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Vertical stiffness and balance control of two-legged hopping in-place in children with and without Down syndrome

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ABSTRACT

Background: Children with Down syndrome (DS) are known for their reduced balance control, and typically take longer to develop motor skills and display less coordinated movement patterns. Hopping in-place is a gross motor skill requiring whole-body vertical stiffness and horizontal movement control, particularly when attempting to modify hopping frequency. However, there is a lack of knowledge of the hopping capacity of children with DS.

Research question: The purpose of this study was to assess the ability of children with DS aged 5–11 years old to continuously hop in-place on two legs and compare their biomechanical patterns to those of typically developing (TD) children.

Methods: This observational study included 14 children with DS and 16 TD children. Subjects were asked to complete 20 s trials of two-legged hopping in-place at a self-selected frequency, and four metronome guided conditions: *preferred* (self-selected frequency), *moderate* (20% increase), *fast* (40% increase) and *slow* (20% decrease). Two sample independent *t*-tests were conducted on whole-body vertical stiffness, horizontal center-of-mass movement, and toe displacement between hops for the self-selected hopping condition and two-way ANOVAs were used for the metronome conditions.

Results and significance: Our findings suggest that children with DS might not be able to continuously hop in-place until the age of 7 years old, and were unable to hop for as long in duration as their TD peers. Children with DS self-selected a faster hopping frequency, and demonstrated an increased medial-lateral center-of-mass movement during the stance phase of hopping, suggesting reduced balance control. Moreover, children with DS were unable to correctly modify their hopping frequency when cued by a metronome and exhibited an inability to modulate whole-body vertical stiffness and constrain horizontal or vertical movement. These results demonstrate the utility of a future hopping intervention to improve whole-body vertical stiffness and balance control in children with DS.

1. Introduction

Individuals with Down syndrome (DS) demonstrate reduced muscle strength and balance control [1,2]. These dysfunctions typically cause a delayed onset of motor skills, such as walking, running, and jumping [3], and result in slower force production and movement initiation [4,5]. In contrast to the numerous studies examining the development of gait in children with DS [5–7], little work has been done on the characterization of their hopping/jumping ability. Hopping is a major gross motor skill commonly used during play. From the biomechanical perspective, hopping follows the constraints of a separate model from gait, i.e. spring-mass model vs. inverted pendulum model. Therefore, the study of hopping examines distinct aspects of motor behavior from walking, for example stretch-shortening cycle function [8] and whole-body vertical stiffness control [9]. Moreover, regulation of whole-body vertical stiffness has implications in injury prevention and movement performance [10].

When hopping in-place without external constraints, individuals hopped at a preferred frequency [9,11]. During single-leg hopping, young adults consistently hopped at frequencies around 2.2 Hz [9,12], while typically developing (TD) children hopped faster at 2.56 Hz [13]. This difference has been proposed to stem from an underdeveloped feed-forward ability in TD children aged 7–11 years old to accurately predict the whole-body vertical stiffness required for landing [14] and an underdeveloped stretch reflex [13]. However, given few studies conducted with children with DS in this regard, the assessment of the

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preferred hopping frequency between children with and without DS can provide insights to their differences in neuromuscular functioning.

Both young adults and TD children aged 7–11 years old have the capacity to modulate hopping frequency when presented an auditory metronome cue [9,13,15]. Specifically, to increase hopping frequency they increase whole-body vertical stiffness by reducing vertical COM displacement, stance time, and horizontal COM movement [9,13]. While adults with DS have been shown to benefit from auditory cues in bimanual coordination [16], it is unknown if children with DS can match whole-body movements with auditory information. Further, two-legged hopping in-place to a metronome has been used to assess sensorimotor integration in special populations such as autism spectrum disorders [17]. Considering children with DS have a limited ability to regulate their movement during walking [7], this metronome-matching hopping paradigm will sufficiently challenge children with DS and help assess their sensorimotor integration while hopping at different frequencies.

The purpose of this study was to characterize vertical stiffness and balance control utilized by children with and without DS during two-legged hopping in-place. We hypothesized that children with DS will self-select slower preferred hopping frequencies with lower whole-body vertical stiffness, but will demonstrate greater horizontal COM range of motion and toe displacements between hops. Our second hypothesis was that during metronome-guided frequency conditions, children with DS will demonstrate reduced ability to change hopping frequency compared to TD children, evidenced by greater frequency deviations and an inability to modulate whole-body vertical stiffness. Moreover, children with DS will not decrease horizontal COM range of motion during stance or toe displacement between hops when attempting to increase hopping frequency.

2. Methods

2.1. Participants

We recruited 14 children with DS and 16 TD children aged 5–11 years for this study. We recruited TD children through personal contacts and children with DS through local parent support groups. TD children had no underlying motor or cognitive disorders, and children with DS had no motor or cognitive deficiencies unrelated to their DS diagnosis. We collected subject anthropometric measurements, including height, body-mass, and leg length which was measured from the anterior superior iliac spine to the medial epicondyle of the femur to the medial malleolus of the ankle. This study was approved by the institutional review board at the hosting university. Informed consents were obtained from the parents and verbal assent was obtained from the children prior to data collection.

2.2. Protocol

We attached a 35-marker Vicon Plug-In Gait PSIS full-body set to the subjects [18]. An 8-camera Vicon motion capture system (Oxford, UK), sampled at 100 Hz, captured kinematic data. A floor-embedded force plate (AMTI, MA, USA), sampled at 1000 Hz, recorded kinetic data, which was synchronized to the kinematic data. We filtered both kinematic and kinetic data using a fourth-order zero-lag Butterworth filter with a 6 Hz cutoff frequency. The beginning and ending of the stance phase was determined when the vertical GRF crossed a threshold of 0N.

The subjects hopped on both legs in-place on the force plate with hands on their hips. Subjects first hopped at a self-selected frequency for 20 s for three trials. The subject's preferred frequency was determined as the average frequency across these trials. The subject's preferred frequency set the following metronome-guided conditions, a *slow* condition (20% decrease from preferred), *preferred* condition (0% change from preferred), *moderate* condition (20% increase from preferred), and *fast* condition (40% increase from preferred). For these conditions, subjects were instructed to hop in time with the metronome and verbally encouraged during the trials if not following the metronome. Subjects completed three trials of 20 s for each metronome-guided condition. The order of the conditions was randomized across subjects to minimize learning effects. Subjects received adequate rest between trials to minimize fatigue.

2.3. Data analysis

During stance phase, vertical GRF was plotted over vertical COM displacement, and the slope of the linear regression line defined whole-body vertical stiffness [19–21]. Consistent with the literature, vertical COM displacement was calculated by double integration of acceleration obtained from the vertical GRF using the central difference method [19,22–24]. We normalized whole-body vertical stiffness by bodyweight and leg length, peak vertical COM displacement by leg length, and peak vertical GRF by bodyweight.

We estimated horizontal COM position using segmental analysis from the full-body marker set [18]. During stance phase, anterior/posterior (AP) and medial/lateral (ML) COM range of motion was calculated as the difference between the maximum and minimum positions. The toe marker displacement between hops was calculated in the AP and ML directions on the dominant leg, which was used to kick a ball [19], to quantify horizontal foot deviation from hop-to-hop. Over the course of the 20 s trial, the range of horizontal foot movement was defined as the difference between the maximum and minimum toe position in the AP and ML directions.

Hopping frequency was calculated as the most prominent frequency using a Fourier transform on the vertical GRF data for the entire trial [17], or hopping cycles stitched together when subjects did not continuously hop for the entire 20 s. For the metronome cued conditions, we calculated percent deviation between actual hopping frequency and cued hopping frequency as (actual frequency − cued frequency)/(cued frequency)*100% [17]. We calculated stance time (foot-strike to following take-off) and flight time (take-off to following foot-strike). Hopping height was calculated from vertical velocity of COM at take-off using kinematic equations to minimize the influence of trunk orientation and ankle plantarflexion during flight phase. In addition, correlation analyses were conducted in each group, separately, to establish the relationship between self-selected frequency and age, leg length, body-mass, and resonance frequency, based on the resonance frequency of a mass supported by a spring (Eq. (1)).

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

where f is resonance frequency, k is subject's preferred whole-body vertical stiffness, and m is subject's body-mass.

2.4. Statistical analysis

Two sample independent *t*-tests were conducted to compare absolute and normalized whole-body vertical stiffness, peak vertical COM displacement, peak vertical GRF, AP and ML COM range of motion, AP and ML toe displacement between hops, AP and ML range of toe placement, stance time, flight time, and hopping height between the DS and TD groups during the self-selected hopping condition. To compare the metronome-cued frequency conditions two-way (2 group × 3 condition) ANOVAs with repeated measures on frequency were conducted on the aforementioned variables, as well as percent deviation of hopping frequency. We assessed normality using the Shapiro-Wilk test and applied a log transformation when necessary. Post-hoc analysis was conducted using pairwise comparisons with Bonferroni adjustments. SAS software (Cary, NC) was used for all statistical analyses. A significance level was set at alpha = 0.05.