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Vertical ground reaction forces during gait in children with and without calcaneal apophysitis

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ABSTRACT

Background: Heightened vertical load beneath the foot has been anecdotally implicated in the development of activity-related heel pain of the calcaneal apophysis in children but is supported by limited evidence.

Research question: This study investigated whether vertical loading patterns during walking and running differed in children with and without calcaneal apophysitis.

Methods: Vertical ground reaction force, peak plantar pressure (forefoot, midfoot, heel) and temporospatial gait parameters (cadence, step length, stride, stance and swing phase durations) were determined in children with (n = 14) and without (n = 14) calcaneal apophysitis. Measures were acquired during barefoot walking and running at matched and self-selected speed using an instrumented treadmill, sampling at 120 Hz. Statistical comparisons between groups were made using repeated measure ANOVAs.

Results: There were no significant between group differences in vertical ground reaction force peaks or regional peak plantar pressures. However, when normalised to stature, cadence was significantly higher (≈ 5%) and step length shorter (≈ 5%) in children with calcaneal apophysitis than those without, but only during running ($P < .05$). Maximum pressure beneath the rearfoot during running was significantly correlated with self-reported pain in children with calcaneal apophysitis.

Significance: Peak vertical force and plantar pressures did not differ significantly in children with and without calcaneal apophysitis during walking or running. However, children with calcaneal apophysitis adopted a higher cadence than children without heel pain during running. While the findings suggest that children with calcaneal apophysitis may alter their cadence to lower pressure beneath the heel and, hence pain, they also highlight the benefit of evaluating running rather than walking gait in children with calcaneal apophysitis.

1. Introduction

Calcaneal apophysitis is a common cause of activity-related heel pain in children, which is characterized by pain involving the secondary growth centre of the calcaneus [1]. Although poorly understood, the condition is widely considered to be a mechanical overuse injury of the chondral physis in children, with elevated vertical ground reaction force often raised as one of several factors anecdotally suggested to be linked to its development [1–3].

Previous research has reported that children with calcaneal apophysitis have 4–10 times higher peak plantar pressure (kPa) beneath the heel during standing (calcaneal apophysitis cases 339 ± 27; healthy controls 83 ± 2) and walking (calcaneal apophysitis cases 880 ± 78; healthy controls 88 ± 11) at self-selected speed than asymptomatic children; suggesting that plantar loading of the heel may be important in calcaneal apophysitis [4]. Surprisingly, despite its well-known clinical link to more dynamic activities such as running and jumping [5], vertical loading beneath the heel during such activities is yet to be investigated in calcaneal apophysitis. This is important because ground reaction forces are known to be influenced by gait speed and changes to basic temporospatial gait parameters [6,7]. The aim of the present study, therefore, was to evaluate peak plantar pressures and vertical ground reaction force parameters during walking and running in children with and without calcaneal apophysitis. Consistent with previous research investigating heel pain in children and adults [4,8,9], it was hypothesized that vertical ground reaction forces during walking and running would be higher in children with calcaneal apophysitis than in those without.

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2. Methods

2.1. Participants

Fourteen children with clinical signs and symptoms of calcaneal apophysitis and 14 healthy children without heel pain participated in the study. Children were 8–14 years of age and recruited from the greater Brisbane metropolitan area via public advertisements and direct referral from health-care providers and local sporting clubs. Calcaneal apophysitis was diagnosed by a healthcare professional with more than 10-years clinical experience using established criteria, which included a comprehensive medical history and physical replication of clinical symptoms with medial and lateral compression of the calcaneal apophysis (squeeze test) [10,11]. Healthy participants were individually matched on age (± 3 yrs), and were free of lower limb pain and pathology on examination. Exclusion criteria for all participants included poorly-defined calcaneal symptoms, a self-reported history of calcaneal fracture, tumour or surgery of the foot within the last 12 months, and a self-reported medical history of autoimmune, neurological, vascular, metabolic or endocrine disorders. No participant presented with lower extremity rotational or angular abnormalities beyond previously reported 'normal' values [12]. Current or past treatment for calcaneal apophysitis were not exclusion criteria in this study.

The mean (± SD) age, height and weight of participants is displayed in Table 1. Of the fourteen children with calcaneal apophysitis, twelve were male and two were female. Eleven children presented with bilateral symptoms, one with symptoms involving only the left foot and two only the right foot. For the purpose of this study, only the right foot was considered in children presenting with bilateral symptoms. In all cases, symptoms had been present for a duration of at least 8 weeks and were exacerbated by physical activity. The median duration of symptoms intermittently experienced by participants prior to assessment was 21 months (range, 6–48 months). Children reported a median heel pain of 3 cm (range, 1–7 cm) on a standard 10-cm visual analogue pain scale (VAS), anchored by the terms "no pain" and "worst pain".

Participant numbers were estimated *a priori* based on previously published ground reaction force data reported for children during treadmill walking [13], and were sufficient to detect a 10% difference in peak vertical ground reaction force (1.03 ± 0.07 BW) at an alpha (α) level of .05 and beta (β) of .20. All participants provided written informed assent with their accompanying guardians providing consent before participating in the study. The methods used in the study received approval from the University Human Research Ethics Committee (Ethics Approval: 1500001041).

2.2. Equipment

An instrumented treadmill system (FDM–THM–S, Zebris Medical GmbH, Isny, Germany) was used to measure vertical ground reaction force, regional plantar pressure and temporospatial gait parameters during barefoot walking and running at self-selected speed (Fig. 1). The treadmill contained a capacitance-based pressure platform with a sensing area of 108.4 x 47.4 cm. The platform incorporated 7168 pressure transducers, each approximately 0.85 x 0.85 cm in size. The belt of the treadmill had a contact surface of 150 x 50 cm, and its speed could be adjusted between 0.2 and 22 km.h^{-1}, in increments of 0.1 km.h^{-1}. Reported coefficients of variation for repeated measures of temporospatial gait parameters in adults is typically below 10% using the system [14,15], but have not been established for paediatric cohorts.

Table 1
Anthropometric data for children with and without calcaneal apophysitis.

Variable	Healthy Control	Calcaneal Apophysitis
n	14	14
Sex (Males: Females)	10:4	12:2
Age (y)	12 ± 2	11 ± 1
Height (cm)	157 ± 13	152 ± 10
Body Mass (kg)	50 ± 16	44 ± 8

n, sample size.

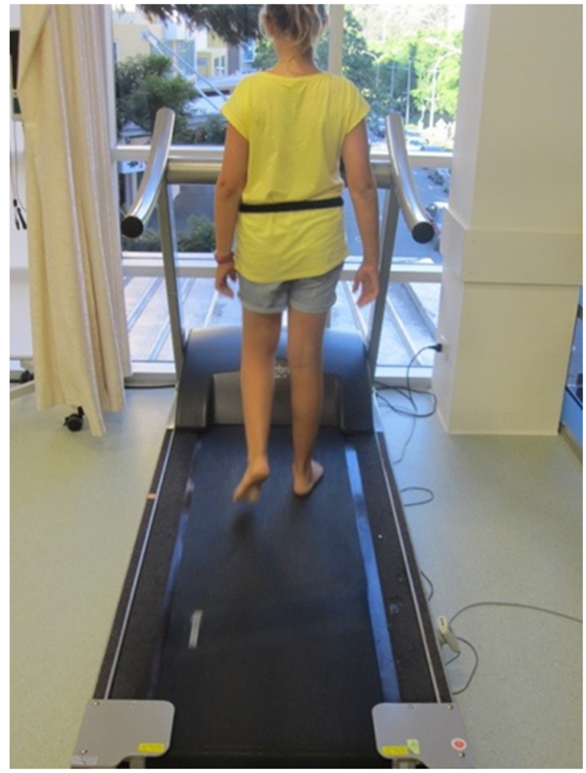

Fig. 1. Vertical ground reaction force, regional plantar pressure and temporospatial gait parameters during barefoot walking and running were estimated *via* an instrumented treadmill system.

2.3. Protocol

Participants reported to the laboratory wearing lightweight, comfortable clothing. Following anthropometric measures of weight and height, children undertook a treadmill acclimatization session which involved a minimum of six minutes of steady-state barefoot treadmill walking and running at a self-selected "comfortable" speed [16,17]. After a further three minutes, plantar pressure and ground reaction force data were then recorded over 10 s of steady-state barefoot walking and running at a sampling rate of 120 Hz [16]. Gait speeds of children without heel pain were individually matched to the self-selected gait speed of children with calcaneal apophysitis to mitigate potentially confounding effects of speed on vertical ground reaction force and temporospatial gait parameters [18,19].

2.4. Data reduction and statistical analysis

As variations in foot strike pattern have been shown to influence peak vertical ground reaction forces in adults [19,20], foot strike patterns during walking and running were determined by visual inspection of each electronic footprint acquired over the 10 s data capture period [21–24]. Foot strike patterns were defined based on previous classifications [23,25] and the following definitions were adopted: a rearfoot foot strike (RFS) was defined as a pattern in which the heel made initial ground contact before the ball of the foot; a forefoot foot strike (FFS) was defined as a pattern in which the forefoot made initial ground contact; a midfoot foot strike (MFS) was defined as pattern in which the middle to upper-middle third of the foot made initial ground contact

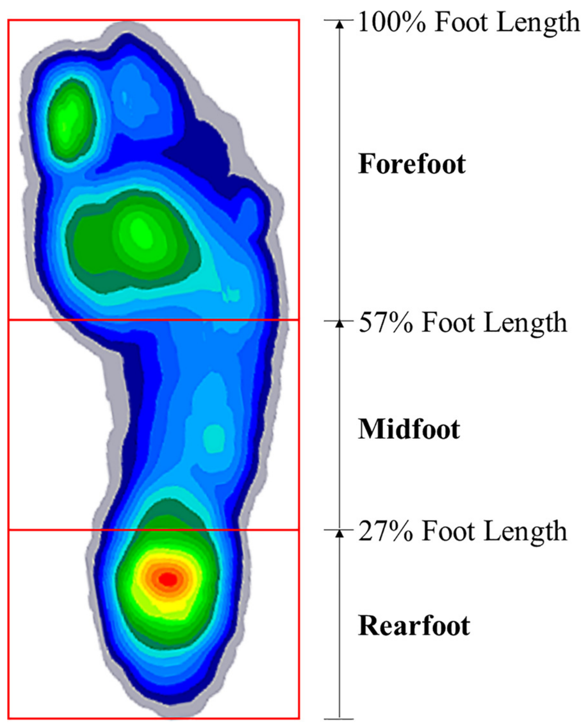

Fig. 2. Each electronic footprint was masked into hindfoot, midfoot and forefoot segments using proprietary software. The maximum plantar pressure in each segment was recorded for each footfall and averaged over 10 s of steady-state barefoot walking and running.

before the remaining sole of the foot. Children that did not display the same consistent footfall pattern (RFS, FFS, or MFS) for more than 70% of foot strikes within the data capture period were classified as having a 'varied' (VFS) foot strike pattern.

Pressure data were exported in ASCII format and custom computer code (Matlab R2012a, MathWorks, Natick, Massachusetts, USA) was subsequently used to determine key temporospatial gait parameters. Walking velocity, cadence and step length were normalised to body height using non-dimensional methods outlined elsewhere [26]. Vertical ground reaction force was normalized to body weight and the magnitude and timing of conventional vertical ground reaction force peaks during walking (two dominant peaks) and running (one dominant peak) was identified for each step. Peak force loading rate, defined as the peak instantaneous force differential during the stance phase of gait, was also calculated using previously outlined methods [27]. Maximum pressure footprints were divided into rearfoot, midfoot and forefoot areas (Fig. 2), and peak regional pressures were subsequently determined [28].

Statistical analysis was performed using IBM-SPSS statistical software (Version 21 for Windows IBM Corp. Armonk, NY, USA). All data were evaluated for normality using the Shapiro Wilk test. As outcome variables were determined to be normally distributed, means and standard deviations have been used as summary statistics. Paired t-tests were used to evaluate potential between-group differences in body anthropometry (height and weight). Foot strike frequency distributions during running were compared between groups using the maximum likelihood ratio Chi-square test. A 2 (gait) x 2 (group) mixed ANOVA model was used to investigate main effects for 'group' and its interactions with 'gait' for vertical ground reaction force, regional plantar pressure and temporospatial gait parameters. Whereby, 'group' (case, control) was treated as the between-subjects factor, and 'gait' (walk, run) was treated as the within-subject factor. Underlying assumptions regarding the uniformity of the variance–covariance matrix were assessed using Mauchly test of sphericity. When the assumption of

Table 2
Mean (SD) temporospatial and kinetic gait parameters during barefoot walking and running on an instrumented treadmill.

	Walk		Run	
	Healthy Control	Calcaneal Apophysitis	Healthy Control	Calcaneal Apophysitis
n	14	14	14	14
Velocity (statures/sec)	0.27 (0.06)	0.28 (0.06)	0.49 (0.04)	0.49 (0.05)
Cadence (dimensionless)	0.38 (0.04)	0.38 (0.04)	0.55 (0.03)	0.58* (0.03)
Step length (statures)	0.35 (0.04)	0.36 (0.05)	0.44 (0.03)	0.42* (0.04)
Stride duration (sec)	1.08 (0.11)	1.05 (0.11)	0.73 (0.04)	0.68 (0.05)
Stance phase duration (% GC)	62 (1)	62 (2)	48 (4)	46 (4)
Swing phase duration (% GC)	38 (1)	38 (2)	52 (4)	54 (4)
First force peak (BW)	1.3 (0.3)	1.2 (0.1)	2.2 (0.5)	2.2 (0.2)
Time first force peak (% SPD)	28 (3)	27 (4)	36 (3)	37 (4)
Minima force (BW)	1.0 (0.3)	0.9 (0.1)	–	–
Time minima force (% SPD)	48 (4)	47 (3)	–	–
Second force peak (BW)	1.3 (0.3)	1.2 (0.1)	–	–
Time second force peak (% SPD)	74 (3)	75 (4)	–	–
Peak force loading rate ($BW{\cdot}s^{-1}$)	0.28 (0.08)	0.31 (0.08)	0.59 (0.20)	0.60 (0.15)
Maximum Pressure Rearfoot (kPa)	230 (66)	240 (34)	262 (67)	242 (89)
Maximum Pressure Midfoot (kPa)	157 (43)	145 (25)	158 (37)	157 (30)
Maximum Pressure Forefoot (kPa)	265 (74)	237 (37)	268 (64)	252 (65)

BW, body weight; *GC*, gait cycle; *SPD*, stance phase duration. *kPa*, kilopascal.
* Indicates a statistically significant difference between children with and without calcaneal apophysitis for the given gait speed ($P < .05$).

uniformity was violated, an adjustment to the degrees of freedom of the F-ratio was made using Greenhouse–Geisser Epsilon, thereby making the F-test more conservative. Post hoc t-tests were used to investigate significant gait by group interactions. Potential relationships among pain, vertical ground reaction force, regional plantar pressure and temporospatial gait parameters were investigated using scatter plots and Pearson product-moment correlations. An alpha level of .05 was used for all tests of significance.

3. Results

Mean absolute walking speed was 1.07 ± 0.23 m/s in children with calcaneal apophysitis and 1.06 ± 0.25 m/s in children without heel pain, while absolute running speed was 1.89 ± 0.23 m/s and 1.91 ± 0.21 m/s, respectively. All participants adopted a RFS pattern during walking. Chi-square analysis revealed there were no significant differences in the frequency of foot strike patterns in children with (RFS 10; FFS 2; MFS 1; VFS 1) and without calcaneal apophysitis (RFS 11;

FFS 1; MFS 0; VFS 2) during running (P = .549).

There was no significant difference in vertical ground reaction force or regional plantar pressure between groups during walking or running (Table 2). There was, however, a significant interaction between 'group' and 'gait' for normalised step length ($F_{1,26}$ = 5.559, P = .026); whereby children with calcaneal apophysitis had a shorter step length than children without heel pain during running but not walking. Similarly, cadence, when normalised to body height, was significantly higher in children with calcaneal apophysitis than those without heel pain but only during running (t_{24} = 2.38, P = .025).

VAS pain scores for children with calcaneal apophysitis were significantly correlated only with the maximum pressure beneath the rearfoot during running (r, 0.77, P = .04) but not walking.

4. Discussion

This study evaluated loading beneath the foot in children with and without calcaneal apophysitis during treadmill walking and running. Contrary to our hypothesis, neither maximum pressure beneath the heel nor vertical ground reaction force parameters differed significantly between groups during treadmill walking and running. Although the findings are at odds with previous studies evaluating plantar pressures during standing and walking [4,8], children with calcaneal apophysitis in the current study had a significantly higher cadence during running than children without heel pain.

The observation that children with calcaneal apophysitis in this research were characterized by an increased cadence when normalized to height during running (≈5%) is consistent with an overuse repetitive injury model [29], in which an increase in the repetition of loading is one mechanism thought to result in the accumulation of fatigue damage at the calcaneal physis [30]. However, it is also possible that children with calcaneal apophysitis may have adopted a higher cadence to ameliorate peak loads and pain beneath the heel during running. In support of such a concept, an increase in cadence as little as 5% in adults has been reported to lower heel loading during running by 2.2% over time [31]. Further, in the current study, self-reported pain in children with calcaneal apophysitis was moderately correlated with peak rearfoot pressure during running; suggesting a potential antalgic gait response at the higher gait speed. It should be noted, however, that self-reported pain was not significantly correlated with cadence in children with calcaneal apophysitis during treadmill running.

Previous research has suggested that foot strike patterns may also influence the magnitude of peak vertical ground reaction force parameters during running in adults [32,33]. In the current study, there was no significant difference in the frequency of foot strike patterns in children with and without heel pain. The majority of children (75%) adopted a RFS pattern during barefoot treadmill running, which is similar to previous research involving children and adolescent populations of similar age, in which the prevalence of RFS during barefoot treadmill/overground running was ≈ 62% [32,34].

There are some limitations in the current study which should be considered when interpreting the results. Firstly, this is a cross sectional study and hence causal relationships cannot be drawn. While it is possible that children with heel pain make gait adjustments in order to maintain consistent loading beneath the foot and potentially avoid pain [35], it is also possible that these differences in gait may contribute to the development of calcaneal apophysitis through more frequent loading. Future research evaluating loading beneath the foot during running with manipulation of cadence or longitudinal studies monitoring loading with resolution of calcaneal apophysitis would seem useful approaches to provide further insight into potential causality. Secondly, there is some evidence that treadmills may induce minor changes in temporospatial and kinetic gait parameters in healthy children when compared to overground walking [36]. While children with and without calcaneal apophysitis participated in the same structured treadmill familiarization process in the current study, it is possible the differences observed in cadence may not be directly transferable to overground gait conditions. Finally, although the age range of children investigated in the current study is consistent with that reported previously in calcaneal apophysitis [37,38], pubertal status is known to influence neuromotor performance in adolescence [39]. Hence it is recommended that potential effects of pubertal status and sex be considered in future investigations when matching participants.

5. Conclusion

The present research identified no significant differences in peak vertical ground reaction force or peak plantar pressures in children with and without calcaneal apophysitis during walking or running. However, children with calcaneal apophysitis adopted a higher cadence than children without heel pain during running. While the findings suggest that children with calcaneal apophysitis may alter their cadence to modulate loading beneath the heel and, hence pain, they also highlight the importance of assessing running as opposed to walking gait patterns in children with painful calcaneal apophysitis.

Author contributions

S. McSweeney: contributed to study conception and design, data collection, data analysis and interpretation, and preparation and approval of the final manuscript.

L. Reed: contributed to study conception and design, data analysis and interpretation, and preparation and approval of the final manuscript.

S. Wearing: contributed to study conception and design, data analysis and interpretation, and preparation and approval of the final manuscript.

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Conflict of interest statement

The authors declare no conflicts of interest, financial or otherwise.

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