Assessing locomotor skills development in childhood using wearable inertial sensor devices: the running paradigm

Ilaria Masci a, Giuseppe Vannozzi a, Elena Bergamini a, Caterina Pesce a, Nancy Getchell b, Aurelio Cappozzo a

a Department of Human Movement and Sport Sciences, University of Rome “Foro Italico”, Piazza Lauro De Bosis 15, 00135 Rome, Italy
b Department of Kinesiology and Applied Physiology, University of Delaware, DE, USA

Abstract

Objective quantitative evaluation of motor skill development is of increasing importance to carefully drive physical exercise programs in childhood. Running is a fundamental motor skill humans adopt to accomplish locomotion, which is linked to physical activity levels, although the assessment is traditionally carried out using qualitative evaluation tests. The present study aimed at investigating the feasibility of using inertial sensors to quantify developmental differences in the running pattern of young children. Qualitative and quantitative assessment tools were adopted to identify a skill-sensitive set of biomechanical parameters for running and to further our understanding of the factors that determine progression to skilled running performance. Running performances of 54 children between the ages of 2 and 12 years were submitted to both qualitative and quantitative analysis, the former using sequences of developmental level, the latter estimating temporal and kinematic parameters from inertial sensor measurements. Discriminant analysis with running developmental level as dependent variable allowed to identify a set of temporal and kinematic parameters, within those obtained with the sensor, that best classified children into the qualitative developmental levels (accuracy higher than 67%). Multivariate analysis of variance with the quantitative parameters as dependent variables allowed to identify whether and which specific parameters or parameter subsets were differentially sensitive to specific transitions between contiguous developmental levels. The findings showed that different sets of temporal and kinematic parameters are able to tap all steps of the transitional process in running skill described through qualitative observation and can be prospectively used for applied diagnostic and sport training purposes.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Worldwide, childhood obesity has climbed at an alarming rate [1], while physical activity levels have declined [2]. These trends are paralleled by a secular decline in motor skill proficiency, emerging already in early childhood, particularly in motor tasks requiring coordination [3,4]. These findings suggest that low motor skill level and poor physical activity correlate and contribute to rising numbers of overweight and obese children.

Among fundamental motor skills, the acquisition of locomotor skills positively correlates with physical activity levels and health-related fitness, laying the foundation for an active lifestyle in adulthood [5,6]. Running is one of the most commonly adopted forms of upright, bipedal locomotion [7] which typically emerges 6–7 months after the arise of independent walking. The ability to run skillfully is essential to successful participation in many organized games and sport activities.

Both quantitative and qualitative methods exist for examining running proficiency. Commonly used outcome measures are time or speed, with the latter being widely recognized as a quantitative running performance indicator sensitive to age-related changes [8]. However, such measures neglect to account for the motor strategy adopted by the growing child. Alternatively, two different qualitative developmental sequences for running have been proposed to identify individual developmental changes [9,10], one based on developmental changes across the whole body [11], and the other based on changes that occur in specific, individual body actions [12]. Assessment using the developmental sequence approach entails a comparison of the observed running movement with the qualitative descriptions of developmental levels, then an assignment into the appropriate level. However, this approach is time consuming and the administrator is required to be trained and tested in order to establish his/her objectivity.
Instrumented movement analysis represents a possible method to complement the use of the above measures by extracting biomechanical variables from laboratory instrumentation [13] or analyzing interlimb coordination within the framework of a dynamical systems approach [14]. Such instrumentation can support quantitative evaluations of motor development in ecological environments. This can be particularly relevant for basic locomotor skills such as running, which has rarely been submitted to instrumented analysis in infancy and childhood.

Wearable Inertial Sensors Devices (WISDs) may offer an appropriate evaluation tool to perform an objective and in-field assessment; they can measure movement-related data without any space limitation and have no cumbersome set-up. WISDs have been increasingly used in the field of human movement analysis and, specifically, to determine quantitative parameters related to running performance in adulthood [15,16]. In spite of this emerging trend, scientific literature lacks of research studies dealing with the assessment of motor development in childhood using this technology [17].

The purpose of the present study was, therefore, to investigate the feasibility of using a single WISD to quantify developmental differences in the running pattern of young children, in order to provide an objective, quantitative tool sensitive to developmental changes. Specifically, the aim was twofold: (1) to identify a set of biomechanical parameters able to discriminate among different running developmental levels and (2) to increase the knowledge of the factors that determine the progression to proficient running by integrating qualitative and quantitative data. We hypothesized the following: the WISD output measures (temporal and kinematic) would be able to discriminate among developmental running levels as they are described by qualitative developmental sequences. This was a first step to accomplish, toward developing an objective and quantitative tool to be used in ecological settings. Movement practitioners such as physical educators, coaches, and physical therapists alike would benefit from the capability to quickly and accurately assess running proficiency.

2. Materials and methods

2.1. Participants and procedures

Fifty-four children between ages 2 and 12 (average age: 5 ± 3 years; mass: 25.6 ± 5.6 kg; leg length: 0.53 ± 0.13 m, recruited from the University of Delaware’s Early Learning Center (Newark, DE, USA) and from a primary school (Rome, Italy), participated in the research. Age range was selected to cover the age period in which most of the qualitative running changes occur [11]. Research methodology was approved by institutional review board. Prior to admission to the study, parental consent was obtained for each participant. After a brief period of familiarization with the environment, participants were taken to a 15 m long path marked by cones at each end, ensuring at least 3 m of space between the second cone for a safe stopping distance. One of the instructors described the task goal (“run as fast as you can to the other cone”) and allowed the child to practice the motor task. A single trial was taken, then recorded and submitted to further processing.

Participants wore a WISD (FreeSense, Senseori S.r.l, Rome, Italy) equipped with a tri-axial accelerometer and gyroscope (±6 g and ±500 °s⁻¹ of full range, respectively). The device was incorporated in an elastic (neoprene) belt, fastened around the participants’ waist, and positioned at the dorsal side of the lower trunk. Data capture was managed using a Bluetooth protocol and directly loaded into a database. Sampling frequency was set to 100 samples per second. Each trial was simultaneously videotaped (Sony DCR-TRV360, Sony Electronics Inc.) to allow for qualitative analysis.

2.2. Data processing

Qualitative assessment was carried out using the Developmental Level of the Arm Action (DLAA) described in Table 1, a widely accepted assessment tool proposed by Robertson and Halverson [12] and based on 15 years longitudinal data [18].

This choice was supported by the different rates of development observed for arms and legs behavior in running. Specifically, the arm action development is slower than that of the leg one: thus, adopting DLAA would result in higher age-related variability in a sample of children. Otherwise, within this age range, observing children who are level 1 or 2 in leg action would be care when compared with those being at level 1 or 2 in the arm action. Based on these considerations, and using the recorded videos, children were categorized by two trained operators in four DLAA. Intra- and inter-observer reliability were assessed using agreement percentage on 20 randomly selected trials. An intra-observer reliability of 95% agreement between two assessments and an inter-observer reliability of 90% agreement between the two operators were obtained.

In order to obtain a quantitative assessment of running development that may parallel adult running performance evaluation [15], selected temporal and kinematic quantities were extracted from the WISD output and processed in the Matlab® software environment (Mathworks Inc., Natick, MA). To remove random noise, a 2nd order zero-lag Butterworth filter was applied on both the acceleration and angular velocity signals. Different cut-off frequencies for the three axes components were obtained after a residual analysis on each trial for each child [19]: 15 Hz for the cephalo-caudal component (CC) and 25 Hz for the other two components (AP, antero-posterior and ML, medio-lateral).

In order to segment each trial, and to define the relevant initial and final time instants, the CC acceleration signal (Fig. 1a) and its time–frequency representation were considered [20]. The latter analysis was carried out considering a Hamming window (size [15], where L is the signal length) and, then, extracting the peak frequency value in each time instant, thus obtaining a 2D time–frequency diagram (Fig. 1b). According to this representation, three running phases could typically be observed, as corresponding to an increasing, constant and decreasing frequency signal (namely acceleration, steady-state and deceleration phases), respectively.

Running start, t₀, was defined as the point with null acceleration before the local peak preceding the first flight phase (Fig. 1a). Each flight phase was defined as the time interval delimited by the take-off and landing contact time instants, using the cephalo-caudal component of the acceleration and its derivative [21]. The definition of running end, t₁, was obtained as the first landing time instant in the descending ramp starting from the typical constant frequency plateau at about 4 Hz [22],(Fig. 1b). Within the segmented trial, the step frequency (SF) was obtained from a Fourier analysis of the CC acceleration component. Furthermore, the root mean square (RMS) of both the acceleration components along the AP, ML and CC axes and the angular velocities about the same axes was evaluated (ωRMScc,ωRMSap,ωRMSml and aRMScc, aRMSap, aRMSml). The following parameters were then, estimated for each stance phase, defined as the time interval between the landing and the consequent take-off instants of time:

- stance duration (SD);
- maximum peak relative to the acceleration for each component (aPcc, aPap, aPml) and for the magnitude of the acceleration (aPM);
vertical stiffness ($K_v$) estimated as follows:

$$K_v = \frac{F_{\text{max}}}{\Delta y_v}$$

where $F_{\text{max}}$ is the peak vertical force and $\Delta y_v$ is the estimated vertical center of mass displacement. $F_{\text{max}}$ and $\Delta y_v$ were estimated from flight and stance time intervals according to the model proposed by Morin et al. [23].

According to the recognized need of normalizing gait data in children [24], normalized SD and SF (SDp and SFp) were obtained using Hef equations [25]. The values assumed by the parameters, defined within each stance phase, generated a time series of values for each child. To obtain a concise value able to generally describe each parameter series, the area under the relevant series of each child was estimated using a trapezoidal integration. Differently, unique frequency and RMS values were obtained for the whole trial. Assumptions of distributional normality among the same step number in children in each DLLA were tested for all parameters, using the Shapiro–Wilks test. All the area parameters and frequency parameters were, then, considered for statistical analysis.

2.3. Statistical analysis

A stepwise discriminant function analysis was carried out on the 13 proposed quantitative variables, aiming at finding the best predictors of the developmental level membership. Furthermore, to gain a thorough insight in each transition between contiguous levels, a Multiple Analysis of Variance (MANOVA) was performed, determining whether the entire set of parameter means was different among the four developmental levels. In order to identify which variable contributed to discriminate among DLLAs, one-way Analysis of Variance (ANOVA) was then carried out to identify a subset of variables of interest. Finally, Student’s t-tests for independent samples (unequal sample sizes, unequal variance), with Bonferroni–Holm correction for multiple comparisons, were conducted on the estimated variables, to investigate the ability of such variables in detecting transitions from a developmental level to the next one (three transitions: DLLA1–2, DLLA2–3 and DLLA3–4). Significance p-value was set to 0.05 and statistical calculations were performed using PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA). A retrospective power analysis was carried out to observe obtained power values, and partial eta squared ($\eta^2_p$) measures were computed to give the proportion of variance accounted for by each dependent variable. Furthermore, to provide meaningful analysis for comparisons from small groups, Cohen’s effect sizes (d) were also calculated for significant effects [26]. An effect size <0.2 was considered trivial, from 0.3 to 0.6 small, 0.7 to 1.2 moderate, and >1.2 large as in Spencer et al. [27].

3. Results

Age and anthropometric characteristics of the subjects in each DLLA are reported in Table 2.

The stepwise discriminant function analysis showed that the model as a whole was significant (Wilks $\lambda = 0.053, F (15, 3) = 142.6, p < 0.001$). The standardized canonical discriminant function coefficients revealed that the important variables discriminating between DLLAs were $K_v$ ($0.756, SD_N (0.839), aPCC (0.714), SF_N (0.401), aRMSp (−0.564)$. The discriminant model was validated performing a leave-one-out cross-validation procedure and the following accuracy percentages in predicting the DLLA membership were obtained: DLLA1 (67%), DLLA2 (67%), DLLA3 (87%), and DLLA4 (87%).

Average values relative to both temporal and kinematic parameters of the subjects in each DLLA are reported in Table 3. MANOVA revealed a significant multivariate main effect for the DLLA factor (Wilks $\lambda = 0.025, F (39, 113.274) = 7.188, p < 0.001, \eta^2_p = 0.71, (1 – \beta) = 1$). Given the significance of the overall test, the univariate main effects were examined. Significant univariate main effects for DLLA are reported in Table 4.

Focusing on transitions between contiguous developmental levels (Table 3), Student’s t-test between contiguous levels revealed that only $SF_N$ is sensitive to DLLA1–2 ($d = 0.62$) and DLLA2–3 transitions ($d = 1.66$). Furthermore, three additional parameters ($SD_N, aRMS_{M2}$ and $aRMS_{CC}$) can be used to identify the DLLA2–3 only ($d = 1.3, 0.76, 0.73$, respectively). Finally, four additional parameters ($K_v, aPCC, aRMS_p$ and $aRMS_{CC}$) were shown to characterize both DLLA3–4 ($d = 0.99, 0.77, 0.67, 0.91$, respectively) and DLLA3–4 ($d = 0.74, 1.25, 1.12, 0.8$, respectively) transitions.

4. Discussion

In this work, the focus was on the quantitative assessment of developmental changes in the execution of running in childhood in order to (1) complement the information derived from qualitative observation methods with that derived from an appropriate set of biomechanical parameters and (2) further our understanding of the factors that determine the progression to skilled running
Table 3

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDH</td>
<td>6.7±0.7</td>
<td>6.3±0.7</td>
<td>(3.648)</td>
<td>5.4±0.6</td>
<td>5±0.6</td>
</tr>
<tr>
<td>SFH</td>
<td>22.3±3.2</td>
<td>19.7±1.8</td>
<td>(6.757)</td>
<td>15.8±1.3</td>
<td>15.3±2.1</td>
</tr>
<tr>
<td>KV (N m⁻¹ kg⁻¹)</td>
<td>3370.6±691.6</td>
<td>2920.3±724.6</td>
<td>(4.122)</td>
<td>1981.3±503.3</td>
<td>(2.73)</td>
</tr>
<tr>
<td>aPFc (ms⁻²)</td>
<td>138.8±20.3</td>
<td>139.5±23.6</td>
<td>(3.983)</td>
<td>108.8±18.4</td>
<td>(4.398)</td>
</tr>
<tr>
<td>aPFs (ms⁻²)</td>
<td>61.3±8.7</td>
<td>68.1±22</td>
<td>71.5±24.6</td>
<td>73.6±18</td>
<td></td>
</tr>
<tr>
<td>aPe (ms⁻²)</td>
<td>43.7±31.5</td>
<td>42.9±22.6</td>
<td>72.5±42.5</td>
<td>46.1±35.5</td>
<td></td>
</tr>
<tr>
<td>aPM (ms⁻²)</td>
<td>166.9±31.1</td>
<td>166.9±25.8</td>
<td>(2.937)</td>
<td>145.2±12.5</td>
<td>(3.347)</td>
</tr>
<tr>
<td>aRMS MCC (ms⁻²)</td>
<td>11.2±2.3</td>
<td>12.1±2.1</td>
<td>11.2±1.6</td>
<td>10.1±1.2</td>
<td></td>
</tr>
<tr>
<td>aRMS MCC (ms⁻²)</td>
<td>5.8±2.3</td>
<td>6.8±1.7</td>
<td>8.3±1.5</td>
<td>7.9±1.2</td>
<td></td>
</tr>
<tr>
<td>aRMS MCC (ms⁻²)</td>
<td>6.2±1.9</td>
<td>6.3±1</td>
<td>8.3±2.1</td>
<td>6.7±1.3</td>
<td></td>
</tr>
<tr>
<td>aRMS MCC (rad s⁻¹)</td>
<td>1.4±0.8</td>
<td>1.8±0.5</td>
<td>(2.692)</td>
<td>2.4±0.7</td>
<td>2.3±0.5</td>
</tr>
<tr>
<td>aRMS MCC (rad s⁻¹)</td>
<td>1.4±0.8</td>
<td>1.6±0.7</td>
<td>1.2±0.4</td>
<td>1.1±0.2</td>
<td></td>
</tr>
<tr>
<td>aRMS MCC (rad s⁻¹)</td>
<td>0.9±0.3</td>
<td>1.1±0.3</td>
<td>1±0.3</td>
<td>0.8±0.2</td>
<td></td>
</tr>
</tbody>
</table>

*p* < 0.05, 
... *p* < 0.01, 
... *p* < 0.001.

Table 4

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>F (3, 50)</td>
<td>17.245</td>
<td>29.841</td>
<td>25.758</td>
<td>27.528</td>
<td>25.36</td>
</tr>
<tr>
<td>p</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>n.s.</td>
</tr>
<tr>
<td>η²j</td>
<td>0.509</td>
<td>0.642</td>
<td>0.61</td>
<td>0.623</td>
<td>n.s.</td>
</tr>
<tr>
<td>1−β</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

The sensitivity of biomechanical parameters to single transitions between contiguous execution levels. On the whole, the results revealed a complex, but coherent pattern of parameter changes when moving along the sequence of developmental levels (Table 3). Temporal parameters were discriminated between early stages of running skill development. Particularly, a decrement in normalized step frequency characterized the DLAA₁ transition, whereas decrements in both normalized step frequency and stance duration characterized the following DLAA₂ transition. Thus, lower limb behavior seems to play a critical role in early running development.

The intermediate transition, DLAA₂−₃, was characterized not only by better lower limb performances, but also by relevant changes in trunk and upper limb action (see biomechanical quantities highlighted in this transition, Table 3), suggesting the emergence of a new multi-joint coordination pattern. It may be supposed that, in this transition, children are freeing degrees of freedom to coordinate trunk, upper and lower limb actions that are initially counterproductive for the forward running progression. This potential explanation is supported by disadvantageous increments in medio-lateral acceleration and angular velocity of the cephalo-caudal axis along with dysfunctional increments in amplitude of alternating forward accelerations and decelerations (aRMSAP). This confirms that a newly acquired, more complex but probably less stable coordination pattern may not initially result in a biomechanically efficient performance [7], even though representing a prerequisite for the last transition.

In fact, in the last transition, DLAA₃-₄, aRMSAP showed a reverse, decremental change. Speculatively, it can be argued that the child became able to master new degrees of freedom and exploit them for coordinating the joint action of trunk, upper and lower limb [30]. The DLAA₂−₃ and DLAA₃-₄ transitions toward skilled running performance are also indexed by decreasing vertical stiffness and maximum peak relative to both the magnitude of the acceleration and its cephalo-caudal component. The parallel decrement of these parameters suggests that proficient runners are characterized by lower stiffness values during foot stance phase, confirming the presence of a stiffness trend during growth [22].

In conclusion, this study provides evidence of the feasibility of using inertial sensors as a quantitative method for an in-field running assessment in children. The use of the inertial device might be broadly useful to provide information for health care, physical education and sport training professionals. In fact, the proposed approach aimed at identifying factors that determine the transition to proficient running performance which cannot be obtained from the relevant output only (i.e., running velocity, time to run a certain distance). As regards youth sports...
environments, the use of the device might help structure training interventions targeted to optimize those parameters of running performance which are most relevant to realize the transition to the highest developmental level.

Acknowledgments

This work was supported in part by the Regione Lazio – Filas (agreement n. 11226 – July 9, 2009), and in part by the project “SIVAM – Wearable Sensors for Motor Ability Evaluation” funded in the framework of the MISE-ICE-CRUI 2010 agreement.

Conflict of interest statement

The authors do not have any financial or personal relationships with other people or organizations that could inappropriately influence the manuscript.

References