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Nonlinear Gait Variability Increases with Age in Children from 2–10 Years Old

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Abstract: Background: Linear methods of analysis of variability are concerned with the magnitude of variability and often consider deviations from a central mean as errors. The utilization of nonlinear tools to examine variability allows for the exploration and measurement of the patterns of variability displayed by the system. This methodology explores the deterministic properties of biological signals, in this case, gait, or how previous iterations within the gait cycle influence subsequent and future iterations. The nonlinear analysis of gait variability of the joint angle time series has not been investigated in developing children. **Methods**: We collected 3 min of treadmill walking data for 28 children between the ages of 2 and 10 years old and analyzed their joint angle time series using nonlinear methods of analysis (sample entropy, largest Lyapunov exponent, and recurrence quantification analysis). **Results**: Our results indicate that the nonlinear variability of children's gait increases as children age. Interestingly, this contrasts with the findings from our previous work that showed a decrease in linear variability as children age. The combination of a decrease in linear variability, or a refined and improved stability of gait, as well as an increase in nonlinear variability, or an increase in the sophistication and quality of movement patterns, suggest an overall maturation of the neuromuscular system. **Conclusions**: Our study indicate that there is a refining of gait with age and motor maturation. This refining speaks to the overall multifaceted organization of systems that defines the maturation of gait.

Keywords: biomechanics; variability; gait; nonlinear; children

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1. Introduction

Researchers interested in the movement sciences have used linear methods to analyze movement variability. When linear tools are utilized, the magnitude of variability becomes the emphasis, while assuming that all repetitions of a behavior, such as gait cycles, are independent from what has happened before or what will happen after [1]. Another way to view variability in the world of movement science is through the lens of nonlinear methods. Nonlinear methods focus on the structure of variability by scrutinizing patterns in the variability across time. Nonlinear methods view the determinism within a series of movements or how one movement influences the next, and so on. Both the magnitude and structure of variability offer valuable information regarding movement and can differ between persons [1]. Interestingly, some movements may fall within the same magnitude of variability, but possess differences in the structure of the variability. This is a key distinction, as structure of variability has been associated with the health of biological systems. Healthy systems are those that possess a certain amount of stability but remain adaptable [2]. Both exceeding regularity across repetitions, with extremely periodic organization of variability, as well as an absence of consistency, with random organization of variability, have been linked to poor health [3,4]. The extrema of variability can be thought of as two ends of a spectrum, but in the middle lives a deterministic but non-periodic pattern that provides a balance between flexibility and stability of behavior. This middle state is associated with maximum complexity, which is defined as the highly variable fluctuation in physiological processes, resembling mathematical chaos [1].

The utilization of nonlinear tools allows for the exploration and measurement of the patterns of variability displayed by the system. These nonlinear tools can be used to study gait in humans [5–8]. Previous work investigating the progression and development of the gait of healthy children has focused mostly on the spatiotemporal, kinematic, and kinetic aspects of children’s gait, with little focus on variability. Of the investigations into variability, there has been even less of a focus with an eye toward the nonlinear dynamics and nonlinear variability. One particular study showed that the variability measures of the spatiotemporal aspect of children’s gait, as well as the nonlinear measures of the dynamics of gait in children, are age-dependent, and do not mature and become adult-like until after 10 years of age [9]. These results were in contradiction to the previously conceived notion that children’s gait was mostly mature by the age of 4 years old [10]. In a previous study, we indicated a lack of early maturation of spatiotemporal measures as well, utilizing both linear and nonlinear methods [11]. The linear methods of variability (standard deviation and coefficient of variation) proved to be extremely age-dependent, with younger children exhibiting more variability than their older counterparts. Nonlinear measures also showed differences with age, as regularity (entropy) and complexity (detrended fluctuation analysis (DFA)) increased with age.

The use of entropy and DFA to analyze the spatiotemporal time series provided new insight into the developmental trajectories of children’s gait, while paving the way for further investigation into different aspects of children’s gait using nonlinear variability methods [9]. A specific aspect of gait that nonlinear methods have been successful at analyzing in adult gait is the joint angle time series during walking. Entropy, largest Lyapunov exponent (LyE), and recurrence quantification analysis (RQA) have all been used to analyze the joint angle time series of the lower extremity to describe gait variability and gait variability changes [12–15]. Specifically, analyzing the joint angle time series with nonlinear measures has enabled the detection of differences between adult walkers, with and without pathology [8,12,14].

Utilizing these nonlinear measures for the investigation of joint angle time series in children has not been examined. To further the understanding of children’s gait and the development of children’s gait variability, nonlinear measures of analysis should be utilized on the joint angle time series of children. Differences in the structure of variability of the joint angle time series of children at different points in their development should be identifiable using nonlinear tools of analysis. The use of nonlinear methods could shed light on the potential control mechanisms being used and the refinement of gait throughout development and will provide a launching point for the comparison of the natural trajectory of gait development. This new information can be used to help understand various types of pathological gait in children.

The purpose of this study was to assess the development of kinematic gait variability in children from ages 2–10 years old using nonlinear methods of analysis. To do this, we grouped children into four separate age groups consisting of 2–3-year-olds, 4–5-year-olds, 6–7-year-olds, and 8–10-year-olds. We then had them walk on the treadmill for three minutes. The joint angle time series of the lower extremity were then analyzed. We hypothesized that as children aged, their gait variability will become more regular and exhibit greater adaptability. We also hypothesized that with age, children will display less stride-to-stride fluctuation in their gait.

2. Materials and Methods

2.1. Subjects

Our study involved 28 boys and girls split into four separate age groups. The age groups consisted of 2–3-year-olds (n = 7), 4–5-year-olds (n = 7), 6–7-year-olds (n = 7), and 8–10-year-olds (n = 7) (Table 1). Power analysis was conducted to determine that groups of four subjects were necessary to achieve adequate power. All participants provided parental informed consent and child assent before any research activities commenced, as approved by the university's Institutional Review Board. Healthy children, free from any musculoskeletal disorders, injuries, or developmental delays, were included in our study.

Table 1. Subject demographics by age group for participants.

	2–3-Year-Olds (N = 7)	**4–5-Year-Olds (N = 7)**	**6–7-Year-Olds (N = 7)**	**8–10-Year-Olds (N = 7)**
Gender (male/female)	4/3	3/4	3/4	3/4
Age (months)	35.9 ± 7.3	58.57 ± 5.7	81.57 ± 6.37	115.6 ± 6.02
Body mass (kg)	13.67 ± 2.5	17.31 ± 1.4	25.99 ± 4.97	38.44 ± 5.23
Body height (m)	0.92 ± 0.08	1.04 ± 0.03	1.22 ± 0.06	1.38 ± 0.03
Onset of walking (months)	12.14 ± 0.69	12.57 ± 2.15	12.21 ± 1.30	13.29 ± 0.95
Walking speed (m)	0.56 ± 0.16	0.78 ± 0.14	0.92 ± 0.08	1.07 ± 0.11

Note: values are shown as mean ± standard deviation.

2.2. Experimental Procedures

All subjects were provided with tight-fitting athletic shorts to be worn during the data collection process to ensure accurate marker placement for the motion capture system. The subject's shoe size was then determined, and they were provided with a standard laboratory shoe (Nike Free 5.0). The lab-provided shoe was employed to eliminate potential differences in footwear styles worn by the children, while also providing a normalized control. The Nike Free 5.0 is considered a "minimalist" style shoe, which mostly mimics barefoot conditions [16]. Study participants were given time to familiarize themselves with the treadmill (Bertec Corp, Columbus, OH, USA) and the lab shoe, while a self-selected comfortable walking speed was determined. Previous work has shown that treadmill walking functions to reduce gait variability compared to overground walking [17]. However, this work analyzed spatiotemporal gait and not the variability of joint angle kinematics. Treadmill walking was selected in comparison to overground walking because of the requirement for a long time-series of unbroken data. Retro-reflective markers were then placed on the subject at specific anatomical locations of the foot, shank, thigh, and pelvis, according to the marker systems established by Nigg et al. [18] and Vaughan et al. [19]. Lower extremity marker locations were acquired for one three-minute trial per condition at 100 Hz using an eight-camera motion capture system (Vicon Motion Systems, Oxford, UK). The participants performed the walking trials positioned 2 m in front of a screen in a virtual reality environment. However, to simulate walking on a stationary treadmill with static optic flow stimulation, a picture of the static room surround was projected on the virtual reality screens. The two conditions consisted of at least 3 min of walking at a self-selected comfortable walking speed while barefoot and while wearing the lab-provided footwear. The data were left unfiltered so as not to affect or influence potential biological signals within the data. It has been shown that filtering the data can lead to altered nonlinear results [20].

2.3. Data Analysis

We computed the joint angle time series in the sagittal plane of the ankle, knee, and hip joints utilizing Visual 3D software (C-Motion Inc., Germantown, MD, USA). Data processing and analysis were conducted using custom Matlab scripts (The Mathworks Inc., Natick, MA, USA). Lower extremity sagittal plane joint angles were analyzed because most bipedal motion occurs in the sagittal plane during gait. Sample entropy (SE) was calculated to determine the organization of the gait variability of each joint angle time series. A lower value of SE alludes to more rigidity and regularity and thus, less variability in the time series. A larger value of SE means more variability in the time series. The structure of the gait variability during the walking trials was evaluated using the LyE. The methodology of the LyE has been outlined in great detail by Wurdeman et al. in a separate publication [13]. In brief, the LyE measures the exponential divergence of the movement trajectories within a reconstructed state space [21]. Recurrence quantification analysis (RQA) of the joint angle time was also performed. RQA is a method of nonlinear data analysis for the investigation of dynamical systems. RQA quantifies the number and duration of recurrences of a dynamical system presented by its phase space trajectory, and it has been proven to be a good way to analyze the predictability and complexity of the system. We evaluated the percent determinism (%Det) and mean line (MLine) for our data. %Det is the percentage of recurrent points forming line segments parallel to the main diagonal line. The presence of these lines reveals the existence of a deterministic structure. MLine is the average length of all the line segments on the RQA plot. The MLine is a good indicator of the predictability of the time series.

2.4. Statistical Analysis

A one-way ANOVA with four factors (four age groups) was performed to determine the statistical significance for each of the dependent variables for the ankle, knee, and hip joints angle time series, respectively. The dependent variables include SE, LyE, %Det, and MLine. When significant effects were determined, post hoc comparisons were performed using the Tukey method. Statistical analysis was completed in SPSS Statistics 29 (IBM Corporation, Armonk, NY, USA).

3. Results

Mean and standard deviations of all variables can be found in Table 2. Significance between the variables is denoted by symbols.

Table 2. Group means for sample entropy, largest Lyapunov exponent, and recurrence quantification analysis for the 2–3, 4–5, 6–7, and 8–10-year-old groups.

	2–3 (N = 7)	**4–5 (N = 7)**	**6–7 (N = 7)**	**8–10 (N = 7)**	**Sig.**
			Sample Entropy		
Ankle	0.322 ± 0.016	0.315 ± 0.037	0.308 ± 0.045	0.282 ± 0.048	
Hip	0.223 ± 0.025	0.226 ± 0.016	0.229 ± 0.016	0.195 ± 0.021	‖¶
Knee	0.230 ± 0.017	0.233 ± 0.036	0.232 ± 0.043	0.261 ± 0.053	
			Largest Lyapunov Exponent		
Ankle	1.06 ± 0.10	1.17 ± 0.10	1.28 ± 0.10	1.43 ± 0.08	†‡‖¶
Hip	0.60 ± 010	0.67 ± 0.13	0.75 ± 0.19	0.89 ± 0.15	‡‖
Knee	1.11 ± 0.08	1.19 ± 0.08	1.24 ± 0.10	1.30 ± 0.10	†‡

Table 2. *Cont.*

	2–3 (N = 7)	4–5 (N = 7)	6–7 (N = 7)	8–10 (N = 7)	Sig.
			Recurrence Quantification Analysis %Determinism		
Ankle	73.2 ± 9.9	78.8 ± 5.6	83.6 ± 6.2	86.9 ± 4.2	†‡
Hip	76.9 ± 6.7	80.9 ± 2.4	90.5 ± 4.9	95.7 ± 2.2	†‡§‖
Knee	71.5 ± 9.8	76.1 ± 13.5	77.5 ± 15.3	83.9 ± 5.3	
			Mean Line		
Ankle	2.51 ± 0.24	2.55 ± 0.44	2.60 ± 0.27	3.06 ± 0.40	‡
Hip	4.87 ± 1.75	5.31 ± 1.04	5.91 ± 1.41	6.10 ± 1.44	
Knee	2.10 ± 0.59	2.66 ± 0.59	2.60 ± 0.39	3.51 ± 1.21	‡

Note: values are shown as mean ± standard deviation. Special characters for the following represent a $p < 0.05$, significant differences between groups 2–3 and 4–5. † $p < 0.05$, significant differences between groups 2–3 and 6–7. ‡ $p < 0.05$, significant differences between groups 2–3 and 8–10. § $p < 0.05$, significant differences between groups 4–5 and 6–7. ‖ $p < 0.05$, significant differences between groups 4–5 and 8–10. ¶ $p < 0.05$, significant differences between groups 6–7 and 8–10.

To see if the results were age-dependent and not a function of biomechanical changes related to growth, we investigated the linear relationship between both age and leg length and age and gait speed. In the present study, both leg length (r = 0.966 $p < 0.001$) and gait speed (r = 0.839 $p < 0.001$) increased linearly with age. Thus, we also conducted comparisons while normalizing the dependent variables with respect to both leg length and gait speed.

3.1. Sample Entropy of Joint Angle Time Series

The results for the SE analysis are shown in Figure 1. There was only a significant effect of age for the SE of the hip joint time series F (3,24) = 4.296, $p = 0.015$. Specifically, post hoc comparisons revealed that the 8–10-year-old group exhibited significantly greater SE at the hip compared to both the 4–5-year-old group ($p = 0.04$) and the 6–7-year-old group ($p = 0.019$). The SE for the ankle and knee joint angle time series did not produce an effect ($p > 0.05$). There was a significant linear trend of age for SE at the hip (r = 0.394, $p < 0.05$), as well as at the knee (r = 0.481, $p < 0.05$), but not at the ankle ($p > 0.05$).

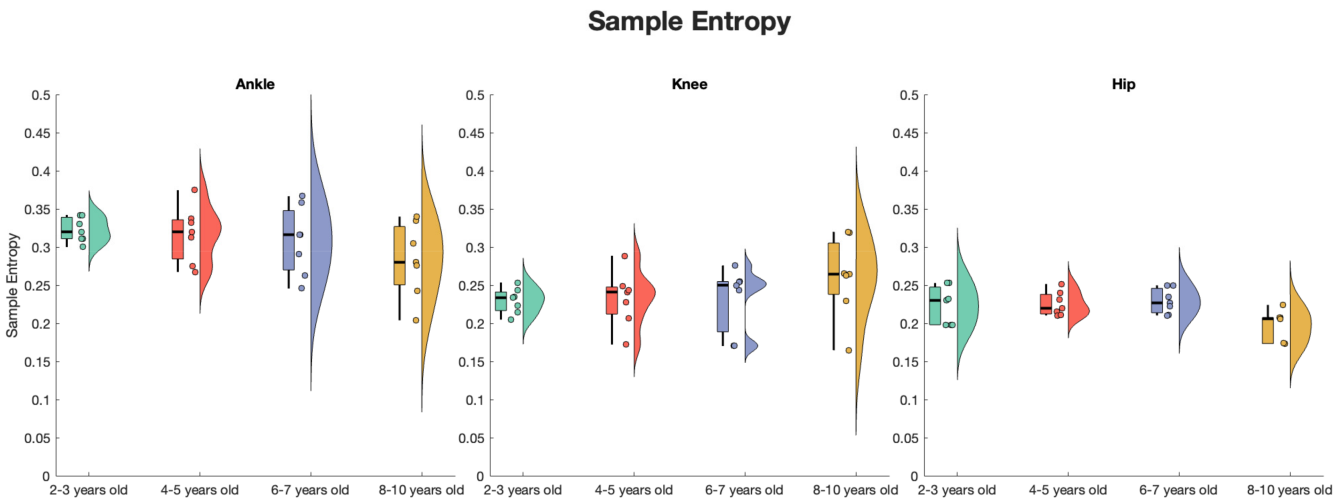

Figure 1. Violin and box plots showing the distribution of the sample entropy of the ankle, hip, and knee joint time series. Data are reported for the age groups.

Normalized comparisons for SE showed a significant effect at both the hip F (3,24) = 29.51, $p < 0.001$, and knee F (3,24) = 10.17, $p < 0.001$, joints. Post hoc comparisons at the hip joint showed that the normalized SE of the hip joint angle time series decreased with age. Specifically, the 2–3-year-old group showed the greatest SE, and it was significantly greater than that of all other age groups ($p < 0.05$). The 4–5-year-old group exhibited significantly greater SE than did the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$). The results for the 6–7-year-old group were also significantly greater than for the 8–10-year-old group ($p < 0.05$). Post hoc comparisons at the knee joint showed that the normalized SE of the knee joint angle time series also significantly decreased with age, except for in the 6–7-year-old group and 8–10-year-old group ($p < 0.05$). Specifically, the 2–3-year-old group exhibited a significantly greater normalized SE at the knee compared to that of the 4–5-year-old, 6–7-year-old, and 8–10-year-old groups ($p < 0.05$). The 4–5-year-old group showed a significantly greater normalized SE at the knee than did the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$), but there was no significant difference between the 6–7-year-old and the 8–10-year-old groups ($p > 0.05$).

3.2. Lyapunov Exponent of Joint Angle Time Series

The results for the LyE analysis are shown in Figure 2. There were significant effects of age group for the LyE of the ankle joint time series F (3,24) = 19.686, $p < 0.001$, the hip joint time series F (3,24) = 4.958, $p = 0.008$, and the knee joint time series F (3,24) = 6.151, $p = 0.003$. Post hoc comparisons at the ankle joint indicate that the 2–3-year-old group exhibited significantly lower LyE compared to that of the 6–7-year-old group ($p = 0.001$) and the 8–10-year-old group ($p < 0.001$). The 4–5-year-old group showed significantly lower LyE values compared to those of the 8–10-year-old group ($p < 0.001$), while LyE of the 6–7-year-old group was also significantly lower than that of the 8–10-year-old group ($p = 0.032$). At the hip joint, post hoc comparisons showed that LyE of the 8–10-year-old group was significantly greater than that of both the 2–3-year-old group ($p = 0.006$) and the 4–5-year-old group ($p = 0.048$). At the knee joint, LyE was significantly lower for the 2–3-year-old group compared to that of both the 6–7-year-old group ($p = 0.043$) and the 8–10-year-old group ($p = 0.002$). There were no significant differences in LyE for the other group comparisons at the respective joints. There was a significant linear effect of age on LyE at the ankle (r = 0.374, $p = 0.05$), at the hip (r = 0.470, $p < 0.05$), and at the knee (r = 0.445, $p < 0.05$).

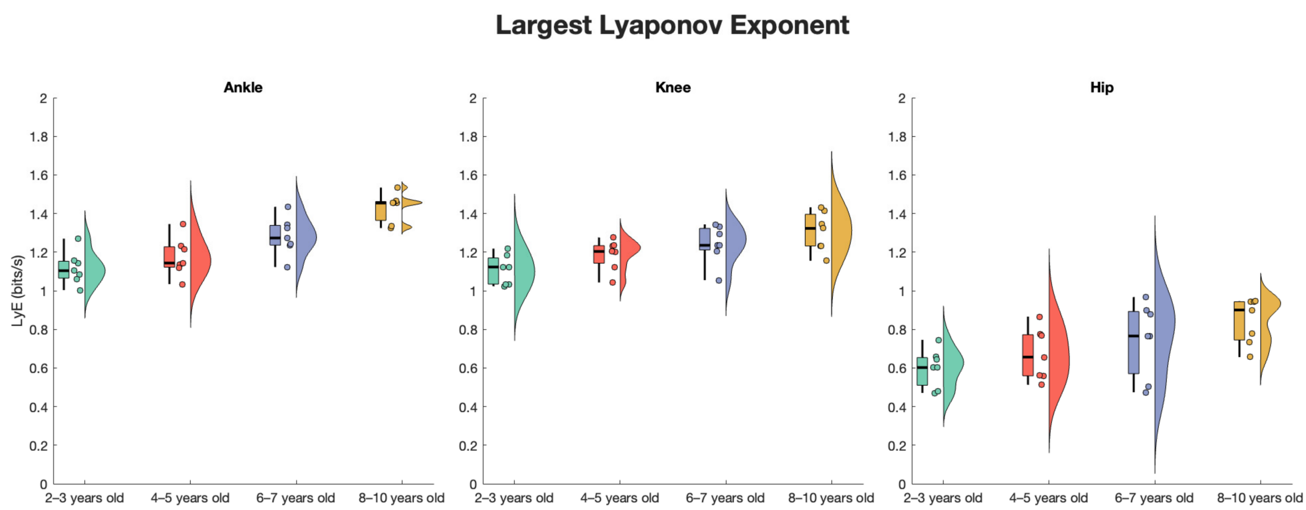

Figure 2. Violin and box plots showing the distribution of the largest Lyapunov exponent of the ankle, hip, and knee joint time series. Data are reported for the age groups.

Normalized comparisons for LyE showed that a significant effect remained for the ankle F (3,24) = 7.592, $p = 0.001$, and knee F (3,24) = 17.533, $p < 0.001$, joint angle time series.

Post hoc comparisons for the normalized LyE at the ankle revealed that the 2–3-year-old group exhibited a significantly lower normalized LyE than did the 6–7-year-old and 8–10-year-old groups ($p < 0.05$). The 4–5-year-old group also displayed a significantly lower normalized LyE at the ankle compared to that of the 6–7-year-old and 8–10-year-old groups ($p < 0.05$). There were no differences between the 2–3-year-old group and the 4–5-year-old group or the 6–7-year-old group and the 8–10-year-old group ($p > 0.05$) for the normalized LyE at the ankle. At the knee joint, post hoc comparisons showed that the normalized LyE significantly decreased with age. Specifically, the 2–3-year-old group showed a significantly greater normalized LyE compared to that of the 4–5-year-old, the 6–7-year-old, and the 8–10-year-old groups ($p < 0.05$). The 4–5-year-old group showed a significantly greater normalized LyE at the knee compared to that of both the 6–7-year-old and the 8–10-year-old groups ($p < 0.05$). There were no significant differences between the 2–3-year-old group and the 4–5-year-old group or the 6–7-year-old group and the 8–10-year-old group.

3.3. Recurrence Quantification Analysis of Joint Angle Time Series

The results for the RQA analysis are shown in Figure 3. There was a significant effect for %Det of the joint angle time series at the ankle F (3,24) = 5.326, $p = 0.006$. Specifically, post hoc tests showed that the 2–3-year-old group exhibited significantly less %Det than did both the 6–7-year-old group ($p = 0.040$) and the 8–10-year-old group ($p = 0.005$). No significant differences were found between the other age groups. There was also a significant effect for %Det at the hip joint F (3,24) = 26.072, $p < 0.001$. Specifically, post hoc tests show that the 2–3-year-old group showed a significantly lower %Det at the hip compared to both the 6–7-year-old group ($p < 0.001$) and the 8–10-year-old group ($p < 0.001$). The 4–5-year-old group also showed a significantly lower %Det than either the 6–7-year-old group ($p = 0.003$) or the 8–10-year-old group ($p < 0.001$). There were no other significant differences at the hip joint for %Det between groups. At the knee joint, there was not a significant effect for %Det. There was a significant linear trend for %Det of the ankle (r = 0.628, $p < 0.05$) and the hip (r = 0.864, $p < 0.05$), but not at the knee ($p > 0.05$).

Normalized comparisons for %Det showed there were significant effects for the ankle F (3,24) = 14.076, $p < 0.001$, hip F (3,24) = 30.874, $p < 0.001$, and knee F (3,24) = 10.518, $p < 0.001$ joints. Specifically, at the ankle joint, normalized %Det was significantly greater for the 2–3-year-old group than for the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$). The 4–5-year-old group also showed significantly greater normalized %Det compared to the 6–7-year-old-group and the 8–10-year-old group ($p < 0.05$), but it was not different from that of the 2–3-year-old group. There were also no differences for normalized %Det at the ankle for the 6–7-year-old and 8–10-year-old groups ($p > 0.05$). At the hip joint, normalized %Det was significantly greater in the 2–3-year-old groups than in all three other groups ($p < 0.05$). The 4–5-year-old group also showed significantly greater normalized %Det than did the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$), but there was no difference between the 6–7-year-old group and the 8–10-year-old group ($p > 0.05$). At the knee joint, normalize %Det was significantly greater in the 2–3-year-old group than in the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$), but the 2–3-year-old group did not differ from from the 4–5-year-old group. The 4–5-year-old group showed significantly greater %Det at the knee joint than did the 6–7-year-old group and the 8–10-year-old group ($p < 0.05$), while the results for the 6–7-year-old group and the 8–10-year-old group did not differ ($p > 0.05$).

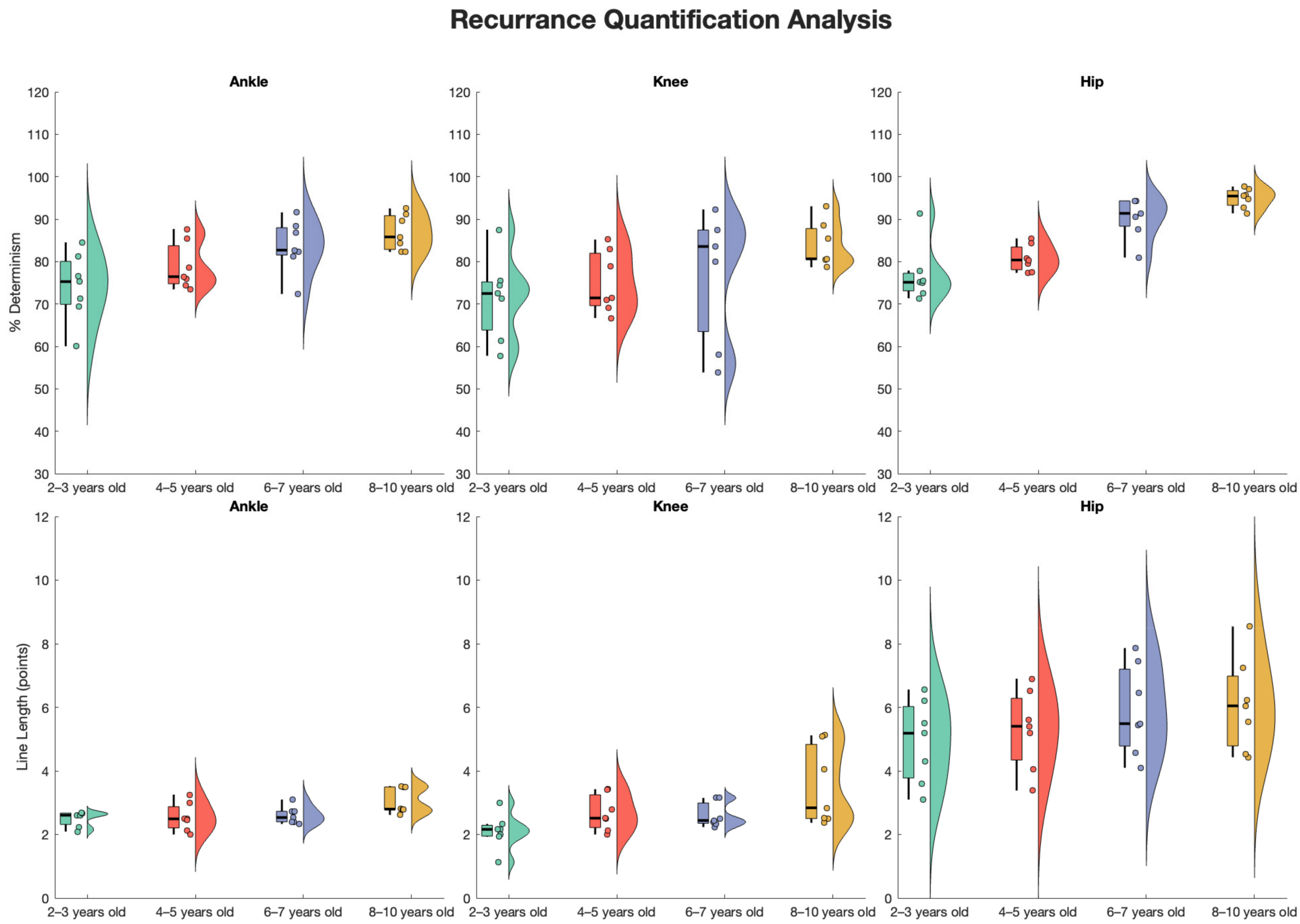

Figure 3. Violin and box plots showing the distribution of the recurrence quantification analysis (%Determinism, mean line) of the ankle, hip, and knee joint time series. Data are reported for the age groups.

There was a significant effect for MLine at the ankle joint F (3,24) = 3.773, $p = 0.024$. Specifically, post hoc tests showed that the 8–10-year-old group had a significantly greater MLine at the ankle joint compared to that of the 2–3-year-old group ($p = 0.031$). There were no other significant group differences for ankle MLine. There was not a significant effect for MLine at the hip joint ($p > 0.05$). There was a significant effect for MLine at the knee joint F (3,24) = 4.175, $p = 0.016$. Specifically, post hoc comparisons show that the 8–10-year-old group displayed a significantly greater MLine at the knee joint compared to that of the 2–3-year-old group ($p = 0.010$). No other significant differences existed between groups for MLine at the knee joint. There was a significant linear trend for MLine at the ankle (r = 0.489, $p < 0.05$) and the knee (r = 0.645, $p < 0.05$) but not at the hip joint ($p > 0.05$).

The normalized comparisons for MLine revealed a significant effect at the ankle joint F (3,24) = 11.826, $p < 0.001$. Post hoc comparisons of the normalized MLine at the ankle joint revealed that the 2–3-year-old group exhibited a significantly greater normalized MLine compared to that of the 4–5-year-old, 6–7-year-old, and 8–10-year-old groups ($p < 0.05$). The 4–5-year-olds also showed a significantly greater normalized MLine compared to that of the 6–7-year-old and the 8–10-year-old groups ($p < 0.05$). There was not a significant difference between the 6–7-year-old and the 8–10-year-old groups ($p > 0.05$).

4. Discussion

The purpose of our study was to assess the development of joint kinematic gait variability in typically developing children using nonlinear methods of analysis. We specifically wanted to investigate the joint angle time series of the lower extremities of children, at various developmental stages, while walking. Previous studies had investigated the spatiotemporal aspect of children's gait throughout development using nonlinear methods, but little emphasis has been placed on the joint angle time series of walking. We hypothesized that there would be an age effect on the gait variability of children. Specifically, as children aged, their gait variability would become more regular and more stable, as well as exhibit less stride-to-stride fluctuation.

Our hypotheses were partially supported for this study. Similar to results obtained by analysis of the spatiotemporal aspect of children's gait variability [8,10], the nonlinear analysis of the joint angle time series showed that the structure of gait variability in children is age-dependent. There was an age effect on the LyE and %Det of the joint angle time series at the ankle, hip, and knee. All three joints showed an increase with age, from youngest to oldest, for both the LyE and %Det. Neither the SE or MLine showed the same pattern of results or possessed the same significant differences. This is especially interesting because the SE of the stride time and stride length time series was age-dependent in the results of previous work [10]. Our results indicated a significant age effect on the nonlinear variability of the joint angle time series, even after normalizing for both leg length and gait speed to account for the natural differences in children due to growth and physical variations.

Interestingly, the direction of the age-dependency of the spatiotemporal variables of previous work contrasts with many of the results found in this study using the kinematic variables. The variability of the spatiotemporal variables decreased with age, while the variability of the kinematic variables increased as the children got older. These results could point to a hierarchy of behaviors to accomplish the desired goal of walking. To achieve the most stable gait, spatiotemporal variability may need to be minimized. Thus, as children age, the variability within their spatiotemporal gait decreases. How they accomplish this may be explained by the increase in their kinematic variability. Using the framework of dynamical systems theory [21], altering the parameter of kinematic variability, or in this case, increasing the complexity of the overall movement patterns, results in less variability in the spatiotemporal variables and an increased stability of gait.

As expected, our results indicate that gait variability and the structure of gait variability are continually changing throughout development in children and are extremely age-dependent. The LyE is able to examine the quality and structure of movement patterns and movement stability [12] and in this case, the joint angles of gait in children. Larger magnitudes of LyE indicate greater attractor divergence of the gait patterns and can be equated with maturing control of the motor system. As our groups increased in age from 2 to 10 years old, the LyE also increased. This was evident at the ankle, hip, and knee joints, respectively. As children gain more walking experience, the quality of their movements become more refined, exhibiting more stable, yet complex, movements. As children age, their gait variability may be becoming more chaotic, but it is also becoming more deterministic as well.

In our study, the RQA measure of %Det proved to also increase as children aged. Like the LyE outcomes, the %Det results span across all three joints of the lower extremity. %Det can be interpreted as a decrease in variability as a system becomes more deterministic. This seems to contradict and go against the premise of this study. However, when coupled with the LyE results, the overall results of our study agree with the theory of optimal movement variability. The theory of optimal movement variability posits that there is a sweet spot of sorts for movement variability. Too much or too little variability is unfavorable and detrimental to the system, as evidenced by a connection with unhealthy systems. Interpreting our results using this theoretical basis shows that the time series is increasingly diverging, while also becoming more deterministic. This behavior shows the complexity and sophistication of the development of movement trajectories.

As children get older and gain more experience walking, their neuromuscular systems and overall motor control are also maturing [22]. The combination of the maturation of the systems and gained experience leads to an overall better organization of movements [9,10]. The increase in divergent patterns, as well as increased determinism, makes for a more robust movement system that is capable of dealing with small perturbations without flaw. When we get older and become more experienced walkers, we can navigate our environment with ease. Small increases in rise or bumps in a path that could elicit falls in the youngest of walkers are hardly noticed by the more adept, experienced walker.

Our results provide a blueprint for the developmental trajectory of gait variability in typically developing children. Investigations into the maturation of gait and the development of movement pathology in children can be weighed against our results to better understand how pathology affects gait variability. This information can then be used to further understand the mechanisms underlying that pathology and aid and assist with the creation of therapies and new movement strategies to eventually overcome pathology. Future studies should consider exploration into the development of neuromuscular control utilizing the combination of nonlinear methods of analysis of children's gait and other measures, such as electromyography. A multifaceted approach to researching the development of motor control in children, utilizing nonlinear analysis, could shed light on many of the unknowns regarding how children self-organize and how their motor movements develop organically throughout childhood. Limitations to our study include the children's potential lack of experience walking on the treadmill. Although all four groups were equally inexperienced walking on a treadmill, to minimize this effect, all participants were given an acclimation period of walking until comfort was perceived. Another limitation is that the children were provided with the specific footwear used for this study to control for varying types of shoes that the children currently wore. The effect of the new shoe was minimized through the acclimation period on the treadmill.

5. Conclusions

In conclusion, we set out to investigate the development of gait variability in children by analyzing the stride-to-stride dynamics of the joint angle times series. Our study was able to advance the understanding of the developmental trajectory of children's gait variability by utilizing nonlinear methods of analysis. Children's gait becomes more refined with age, gaining sophistication by increasing adaptability, as well as organization. Walking experience alone is not the driving force, as many systems within the developing child are maturing. This type of investigation merely scratches the surface regarding obtaining a full understanding of the maturation dynamics of children's gait. A multifaceted approach to understanding motor control should be utilized in future research.

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