Gait & Posture 63 (2018) 33–38

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Developmental changes in spatial margin of stability in typically developing children relate to the mechanics of gait

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ARTICLE INFO

Keywords:
Gait
Child
Development
Balance control
Margin of stability
Step-time parameters

ABSTRACT

Background: Immature balance control is considered an important rate limiter for maturation of gait. The spatial margin of stability (MoS) is a biomechanical measure of dynamic balance control that might provide insights into balance control strategies used by children during the developmental course of gait.

Research hypothesis: We hypothesize there will be an age-dependent decrease in MoS in children with typical development. To understand the mechanics, relations between MoS and spatio-temporal parameters of gait are investigated.

Methods: Total body gait analysis of typically developing children (age 1–10, n = 84) were retrospectively selected from available databases. MoS is defined as the minimum distance between the center of pressure and the extrapolated center of mass along the mediolateral axis during the single support phases.

Results: MoS shows a moderate negative correlation with stride length (rho = −0.510), leg length (rho = −0.440), age (rho = −0.368) and swing duration (rho = −0.350). A weak correlation was observed between MoS and walking speed (rho = −0.243) and step width (rho = 0.285). A stepwise linear regression model showed only one predictor, swing duration, explaining 18% of the variance in MoS. MoS decreases with increasing duration of swing (β = −0.422). This relation is independent of age.

Significance: A larger MoS induces a larger lateral divergence of the CoM that could be compensated by a quicker step. Future research should compare the observed strategies in children to those used in adults and in children with altered balance control related to pathology.

1. Introduction

At walking onset, between 10 and 15 months of age, infants walk at slow speed with steps shorter than their leg length [1,2]. A high variability and low stability of gait is characteristic [3]. Already a few months after the onset of walking, speed and step length dramatically increase [1,4] and occasionally steps larger than leg length can be observed [2]. Other features of an immature gait pattern are a wide base of support and a prolonged duration of stance as well as increased double support [5,6]. Generally, walking gait is considered to be adult-like around the ages of 7–8 years old [5,7]. Nevertheless, recent work has shown that immature gait characteristics retain during late childhood and early adolescence when walking at adult-like speeds and this relation is dependent upon leg length [8]. Parameters such as double support time, single support time and base of support are only mature in females around the age of 14 years and in males age of maturation is as high as 18 years [8]. Also consistency in variability of gait develops well into adolescence [9].

Thus, maturation of walking continues well after childhood. Changes in gait parameters can partially be explained by growth and changes in the dimensions of body segments [7,8]. It is accepted that maturation of balance control is another contributing factor in the maturation of gait [9–11]. Features of an immature gait, such as the prolonged duration of stance, increased double support time and the wider base of support are considered characteristic for an immature control of balance.

In a static (standing) situation, balance is achieved when the vertical projection of the center of mass falls within the base of support [12–14]. However, this condition is insufficient in dynamic situations and the velocity of the center of mass should also be accounted for [14]. Based on the inverted pendulum model, Hof [14] showed it can be simply done by replacing the CoM by the XCoM, a point defined as

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https://doi.org/10.1016/j.gaitpost.2018.04.019
Received 21 September 2017; Received in revised form 27 March 2018; Accepted 13 April 2018
0966-6362/

projection on the ground of the COM augmented by a quantity proportional to its velocity. By doing so, similar balance principles apply: the XCoM moves away (diverges exponentially) from the center of pressure and balance can be maintained only if the CoP can be placed outward of the XCoM. As the CoP is constrained to remain within the BoS, there are two possible situations: 1) the XCoM lies within the BoS and it can be captured by shifting the CoP within the BoS, or 2) it lies ouside and a step has to be performed in order to enlarge the BoS before being abble to capture the XCoM.

Regarding gait stability, balance control is more critical in the ML direction, where it is ensured by active foot placement strategies that require central nervous system control [15]. Based on the above mentioned balance principles, Hof showed that this foot placement strategy is primarily driven by the distance between the CoP and the XCoM at foot-of [16], referred to as “spatial margin of stability (MoS)”. If the MoS is too small, there is a risk of crossover steps, if it is too large, it forces the person to have a large step width and/or a small stance time leading to a non-efficient gait. Since, this quantity has proved to be a very interesting window into the balance control of gait [15].

So, control of balance is immature at the onset of walking and is a factor that drives changes in gait pattern throughout childhood. The spatial margin of stability is a measure derived from biomechanics characterizing dynamic balance control mechanisms during gait. We hypothesize there will be an age-dependent decrease in the spatial margin of stability in children with typical development that can be related to changes in the spatio-temporal characteristics of gait.

2. Methods

2.1. Study design

Data on 3D gait analysis in typically developing children (age 1–10) were retrospectively included in this cross-sectional study to investigate age-related changes in gait stability using the extrapolated center of mass and spatial margin of stability concepts. The study protocols have been approved by the local ethical committees. Parents gave written informed consent at the time of study inclusion and were aware that data could be used retrospectively for further research. Data collection took place between October 2002 and November 2012.

2.2. Setting

Gait analysis data were collected using an integrated set-up with an optometric movement registration system (6–8 cameras, Vicon Mcam 460 or T10 series, Vicon®, Oxford, UK or Motion Analysis® system with 8 Eagle® cameras, Motion Analysis Corporation, Santa Rosa, USA) and multiple force plates (2–4 platforms, AMTI OR6-7 or Bertec®, Columbus, USA, dimensions 0.4 × 0.5 m). Both systems were integrated in the walkway and synchronized at sampling frequencies of 100 Hz and 1000 Hz, respectively. Reflective markers (diameter 14 mm) were attached following the Davis model [17] or custom [18].

Children were introduced to the walkway and were given time to explore and get used to the surroundings. After attaching the markers, again a short habituation period was provided. Data registration was started after the children were no longer aware of the attached markers when moving around. After performing a static anatomical calibration trial in which all markers were visible, dynamic trials were collected. During the dynamic trials one or two caregivers were standing on each end of the walkway to encourage the child to move towards them in a straight line. All children walked barefoot at self-selected speed.

2.3. Participants

Out of databases from previous studies all 3D gait analysis of typically developing children that met following inclusion criteria were selected: a total body gait analysis with clear foot strikes on the force plates and full marker visibility for at least two consecutive strides. Details of participant selection in the previous studies is dependent upon the study and can be found in previous publications [18–22].

2.4. Variables of interest

2.4.1. Anthropometric measurements

For each subject, information was obtained on age (in years), body mass, body length and leg length. All measures were taken according to standard procedures.

2.4.2. Gait parameters

Walking speed, stride length, step width and duration of swing were used to characterize the temporo-spatial characteristics of gait. Gait parameters were considered as absolute as well as dimensionless values, i.e. normalized to leg length according to Hof [23].

2.4.3. Extrapolated center of mass (XCoM)

The “position of the extrapolated center of mass” (XCoM) is the vector sum of the center of mass position and a proportion of its velocity. In human movement, balance is typically related to the vertical projection of the body center of mass on the ground, that should fall within the base of support. This condition is insufficient in dynamic situations, in this case the velocity of the center of mass should also be accounted for. Thus, Hof (2005) defined this new vector quantity (XcoM) where the center of mass position is extrapolated in the direction of its velocity.

2.4.4. Spatial margin of stability (MoS)

The minimum spatial margin of stability was defined as the minimum distance between the center of pressure and the XCoM along the mediolateral axis during the single support phases. The medio-lateral axis was defined as the axis in the transversal plane (XY plane) perpendicular to the walking direction, which was derived from the CoM coordinates. The spatial margin of stability is expressed in absolute values (mm, MoS) and normalized relative to leg length (MoS_LL)

2.5. Data measurement

Marker trajectories were labeled in the Vicon Workstation (version 4.6 for Windows) or Nexus (version 1.8.x for Windows) software or Cortex software (Motion Analysis). Based on the force plate data and the ankle marker (malleolus lateralis) trajectories instances of foot strike and foot off were determined [19].

The total body center of mass was calculated using either the standard Vicon clinical model (Plug-In Gait application for Vicon Workstation and Nexus software) or custom (Appendix A see Supplementry).

The .c3d files were then exported to Matlab and a custom written script was used to calculate the XCoM and MoS according to the formulas described by Hof [14,16]. Spatio-temporal parameters were calculated from the left and right ankle marker (malleolus lateralis) trajectories.

2.6. Bias

All children in this study were volunteers so some form of selection bias cannot be excluded. Children were assumed to show a typical development if no developmental problems were reported by the parents. No additional developmental tests were performed. It is therefore possible that a small number of children might be diagnosed with developmental problems or delay at a later age, especially in the younger age groups.