



## Original research

# Repeatability of tibial acceleration measurements made on children during walking and running



Oren Tirosh<sup>a,\*</sup>, Guy Orland<sup>b</sup>, Alon Eliakim<sup>c</sup>, Dan Nemet<sup>c</sup>, Nili Steinberg<sup>b</sup>

<sup>a</sup> School of Health Sciences, Swinburne University of Technology, Australia

<sup>b</sup> The Wingate College of Physical Education and Sports Sciences at the Wingate Institute, Israel

<sup>c</sup> Child Health and Sport Center, Pediatric Department, Meir Medical Center, Sackler School of Medicine, Tel Aviv University, Israel

## ARTICLE INFO

## Article history:

Received 9 September 2017

Received in revised form 5 April 2018

Accepted 13 April 2018

Available online 5 June 2018

## Keywords:

Tibial accelerometer

Gait

Ground impact acceleration

## ABSTRACT

**Objectives:** To determine the between-visit reliability of an accelerometer as a measure of lower-extremity impact acceleration at a variety of gait speeds in children.

**Design:** Absolute reliability assessment.

**Methods:** Ten children with no known gait pathology attended two testing sessions, three weeks apart. A tri-axial accelerometer was fixed to the child's distal tibia to measure peak positive acceleration responses while walking and running on the treadmill at three different speeds (comfortable walking, threshold walking, and jogging). Reliability of the average and standard deviation Peak Positive Acceleration (avgPPA and sdPPA, respectively) was calculated by intra-class correlation coefficients (ICC) and Minimum Detectable Change (MDC).

**Results:** Excellent reliability was indicated with ICC values for avgPPA of 0.90, 0.95, and 0.81 for comfortable walking, threshold walking, and jogging, respectively. Moderate reliability was found for the sdPPA measures. MDC values were calculated to be 18%, 26%, and 23% for comfortable walking, threshold walking, and jogging, respectively, indicating the amount by which an avgPPA value would need to change to ensure that the change is greater than a measurement error.

**Conclusions:** An accelerometer attached to the distal tibia is practical for use in a clinical environment to collect lower extremity acceleration data in children. Clinicians can utilise this technique for assessing a change following an intervention, such as biofeedback gait retraining.

© 2018 Sports Medicine Australia. Published by Elsevier Ltd. All rights reserved.

## 1. Introduction

Accelerometers fixed to the anterior-medial aspect of the tibia have been used to measure lower extremity acceleration during running.<sup>1,2</sup> Increased lower extremity acceleration at initial foot-ground contact, reflected in high peak positive acceleration (PPA) of the tibia, was reported to be associated with tibial stress fractures.<sup>3,4</sup> Crowell and Davis<sup>1</sup> argued that running PPA above 8 g potentially presents injury risk to the lower extremity. Their argument was based on the calculation of one standard deviation above the mean of uninjured young adult runners ( $n = 171$ ). Knowing that the PPA of running can provide substantial information on gait quality may, most importantly, reflect the risk of lower extremity injury. A clinical problem may arise if this measurement technique is found to be unreliable, potentially increasing errors in

diagnosis or the interpretation of the effect of a targeted intervention. It is therefore a requirement that measurement techniques produce consistent values between measurements administered over time.

Gait measurements must be accurate and reproducible if they are to provide data that can be used for clinical or scientific purposes. This is challenging when measuring children's gait patterns. Gait development in children is a gradual process, with Sutherland et al.<sup>5</sup> suggesting that mature gait patterns are well established by 3 years of age, but can be as late as 12 years according to Peterson et al.,<sup>6</sup> depending on the variables explored. Others<sup>7–9</sup> suggested that normalized basic gait parameters, such as step length and gait speed, stabilize from the ages of 5 to 13 years, with little change after age 7. However, Ganley and Powers,<sup>10</sup> suggested that gait is not fully developed by 7 years because at that age children may still lack the neuromuscular maturity to generate adult-like gait patterns. Furthermore, Tirosh et al.<sup>11</sup> showed that in non-preferred walking speeds (slower or faster) children had significantly greater

\* Corresponding author.

E-mail address: [otirosh@swin.edu.au](mailto:otirosh@swin.edu.au) (O. Tirosh).

variability in muscle activity, indicated by a linear envelope and instantaneous mean frequency.

It is acknowledged that walking speed is a key factor influencing gait parameters, including local dynamic stability,<sup>12</sup> foot loading characteristics,<sup>13</sup> stride duration fluctuation,<sup>14</sup> and muscle activity.<sup>11,15</sup> Rosenbaum et al.<sup>13</sup> 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.<sup>14</sup> examined the fluctuation dynamics and magnitude of gait variables in adults and children during 15–30 min of 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 that 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,<sup>15,16</sup> but with relatively stable phasing.<sup>15</sup>

Recently, Raper et al.<sup>2</sup> investigated the reliability of the ViPerform (ViPerform v5, DorsaVi, Melbourne, Australia) in measuring tibial acceleration in adult athletes during overground running at constant speed. The ViPerform is attached to the medial border of the tibia and uses an accelerometer to measure lower extremity acceleration. Absolute reliability was measured between 4 repetitive strides during a 50 m running trial at ~5.19 m/s. Ten professional triathletes performed 10 trials each. The authors reported excellent between-strides and between-trials (within-visit) reliability (ICC of 0.877, 95% CI 0.825–0.917). Although these results are encouraging, they fail to provide substantial information on between-visits reliability, i.e., the same assessor on different days and test-retest reproducibility. Knowing the between-visits reliability of the accelerometer in quantifying ground impact acceleration is crucial when following up a prolonged intervention, such as one that lasts several weeks. Furthermore, Raper et al.<sup>2</sup> did not investigate the effect of gait speed on reliability. Knowing that speed has an effect on gait outcomes, the effect of speed on between-visits reliability is of substantial importance.

The fundamental question of the current study was whether tibial acceleration measured with an off-the-shelf accelerometer device attached to the medial border of the tibia will produce consistent measurements administered over time in children at a variety of gait speeds. The aim of the present study was, therefore, to determine the between-visit reliability (3 weeks apart) of an accelerometer as a measure of lower-extremity impact acceleration in children at a variety of gait speeds.

## 2. Methods

Ten typically-developing children participated in the study. Participants were included in the study if they were between 7 and 12 years of age, non-obese within the 50% percentile BMI, and without neurological, orthopaedic, or any other conditions that may affect their gait. The parents of all participants gave written informed consent before the study, and all procedures were reviewed and approved by the Institutional Review Board of Meir Medical Center, Israel.

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 is small with dimensions of 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](http://www.python.org)).

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 a conversation during exercise, and it has been used to define the recommended exercise intensity limit for cardiorespiratory training.<sup>17,18</sup> Quinn and Coons<sup>18</sup> showed that participants exercised at  $64 \pm 5\%$  VO<sub>2</sub>max,  $82 \pm 7\%$  maximal heart rate ( $12 \pm 2\%$  Rating of Perceived Exertion – RPE), in the “comfortable” speaking condition, and  $71 \pm 6\%$  VO<sub>2</sub>max,  $90 \pm 6\%$  maximal heart rate ( $15 \pm 2\%$  RPE) in the reported “not sure” speaking trial. In this study, the participants were allocated to groups of two or three children escorted by two instructors. The groups of participants started to walk together along a 1 km track (cycle of 300 m); participants were instructed to proceed at their own walking speed. Then, the participants were asked to walk at the “not sure” walking speed with their friends and instructors. The final instruction was to “walk as fast as possible, but not run, at a speed at which it is difficult to talk comfortably to your walking partner (friend or instructor)”. Baseline walking speed (Bs) for each participant was calculated by dividing the 1 km walking distance by the time it took to complete the walk.

Following the “Talk Test” participants were asked to attend 2 sessions (test and retest) held 3 weeks apart to determine the reliability of the acceleration measurements. In each session the IMU was aligned with the long axis of the tibia and securely taped to the anteromedial aspect of the distal tibia using double-sided adhesive tape wrapped with FabriFoam<sup>®</sup> (see supplemental material). The IMU was positioned with the sensing axes X, Y, and Z orientated right, posterior, and vertically, respectively. Similar to previous studies, the participants wore their own running shoes during all sessions.<sup>19</sup>

The testing session included 3 gait trials that differed 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 (–20Bs and Bs) or ran (+20Bs) on a treadmill for 2 min in each of the testing gait trials, with no rest between trials. In each trial, 30 s of acceleration data were captured from the IMUs for further analysis.

Data processing and analysis was performed offline using MATLAB<sup>®</sup> version R2014b (MathWorks, Inc). A fourth order recursive Butterworth low-pass filter was used to filter the tibia accelerometer data at 60 Hz.<sup>20</sup> The PPA tibial acceleration during each foot strike was then identified using an in-house MATLAB code from the filtered tibia acceleration data. For each participant, the average and standard deviation values from all identified PPAs in each gait speed trial and testing session were calculated (avgPPA and sdPPA, respectively). These values were used for the repeatability calculation for each output variable and gait speed.

For statistical analysis the average and standard deviation PPA (avgPPA and sdPPA, respectively) for each speed trial (–20Bs, Bs, and +20Bs) and testing session (S1 and S2) were calculated. The calculation of reliability started with the performance of a repeated-measures analysis of variance (ANOVA). The reliability was estimated by means of the intraclass correlation coefficient (ICC) between 10 pairs of observations. In particular, we used an ICC 3,k type (Model 3, Form k) because the rater was fixed and the data used to calculate the ICC were the mean data from consecutive gait cycles performed by the 10 participants in each of the 30 s gait speed conditions.<sup>21</sup> ICC was calculated using SPSS software version 24 (SPSS Inc., Chicago, IL, USA). We selected the option “Absolute agreement” to take into account the systematic error between the two sessions. Reliability was classified as low, moderate, or excellent, according to the following criteria: an ICC greater than 0.75 was considered excellent, an ICC between 0.40 and 0.75 was moderate, and an ICC lower than 0.40 was classified as low.<sup>22</sup> Standard error of measure (SEM) and minimal detectable change (MDC) were calculated utilising the same methodology as previous dynamometry studies.<sup>23</sup> SEM was calculated as  $SD \times \sqrt{1 - ICC}$ , where SD is the standard deviation of all scores of the participants. SEM is also pre-

**Table 1**  
Participants' characteristics and gait speeds, 20% below baseline speed (−20Bs), baseline speed (Bs), and 20% above baseline speed (+20Bs).

	Mean (SD)
Age (years)	10.7 (1.27)
Weight (kg)	33.51 (6.81)
Height (cm)	145.75 (11.45)
Slow walking speed (−20Bs) (m/s)	1.4 (0.10)
Baseline walking speed (Bs) (m/s)	1.75 (0.12)
Running speed (+20Bs) (m/s)	2.10 (0.14)

sented as a SEM% by dividing the SEM with the average of the test and retest values. The SEM was used for calculating the minimal detectable change (MDC), and was calculated as  $SEM \times 1.96 \times \sqrt{2}$  to construct 95% CI.<sup>21</sup> Statistical significance was set at  $p < 0.05$  for all calculations.

### 3. Results

The participants' characteristics and gait speeds are summarized in Table 1. The mean age, height, and weight were  $10.7 \pm 1.27$  years,  $145.75 \pm 11.45$  cm, and  $33.51 \pm 6.81$  kg, respectively. The −20Bs walking speed was significantly slower than the Bs and the +20Bs, and the Bs speed was significantly lower than the +20Bs speed (1.4, 1.75, 2.1 m/s for −20Bs, Bs, and +20Bs, respectively;  $F(2,30) = 44.25$ ,  $p < 0.01$ ).

Peak positive acceleration for all participants in the 3 gait speed conditions (−20Bs, Bs, and +20Bs) for testing sessions 1 and 2 are illustrated in Fig. 1. The reliability of individual avgPPA measurements is presented in Table 2. Single measure of reliability for avgPPA was calculated to be excellent for all gait speeds, with an ICC of 0.90, 0.95, and 0.81 for −20Bs, Bs, and +20Bs, respectively. Measurement variation was 6%, 9%, and 8% for −20Bs, Bs, and +20Bs speeds, respectively.

The reliability of individual sdPPA measurements is presented in Table 2. Single measure of reliability for sdPPA was calculated to be excellent for below baseline speed (−20Bs) with an ICC of 0.85. For baseline walking and running, the reliability was moderate, with ICC of 0.63 and 0.51, respectively. Measurement variation was 30%, 30%, and 20% for −20Bs, Bs, and +20Bs speeds, respectively.

### 4. Discussion

This study was stimulated by the need to assess the reliability of an accelerometer attached to the distal medio tibia for evaluating ground impact acceleration in children's gait. If such a technique is to be used in evaluating gait improvement due to rehabilitation, it is necessary to consider the values of test-retest reliability based on testing sessions that differ by days or weeks. For example, Crowell and Davis<sup>1</sup> used this technique in adults to investigate the use of two-week biofeedback gait retraining in reducing ground impact acceleration in running. Moreover, since gait can be performed at different speeds, accurate measurement of different speeds is necessary. Therefore, this study is the first to assess the reliability of an accelerometer fixed to the distal tibia to evaluate ground impact acceleration in children's gait at several speeds.

In this study, the technique used to assess ground impact acceleration in children's gait showed excellent reliability. Other studies found similar reliability in adult athletes using the ViPerform system (ViPerform v5, DorsaVi, Melbourne, Australia).<sup>2</sup> In a different study, for example, Liikavainio et al.<sup>24</sup> fixed tri-axial accelerometers below the knee joint in healthy young men while walking at preferred speed (1.3 m/s), to measure the repeatability of the peak acceleration at foot ground contact in two testing sessions separated by 2 days. The authors found a good inter-day repeatability ( $CV < 15\%$ ) and concluded that skin-mounted accelerometers

are practical for use in clinical environments to collect acceleration data. A limitation of both studies was that repeatability was assessed only during a single gait speed, while it is well known that walking speed is a key factor influencing gait parameters.<sup>12</sup> In this study we showed excellent reliability at different gait speeds, indicated by ICC measures of 0.9, 0.95, and 0.81 for −20Bs, Bs, and +20Bs speed conditions, respectively.

The excellent reliability for the avgPPA measure found in this study is encouraging, as children's gait is known to be less developed and still lacking in the neuromuscular maturity to generate adult-like gait patterns.<sup>10</sup> This is further challenged in non-preferred walking speeds, as children demonstrate significantly greater variability in muscle activity during slow and fast walking speeds.<sup>11</sup> While in this study we found that avgPPA significantly increased with increased gait speed, the reliability remained excellent in all speeds having ICC values of 0.90, 0.95, and 0.81 for −20Bs, Bs, and +20Bs, respectively. This, however, was not the case in the sdPPA measure, which only had moderate ICC values in the Bs and +20Bs speeds, 0.63 and 0.51 respectively. The sdPPA is a measure of stride-to-stride variability that provides information about the fluctuation of an individual's ability to control ground impact at initial foot contact. A stride-to-stride gait variability is an important predictor for various neurological and age-related diseases.<sup>25</sup> It is clear from our results that the children had a large stride-to-stride PPA variability, which affected the between-visits reliability. The sdPPA found in this study strengthens previous findings suggesting that children's gait is not fully matured by the age of 10 years. The use of sdPPA as a measure for investigating the effect of interventions, therefore, may not be suitable in children's gait, and must be used with caution.

Overall, the results indicate that a high level of reliability for avgPPA can be obtained using an accelerometer attached to the distal tibia. Although ICC is usually reported in studies of reliability, SEM and MDC are more important and useful from the clinical point of view. Contrary to ICC, these measures allow the estimation of real changes for one individual, as they are not influenced by between-subject variability.<sup>21</sup> SEM determines the difference between the real value of PPA and the value obtained in one measurement for each participant. On average, the avgPPA SEM% calculated from all gait speeds was only 7.6%, which supports the claim that the instrument yields repeatable measurements, and its use is likely to be of help in both the clinical and research setting. This, however, was less clear for the sdPPA measure, which showed an average SEM% of 26.6%.

The MDC analysis plays a role when the smallest amount of change between two measurements during specific time period is needed for the change to be considered statistically significant. In this study the MDC explains the difference needed for a change in the PPA of one participant to be considered real. The MDC values for the avgPPA increased with increased gait speed, having 0.25, 0.52, and 0.72 for −20Bs, Bs, and +20Bs, respectively. These values indicate the amount by which a patient's acceleration value would need to change to ensure that the change detected is greater than the measurement error. For example, in Bs walking a change in a patient's avgPPA following intervention greater than 0.52 g, would be considered a real change due to intervention. Raper et al.<sup>2</sup> showed MDC (%) values for the ViPerform to be 19.29%, indicating the amount by which an athlete's ViPerform value would need to change to be sure that the change is greater than the measurement error. This study found similar MDC (%) avgPPA values, calculated to be 18%, 26%, 23% for −20Bs, Bs, and +20Bs gait speeds, respectively. This is relevant in clinical settings for clinicians looking to utilise this technique for assessing a change following an intervention, such as biofeedback gait retraining.

A limitation of this study is the possibility that it included one source of systematic error in clinical studies referred as "the learn-

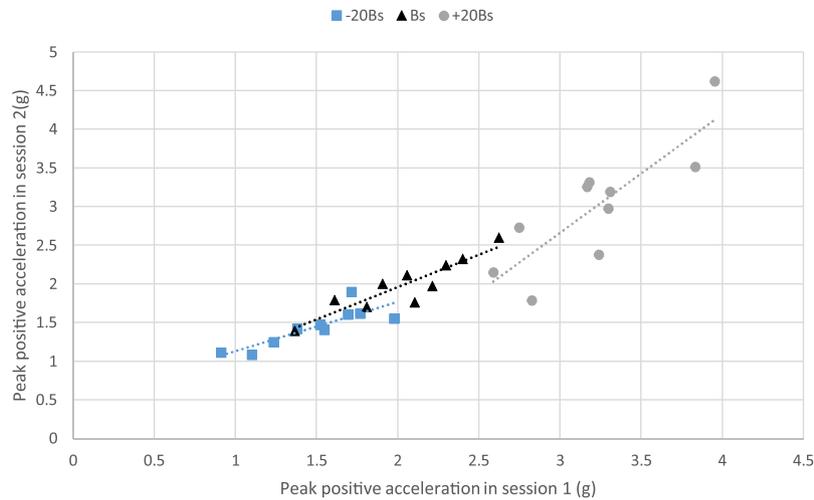


Fig. 1. Accelerometer taped to the anteromedial aspect of the participant's distal tibia.

**Table 2**  
Reliability and minimal detectable change for measurements of average peak positive acceleration (avgPPA, g) and standard deviation peak positive acceleration (sdPPA, g) using accelerometer fixed to distal tibia. Results are presented for the three gait speeds, 20% below baseline speed (–20Bs), baseline speed (Bs), and 20% above baseline speed (+20Bs). (SD = standard deviation, ICC = intra-class co-efficient, MDC = minimal detectable change, SEM = standard error of measure).

	Speed	Test Mean (SD)	Retest Mean (SD)	Difference test-retest Mean (SD)	ICC (CI 95%)	SEM	SEM (%)	MDC	MDC (%)
avgPPA (g)	–20Bs	1.46 (0.32)	1.45 (0.24)	0.01 (0.18)	0.90 (0.63–0.98)	0.09	6%	0.25	18%
	Bs	2.01 (0.37)	2.06 (0.39)	–0.05 (0.33)	0.95 (0.83–0.98)	0.18	9%	0.52	26%
	+20Bs	3.20 (0.41)	2.97 (0.76)	0.22 (0.44)	0.81 (0.28–0.95)	0.25	8%	0.72	23%
sdPPA (g)	–20Bs	0.61 (0.31)	0.53 (0.54)	0.07 (0.36)	0.80 (0.25–0.95)	0.17	30%	0.48	83%
	Bs	0.56 (0.18)	0.53 (0.23)	0.02 (0.26)	0.63 (–0.40–0.91)	0.16	30%	0.46	84%
	+20Bs	1.48 (0.32)	1.23 (0.4)	0.24 (0.41)	0.51 (–0.85–0.87)	0.27	20%	0.77	57%

ing effect”. Children are likely to improve their performance when repeating a task. In this study, we attempted to diminish this effect by giving proper instructions to the participants and allowing them to adequately familiarize themselves with the test procedures. In addition, we ensured that all participants were familiar with treadmill walking and running.

**5. Conclusions**

The current study presented the test-retest repeatability measures of PPA in children walking and running on a treadmill for the first time. The study suggests that the use of an accelerometer fixed to the distal tibia is a reliable technique for measuring lower extremity acceleration in children’s gait at different speeds. The stride-to-stride PPA variability measure, however, is less reliable, and therefore additional caution is recommended when interpreting the effect of an intervention in children’s gait using this measure. Future research should look into determining the reliability of such a technique in adults across a variety of gait speeds.

**Practical implications**

- An accelerometer fixed to the distal tibia is reliable method to measure tibia acceleration during walking and running in children.
- The accelerometer can therefore, be used to investigate interventions aiming to reduce tibia acceleration in children during walking and running.
- Tibia acceleration variability may be used to explore immature running styles in children.

**Acknowledgments**

The Authors would like to acknowledge the Child Health and Sport center for assisting with participant recruitment for this study. This study did not receive any financial assistance from Child Health and Sport center or the accelerometer vendor, YEI Corporation.

**Appendix A. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.jsams.2018.04.006>.

**References**

1. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech* 2011; 26(1):78–83.
2. Raper DP, Witchalls J, Philips EJ et al. Use of a tibial accelerometer to measure ground reaction force in running: a reliability and validity comparison with force plates. *J Sci Med Sport* 2017.
3. Davis IS, Milner CE, Hamill J. Does increased loading during running lead to tibial stress fractures? A prospective study. *Med Sci Sports Exerc* 2004; 36:S58.
4. Milner CE, Ferber R, Pollard CD et al. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc* 2006; 38(2):323–328.
5. Sutherland DH, Olshen R, Cooper L et al. The development of mature gait. *J Bone Joint Surg Am* 1980; 62(3):336–353.
6. Peterson ML, Christou E, Rosengren KS. Children achieve adult-like sensory integration during stance at 12-years-old. *Gait Posture* 2006; 23(4):455–463.
7. Lythgo N, Wilson C, Galea M. Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait Posture* 2009; 30(4):502–506.
8. Holm I, Tveter AT, Fredriksen PM et al. A normative sample of gait and hopping on one leg parameters in children 7–12 years of age. *Gait Posture* 2009; 29(2):317–321.
9. Dusing SC, Thorpe DE. A normative sample of temporal and spatial gait parameters in children using the GAITRite electronic walkway. *Gait Posture* 2007; 25(1):135–139.

10. Ganley KJ, Powers CM. Intersegmental dynamics during the swing phase of gait: a comparison of knee kinetics between 7 year-old children and adults. *Gait Posture* 2006; 23(4):499–504.
11. Tirosh O, Sangeux M, Wong M et al. Walking speed effects on the lower limb electromyographic variability of healthy children aged 7–16 years. *J Electromyogr Kinesiol* 2013; 23(6):1451–1459.
12. England SA, Granata KP. The influence of gait speed on local dynamic stability of walking. *Gait Posture* 2007; 25(2):172–178.
13. Rosenbaum D, Westhues M, Bosch K. Effect of gait speed changes on foot loading characteristics in children. *Gait Posture* 2013; 38(4):1058–1060.
14. Bollens B, Crevecoeur F, Detrembleur C et al. Effects of age and walking speed on long-range autocorrelations and fluctuation magnitude of stride duration. *Neuroscience* 2012; 210:234–242.
15. den Otter AR, Geurts AC, Mulder T et al. Speed related changes in muscle activity from normal to very slow walking speeds. *Gait Posture* 2004; 19(3):270–278.
16. Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. *J Biomech* 2008; 41(8):1639–1650.
17. Persinger R, Foster C, Gibson M et al. Consistency of the talk test for exercise prescription. *Med Sci Sports Exerc* 2004; 36(9):1632–1636.
18. Quinn TJ, Coons BA. The Talk Test and its relationship with the ventilatory and lactate thresholds. *J Sports Sci* 2011; 29(11):1175–1182.
19. Fortune E, Morrow MM, Kaufman KR. Assessment of gait kinetics using triaxial accelerometers. *J Appl Biomech* 2014; 30(5):668–674.
20. Clansey AC, Hanlon M, Wallace ES et al. Influence of tibial shock feedback training on impact loading and running economy. *Med Sci Sport Exer* 2014; 46(5):973–981.
21. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res* 2005; 19(1):231–240.
22. Fleiss JL. *The Design and Analysis of Clinical Experiments*, Hoboken, NJ, USA, New York, John Wiley & Sons, Inc., 1999.
23. Thorborg K, Petersen J, Magnusson SP et al. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports* 2010; 20(3):493–501.
24. Liikavainio T, Bragge T, Hakkarainen M et al. Reproducibility of loading measurements with skin-mounted accelerometers during walking. *Arch Phys Med Rehabil* 2007; 88(7):907–915.
25. Hausdorff JM, Cudkovicz ME, Firtion R et al. Gait variability and basal ganglia disorders: stride-to-stride variations of gait cycle timing in Parkinson's disease and Huntington's disease. *Mov Disord* 1998; 13(3):428–437.