Assessing Hopping Developmental Level in Childhood Using Wearable Inertial Sensor Devices

Ilaria Masci, Giuseppe Vannozzi, Nancy Getchell, and Aurelio Cappozzo

Assessing movement skills is a fundamental issue in motor development. Current process-oriented assessments, such as developmental sequences, are based on subjective judgments; if paired with quantitative assessments, a better understanding of movement performance and developmental change could be obtained. Our purpose was to examine the use of inertial sensors to evaluate developmental differences in hopping over distance. Forty children executed the task wearing the inertial sensor and relevant time durations and 3D accelerations were obtained. Subjects were also categorized in different developmental levels according to the hopping developmental sequence. Results indicated that some time and kinematic parameters changed with some developmental levels, possibly as a function of anthropometry and previous motor experience. We concluded that, since inertial sensors were suitable in describing hopping performance and sensitive to developmental changes, this technology is promising as an in-field and user-independent motor development assessment tool.

**Keywords:** hopping, inertial sensor, children, motor development, biomechanics

During childhood, the acquisition of motor skills is crucial not only for the development of specific motor behaviors, but also for cognitive, affective and social personality development (Payne & Isaacs, 2008; Thelen, 1995). Researchers have suggested that the acquisition of fundamental movement skills (FMS), such as running, throwing or jumping, may positively correlate with physical activity levels, health-related fitness and self-esteem (Stodden, Langendorfer, & Roberton, 2009; Stodden & Goodway, 2007). In other words, as motor skill proficiency improves, children may become more active and fit (Stodden et al., 2008), laying the foundation for a more physically active adulthood (Clark & Metcalfe, 2002; Tammelin, Naya, Hills, & Jarvelin, 2003). This suggests that knowledge of individuals’ motor development is critical to understand their overall development.
One major finding in developmental research is that, throughout childhood, children transition from lower to higher motor skill proficiency (Haywood & Getchell, 2009). One goal for those interested in motor development is to describe qualitative changes occurring in children's motor behavior from the early appearing patterns of coordination to the later/advanced patterns (Roberton & Halverson, 1988). This information can be used in several fields and with different purposes: to identify or to predict the presence of eventual motor disorders; to evaluate changes occurring during motor development; to classify children according to movement skill level; to assess the effectiveness of intervention studies; to compare motor competency in cross-cultural studies (Payne & Isaacs, 2008). For these reasons, movement skill assessment is widely considered as a critical issue in several disciplines, including clinical pediatrics and physical education. In particular, professionals who deal with movement activities in healthy children need to assess the level of movement skills in different age periods. However, it cannot be assumed that children of the same age will be at the same level of a developmental sequence. Despite this interindividual variability, the scientific community agrees that in passing from the least proficient to the most proficient pattern, each child goes through sequential and predictable qualitative steps. Many specific skills show a common developmental trajectory among children, described as developmental levels within sequences (Haywood & Getchell, 2009; Roberton & Langendorfer, 1980).

Among fundamental motor skills, hopping over distance is one of the five distinctive skills (walking, running, galloping, hopping and skipping) humans adopt to accomplish the important task of upright locomotion (Whitall, 2003). It is a specialized form of one-legged forward jumping, often repeated (Roberton & Halverson, 1984; Wickstrom, 1983), that typically developing children begin to perform around the age of three and that they improve during early and middle childhood. A widely used approach for identifying individual hopping ability level is the adoption of developmental sequences of the leg and arm action proposed by Roberton and Halverson (1984) and validated cross-sectionally by Halverson and Williams (1985) and longitudinally by Roberton and Halverson (1988). According to this approach, as a child hops over distance, a trained specialist watches their leg and arm action separately and then makes a decision based on matching performance to qualitative descriptions of each developmental level (either in real-time or after video analysis).

Qualitative assessment of hopping presents advantages and limitations. In fact, the administration of both developmental sequences and in-field tests is relatively fast and easy, providing developmental information without complex data post-processing. On the other hand, both have difficulties in: a) discriminating among participants positioned in one extreme of the scale of the performance level ("ceiling effect" / "floor effect"; Miller, Vine, & Larkin, 2007); b) detecting small changes in the motor behavior during its development. Moreover, they are dependent upon subjective evaluations carried out by a trained operator (Langendorfer, 2001; Nitko, 2001). Therefore, researchers have suggested that a better way for assessing motor competence may be to correlate qualitative with quantitative measures (Burton & Miller, 1998; Langendorfer, 2001; Zhu & Cole, 1996). Such an endeavor requires an instrument that can provide an objective, sensitive measure of motor performance at any given time (Miller, Vine, & Larkin, 2007). Traditional instrumented movement analysis may be considered as an alternative approach for assessing motor behavior,
providing mechanical and neuromuscular parameters that are highly sensitive to the level of execution. For instance, using a force plate for the study of the vertical ground reaction during hopping and a video camera, Getchell and Roberton (1989) identified the landing leg stiffness as a quantitative parameter related to different developmental levels in hopping over distance. However, this approach is usually time consuming and expensive, requiring access to specialized equipment, dedicated laboratory set-ups and demanding data postprocessing.

Nowadays, wearable devices appear to be the best compromise between field and laboratory requirements. Among these, inertial sensors can measure physical quantities related to movement, such as linear acceleration of a rigid body segment. Wearable devices based on inertial sensors have been widely used in the field of human movement analysis. For instance, in research on gait analysis, the use of these devices was shown to be well-established in the literature (Dejnabadi, Jolles, Casanova, Fua, & Aminian, 2006), for example in the estimation of lower limb joint kinematics (Picerno, Cereatti, & Cappozzo, 2008) or to analyze the mechanics of the upper body (Kavanagh, Morrison, James, & Barrett, 2006; Mazzà, Zok, & Cappozzo, 2010). Interestingly, even when using only one inertial sensor device, spatio-temporal parameters could be provided for a quantitative assessment of a motor skill (Zijlstra & Hof, 2003; Innocenti, Facchielli, Torti, & Verza, 2006). This circumstance clearly suggests that inertial sensors may be a feasible tool for assessing motor development in children.

The purpose of this study was to examine the ability of a Wearable Inertial Sensor Device (WISD) to quantify developmental level differences in hopping over distance. This was carried out as a necessary first step toward providing an objective, quantitative tool sensitive to developmental changes. We hypothesized the following: the WISD output measures (temporal and kinematic) are able to discriminate among developmental levels of hopping over distance.

**Materials and Methods**

**Participants and Procedures**

Children between ages 3 and 12 were recruited from the University of Delaware’s Early Learning Center (Newark, DE). The dimension of the sample size ($\alpha = 0.05$; $\beta = 0.8$; ES = 0.5) was determined for MANOVA, one-way ANOVA and $t$ test for independent samples (Cohen, 1977). According to this sample size estimation procedure, the inclusion of at least 9 children was recommended for each of the four hop developmental levels described below. Therefore, after a screening phase carried out using a qualitative hopping assessment and involving a wide number of children, a sample of 40 children (average age: $7 \pm 3$ years; mass: $25.1 \pm 9$ kg; leg length: $0.61 \pm 0.1$ m) was recruited for the study, ten for each developmental level. Research methodology was approved by the University of Delaware institutional review board. Before admission to the study, parental consent was obtained.

Children came into the gymnasium and were greeted by two investigators with backgrounds in physical education. After a brief period of familiarization, during which participants were asked to briefly describe their previous experience in sport, their height and body mass were measured. Children were taken to a 5 m long pathway marked by cones at each end; one of the instructors described the
task goal (“hop from one cone to the other without stopping”), and then demonstrated the task. Children were then asked whether they understood the task, and if they agreed, they then performed a trial of at least 5 consecutive hops along on the preferred foot. Some children at the earliest developmental levels did not hop continuously for 5 hops, but their data were not excluded as long as they did not revert to a different locomotor pattern. Participants were always asked to hop at their preferred speed. After successful completion of one trial, the children were then asked to repeat a further hopping trial that was taken into account for the analysis.

Participants wore a WISD (FreeSense, Sensorize S.r.l., Rome, Italy) equipped with a triaxial accelerometer and two biaxial gyroscopes. The device was incorporated in an elastic (neoprene) belt, fastened around the participant’s waist, and positioned at the dorsal side of the lower trunk. Data were collected in stand-alone mode with a sampling frequency of 100 samples per second. Each trial was simultaneously videotaped (Sony DCR-TRV360, Sony Electronics Inc.) to qualitatively assess each participant’s execution level.

Data Processing

Since the shape of the acceleration curve differed in the first hop over all others (due to the fact that children started from a stationary position), the first hop was discarded and subsequent four hops were used in the analysis. Based on the recorded videos, a single expert operator, trained in using developmental sequences, categorized the participants in four levels, according to the Developmental Levels of the Leg Action (DLLA) reported in Table 1 (Roberton & Halverson, 1984). Intraoperator

<table>
<thead>
<tr>
<th>DLLA Description</th>
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<tbody>
<tr>
<td>1. Momentary flight</td>
</tr>
<tr>
<td>The support knee and hip quickly flex, pulling (instead of projecting) the foot from the floor. The flight is momentary. Only one or two hops can be achieved. The swing leg is lifted high and held in an inactive position to the side or in front of the body.</td>
</tr>
<tr>
<td>2. Fall and catch; swing leg inactive</td>
</tr>
<tr>
<td>Forward lean allows gravity to combine with minimal knee and ankle extension to help the body “fall” forward of the support foot; through quick knee and hip flexion in the support leg, balance is recovered in the landing or “catch.” The swing leg is inactive and is usually held in front of the body. Repeated hops are achieved.</td>
</tr>
<tr>
<td>3. Projected takeoff; swing leg assists</td>
</tr>
<tr>
<td>Perceptible pretakeoff extension occurs in the support hip, knee, and ankle. There is little delay in changing from knee and ankle flexion on landing to takeoff extension. The swing leg now pumps up and down to assist in projection, but range is insufficient to carry it behind the support leg when viewed from the side.</td>
</tr>
<tr>
<td>4. Projection delay; swing leg leads</td>
</tr>
<tr>
<td>The weight of the child on landing is smoothly transferred to the ball of the foot before the knee and ankle extend to takeoff. The swing leg now begins forward action well before initiation of knee extension in the support leg. The range of pumping action in the swing leg increases so that it passes behind the support leg when viewed from the side.</td>
</tr>
</tbody>
</table>
reliability was assessed through a recategorization of 20 randomly selected trials; there was a 95% agreement between the two assessments.

To obtain a quantitative assessment of hopping development, time duration of each task phase and selected kinematic quantities were extracted from the accelerometric WISD output and processed in the Matlab software environment (Mathworks Inc., Natick, MA). A moving average filter with a two-sized window and a Kalman filter (Luinge & Veltink, 2005) were applied to both gyroscope and accelerometer signals along the three axes to refer accelerations to an inertial frame of reference (vertical, \( V \); medio-lateral, \( ML \); antero-posterior, \( AP \)). Temporal parameters, the validity of which was already assessed for walking, running and vertical jumping (Brandes, Zijlstra, Heikens, van Lummel, & Rosenbaum, 2006; Lee, Mellifont, & Burkett, 2010; Moe-Nilssen & Helbostad, 2004; Picerno, Camomilla, & Capranica, 2011), were extracted from the vertical acceleration signal measured in four consecutive hops of each trial. Single hop cycle duration (\( CD \)) was calculated by considering the impact acceleration peak during each landing and calculating the time interval between two consecutive peaks. Flight duration (\( FD \)) was set as the interval of time in which vertical acceleration was equal to gravity acceleration (9.81 \( \pm 0.2 \) m·s\(^{-2} \)). Stance duration (\( SD \)) was calculated as the time difference between \( CD \) and \( FD \). Hopping frequency (\( HF \)) was obtained as the ratio between the number of hops in each trial and the duration of the whole trial, the latter defined as the time interval between the first peak (beginning of the second hop) and the last peak (end of the fifth hop). Each time parameter \( t \) was also normalized according to Hof (1996), as follows:

\[
N_t = \frac{t}{\sqrt{L/g}}
\]

where \( t_N \) is the normalized time parameter (\( CD_N, FD_N, SD_N \) and \( HF_N \)), \( L \) the leg length and \( g \) the gravitational acceleration (9.81 m·s\(^{-2} \)). Within each hop cycle, peak to peak difference of the acceleration relative to each axis was calculated (\( PP_V, PP_{ML}, PP_{AP} \)).

Within-participant hopping variability in the stance phase was also investigated. In this respect, for each single hop stance, acceleration signal along each axis was represented as a percentage of the relevant \( SD \), obtaining a 100–sample signal. Within-participant variability among the single hop acceleration waveforms during each trial was estimated using the Coefficient of Multiple Correlation (CMC, Kadaba et al., 1989). CMC was calculated relative to the acceleration along the vertical axis (\( CMC_V \)), the medio-lateral axis (\( CMC_{ML} \)) and the antero-posterior axis (\( CMC_{AP} \)).

For the sake of comparison between different DLLA for the four hop cycles, the mean value of each variable was calculated, for each subject and each DLLA. Temporal and kinematic variables were checked for collinearity (Aiken & West, 1991). In presence of high Pearson's correlation coefficients, deviation scores were calculated by subtracting from each variable the relevant mean value. A Multiple Analysis of Variance (MANOVA) was performed to determine whether the entire set of means is different among the four developmental levels. To identify which variable contributes to discriminate among DLLAs, one-way ANOVAs were then carried out allowing the identification of a subset of variables of interest. Then, Student's \( t \) tests for independent samples, with step-down Holm-Bonferroni corrections for multiple comparisons, were conducted on the identified variables to
investigate the ability of such variables to detect differences between contiguous developmental levels (three comparisons: DLLA1–2, DLLA2–3 and DLLA3–4). Finally, a stepwise discriminant function analysis was carried out aiming at finding which quantitative variable, among the 11 proposed, was able to predict the developmental level membership. The alpha level was set to 0.05 and statistical calculations were performed using PASW Statistics 18.0 (SPSS Inc., Chicago, IL, USA).

**Results**

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

**Table 2** Ages and Anthropometric Characteristics of the Participants in Each Developmental Level of Leg Action (DLLA)

<table>
<thead>
<tr>
<th>DLLA1 (10)</th>
<th>DLLA2 (10)</th>
<th>DLLA3 (10)</th>
<th>DLLA4 (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y.)</td>
<td>4.6 ± 0.9</td>
<td>4.7 ± 1.10</td>
<td>7.3 ± 2.9</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>19.7 ± 1.8</td>
<td>20.2 ± 2.8</td>
<td>26.7 ± 9.7</td>
</tr>
<tr>
<td>Leg Length (m)</td>
<td>0.53 ± 0.04</td>
<td>0.6 ± 0.06</td>
<td>0.63 ± 0.09</td>
</tr>
</tbody>
</table>

For each parameter, mean ± SD is reported. The number of children categorized in each DLLA is also reported between brackets.

**Table 3** Actual and Normalized Time Parameters and Kinematic Parameters for Participants in Each Developmental Level of Leg Action (DLLA): Cycle, Flight and Stance Durations (CD, FD and SD, respectively), Hopping Frequency (HF) and Peak-to-Peak Acceleration Relative to Each Axis (PPV, PPML, PPAP).

<table>
<thead>
<tr>
<th>DLLA1</th>
<th>DLLA2</th>
<th>DLLA3</th>
<th>DLLA4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD (s)</td>
<td>0.36 ± 0.02</td>
<td>0.4 ± 0.03</td>
<td>0.42 ± 0.04</td>
</tr>
<tr>
<td>CDN</td>
<td>0.16 ± 0.01</td>
<td>0.17 ± 0.02</td>
<td>0.16 ± 0.01</td>
</tr>
<tr>
<td>FD (s)</td>
<td>0.22 ± 0.02</td>
<td>0.24 ± 0.03</td>
<td>0.25 ± 0.02</td>
</tr>
<tr>
<td>FDN</td>
<td>0.09 ± 0.01</td>
<td>0.1 ± 0.01</td>
<td>0.1 ± 0.01</td>
</tr>
<tr>
<td>SD (s)</td>
<td>0.15 ± 0.02</td>
<td>0.17 ± 0.02</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>SDN</td>
<td>0.06 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td>0.07 ± 0.01</td>
</tr>
<tr>
<td>HF (Hz)</td>
<td>2.73 ± 0.13</td>
<td>2.53 ± 0.2</td>
<td>2.42 ± 0.24</td>
</tr>
<tr>
<td>HFN</td>
<td>6.4 ± 0.4</td>
<td>6.07 ± 0.54</td>
<td>6.14 ± 0.41</td>
</tr>
<tr>
<td>PPV (m·s⁻²)</td>
<td>49.2 ± 10.2</td>
<td>49.6 ± 5.4</td>
<td>50.3 ± 6.9</td>
</tr>
<tr>
<td>PPM (m·s⁻²)</td>
<td>24.3 ± 9.5</td>
<td>24.9 ± 6.8</td>
<td>28.8 ± 10.8</td>
</tr>
<tr>
<td>PPA (m·s⁻²)</td>
<td>23.4 ± 5.9</td>
<td>26.1 ± 2.6</td>
<td>28.1 ± 4.3</td>
</tr>
</tbody>
</table>
Time and kinematic parameters for each DLLA are reported in Table 3. Participants who displayed different DLLAs exhibited different average time parameters. In particular, CD, FD, and SD increased as a function of DLLA, while HF decreased as the developmental level increased. However, after normalization, almost all time parameters seemed to lose the mentioned differences between DLLAs, except for DLLA4. Similar observations were carried out for PPAP and PPML in DLLA2-3 and DLLA3-4 comparisons (Table 3).

The analysis of kinematic variability allowed for identifying repeatable time characteristics for the vertical component of the acceleration (mean CMCV ranging from 0.85 to 0.93 and highest in DLLA1), while the other two presented lower coefficients (mean CMCML and CMCAP ranging from 0.52 to 0.71 and from 0.57 to 0.68, respectively, and highest in DLLA4).

Analysis of collinearity confirmed the high correlation among variables, thus deviation scores were calculated and considered for further statistical analysis.

MANOVA revealed a significant multivariate main effect for the DLLA factor (Wilks’s Λ = 0.000; F (33, 77.305) = 3.5; p < .01). Given the significance of the overall test, the univariate main effects were examined. Significant univariate main effects for DLLA were obtained for CD (F (3, 36) = 20.339, p < .01), CDN (F (3, 36) = 5.586, p < .01), FD (F (3, 36) = 10.795, p < .01), SD (F (3, 36) = 11.827, p < .01), SDN (F (3, 36) = 3.351, p < .05), HF (F (3, 36) = 19.015, p < .01), HFN (F (3, 36) = 4.926, p < .01), PPML (F (3, 36) = 6,565, p < .01) and PPAP (F (3, 36) = 29.926, p < .01).

Focusing on the differences between contiguous developmental levels, Student's t test highlighted the presence of significant differences as reported in Table 4.

The stepwise discriminant function analysis showed that the model as a whole was significant (Wilks's Λ = 0.215, F(6, 2) = 55.314, p < .01). The standardized canonical discriminant function coefficients revealed that the important variables discriminating between DLLAs were PPAP (-0.720) and CD (0.879). The discriminant model was able to predict the membership to the extreme groups, DLLA1 and DLLA4, with an accuracy of 80% and 90%, respectively. Conversely, the same model lowered its performance in classifying children to DLLA2 and DLLA3 (40% and 50% of accuracy, respectively).

**Discussion**

The purpose of this research was to examine the efficacy of a wearable inertial sensor device to represent changes in motor proficiency in hopping. Specifically, we wanted to determine if temporal and kinematic output measures derived from WISD would discriminate among the different, qualitatively described developmental levels exhibited in the hop.

Qualitative assessment revealed that DLLA did not increase strictly as a function of age, since children of the same age were not necessarily at the same developmental level. This can be noted by the similar mean age between the first two DLLAs, as well as the higher age standard deviation values for the latter two DLLAs (Table 2). This suggests that DLLA is age-related but not age-dependent, which in turn suggests that individual constraints may play an important role in determining developmental level (Newell, 1986). This finding highlights the well known developmental paradox of ‘universality vs. variability’ (Thelen & Ulrich, 1991). Individuals show great similarity in their motor development, accounting
Table 4  Results of Student’s t Test Carried Out on Deviation Scores of the Six Variables Indicated by the ANOVA: Cycle and Normalized Cycle (CD and CDN), Stance Duration and Hopping Frequency (SD and HF), Peak-to-Peak Acceleration Relative to Antero-Posterior (PPAP) and Medio-Lateral (PPML) Axes.

<table>
<thead>
<tr>
<th></th>
<th>DLLA₁</th>
<th>DLLA₂</th>
<th>t</th>
<th>DLLA₂</th>
<th>DLLA₃</th>
<th>t</th>
<th>DLLA₃</th>
<th>DLLA₄</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD (s)</td>
<td>-0.05±0.02</td>
<td>-0.02±0.03</td>
<td>-2.596*</td>
<td>-0.02±0.03</td>
<td>-0.001±0.04</td>
<td>-1.138</td>
<td>-0.001±0.04</td>
<td>0.07±0.04</td>
<td>-3.651*</td>
</tr>
<tr>
<td>CDN</td>
<td>-0.01±0.01</td>
<td>0±0.02</td>
<td>-1.651</td>
<td>0±0.02</td>
<td>-0.003±0.01</td>
<td>0.429</td>
<td>-0.003±0.01</td>
<td>0.01±0.01</td>
<td>-2.803*</td>
</tr>
<tr>
<td>SD (s)</td>
<td>-0.02±0.02</td>
<td>-0.01±0.02</td>
<td>-1.516</td>
<td>-0.01±0.02</td>
<td>-0.001±0.03</td>
<td>-0.482</td>
<td>-0.001±0.03</td>
<td>0.04±0.02</td>
<td>-3.344*</td>
</tr>
<tr>
<td>HF (Hz)</td>
<td>0.29±0.13</td>
<td>0.08±0.2</td>
<td>2.561*</td>
<td>0.08±0.2</td>
<td>-0.02±0.24</td>
<td>1.110</td>
<td>-0.02±0.24</td>
<td>-0.4±0.2</td>
<td>3.481*</td>
</tr>
<tr>
<td>PPₘₑ (m·s⁻²)</td>
<td>-5±9.5</td>
<td>4.4±6.8</td>
<td>-0.165</td>
<td>4.4±6.8</td>
<td>-0.56±10.8</td>
<td>-0.947</td>
<td>-0.56±10.8</td>
<td>9.5±4.7</td>
<td>-2.715*</td>
</tr>
<tr>
<td>PPₘᵦ (m·s⁻²)</td>
<td>6.23±5.9</td>
<td>-5.5±2.6</td>
<td>-0.404</td>
<td>-5.5±2.6</td>
<td>-1.5±4.3</td>
<td>-2.509*</td>
<td>-1.5±4.3</td>
<td>9.9±3.8</td>
<td>-6.323*</td>
</tr>
</tbody>
</table>

Note. * indicates a p-value lower than the threshold corrected for multiple testing according to the step-down Holm-Bonferroni correction (p < .05 or p < .025 or p < .017). Df for DLLA₁ vs DLLA₂ and DLLA₂ vs DLLA₃ was 14. Df for DLLA₃ vs DLLA₄ was 12.
for the existence of developmental sequences; however, individual differences in
the rate of development also occur, leading to a broad range of ages when individu-
als may exhibit any particular developmental level (Haywood & Getchell, 2009).

In accordance with previous research (Roberton & Halverson, 1988), actual
time parameters changed as a function of DLLA. In particular, while time dura-
tions ($CD$ and $SD$) increased with DLLA, hopping frequency decreased to a value
of about 2 hops per second (Farley, Blickan, & Taylor, 1985). These results seem
to indicate that those timing parameters obtained from accelerometric data are
sensitive to the different hopping execution levels, specifically in distinguishing
DLAA1 from DLAA2 and DLAA3 from DLAA4 (Table 4). However, anthropom-
etric characteristics seem to influence the way in which the child accomplishes the
hopping task. That is, mass and leg length, which covary with age (see Table 2),
may be driving changes in timing parameters in the DLLAs. In fact, the mentioned
differences among DLLAs were almost flattened when analyzing normalized timing
parameters (Table 3). This suggests that children may be constrained by their own
anthropometric characteristics to hop at a specific developmental level.

In the past, changes in hopping frequency have been explained using mechanical
models (Roberton & Halverson, 1988). One popular model is the inverted pendu-
lum (Cavagna, Thys, & Zamboni, 1976) or the spring-loaded inverted pendulum
(Full & Koditschek, 1999), hinged distally and moving proximally. Using this kind
of model, an increase in leg length would explain a hopping rate reduction, sug-
gestig that anthropometry largely induces changes in hopping timing, which is
consistent with our findings.

Even though normalization almost deleted specific increasing/decreasing trends
in timing parameters among DLLAs, DLLA4 children still presented a different
behavior if compared with the other developmental levels. This circumstance was
highlighted in both the ANOVA results, where three normalized variables ($CD_N$,
$SD_N$ and $HF_N$) out of four showed the ability to discriminate between at least two
developmental levels, and, more interestingly, in the DLLA3–4 comparison using
the $CD_N$ variable (Table 4). The latter finding might suggest that transition from
DLLA3 to DLLA4 is more influenced by an increased individual sport experience
and practice than by a change in anthropometry. Supporting this notion was the fact
that, in our sample, a) all the children categorized in DLLA4 had previous experi-
ence in track and field and b) some children categorized in DLLA3 showed similar
anthropometric characteristics with respect to DLLA4 children, but did not have
track and field experience. Anyway, this hypothesis should be better investigated
by recruiting a larger sample of participants with a broad range of physical activity
experiences.

The aforementioned difference between DLLA4 and the previous developmental
levels were confirmed by the results relative to the biomechanical parameters, mainly
by the $PP_{ML}$ and $PP_{AP}$ variables (Table 4). Moreover, the latter parameter detected
differences in the DLLA2–3 comparison. We attributed all these differences to the
swing leg action typically observed in the highest developmental levels. $PP_{ML}$ and
$PP_{AP}$, in fact, were smaller in DLLA1 and DLLA2 than in DLLA3 and DLLA4, the
differences being statistically significant. These findings are consistent with Rober-
ton and Halverson (1988), who found that the most dramatic, qualitative changes
in hopping over distance occurred between DLLA2 and DLLA3. While in DLLA1
and DLLA2 the opposite leg is suspended and held in an inactive position to the
side or in front of the body, in the two highest DLLAs a swing of the opposite leg occurs. This progression of the swinging action was associated with the mentioned differences in $PP_{ML}$ and $PP_{AP}$ values. Small increases of these two variables were observed in DLLA$_3$ children, which typically present a limited range of the swing leg that is insufficient to carry it behind the support leg. Large increases of the same variables were, consistently, obtained in DLLA$_4$ children, typically showing an increased pumping action of the swing leg that increased the take-off phase duration (as confirmed also by the results about $SD$ and $SD_N$, Table 3).

When defining a model able to discriminate among developmental levels and based on quantitative parameters, the results of the stepwise discriminant function analysis assessed that time and kinematic variables ($CD$ and $PP_{AP}$, respectively) might be used to predict DLLA membership, with high classification performances in detecting DLLA$_1$ and DLLA$_4$ execution levels.

The results of this research may be limited somewhat by the exclusion of arm developmental levels, which may account for some of the variability observed in the data. In this respect, the combined use of both developmental sequences for arm and leg action would contribute to further improve the classification performance, eventually leading to a reduction of interindividual variability observed within each developmental level thus obtained.

Future research that considers further biomechanical parameters and potentially having a larger participant sample will enable improvement in the classification performance of the proposed model, particularly for correctly classifying children with intermediate developmental levels. This is a required step before proposing the use of inertial sensors as a stand-alone method for quantifying hop developmental changes in childhood.

In conclusion, inertial sensor devices appear to be promising for quantifying the presence of developmental level differences in leg action in hopping over distance, allowing the estimation of biomechanical parameters able to detect differences between two contiguous hopping developmental levels. Future research in this context would include the definition and the analysis of further biomechanical parameters using the device, opening to the use of this technology as an in-field and user-independent assessment for those interested in hopping development.

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