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# Tibial impact accelerations in gait of primary school children: The effect of age and speed

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ABSTRACT

Tibial stress fractures are associated with increased lower extremity loading at initial foot-ground contact, reflected in high peak positive acceleration (> 8 g) of the tibia in adults. There is no reported data on peak positive acceleration of the tibia in children during walking and running. The aim of this study was to establish tibial peak positive acceleration responses in children across a range of age and gait speeds. Twenty-four children aged 8.5 ± 1.4 years with no known gait pathology comprised two age groups; Young (7–9 year, n = 12) and Older (10–12 years, n = 12). Wireless Inertial Measurement Unit comprising a tri-axial accelerometer was securely taped to the anteromedial aspect of the distal tibia to measure peak positive acceleration responses while walking and running on the treadmill at 3 different speeds (20% below baseline, baseline, and 20% above baseline). Results showed significant increase in peak positive acceleration with increased gait speed and greater variability in young children compared to older children. The study suggests that ground impact in walking, but not running, is mature by age 7 years. Future studies should explore strategies using peak positive acceleration responses to monitor ground impact during sport activities and its application in gait retraining.

## 1. Introduction

Repeated bouts of dynamic activity comprising high foot-ground reaction forces and loading rates can be beneficial to bone health [1,2]. Such benefits may, however, be compromised by associated tibial stress fractures, which is among the 10 most common injuries in runners [3,4]. Tibial stress fractures are associated with increased lower extremity loading at initial foot-ground contact, reflected in high peak positive acceleration (PPA) of the tibia [5,6]. Crowell et al. [5] argued that running PPA above 8 g potentially present injury risk to the lower extremity. Their argument was based on the calculation of one standard deviation above the mean of uninjured runners (n = 171). Knowing the PPA of running can provide substantial information on gait quality and most importantly, may reflect the risk of lower extremity injury. To our knowledge PPA of the tibia in children has not previously been reported for either walking or running.

Gait development in children is a gradual process with Sutherland et al. [7] suggesting that mature gait patterns are well established by 3 years of age but according to Peterson et al. [8] as late as 12 years, depending on the variables explored. Others [9–11] suggested that normalized basic gait parameters such as step length and gait speed stabilize from 5 to 13 years with little change from age 7. Ganley and Powers [12], however, suggested that gait is not fully developed by 7 years because at that age they may still lack the neuromuscular maturity to generate adult-like gait patterns. Gait maturation rate, as reflected in muscle activation, is also inconclusive [7,13–15]. Shiavi et al. [15], for example, compared muscle activity patterns of children aged 4 and 7 years with a group 8–11 years and revealed significant changes in the intensity and phases of activity in the Rectus Femoris and the Hamstrings but not the Tibialis Anterior. In contrast, Detrembleur et al. [16] found that muscle activation onset and duration during comfortable speed walking in children 4–7 years was not different to that of a group aged 8–11 years, later confirmed by Chang et al. [13]. Using variability measurements, Tirosh et al. [17] reported greater variability in the lower limb muscle activity patterns of children between 7 and 9 years compared to children aged 13 to 16 years but the effects were more accentuated in slow and fast walking than at preferred speed. PPA variability may, therefore, be a good indicator understanding gait maturation.

It is acknowledged that walking speed is a key factor influencing gait parameters including local dynamic stability [18], foot loading characteristics [19], stride duration fluctuation [20], and muscle

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activity [17,21]. Increased walking speed also reduces dynamic stability, indicated by increased finite-time Lyapunov exponents calculated at the ankle, knee, and hip [18]. Rosenbaum et al. [19] investigated gait speed effects on foot loading in 20 typically-developing children and found that systematically manipulating gait speed influences foot loading characteristics. Using a treadmill protocol Bollens et al. [20] examined the fluctuation dynamics and magnitude of gait variables in adults and children during 15–30 min continuous walking in 6 conditions, representing 20, 40, 70, 100, 130, and 160% of comfortable walking speed. They found that lower speeds increased the coefficient of variation of stride duration and the fluctuation magnitude was significantly greater for children compared with young and older adults. Increased walking speed also caused a significant increase in muscle activation amplitude [21,22], but with relatively stable phasing [21]. Tirosh et al. [17] showed that in non-preferred walking speed (slower or faster) children had significant greater variability in muscle activity indicated by linear envelope and instantaneous mean frequency.

The aims of the present study was to establish tibial PPA responses in children across a range of gait speeds and age.

## 2. Methods

### 2.1. Participants

Twenty-four typical developing (TD) children aged 8.5 ± 1.4 years with no known gait pathology comprised two age groups; Young (7–9 year, n = 12) and Older (10–12 years, n = 12). All participants' guardians provided informed consent according to procedures approved by the Helsinki review board of Tel Aviv Sourasky Medical Center.

### 2.2. Equipment

Wireless Inertial Measurement Units (IMU) comprising a tri-axial accelerometer (YEI 3-space sensor, YEI Corporation) were used to measure the magnitude and direction of acceleration in 3 dimensions. The device does not encumber young children with dimensions 35 mm × 60 mm × 15 mm and 28 g mass. For this study the IMUs sampled at 150 Hz (range ± 16 g) using in-house software written in Python (Python Software Foundation, www.python.org).

### 2.3. Procedure

Initially participants undertook the "Talk Test" to identify their individual baseline walking speed. The "Talk Test" is a method for recommending exercise intensity based on the ability to maintain conversation during exercise and it has been used to define the recommended exercise intensity limit for cardiorespiratory training [23,24]. Quinn and Coons [24] showed that participants exercised at 64 ± 5% VO2max, 82 ± 7% maximal heart rate (12 ± 2% Rating of Perceived Exertion – RPE), in the "comfortable" speaking condition and 71 ± 6% VO2max, 90 ± 6% maximal heart rate (15 ± 2% RPE), in the reported "not sure" speaking trial. In this study participants were allocated to groups of three, walking together along a 1 km track. The instruction was to "walk as fast as possible, but not run, at a speed in which it is difficult to talk comfortably to your walking partner". Baseline walking speed for each participant was calculated by dividing the 1 km walking distance by the time to complete the walk.

Following the "Talk Test" participants were asked to attend one testing session. The IMU was aligned with the long axis of the tibia and securely taped to the anteromedial aspect of the distal tibia. The IMU was positioned with the sensing axes X–Z orientated right, posterior and vertically, respectively. Similar to previous studies, participants wore their own running shoes during all sessions [25].

The testing session included 3 gait trials differ by speed; 20% below baseline (−20Bs), baseline (Bs), and 20% above baseline (+20Bs), multiples of 0.8, 1.0, and 1.2 respectively from the walking speed established in the "Talk Test". Participants walked for 2 min in each of the walking trials with no resting between trials. In each walking trial 30 s of acceleration data was captured from the IMUs for further analysis.

### 2.4. Data processing

Data processing and analysis was performed offline using MATLAB® version R2014b (MathWorks, Inc). A fourth order, recursive, Butterworth, low-pass filter was used to filter the tibia accelerometer data at 60 Hz [26]. The PPA tibial acceleration during each stance phase was then identified using in house MATLAB code from the filtered tibia acceleration data.

### 2.5. Data analysis

For statistical analysis the average (avgPPA) and standard deviation (sdPPA) PPA for each gait trial was calculated. To examine the effects of walking speed (−20Bs, Bs, and +20Bs), and age (young vs older children) on avgPPA and sdPPA, a Multivariate Measures Analysis of Variance (MANOVA) was used. Bonferroni's test was used for post-hoc analysis of between-group and between-condition means and standard deviations. The level of significance for the statistical tests was set at 0.05.

## 3. Results

Participant characteristics and gait speeds are summarized in Table 1. The mean age of the young group (7.8 ± 0.9 years) was significantly lower than the older group (9.2 ± 0.9 years), $p < 0.05$. The −20Bs walking speed was significantly slower than the Bs and the +20Bs, and the Bs speed was significantly lower than the +20Bs speed ($p < 0.01$).

### 3.1. Tibial loading measurements

#### 3.1.1. Speed-condition

Main speed effect ($F(4,130) = 23.05$, $p < 0.01$) was found showing significant increased avgPPA and sdPPA in the +20Bs trial compared to the −20Bs and Bs trials ($p < 0.01$, see Fig. 1). Post hoc analysis also revealed that the avgPPA during Bs walking was significantly greater than the avgPPA during the −20Bs gait trial (1.97 ± 0.41 g and 1.38 ± 0.24 g, respectively, $p < 0.01$).

#### 3.1.2. Age-group

Main age effect showed that younger children had significantly greater avgPPA and sdPPA values compared to older children ($F(2,66) = 3.15$, $p < 0.05$, for avgPPA 2.38 ± 1.18 g and 2.01 ± 0.73 g, respectively, and for sdPPA 1.14 ± 0.97 g and 0.81 ± 0.62 g, respectively, see Fig. 2).

## 4. Discussion

The present study is the first to report PPA of the tibia in children

**Table 1**
Participant characteristics and gait speeds.

| Age group | Young Children | Older Children |
|---|---|---|
| Number | N = 12 | N = 12 |
| Age (yrs) | 7.80 ± 0.9 | 9.20 ± 0.9 |
| Height (cm) | 128 ± 7.2 | 141 ± 4.3 |
| Weight (kg) | 41.10 ± 9.9 | 48.30 ± 4.8 |
| Comfortable walking speed (m/s) | 1.27 ± 0.2 | 1.37 ± 0.1 |
| Threshold walking (m/s) | 1.61 ± 0.2 | 1.72 ± 0.2 |
| Jogging (m/s) | 1.91 ± 0.2 | 2.05 ± 0.2 |