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Obesity, but not overweight, is associated with plantar light touch sensation in children aged 8 to 16 years: A cross-sectional study

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Summary

Objective: Increased foot-ground contact loading engenders adaptive glabrous skin thickening and can decrease mechanoreceptor acuity and alter plantar cutaneous sensation. There has not been any research on whether overweight and obesity are similarly associated with normal plantar cutaneous sensation scores in children. This study investigated the associations between normal plantar cutaneous sensation scores and weight status (i.e., healthy weight, overweight, and obesity) in a sample of youth.

Methods: Plantar sensation was tested among 122 participants aged 8 to 16 years (10.3 ± 1.8 years; 140.0 ± 11.2 cm; 44.2 ± 16.0 kg) across the forefoot, midfoot, and rearfoot using Semmes-Weinstein pressure aesthesiometry (0.07 g and 0.4 g monofilaments). Weight status was determined using the Centers for Disease Control and Prevention growth charts. Age- and sex-adjusted models were used to explore the relationships between normal plantar sensation scores and weight status. Significant two-tailed tests were set at $p < .05$.

Results: Only obesity was inversely associated with normal plantar sensation scores on the left ($\beta = -.241$; $p = .009$) and right ($\beta = -.222$; $p = .018$) forefeet, left ($\beta = -.322$; $p = .001$) and right ($\beta = -.253$; $p = .007$) midfeet, and left ($\beta = -.286$; $p = .002$) and right ($\beta = -.228$; $p = .014$) wholefeet (relative to healthy weight) when using the 0.07 g monofilament. There was no association between obesity and plantar sensation when using the 0.4 g monofilament.

Conclusions: Obesity is associated with diminished light touch plantar sensation. Considering previously reported higher mechanical loading and the fact that Merkel cells and the Aβfibers that innervate them are superficial to the hypodermis, adaptive glabrous skin thickening (rather than fat pad thickness) may underlie this association. Contrary to previous suggestions, overweight is not associated with decreased plantar cutaneous sensation.

KEYWORDS

glabrous skin, mechanosensation, obesity, plantar cutaneous sensation

1 | INTRODUCTION

Decreased tactile sensitivity has been implicated in adverse postural outcomes in children with obesity [1]. Decreased plantar cutaneous sensation adversely impacted critical movement performance determinants like leg stiffness regulation during hopping [2]. The foot is often the primary point of contact during stance and locomotion. Mechanoreceptors in its glabrous skin relay tactile information that are important for postural coding and spatial representation [3]. This tactile input is considered integral to postural regulation during sensorimotor tasks where the feet interface with the support surface [4,5]. Balance deficits among 8 to 15 year olds with obesity were thought to be due to decreased sensory acuity rather than strength [6].

Despite having increased foot contact area, children with obesity generate higher peak plantar pressures in most regions of the foot, including the forefoot and midfoot, compared to children with healthy weight during standing [7,8] and walking [9,10]. The highest overall pressure was observed in the rearfoot in both groups [8]. Children with obesity had higher static and dynamic plantar pressures under the midfoot and forefoot than children below the body mass index (BMI) centile threshold for obesity during weight bearing tasks [7]. A separate study found that children with overweight (like age-matched peers with obesity) showed greater midfoot and forefoot loading than peers with healthy weight [11]. The pervasive notion is that increased foot loading in children with obesity may magnify the risk of foot pathologies [7] and altered plantar sensitivity [8]. Perhaps relatedly, 26% of a previous sample of overweight and obese children presented with foot pain [12]. However, many of the findings have resulted from combined analyses of children with overweight and obesity. Weight bearing loading magnitudes differ between the two groups [11], so any attributable deficits may in fact vary.

Childhood obesity has been linked with medial longitudinal arch collapse and increased foot contact area [7]. This association formed the basis for the suggestion of lower mechanoreceptor density relative to available foot contact surface area in children with obesity [8]. Obesity is associated with greater midfoot fat pad thickness [13,14] and peak plantar pressures in children [13]. Increased foot contact area exposes more glabrous skin to increased loading in children with overweight and obesity. The outer (epidermal) layer of the glabrous skin adaptively thickens with increased mechanical demands (i.e., increased keratinocyte proliferation) [15,16]. This thickening was hypothesized to blunt mechanoreceptor acuity and alter plantar cutaneous sensation [17]. Loading expectedly varies by foot region and movement type and phase [11]. Relatedly, adaptive thickening likely varies by foot region. Adult plantar soft tissue was found to be 36% to 48% thicker in the rearfoot compared to that in the forefoot [18]. Plantar fascia was thicker underneath the medial calcaneus compared to sites at the midfoot and forefoot among young adults [19]. Females had thinner plantar fascia at midfoot and forefoot sites compared to males [19]. Increased rearfoot skin thickness seems an adaptation that is consistent with its shock absorbing role [20]. The rearfoot and the fifth metatarsal head had greater glabrous skin hardness and decreased sensitivity to vibration compared to the first and second metatarsal heads in young adults [17]. It is important to explore associations between both regional and wholefoot sensation and weight status within the context of normal plantar cutaneous sensation scores in children.

According to the Weber law, the ability to detect change in a tactile signal depends directly on whether the change exceeds some constant percentage of initial signal [21].

$$\Delta I = k \cdot I \tag{1}$$

where I is the initial intensity of the stimulus and k is the Weber fraction. Considering baseline differences in plantar pressures, this law posits a mechanism for differences in the capacity to detect changes in body weight-induced plantar loading between persons with overweight, obesity, and healthy weight during activities involving stance. However, dissimilar to these body-weight dependent variations, the loading signal (i.e., force-gram) engendered by commonly deployed Semmes-Weinstein monofilaments is consistent and independent of body weight. Processing the type of sustained focal indentation and low skin displacement (≤15 μm in humans) likely induced by 0.07 and 0.4 g Semmes-Weinstein monofilaments has been primarily linked with slowly adapting type I (SA-I) low threshold mechanoreceptors and the Merkel cell complex [22]. These mechanosensory end organs are located in the stratum basale of the epidermis and have a small receptive field (2–3 mm) and consequent high spatial resolution [22,23]. These attributes and the fact that they generate action potentials throughout the static phase of a stimulus make SA-I mechanoreceptors especially specialized for tactile discrimination [24].

Although children with overweight and obesity have been reported to have decreased plantar cutaneous sensation [8], the extant literature has grouped children with overweight and obesity together and compared them to peers with healthy weight. Therefore, it is unclear whether overweight and obesity are similarly associated with normal plantar cutaneous sensation scores in children. Studies on foot aesthesiometry have typically employed the full range of the Semmes-Weinstein monofilament foot kit and reported plantar cutaneous sensation scores without any context or implications for normal sensation [8]. Specifically, it is unclear whether the decreased plantar sensation scores reported in children with overweight and obesity implies the absence of normal plantar cutaneous sensation. This study aimed to elucidate associations between normal plantar cutaneous sensation scores and having healthy weight, overweight, and obesity among youth. It was hypothesized that obesity will be inversely associated with normal plantar cutaneous sensation scores.

2 | METHODS

2.1 | Participants

A cross-sectional assessment of plantar cutaneous sensation among 127 school children aged eight through 16 years was conducted in

Corpus Christi, Texas between April 2018 and April 2019. Sample size was informed by a priori power analysis using G*Power (Dusseldorf, Germany), which indicated a minimum of 89 participants for 90% power with a moderate effect size (f^2 = 0.15) for significant two-tailed tests at $p < .05$. The sample was 87% Hispanic, 5% African American, and 8% White. Participants were excluded, if they had any neurologic involvement, were previously diagnosed with diabetes, presented with lacerations or lesions on the plantar surface of the foot, or reported feeling unwell. One set of data was excluded from further analyses, because investigators deemed the participant's responses unreliable. Texas A&M University-Corpus Christi Institutional Review Board approved this study (IRB # 143-17).

2.2 | Anthropometrics

Participant's standing height (m) and body mass (kg) were measured using a seca 286 dp wireless ultrasonic measuring station (seca, Hamburg, Germany). BMI percentiles were determined using the Centers for Disease Control and Prevention's BMI Percentile Calculator for Child and Teen [25]. The output from the online calculator delineated underweight, healthy weight, overweight, and obesity as previously described [26]. BMIs that equaled or exceeded the 95th percentile were further delineated obese class 1 (95th percentile to <120% of the 95th percentile), severe obesity class 2 (120% to <140% of the 95th percentile or BMI 35.0 to <40.0 kg/m^2), and severe obesity class 3 (BMI ≥ 140% of the 95th percentile or BMI ≥ 40.0 kg/m^2) [27].

Given the unequal distances between the percentile-based classifications, the weight classes were treated as categorical data. Healthy weight was coded as "1," overweight was coded as "2," and obesity was coded as "3." The prevalence of underweight in the sample was only 1.6%; therefore, four associated data sets were excluded from further analysis.

2.3 | Plantar cutaneous sensation testing and scoring

Each participant's plantar cutaneous sensation was tested by one of four assessors who were trained to use the Semmes-Weinstein pressure aesthesiometry (DanMic Global, LLC, San Jose, CA, USA). The assessors' interrater reliability (α = .710; p = .005; 95% CI [0.156, 0.856]) was previously established and considered good [28]. The assessors tested plantar cutaneous sensation (dermatomes L4, L5, S1, and S2) at one of four testing stations in the data collection room. The foot aesthesiometer set consisted of six nylon monofilaments of different diameters but equal length. Each monofilament is associated with a requisite force that will cause it to buckle when orthogonally pressed against the plantar surface of the foot. This ensures the application of repeatable graded force to the skin and its mechanoreceptors, thereby allowing the evaluation and determination of tactile thresholds. Nylon monofilaments were previously used to evaluate the integrity of cutaneous nerve distribution and detect early abnormalities [29]. Their use for detecting sensory thresholds is well documented [8,29]. Although the foot kit consisted of six monofilaments, only the two that are related to normal sensation to the foot (0.07 g and 0.4 g) are presented in this study.

Prior to testing, each participant was familiarized with the general feel of a Semmes-Weinstein monofilament. The respective assessors pressed a 2.0 g monofilament against the palm of the participant's hand in order to allay any anxieties about pain or discomfort. During testing, the assessor pressed the monofilament perpendicularly against each designated plantar site while participants lay supine with their feet overhanging the table edge and eyes fixated on a point in the ceiling. Normal plantar cutaneous sensation was tested at nine plantar sites (Figure 1) delineated as the forefoot (i.e., first, middle, and fifth metatarsal heads, big toe, third toe, and fifth toe), midfoot (i.e., medial and lateral midfoot), rearfoot, and wholefoot (i.e., forefoot, midfoot, and rearfoot) [8].

Participants' right and left feet were tested in a randomized order to counteract any order effects. During testing, the 0.07 g monofilament was always presented first [29]. The assessor pressed the monofilament until it just buckled, then sustained the touch for an additional 1 second while asking the participant if they sensed any touch or pressure (on the bottom of their foot) [23]. Participants were instructed to answer "yes" if they sensed touch or pressure and "no" if they did not. The equivalent gram-force of the monofilament was assigned to each tested site, if a student verbally indicated sensing touch or pressure by answering "yes." A zero was assigned, if the participant verbally responded not sensing touch or pressure by saying "no." To check for false positives, assessors randomly withheld touch a minimum of three times and asked if the student sensed touch or pressure. If a student reported sensing touch or pressure during at least two of the three checks (when touch was withheld), their responses were deemed unreliable and their data were excluded from further analyses. The gram-force values were totaled for each foot region [8]. Higher gram-force values indicated greater plantar cutaneous sensitivity. Minimum possible score for each delineated foot region was 0 g irrespective of the monofilament. Maximum possible scores for the 0.07 g monofilament were 0.42 g (forefoot), 0.14 g (midfoot), 0.07 g (rearfoot), and 0.63 g (wholefoot). Maximum possible scores for the 0.4 g monofilament were 2.4 g (forefoot), 0.8 g (midfoot), 0.4 g (rearfoot), and 3.6 g (wholefoot).

2.4 | Statistical analysis

Data was explored for normality and outliers using Kolmogorov-Smirnov test and box plots, respectively. Variance Inflation Factors were computed and examined to detect any instances of multicollinearity. A series of multiple linear regression models were built to explore associations between normal plantar cutaneous sensation and weight status. Healthy weight was the referent category when associations between normal plantar cutaneous sensation scores and having overweight or obesity were explored. A second set

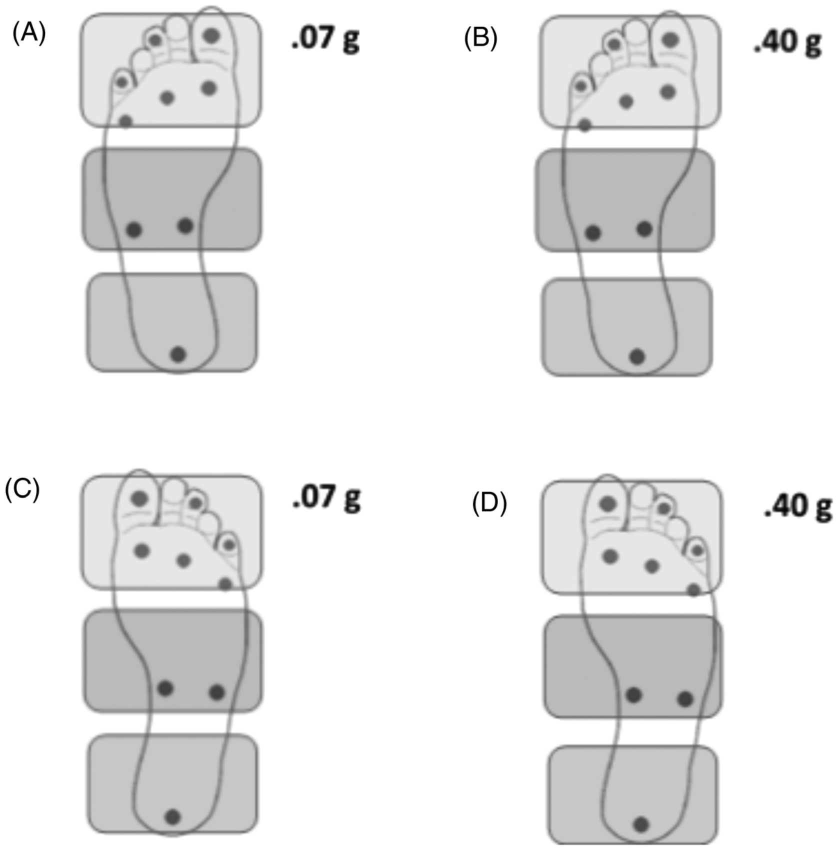


FIGURE 1 Illustration of the sites tested on: (A) the right foot using the 0.07 g monofilament, (B) the right foot using the 0.4 g monofilament, (C) the left foot using the 0.07 g monofilament, and (D) the left foot using the 0.4 g monofilament

of models were implemented to explore associations between normal plantar cutaneous sensation scores and having overweight (relative to having obesity). Associations were explored using both unadjusted and adjusted (with age and sex as covariates) models. The respective standardized beta coefficients and corresponding 95% confidence intervals (CIs) are presented in the results section. Significant two-tailed tests were set at 5% (i.e., $p < .05$).

3 | RESULTS

The data presented was from 122 participants (81 males and 41 females; 10.3 ± 1.8 years; 140.0 ± 11.2 cm; 44.2 ± 16.0 kg) (Table 1). The respective prevalence of healthy weight, overweight, and obesity in the sample were 42%, 18%, and 40%. Ninety-two percent of the participants with obesity were categorized as class 1, 8% were class 2, and none had class 3 obesity (Table 1).

Having obesity was inversely associated with sensation scores on the left (β = –.241; p = .009) and right (β = –.222; p = .018) forefeet, relative to having healthy weight when using the 0.07 g monofilament (Table 2a). There was a positive association between having overweight and plantar sensation scores on the left (β = .223; p = .016) and right forefoot (β = .216; p = .022), relative to having obesity (Table 2b). There were no significant associations between having overweight and plantar sensation scores on either forefoot, relative to having healthy weight (Table 2a). Age was inversely associated with forefoot sensation scores bilaterally (Table 2a).

Having obesity was inversely associated with plantar sensation scores on the left (β = –.322; p = .001) and right (β = –.253; p = .007) midfeet, relative to having healthy weight (Table 2a). There was a positive association (β = .223; p = .016) between having overweight and scores on the left midfoot, relative to having obesity (Table 2b). There were no significant associations between

TABLE 1 Descriptive and anthropometric data (Mean [SD]) for youth with healthy weight, overweight, and obesity

	Healthy Weight	Overweight	Obese
Number of participants	51	22	49
Male to female ratio	32:19	14:7	35:15
Age (years)	10.4 ± 1.8	10.6 ± 2.1	10.1 ± 1.7
Height (cm)	136.6 ± 10.7	142.2 ± 13.4	143.1 ± 9.6
Body mass (kg)	32.8 ± 8.2	44.4 ± 13.7	56.7 ± 13.5
BMI (kg/m^2)	17.3 ± 1.8	21.5 ± 2.8	27.4 ± 4.4
Obesity classification			
Number of obese class 1			45
Number of obese class 2			4

Abbreviation: BMI, body mass index.

TABLE 2A Age- and sex-adjusted associations between weight status and normal plantar cutaneous sensation scores in youth (reference group: healthy weight): 0.07 g monofilament

Foot Region	Predictor Variable	*p*-Value	Standardized Beta Coefficient	95% CI
Left forefoot	Overweight	.676	.038	(−0.051, 0.078)
	Obese**	.009	−.241	(−0.115, −0.017)
	Age (years)**	<.001	−.307	(−0.305, −0.010)
	Female*	.040	.174	(0.001, 0.049)
Left midfoot	Overweight	.801	−.023	(−0.028, 0.022)
	Obese**	.001	−.322	(−0.053, −0.014)
	Age (years)*	.003	−.256	(−0.012, −0.002)
	Female	.824	.019	(−0.010, 0.008)
Left rearfoot	Overweight	.690	.038	(−0.014, 0.021)
	Obese	.087	−.167	(−0.025, 0.002)
	Age (years)*	.022	−.207	(−0.007, −0.001)
	Female	.513	−.059	(−0.009, 0.004)
Left wholefoot	Overweight	.761	.028	(−0.076, 0.104)
	Obese**	.002	−.286	(−0.181, −0.042)
	Age (years)**	<.001	−.323	(−0.051, −0.017)
	Female	.202	.107	(−0.012, 0.055)
Right forefoot	Overweight	.627	.045	(−0.053, 0.088)
	Obese*	.018	−.222	(−0.121, −0.012)
	Age (years)*	<.001	−.317	(−0.039, −0.012)
	Female	.444	.066	(−0.016, 0.036)
Right midfoot	Overweight	.849	−.018	(−0.028, 0.023)
	Obese**	.007	−.253	(−0.047, −0.008)
	Age (years)**	<.001	−.327	(−0.014, −0.005)
	Female	.952	−.005	(−0.010, 0.009)
Right rearfoot	Overweight	.048	.192	(0.000, 0.035)
	Obese	.917	.010	(−0.013, 0.014)
	Age (years)*	.023	−.205	(−0.007, −0.001)
	Female	.793	−.023	(−0.007, 0.006)
Right wholefoot	Overweight	.503	.061	(−0.063, 0.128)
	Obese*	.014	−.228	(−0.166, −0.019)
	Age (years)**	<.001	−.353	(−0.057, −0.020)
	Female	.612	.043	(−0.026, 0.044)

Abbreviation: CI, confidence interval.
*Indicates statistical significance at the level of $p < .05$.
**Indicates statistical significance at the level of $p < .01$.

having overweight and plantar sensation scores for the 0.07 g monofilament on either midfoot, relative to having healthy weight (Table 2a). There was no significant association between having overweight and plantar sensation scores on the right midfoot, relative to having obesity (Table 2b). Age was inversely associated with midfoot scores bilaterally (Table 2a).

There were no significant ($p > .05$) associations between having overweight and plantar sensation scores in the rearfeet, relative to having healthy weight (Table 2a). Similarly, there were no significant associations between having obesity and sensation scores on the right and left rearfeet, relative to having healthy weight (Table 2a). There were no significant associations between having overweight and plantar sensation scores on the right and left rearfeet, relative to having obesity (Table 2b). Age was inversely associated with rearfoot scores bilaterally (Table 2a).

Having obesity was inversely associated with plantar sensation scores on the left ($\beta = -.286$; $p = .002$) and right ($\beta = -.228$; $p = .014$) wholefeet, relative to having healthy weight (Table 2a). There was a significant association between having overweight and sensation scores on the left ($\beta = .247$; $p = .007$) and right ($\beta = .236$; $p = .011$) wholefeet, relative to having obesity (Table 2b). There were no significant associations between having overweight and plantar sensation

TABLE 2B Age- and sex-adjusted associations between weight status and normal plantar cutaneous sensation scores in youth (reference group: obese): 0.07 g monofilament

Foot Region	Predictor Variable	*p*-Value	Standardized Beta Coefficient	95% CI
Left forefoot	Overweight*	.016	.223	(0.015, 0.144)
Left midfoot	Overweight*	.017	.224	(0.005, 0.055)
Left rearfoot	Overweight	.089	.167	(−0.002, 0.033)
Left wholefoot	Overweight**	.007	.247	(0.034, 0.216)
Right forefoot	Overweight*	.022	.216	(0.012, 0.155)
Right midfoot	Overweight	.059	.177	(−0.001, 0.050)
Right rearfoot	Overweight	.059	.185	(−0.001, 0.034)
Right wholefoot	Overweight*	.011	.236	(0.029, 0.221)

Note. The values for age and sex in the respective models are as reported in Table 2a.
Abbreviation: CI, confidence interval.
*Indicates statistical significance at the level of $p < .05$.
**Indicates statistical significance at the level of $p < .01$.

scores for the 0.07 g monofilament on the left (β = .028; p = .761) and right (β = .061; p = .503) wholefeet, relative to having healthy weight (Table 3a). Age was inversely associated with wholefoot scores bilaterally (Table 2a). Mean (SD) bilateral forefoot, midfoot, rearfoot, and wholefoot plantar sensation scores for the 0.07 g monofilament are presented in Figure 2A,B.

Having overweight was positively associated with plantar sensation scores on the left midfoot (β = .195; p = .044) relative to having obesity when using the 0.4 g monofilament. Age was inversely associated with left midfoot (β = −.262; p = .004) and right rearfoot (β = −.196; p = .033) scores (Table 3a). There were no significant (p > .05) associations between having overweight and plantar sensation scores on the right and left forefeet, relative to having healthy weight (Table 3a). Similarly, there were no significant associations between having obesity and scores on the right and left forefeet, relative to having healthy weight (Table 3a). There were no significant associations between having overweight and plantar sensation scores on the right and left forefeet relative to having obesity (Table 3b). The absence of significant associations persisted for the midfoot, rearfoot, and wholefoot bilaterally. Mean (SD) bilateral plantar sensation scores for the 0.4 g monofilament across all foot regions are presented in Figure 3A,B.

4 | DISCUSSION

This study investigated associations between weight status and normal plantar cutaneous sensation scores among youth. Obesity was highly prevalent (40%) in the current sample [30]. Obesity was inversely associated with normal plantar sensation scores (relative to having healthy weight) only when using the 0.07 g monofilament. Also, overweight was positively associated with wholefoot scores relative to having obesity.

The same nine sites previously established in the literature were assessed [8]. However, rather than simply delineate groups with and without obesity using age adjusted BMI range between 20.10 and 24.89 kg/m^2 [8], we categorized participants into groups with healthy weight, overweight, and obesity using age- and sex-adjusted BMI. Although the findings confirm previous reports of altered plantar sensation in children with obesity [8], this study provides a critical context that was previously missing in the literature. Specifically, inverse associations between obesity and plantar cutaneous sensation scores were observed only for the 0.07 g monofilament. This implies that obesity was only linked with decreased light touch plantar sensation. This decrease may be symptomatic of higher plantar pressures and adaptive skin thickening previously reported in children with obesity [7-10]. This study did not evaluate plantar pressures or glabrous skin thickness; therefore, we could not definitively claim that the observed associations were secondary to loading-induced skin thickening. Nevertheless, the extant literature on the relationships between weight status, loading, and plantar tissue thickness provide a basis for this argument [16,18,20]. Previous research revealed deficits related to pressure sensor systems likely involving Meissner and Pacinian corpuscles when children with obesity were deprived of visual input during quite bipedal stance [6]. The inverse weight-adjusted associations between age and normal plantar cutaneous scores in all foot regions, including the heel, appear to support a plausible mechanism involving chronic loading exposure, adaptive glabrous skin thickening, and consequent mechanosensory dampening.

Overweight was positively associated with scores related to the 0.07 g monofilament relative to having obesity. This suggests that overweight may not yet engender glabrous skin adaptions to the order that may result in diminished light touch sensation. Children with overweight generated 13%, 63%, and 23% more pressure in the heel, midfoot, and forefoot, while age-matched peers with obesity generated 30%, 90%, and 40% more pressure in the heel, midfoot, and forefoot, respectively, during level walking [11].

Although obesity was inversely linked with light touch sensation scores underneath the forefoot, midfoot, and wholefoot bilaterally, these associations did not persist underneath the rearfoot. While this is consistent with prior research conclusion that the greater fat pad thickness in the rearfoot may blunt tactile sensitivity [20], it is important to clarify potential roles of fat pad and plantar tissue thickness. Rearfoot plantar tissue is 36% to 48% thicker

TABLE 3A Age- and sex-adjusted associations between weight status and normal plantar cutaneous sensation scores in youth (reference group: healthy weight): 0.4 g monofilament

Foot Region	Predictor Variable	*p*-Value	Standardized Beta Coefficient	95% CI
Left forefoot	Overweight	.585	.054	(−0.178, 0.314)
	Obese	.449	−.075	(−0.262, 0.117)
	Age (years)	.139	−.136	(−0.083, −0.012)
	Female	.488	.063	(−0.059, 0.123)
Left midfoot	Overweight	.544	.058	(−0.079, 0.150)
	Obese	.063	−.178	(−0.172, 0.005)
	Age (years)**	.004	−.262	(−0.055, −0.011)
	Female	.788	−.024	(−0.048, 0.037)
Left rearfoot	Overweight	.328	−.096	(−0.143, 0.048)
	Obese	.200	−.126	(−0.122, 0.026)
	Age (years)	.059	−.173	(−0.036, 0.001)
	Female	.672	−.038	(−0.043, 0.028)
Left wholefoot	Overweight	.777	.028	(−0.333, 0.445)
	Obese	.180	−.132	(−0.504, 0.095)
	Age (years)*	.024	−.206	(−0.162, −0.012)
	Female	.799	.023	(−0.125, 0.162)
Right forefoot	Overweight	.985	.002	(−0.245, 0.250)
	Obese	.314	−.101	(−0.288, 0.093)
	Age (years)	.274	−.101	(−0.074, 0.021)
	Female	.894	.012	(−0.085, 0.098)
Right midfoot	Overweight	.328	−.097	(−0.144, 0.049)
	Obese	.252	−.115	(−0.117, 0.031)
	Age (years)	.611	−.047	(−0.023, 0.014)
	Female	.749	−.029	(−0.041, 0.030)
Right rearfoot	Overweight	.772	.028	(0.081, 0.109)
	Obese	.782	−.027	(−0.083, 0.063)
	Age(years)*	.033	−.196	(−0.038, −0.002)
	Female	.369	−.082	(−0.051, 0.019)
Right wholefoot	Overweight	.869	.016	(−0.407, 0.345)
	Obese	.305	−.102	(−0.440, −0.139)
	Age (years)	.165	−.128	(−0.124, −0.021)
	Female	.825	−.020	(−0.155, 0.124)

Abbreviation: CI, confidence interval.
*Indicates statistical significance at the level of $p < .05$.
**Indicates statistical significance at the level of $p < .01$.

than the forefoot [18]. This may explain why having healthy weight did not protect against diminished light touch sensation in the rearfoot in this study. The rearfoot was similarly subjected to the greatest overall pressure among children with healthy weight, overweight, and obesity [11]. It is plausible that previously reported increased plantar tissue thickness is (at least in part) an adaptation to greater recurrent mechanical loading in the rearfoot. Given their location in the epidermis, Merkel cells and the Aβfibers that innervate them are superficial to the hypodermis. The hypodermis is deep to the dermal layer, which houses other slowly and rapidly adapting mechanoreceptors, namely Ruffini, Meisnner, and Pacinian corpuscles [22]. This spatial separation does not support the theory that fat pad thickness may impact tactile sensitivity. Stratum corneum is the most superficial layer of the epidermis and accounts for most of the epidermal layer thickness. Therefore, it seems more plausible that the varying thickness of the epidermal strata (primarily the corneum) (rather than fat pad thickness) mediates tactile sensitivity. Plantar soft tissue, including epidermal layers, was thicker in the rearfoot [18]. Plantar epidermis features robust and spatially peculiar sequencing of keratin filaments, and these are modulated based on the mechanical demands on the epidermis [16]. Because the rearfoot is subjected to relatively greater mechanical loading and functions to absorb shock, its adaption will expectedly be consistent irrespective of weight status.

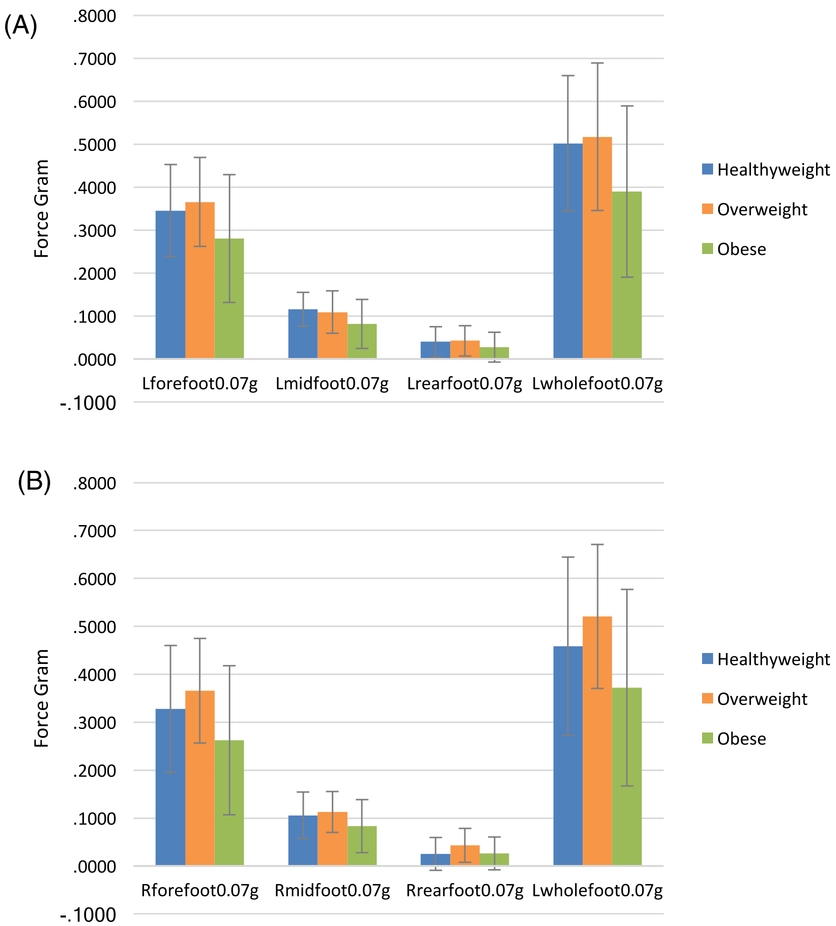


FIGURE 2 Mean (SD) plantar cutaneous sensation scores (in g) among children with healthy weight, overweight, and obesity using the 0.07 g monofilament on: (A) the left forefoot, midfoot, rearfoot, and wholefoot, and (B) the right forefoot, midfoot, rearfoot, and wholefoot

TABLE 3B Age- and sex-adjusted associations between weight status and normal plantar cutaneous sensation scores in youth (reference group: obese): 0.4 g monofilament

Foot Region	Predictor Variable	*p*-Value	Standardized Beta Coefficient	95% CI
Left forefoot	Overweight	.263	.111	(−0.107, 0.388)
Left midfoot	Overweight*	.044	.195	(0.003, 0.234)
Left rearfoot	Overweight	.992	.001	(−0.096, 0.097)
Left wholefoot	Overweight	.191	.128	(−0.131, 0.651)
Right forefoot	Overweight	.429	.079	(−0.149, 0.348)
Right midfoot	Overweight	.925	−.009	(−0.101, 0.092)
Right rearfoot	Overweight	.617	.049	(−0.071, 0.120)
Right wholefoot	Overweight	.534	.062	(−0.259, 0.498)

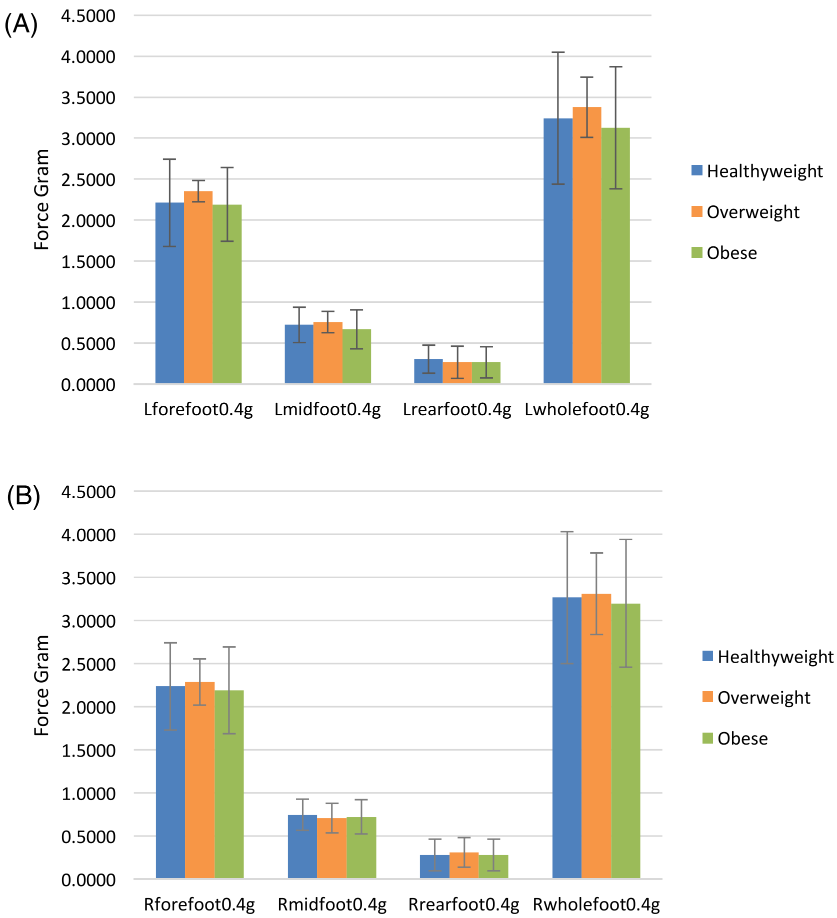
Note. The values for age and sex in the respective models are as reported in Table 3a.
Abbreviation: CI, confidence interval.
*Indicates statistical significance at the level of $p < .05$.

The lack of associations between healthy weight, overweight, and obesity, and regional and wholefoot plantar cutaneous sensation scores when using the 0.4 g monofilament suggests that children across all weight categories similarly sensed the 0.4 g monofilament. This is important, because it implies that while children with obesity likely have diminished light touch sensation (evidenced by the inverse association between obesity and 0.07 g plantar sensation scores), their sensation remains within normal classification. Clinically, this finding implies that barring progressive metabolic changes that may precipitate type II diabetes and associated neuropathy, youth with obesity likely present with intact protective sensation.

5 | STRENGTHS AND LIMITATIONS

This study features a number of strengths. In contrast to previous research, the sole use of the two monofilaments that exclusively test

FIGURE 3 Mean (SD) plantar cutaneous sensation scores (in g) among children with healthy weight, overweight, and obesity using the 0.4 g monofilament on: (A) the left forefoot, midfoot, rearfoot, and wholefoot, and (B) the right forefoot, midfoot, rearfoot, and wholefoot



for normal plantar sensation provides a focused framework to interpret findings in a manner that is specific only to normal plantar sensation. Findings provide a rationale for separately analyzing children with overweight and those with obesity when evaluating parameters thought to be associated with weight status.

There were several limitations of this study. The research team did not establish leg preference in the current sample. Laterality may moderate plantar loading and the degree to which glabrous skin may adaptively thicken. While this information could potentially explain variations in between sides, each foot region was independently analyzed without side-to-side comparisons. This study lacks information on how long participants may have been at their current weight. Also, the research team did not measure glabrous skin thickness. The cross-sectional design of this study precludes any insight into changes in normal plantar cutaneous sensation or glabrous skin thickness during progressive weight gain in children. Although the sample size was not particularly large, it exceeded the size indicated in a priori power analysis for a medium effect size (i.e., f^2 = 0.15). Some of the significant findings may be due to bias related to the lack of adjustment for multiple testing.

6 | CONCLUSIONS

The lack of association between obesity and scores related to the 0.04 g monofilament suggests that children with obesity may have normal plantar sensation, albeit with decreased sensation to light touch. A combination of decreased light touch sensation and previously described increased sensation threshold related to Weber law could potentially exacerbate adverse postural outcomes in children with obesity, particularly during movements involving pedal support. Although the extent to which such postural exacerbations may occur remains unclear, a mechanosensory-related intervention may be warranted in children with obesity. Overweight was not linked with decreased plantar cutaneous sensation to light touch. Considering that Merkel cells and the Aβfibers that innervate them and other slowly and rapidly adapting mechanoreceptors are superficial to the hypodermis, it is likely that adaptive glabrous skin thickening (rather than increased fat pad thickness) underlies the link between obesity and decreased light touch sensation. Future work should explore the principle of stochastic resonance (achieved through plantar vibratory signal delivery) on postural regulation parameters in children with obesity.

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CONFLICT OF INTEREST

The authors declared no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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