity in perception between these regions. However, Johansson and Vallbo (1979) argued this was not the case since sub sensory stimuli at the palm still evoked firing in cutaneous afferents. Their investigation suggests that perceptual threshold can be set by the firing capacity of the most sensitive primary cutaneous afferents in some regions (e.g., in the fingers); while additional factors may raise perceptual threshold in less sensitive skin regions (e.g., in the palm).

The soles of the feet are not as sensitive as the hands, where in the feet, both perceptual thresholds (Hennig and Sterzing, 2009) and cutaneous afferent firing thresholds (Kennedy and Inglis, 2002) are reportedly higher. Perceptual threshold differences have been reported across the foot sole (Kekoni et al., 1989; Hennig and Sterzing, 2009; Strzalkowski et al., 2015); while mechanoreceptor density is thought to be evenly distributed (Kennedy and Inglis, 2002). A direct comparison between foot sole cutaneous afferent firing and perceptual sensitivity has not been made at the foot sole, and the neural mechanisms underlying regional differences in perceptual threshold are not well understood.

Mechanical properties of the skin have been shown to differ across the sole of the foot (Strzalkowski et al., 2015) and between the foot sole and hand (Hoffmann et al., 1994). The ability of skin to deform and transmit force will presumably impact afferent firing, and differences in skin properties have been proposed to account for disparities between cutaneous afferent firing and perceptual thresholds between these regions (Kekoni et al., 1989; Kowalzik et al., 1996; Kennedy and Inglis, 2002). While an attempt has been made to link mechanical properties with afferent firing in the glabrous skin of raccoons (Pubols & Pubols 1983), and with perceptual threshold in the foot (Strzalkowski et al., 2015), the influence of skin mechanics on the actual firing of foot sole cutaneous afferents has not been investigated.

The aim of the present study was to investigate the relationship between tactile perceptual threshold and cutaneous afferent firing thresholds across the human foot sole. Skin hardness within each afferent's receptive field was also investigated to better understand the potential influence of skin mechanics on afferent firing and perceptual threshold. In following with previous work in the hand, FA afferents were expected to be more sensitive to light touch (i.e., fire at lower forces) compared to SA afferents, and have firing thresholds most similar to perceptual thresholds across the foot sole. Afferent firing thresholds are expected to increase with skin hardness and, at least partially, account for perceptual threshold differences across the foot sole.

Materials and Methods

Subjects

Fifty-nine recording sessions were performed on 21 healthy subjects (12 male 9 female, mean age 24, range 20-27). None of the participants had any known neurological or musculoskeletal disorders. All subjects gave written informed consent to participate in the experiment. The protocol was approved by the University of Guelph research ethics board and complied with the declaration of Helsinki.

Microneurography

Microneurography was used to identify and record the firing patterns of single cutaneous afferents from the right tibial nerve. Subjects lay prone on an adjustable table with both legs extended, and supported with Versa Form positioning pillows. The path of the tibial nerve and microelectrode insertion sites were located at the level of the popliteal fossa using transdermal electrical stimulation (1-ms square wave pulse, 1Hz 0-10mA, Grass S48, SIU-Isolation Unit, Grass Instruments). A low impedance reference electrode (uninsulated, tungsten, 200μm diameter; FHC Inc. Bowdoinham, ME, USA) was inserted percutaneously to a depth of 0.5cm, 2cm medial to the predetermined recording site. A recording electrode (insulated 10MΩ, tungsten, 200μm diameter, 1-2 μm recording tip, 55mm length; FHC Inc.) was then inserted at the recording site and manipulated by hand to penetrate the nerve and to isolate single units. Electrode manipulations were guided by subject sensations as well as audio feedback of the neural activity initiated by mechanical activation (light tapping, stroking and stretching) of the foot sole skin. Neural recordings were amplified and band-pass filtered (gain 10^4, bandwidth 300Hz-3kHz, model ISO-180; World Precision Instruments, Sarasota, FL), digitally sampled (40kHz), and stored for analysis (CED 1401 and Spike2 version 6; Cambridge Electronic Design). Spike morphology was used to generate templates for the visual classification of single units. The sample of cutaneous afferents through microneurographic recordings is thought to be random, and the ratio of afferent classes and distribution of receptive fields in the present study are thought to reflect a representative sample of the cutaneous population in the foot sole.

Cutaneous mechanoreceptor identification

Single afferents were classified as fast adapting type I (FAI) or II (FAII), and slowly adapting type I (SAI) or II (SAII) based on previously described criteria (Johansson, 1978; Kennedy and Inglis, 2002). Briefly, FA afferents adapt quickly to sustained indentations and are highly sensitivity to dynamic events. In contrast, SA afferents respond throughout sustained indentations, and demonstrate a firing rate proportional to the magnitude of skin displacement. Type I afferents typically have small receptive fields with distinct borders and multiple hotspots, while type II afferents have large receptive fields with less well defined borders and a single hotspot.

Afferent firing and perceptual threshold testing

After a single afferent was isolated, Semmes-Weinstein monofilaments (Touch Test®, North Coast Medical Inc, Gilroy, California) were used to measure afferent firing thresholds (AFT), perceptual threshold, and to measure receptive field location and size. AFT was defined as the minimum monofilament force (mN), which reliably (100% confidence of unit identification) evoked an afferent discharge in at least three of four applications. AFT was determined at the most sensitive receptive field location (hotspot) for each identified cutaneous afferent. Perceptual threshold was also measured at each afferent's receptive field hotspot following single unit recordings. The AFT test site was marked with a pen to ensure perceptual threshold was measured at the same location. A modified 4-2-1 search method was employed (Dyck et al., 1993), and subjects were instructed that there would be multiple catch trials in which no monofilaments would be applied. Subjects were instructed to answer with a simple yes/no response when they were at least 90% confident that they perceived the tactile stimulus. Perceptual thresholds were determined to be the lowest monofilament force (mN) correctly perceived on at least 75% of applications. It is notable that perceptual threshold is the perception of force within an identified region (RF). Given the nature of microneurography, where we are recording from one single afferent, it may be possible for perception threshold to be lower than AFT when we are not recording from the most sensitive afferent.

Receptive field characteristics

Afferent receptive fields were measured with monofilaments that applied a force 4-5 times greater than AFT, and were drawn on the skin using a fine tip pen (Figure 1). Receptive fields were always oval or circular in shape, and the major and minor axes were used to calculate receptive field area (mm^2) (Table 1). Efforts were made to identify and map all isolated single afferents, however searching was focused to the foot sole, and only afferents with their receptive field in the plantar surface were included in AFT and perceptual threshold analyses.

Hardness measurements were taken at the receptive fields of each identified cutaneous afferent using a handheld durometer (Type 1600-OO, Rex Gauge, Brampton, Ontario, CAN). The durometer had a 2mm diameter column-shaped indenter, which is ideally suited for skin measurements (Kissin et al., 2006). Durometers provide hardness measurements in arbitrary units (au) between 1 (softest) and 100 (hardest), based on the penetration depth of the indenter. Two measurements of hardness were taken at each receptive field and averaged. Hardness measurements were not taken at some toe sites (10 of 30) due to the receptive field being too close to the nail, or an inability for the durometer to fit on the toe.

Data analysis

The dependent variable assessed for both afferent firing threshold and perceptual threshold was the applied monofilament force level (mN) necessary to evoke an afferent discharge or a percept, respectively. Analysis of variance (ANOVA) procedures were conducted on log-transformed AFT and perceptual threshold data to correct for violations of normality and homogeneity. A one-way ANOVA was used to determine if AFTs differed between afferent classes (FAI, FAII, SAI, SAII). Significant effects were followed up with a Gabriel post hoc analysis. Additionally, a mixed design ANOVA was performed to determine if there were differences between afferent class firing threshold and associated perceptual thresholds (within factor), and if these differences were present at different foot sole locations (between factor). Significant effects were followed up with one-way ANOVAs and a Gabriel post hoc test.

Pearson's product-moment coefficients were calculated to measure the relationship between afferent class firing thresholds and associated perceptual thresholds. Relationships between receptive field hardness and AFT as well as receptive field hardness and perceptual threshold were also explored using Pearson's correlations.

The cumulative probabilities of afferent firing and the generation of a percept were calculated across monofilament force levels. These data demonstrate the proportion of afferents within each class that reached threshold, as well as the proportion of percepts evoked, at a given monofilament force application.

Results

One hundred and two afferents were successfully identified with receptive fields in the plantar surface of the foot sole. These included 48 FAI (47%), 13 FAII (13%), 21 SAI (20%) and 20 SAII (20%) (Figure 1). An additional 9 units were identified in the nail bed, dorsum and back of the ankle (nail bed: 2 SAII, dorsum: 1 SAII, ankle: 1 FAI, 2 FAII, 1 SAI, 2 SAII), however all non-foot sole units were excluded from analysis. Cutaneous afferent class characteristics are presented in Table 1.

Afferent class firing threshold

One-way repeated measures ANOVA revealed that there was a significant difference in afferent firing threshold between afferent classes ($p<0.001$) (Figure 2). Post hoc analysis indicated that AFT did not significantly differ between FAI (mean 13.2mN) and FAII (mean 12.0mN) afferents ($p=0.498$), and that both FAI and FAII afferents had significantly lower thresholds compared to SAI (mean 49.6mN) and SAII (222.5mN) afferents (all p-values <0.001). In addition, SAI AFT was significantly lower than SAII AFT ($p=0.001$).

Across foot sole locations, FAI AFTs were found to be significantly different (*p*=0.005), while location differences were not found for FAII (*p*=0.174), SAI (*p*=0.143), or SAII (*p*=0.964) afferent classes (evaluated using one-way repeated measures ANOVAs). It should be noted that FAI afferents were the most abundant (n=48), thus the relatively lower sample size of the other classes may have contributed to the absence of observed differences in AFT across foot sole locations. Post hoc analysis revealed FAI AFTs to be significantly lower at the Arch compared to the Heel (*p*=0.019) and Toes (*p*=0.043), and there was a trend toward a lower threshold at the Arch in comparison to the Met (p=0.073) (Figure 3.A).

Perceptual thresholds

Perceptual thresholds significantly differed across foot sole locations (*p*<0.001; One-way repeated measures ANOVA). Similar to FAI AFT, the Arch displayed the lowest perceptual thresholds; post hoc analysis revealed that perceptual threshold at the Arch was significantly lower in comparison to the Heel (*p*<0.001), Met (*p*=0.003) and Toes (*p*=0.007) (Figure 3.B).

Relationship between afferent firing threshold and perceptual threshold

Overall, perceptual threshold (mean 14.63mN) was found to be most similar to both FAI (mean 13.2mN) and FAII (mean 12.0mN) AFTs (Figure 2). Two-way mixed ANOVA results indicated that across the foot sole, there were no significant differences between perceptual threshold and FAI or FAII AFT (*p*>0.05) (Figure 4). In contrast, SAI and SAII AFTs were found to be significantly higher than perceptual threshold (SAI *p*=0.004, SAII *p*=0.001), (Figure 2). Post hoc analysis showed that SAI AFT at the Toes was significantly higher compared to perceptual threshold (*p*=0.011), with a similar trend at the arch (p=0.073), and an opposite trend of lower SAI AFT compared to perceptual threshold at the Heel (p=0.053) (Figure 4). SAII AFTs were significantly higher than perceptual threshold at the Arch and Met (p<0.001) (Figure 4). Minimum, maximum and median threshold values across foot sole sites are represented in Table 2. The small sample sizes at some locations (one FAII and SAII at the Heel, and 1 SAII at the toes) limited the comparisons that could be made.

The cumulative probability of afferent firing and perceptual threshold across monofilament forces (mN) is presented in Figure 5. These data demonstrate differences in the proportion of afferents recruited in each class across monofilament force levels. FAII afferents were shown to be the most sensitive, exhibiting a higher percentage of recruitment at lower forces compared to the other classes. By 1mN of force, 40% of FAII afferents reached threshold whereas 20% of FAI, and 0% of SAI and SAII afferents were firing. The proportion of trials perceived, increased with larger monofilament force and most closely related to the recruitment of FA afferents. Perceptual threshold was reached in 10% of trials before any SAI or SAII afferents reached firing threshold. At approximately 6mN of force, 50% of monofilament applications were perceived, while only 14% of SAI and 0% of SAII afferents reached threshold. In contrast 56% of FAI and 63% FAII were recruited by 6mN of force. These data demonstrate that FAI and FAII afferent firing thresholds are lower than perceptual threshold in some instances, and that perception threshold is likely reached in the absence of SAI and SAII firing. Furthermore, a significant correlation was found between FAI AFT and perceptual threshold (r=0.489, p=<0.001). In contrast, significant correlations were not found between perceptual threshold and AFT for any other afferent classes (Table 3).

Receptive field hardness influences FA afferent firing threshold and perceptual threshold

Receptive field hardness was found to significantly correlate with perceptual threshold (r=0.433, *p*=<0.001). Similarly, receptive field hardness was found to significantly correlate with FAI AFT (r=0.357, *p*=0.018), as well as FAII AFT (r=0.758, *p*=0.007) (Table 3). No significant correlations were found between SAI or SAII receptive field hardness and AFT, although a trend was found for SAII afferents (SAI: r=-0.109, *p*=0.678, SAII: r=0.422, *p*=0.064). These data suggest that the effects of skin hardness on perceptual threshold parallel the effects of skin hardness on FA afferent firing.

Discussion

The present study examined the relationship between cutaneous afferent firing thresholds and perceptual thresholds across the human foot sole. We have demonstrated that monofilament perceptual threshold is mediated by the activity of fast adapting afferents, and, in turn, that both fast adapting afferent firing and perceptual thresholds may be influenced by skin hardness. Across all foot sole locations, perceptual thresholds did not significantly differ from the firing thresholds of FAI and FAII afferents. The Arch was perceptually the most sensitive region and also contained the most sensitive FAI afferents. In contrast, SAI and SAII afferents were significantly less sensitive than perceptual threshold across the foot sole and are thus not thought to mediate monofilament perceptual threshold.

Psychophysical Detection

Cutaneous afferents are the fundamental units that convey tactile feedback to the central nervous system. The lower envelope principle postulates that perceptual thresholds are set by the most sensitive afferents, and predicts that perceptual variability can be accounted for in the variability of individual afferent firing (Parker and Newsome, 1998). Alternatively, afferent temporal or spatial summation may be required for tactile stimuli to have perceptual significance. In such pooling-models, the relationship between perception and afferent firing thresholds is expected to be small, as fluctuations in the activity of single neurons would have a minimal impact on whether cutaneous activity is perceived (Parker and Newsome, 1998). Microneurography provides a tool to obtain single unit recordings from awake human subjects, and thus permits the relationship between cutaneous afferent firing and perception to be directly examined. This is the first study to link the activity of single cutaneous afferents to perceptual threshold across the foot sole.

Afferent and perceptual thresholds across the foot sole

Previous reports of foot sole cutaneous afferent firing thresholds exhibit a range in median values, which are similar to the threshold ranges measured in the present study. In all cases FAII afferents were found to have the lowest monofilament thresholds, with median values reported from 0.73-4mN (3.9mN in the present study). In most cases FAI afferents had the second lowest thresholds (3.84-11.8mN, 5.9mN present study), followed by SAI (4.08-35.6mN, 39.2mN present study) and SAII afferents (1.42 – 115.3mN, 122.6mN present study) (Kennedy and Inglis, 2002; Fallon et al., 2005; Bent and Lowrey, 2013; Lowrey et al., 2013). Collectively, these median values demonstrate that large ranges in afferent firing thresholds may exist within classes, however, these afferent firing thresholds are averaged across the foot sole and not distinct by region. We made the link between afferent location and firing threshold because it is an important measure to identify factors contributing to both AFT and perceptual threshold. FAI AFT was found to be significantly lower at the arch compared to the Heel and Toes, while SA afferents did not show significant differences in threshold across the foot sole. Interestingly, perceptual threshold was also found to be lowest in the Arch region compared to the Heel, Met and Toes, which is in agreement with previous work (Nurse and Nigg, 1999; Eils et al., 2002; Hennig and Sterzing, 2009; Zhang and Li, 2012). In general, we found that across the foot sole, regional perceptual threshold differences closely mirrored the firing thresholds of FAI and FAII afferents; the force required to activate these fast adapting afferents was not significantly different from those required to reach perceptual threshold. Although the relative perceptual contributions between FAI and FAII afferents cannot be determined from the present data, our results provide strong evidence that only FA, and not SA, afferent firing contributes to monofilament perceptual thresholds across the foot sole.

Regional differences: Receptive field hardness

The ability of cutaneous afferents to fire is set by the capacity of the skin and surrounding tissue to deform and transmit force to the mechanoreceptor endings. Mechanical property differences between the hands and feet and across the foot sole have been suggested to account for perceptual and afferent firing differences between these regions, however, this relationship has not been previously investigated (Kekoni et al., 1989; Trulsson, 2001; Kennedy and Inglis, 2002). Significant differences in hardness were found across the foot sole regions investigated in the current study. Additionally, we found significant correlations between both FAI and FAII AFT with receptive field hardness, which supports an influence of skin hardness on FA AFT. Perceptual thresholds were also found to correlate with receptive field hardness. As a whole, these correlational data suggest that across the foot sole, higher FA AFTs may be the result of harder skin, and as a consequence, perceptual thresholds are increased. These data cannot make this link unequivocally, but when considered along with the significant regional differences observed in FAI AFT and perceptual thresholds, it appears that indeed, receptive field hardness has an influence on these measures. These data suggest that regional differences in foot sole hardness may partially explain the consistent regional differences in foot sole monofilament thresholds reported in the literature.

Afferent characteristics between the hands and feet

The hands and feet purportedly contain the same classes of mechanoreceptive afferents, despite serving distinct functional roles. Tactile feedback from the feet aids in the control of posture and upright stance by providing information about sway and weight distribution under the feet (Kavounoudias et al., 1998). In contrast, the hands are commonly used to manipulate objects and require high tactile acuity. It is therefore not surprising that firing thresholds of afferents in the hands are reported to be lower than those in the feet (Johansson et al., 1980; Kennedy and Inglis, 2002). Median monofilament afferent firing thresholds of RA (FAI), FAII, SAI and SAII afferents in the hand have been reported to be 0.58, 0.54, 1.3 and 7.5mN respectively (Johansson et al., 1980); these are 7-30 times more sensitive than the median afferent class thresholds found in the present study and in other studies examining cutaneous receptors in the feet (Kennedy and Inglis, 2002; Fallon et al., 2005; Bent and Lowrey, 2013; Lowrey et al., 2013). Elevated thresholds across the foot sole may reflect a peripheral adaptation of foot sole afferents that enables them to optimally function under loaded conditions. Despite these observations of overall elevated thresholds in the foot sole, the relative thresholds between afferent classes appear to be preserved in the feet; in both the hands and feet, FAII afferents are typically the most sensitive to perpendicular light touch followed by FAI and SAI afferents, while SAIIs characteristically are the least sensitive (Johansson et al., 1980; Kennedy and Inglis, 2002).

Previous seminal work in the hand investigated the mechanisms behind the perception of light touch in the glabrous skin of the palm and fingers (Johansson and Vallbo, 1979). These authors found FAI and FAII afferent firing thresholds to mirror perceptual thresholds in the fingers and lateral boarder of the hand; which is similar to the relationship we found in the foot sole. However, while we found FA AFT and perceptual threshold to correlate across the entire foot sole, they found a discrepancy in the palm of the hand, where FA afferent firing thresholds were considerably lower than perceptual thresholds. This disparity suggests that perception at the palm of the hand may be limited by noise or processing inefficiencies within the central nervous system. Such a discrepancy between AFT and perceptual threshold was not found in any regions of the foot sole. The alignment of FA afferent firing thresholds with perceptual thresholds in the most sensitive regions of the hands (fingers and lateral boarder) are consistent with the lower envelope principle and with the present observations across the foot sole whereby minimal input from a few afferents is able to generate a percept.

Functional implications

This study extends the large body of work that has investigated cutaneous afferent firing and sensory perception in the hand and the foot sole. Considering the importance of detailed tactile feedback from the fingers, it makes functional sense that minimal afferent input from the fingers would have a significant impact on perception (Johansson and Vallbo, 1979). It may then be a surprise that a similar relationship, albeit at elevated thresholds, is present in the foot sole where high tactile discrimination may not be necessary for the control of standing balance. Research has identified a large proportion of FAI afferents in the foot sole, which highlights skin's important role in dynamic balance (Kennedy and Inglis 2002, Fallon et al 2005). The transmission of FAI afferent information, with minimal firing and low signal noise, would ensure the fidelity of cutaneous dynamic input for balance and locomotor tasks. In the present study, the FA afferent-perceptual correspondence supports that small changes in FA afferent firing thresholds can have a significant impact on perceptual threshold, and potentially on balance control. In support of this concept, low amplitude white noise vibration applied to the foot sole has been shown to improve balance control in stroke and diabetic patients (Priplata et al., 2005). These vibrations are thought to increase the detection of weak cutaneous signals from the soles of the feet. Therefore, small changes in FA afferent firing are thought to impact both tactile perception, and balance control.

While the current study was conducted in a young healthy population, these data can help inform clinical assessments of tactile sensitivity. Diabetic neuropathy, which is present in 80% of both type 1 and 2 diabetics, is commonly diagnosed and assessed with monofilament testing (Valk et al., 1997; Collins et al., 2010). In these patients, the standard which is used to diagnose sensory neuropathy is a threshold of 10g (98mN) or higher, typically in the plantar surface of the great toe (Kumar et al., 1991; Lambert et al., 2009). The current data suggests that monofilament thresholds in the foot sole are mediated by the activity of FA afferents, and monofilament testing does not provide a measure of SA afferent function. Clinically, monofilaments remain a simple tool to assess tactile sensibility, however, other techniques, such as vibration, grating orientation tasks and temperature thresholds are needed to understand the function of the complete peripheral sensory system.

Limitations

Microneurography is a powerful technique in that it provides a comparison between afferent activity and perception in human subjects. A limitation of studying single neurons is the inability to measure population behaviour at different levels within the nervous system. The number of afferents responding to each monofilament application is unknown, but almost certainly includes more than the individual afferent being recorded. Consequently, the influence of spatial summation on these monofilament threshold outcomes remains unknown. Additionally, foot sole location and afferent class comparisons would be strengthened with large sample sizes, however microneurography does not permit the selection of skin units based on class or foot sole location. Perceptual threshold is a relatively simple psychophysical measure, and may only be mediated by FA afferents. Understanding the perceptual contributions of SAI and SAII afferents could be achieved with different tactile stimuli and associated psychophysical tasks; such as stimulus intensity threshold, location, and texture perception (Johnson and Hsiao, 1992).

Conclusions

The current findings indicate that minimal FA afferent input from the foot sole can give rise to tactile percepts. These findings are in agreement with the lower envelope principle in that perception is set by the activity of the most sensitive FA afferents. SAI and SAII afferents were found to have elevated firing thresholds compared to FA afferents, and their firing did not contribute to foot sole light touch perceptual thresholds. Additionally, regional differences in receptive field hardness appear to relate to, and influence, the firing thresholds of FA afferents; this is thought to contribute to regional differences in perception across the foot sole.

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Table Captions

Table 1: The number and percent of each afferent class identified as well as the monofilament threshold and receptive field area (mean and range)

Table 2: Afferent firing threshold (AFT) values across foot sole locations (mN). Data represented are minimum (min), maximum (max) and Median values.

Table 3: Correlation data for comparisons between afferent firing threshold and perceptual threshold, afferent firing threshold and receptive field hardness, and perceptual threshold and receptive field hardness.

Figure Captions

Figure 1: Afferent class receptive field distribution. Grey ovals indicate the relative size and location of cutaneous afferent receptive fields identified across the foot sole. FAI (fast adapting type I), FAII (fast adapting type II), SAI (slowly adapting type I), SAII (slowly adapting type II). These represent the receptive fields for all afferents included in the current study.

Figure 2: Mean (±SD) monofilament perceptual threshold (hashed bar) and afferent class firing thresholds (black bars). FAI and FAII afferent firing thresholds were significantly lower than SAI and SAII (all *p*-values <0.001) but were not different than perceptual threshold ($p>0.05$). SAI afferent firing threshold was significantly lower than SAII ($p=0.001$) and both SAI and SAII afferent firing thresholds were significantly higher than perceptual threshold (SAI $p=0.004$; SAII $p<0.001$). The letters a, b and c identify threshold categories that significantly differ from each other.

Figure 3: (A) Mean (±SD) FAI afferent firing thresholds at the Heel, Arch, Met and Toes. FAI AFTs were significantly lower at the Arch compared to the Heel ($p=0.019$) and Toes ($p=0.043$). (B) Mean (±SD) perceptual thresholds at each foot region. Perceptual thresholds were lowest in the Arch compared to all other sites ($p<0.05$).

Figure 4: Mean (±SD) afferent firing and perceptual threshold at the Heel, Arch, Met and Toes for each afferent class (FAI, FAII, SAI, SAII). There were no significant differences between FAI or FAII afferent firing (AFT) and perceptual threshold at any foot sole location. SAI AFTs were significantly higher than perceptual threshold at the Toes ($p=0.011$) and SAII AFTs were significantly higher than perceptual threshold at the Arch and Met (*p*-values<0.001).

Figure 5: Cumulative probability of afferent class firing and perceptual threshold. This demonstrates the proportion of percepts evoked and afferent firing thresholds reached at a given monofilament force level. Lines represent FAI (single black line), FAII (double black line), SAI (single grey line), SAII (double grey line) and perception (dotted line). These data demonstrate that some FAI and FAII AFTs were lower than perceptual threshold, and perceptual threshold was reached in 60% of trials in the absence of substantial SAI and SAII contributions.