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Patterns of Gait Variability Across the Lifespan in Persons With and Without Down Syndrome

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Using Nonlinear Measures to Understand Patterns of Gait Variability Across the Lifespan in Persons with and without Down Syndrome.

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ABSTRACT

Background and Purpose: Our aim here is to build upon the observation of higher amounts of gait variability in persons with Down syndrome (DS) and describe the *patterns* of that variability across the lifespan. Without knowing what baseline patterns look like and how they relate to adaptive use of variability during gait it is difficult for physical therapists to determine if and when to intervene and if increasing or decreasing variability is better. **Methods:** We examined differences in patterns of gait variability in new walkers, preadolescents, and adults with DS and typical development (TD) using the nonlinear measures of Lyapunov Exponent (LyE) and Approximate Entropy (ApEn). Participants walked on a treadmill while we collected 3-D motion analysis data. **Results/Discussion:** Within the higher amount of gait variability persons with DS demonstrate across age compared to peers with TD, we found significant differences in nonlinear measures of *patterns* of variability. Preadolescents demonstrated higher LyE and ApEn values than new walkers and adults, suggesting they are more adaptive in their use of variability during gait. **Clinical Interpretation/Conclusion:** From a clinical perspective, our results suggest that physical therapists may focus interventions on increasing adaptive use of variability during gait in new walkers and adults with DS. Experience with increased variability through practice under variable conditions or with perturbations may improve adaptive use of variability during gait.

BACKGROUND AND PURPOSE

People often demonstrate increased amount of variability in movement trajectories with aging.[1-7] Consequently, a decrease in the amount of gait variability, finger force variability and finger movement variability are all cited as positive outcomes of rehabilitation interventions for older adults.[8-11] Although decreasing variability toward levels similar to younger persons can have a positive effect, a full understanding of how variability relates to the control of movement is still being discovered. Recently, scientists and clinicians have recognized that both the amount and pattern of variability observed within movement trajectories over time can affect control of movement. Impaired movement patterns can contain too much or too little variability, and additionally the patterns of variability present within any amount of variability may contribute to more or less adaptive control of movement.[12-15] Thus both amount and pattern of variability should be considered when trying to understand adaptive control of movement.

Down syndrome (DS) is one example of a population often described as demonstrating increased amount of variability. Across the lifespan, persons with DS demonstrate more variability in movement trajectories compared to their peers with typical development (TD).[16-19] Persons with DS differ from persons with TD in some neurophysiologic and musculoskeletal characteristics, including hypotonia, high ligamentous laxity and reduced capacity to produce muscle force. We believe these conditions increase the challenge of dynamic upright posture, especially in the earlier and later stages of life, and lead to the emergence of not only more variable but also unique gait patterns.[16-18,20] Although persons with DS demonstrate higher amounts of variability in movements like walking and gripping compared to their peers with TD, some research suggested that they use this variability functionally, to compensate for their biomechanical instability, thus this variability level is optimal for them.[21,22] If this is uniformly true, then it might not be advisable for physical therapists to intervene with the intention of decreasing the amount of variability in functional behaviors. One way to investigate this is to study the patterns of variability within the higher amount of variability and relate them to adaptive control of movement.

Current literature suggests that physical therapists should have their patients practice with increased or decreased amounts of movement variability, as needed, to help them learn adaptive use of variability.[13-15] Without an understanding of what baseline amount and pattern of variability looks like within a particular population and how it relates to functional control of movement these are very difficult choices to make. In the case of adults with DS, we know they demonstrate higher amounts of variability in gait and are more likely to have a history of falls than their peers with TD.[23] Although increased amount of gait variability is related to increased likelihood of falls and mobility disability in older adults with TD[24-27] it is not clear whether a causal link exists for adults with DS. Although adults with DS demonstrate increased amount of gait variability, younger persons with DS also have high amounts of variability. It is possible that adults have similar amounts and patterns of gait variability to preadolescents and other factors contribute to their falls, or it is possible that adults have experienced changes in their ability to adaptively use variability during gait and these changes negatively affect their gait patterns and possibly link to an increased likelihood of falls. Our aim here is to expand our knowledge of increased amounts of gait variability in persons with DS by describing their *patterns* of gait variability across the lifespan. We will interpret our findings in relation to decisions physical therapists need to make regarding efforts to affect gait variability in this population.

We examined changes in patterns of walking variability across the lifespan in persons with and without DS using the nonlinear tools of Lyapunov Exponent (LyE) and Approximate

Entopy (ApEn). We used LyE to quantify the local stability (overlap or dispersion) of trajectories of knee movement from one stride to the next. We used ApEn to quantify the regularity of the patterns observed in size of successive step widths and step lengths. Previous work has shown that 8-10-year-old children with DS had higher LyE and ApEn values indicating less local stability and less regularity in their patterns of lower extremity segmental angles during walking compared to their peers with TD.[19] We hypothesized here that because preadolescents are at their performance peak in terms of skill and efficiency, new walkers and adults with DS would show less locally stable, less regular trajectories of movement (larger LyE and ApEn values) than preadolescents with DS. Further, due to the inherent group differences in body structure and function, we predicted that persons with DS would demonstrate less locally stable, less regular trajectories of movement (larger LyE and ApEn values) across the lifespan, compared to their peers with TD.

METHODS

Data Collection

Participants with DS and TD, representing three developmental levels: new walkers, preadolescence and adulthood, came to the Developmental Neuromotor Control Laboratory at the University of Michigan (total n= 58; Table 1). Participants were recruited through various community activity and support groups in Michigan and Northern Ohio. They all participated in adequately-powered studies with similar protocols in which gait measures (but not nonlinear measures) were the primary dependent variables. The University of Michigan Institutional Review Board approved all procedures. Prior to participation, we explained our study to participants and caregivers. Participants signed an assent or consent form as appropriate, with consent for assenting adults and children provided by legal guardians. Toddlers wore diapers covered by black tights. Preadolescents and adults wore bathing suits or close-fitting shorts and tank tops. We attached markers (2.5 cm diameter) bilaterally at the temporomandibular joint, acromion process, lateral humeral epicondyle, styloid process, greater trochanter, femoral condyle, 10 cm above lateral malleolus, heel bony prominence and third metatarsophalangeal joint. We used a 6-camera Vicon Peak Motus[*] real-time system to collect 3-dimensional reflective marker position data at a sampling rate of 60 Hz.

<<insert Table 1 approximately here>>

Participants walked barefoot over a 5.3-m GAITRite mat[†] 4-6 times at their preferred speed. We used GAITRite software to calculate average walking speed for each participant and subsequently determine belt speeds for treadmill trials.[‡] Based on previous work in our lab[16,17], we operationalized comfortable treadmill speed for all participants as 75% of their self-selected overground speed. Comfortable speeds on a treadmill are slower than overground[28] and participants with DS are cognitively not able to select their most comfortable speed in this novel context. Participants performed two 30 s trials each at 45%, 75% and 110% of their overground walking speed; trials progressed from slow to fast speeds. All participants walked without touching the handrail and were guarded closely as they walked. Here we present results from the 75% speed only.

We used a Healthometer[§] scale to obtain body weight and a GPM anthropometer[‖] to record height and body segment lengths. To assess motor task performance and developmental

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[†] CIR Systems Inc, 60 Garlor Dr, Havertown, PA 19083.

[‡] Parker brand, LET Medical Systems Corp., 5755 NW 151st Ave, Miami Lakes, FL 33014.

[§] Precision Weighing Balances, 10 Peabody St, Bradford, MA 01835.

levels, we used age-appropriate instruments: the motor component of the Bayley Scales of Infant Development[#] (new walkers); the 8-item balance subtest of the Bruininks-Oseretsky Test of Motor Proficiency[**] (preadolescents) and Berg Balance Scale[29,30] (adults).

Data Analysis: Theory and Definitions

Stability, regularity and adaptability of gait can be defined in multiple ways. We use the term stability here in reference to the LyE values, which quantify the local stability (overlap or dispersion) of trajectories of movement from one repetition to the next. We use the term regularity in reference to the patterns observed in size of successive step widths and step lengths, as calculated by ApEn. We define the most adaptable gait patterns as those that are mid-range (although not necessarily the middle) on the continuum of LyE and ApEn values.[13,14,31] Mid-range LyE values are considered adaptive as they represent patterns of variability that are neither too stable (i.e., rigid) or too unstable, while mid-range ApEn values are considered adaptive as they represent patterns of variability that are neither too regular (i.e., rigid) or too irregular.[13,14]

We have not provided a tutorial on the use of nonlinear measures here because previous publications have done so and discussed clinical applications.[13,32,33] Briefly, LyE measures the divergence within the trajectories of entire movement cycles, such as walking strides, by quantifying their exponential separation in state space. We used LyE to measure the divergence

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[††] Applied Nonlinear Sciences, LLC and Randle, Inc, Del Mar, CA 92014.

[‡‡] MATLab, The Mathworks Inc., 3 Apple Hill Dr., Natick, MA 01760.

[§§] SPSS Inc., and IBM company, 233 S Wacker Dr., Chicago, IL 60606.

in the trajectory of the knee joint marker from one stride to the next. Figure 1 shows an example of how we calculated LyE from the knee marker displacement in the vertical direction. Larger values (closer to 0.5) indicate more dispersion, possible randomness and less similarity between the trajectories of successive walking strides. Shifts toward smaller values (close to 0) indicate less divergence, possible rigidity and more similarity between the trajectories of successive walking strides.[34] ApEn quantifies the regularity of the pattern within a time series. ApEn values exist on a continuum of 0 (completely regular pattern) to 2 (completely irregular, lack of pattern).[34] A long stride alternating consistently with a short stride represents a more regular pattern than a random series of unique stride lengths, although both behaviors would be recognizable as a cyclic pattern of walking with similar values for mean and range of stride length as traditionally calculated.

<<insert Figure 1 approximately here>>

We also would like to point out that LyE calculations are based on continuous kinematic data, in this case of the knee marker trajectory throughout the stride, while ApEn calculations are based on discrete spatial-temporal variables, here we used step length and step width. We made these nonlinear tool choices deliberately; LyE allowed us to assess the stability of the knee trajectory throughout and across continuous successive strides, while ApEn calculations allowed us to assess the regularity in step length and width from one step to the next. These are specific gait characteristics often reported for typical and atypical populations.

Data Analysis: Procedures

For the LyE analysis, we needed to identify a reflective marker to represent the cyclical motion of each stride through space. Our pilot analyses showed that the knee marker provided cleaner and more clearly cyclic data than the hip, ankle, heel and toe markers. We analyzed only the anterior-posterior and vertical direction time series of the left knee 3-D data as lateral motion of the knee is not a significant contributor to stride dynamics during walking. We analyzed displacement of the marker, as opposed to joint angles or acceleration or other possible variables, because we measured displacement directly and using a direct measurement as the basis for nonlinear calculations is particularly important to minimize error due to the nature of the calculation. Time series lengths for LyE calculation were 276 points for new walkers and 1800 points for preadolescents and adults. For toddlers, these points reflect 7 or 8 strides, the maximum number they can produce continuously on a treadmill at this point in developmental time. For preadolescents and adults these points represent approximately 24-39 strides [See Smith, Stergiou and Ulrich for examples of time series and toe, knee and hip time series and discussion of application of LyE to short new walker data sets[35]]. Time series lengths for ApEn calculation were 48-78 steps for preadolescents and adults and 14-16 continuous steps for new walkers.

Once all data sets were cropped, as necessary, to the correct length we extracted knee and heel marker data and calculated step width, step length and stride length. In Table 2 we provide group means for the gait parameters for the walking strides used here to calculate LyE and ApEn.

<<insert Table 2 approximately here>>

Next we determined the parameters and tested assumptions necessary for LyE and ApEn calculations; these methods have been explained in depth previously.[34] We calculated time delay and embedding dimension values using Tools for Dynamics software.[††] We found an average

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time delay of 3 and embedding dimensions of 8 for toddlers' knee time series and 5 for preadolescents and adults. The increased number for toddlers reflects the increased 'noise' present in their movements.[35] We tested our data for deterministic structure (mathematically defined as a non-random structure) using a surrogate data comparison method and Chaos Data Analyzer (CDA) software Professional Version.[36] We did not find significant differences between LyE values for the original and surrogate anterior-posterior direction new walker LyE data, and thus excluded these data from further analysis. Failed surrogation indicated that these data, although they were collected during walking, were not mathematically definable as having a periodic structure, again reflecting the increased 'noise' present in toddlers' movements.[35] Finally, we calculated LyE and ApEn. We used CDA software to calculate LyE data and custom MATLab[‡‡] programs for ApEn values. We calculated ApEn for the successive step lengths or widths using ApEn input parameters of m = 2 and r = 0.2. [34]

Statistical Methods

Statistics were calculated using an alpha level of 0.5 and SPSS software, version 17.0[§§]. In most cases, we used 2 (group) by 3 (age) ANOVA full factorial models with Bonferroni corrections and follow-up tests for linear and quadratic trends. For the anterior-posterior LyE data, because new walker data could not be included, we used a 2 (group) by 2 (age) ANOVA with Bonferroni corrections and follow-up tests for linear trends only as a quadratic trend is not possible with only two data points. We used linear and quadratic trend tests within the ANOVA to assess the shape of change across the lifespan within each group, using one test to examine the trend across the groups with DS and another to examine the groups with TD. A linear trend would indicate increase or decrease in the measure across the lifespan, while a quadratic trend

[§§] SPSS Inc., and IBM company, 233 S Wacker Dr., Chicago, IL 60606.

would indicate a “U” or inverted “U” shape across the lifespan. It is also possible to have significant linear and quadratic trends simultaneously. In this case, it means the data increase or decrease greatly and then flatten out, so that the “U” or inverted “U” (quadratic trend) is significant and the data also show a significant overall increase or decrease over time (linear trend).

RESULTS

LyE: Local Stability of Limb Trajectories Across Successive Strides

To test for differences in stability of knee trajectories in the vertical direction across strides, we used a 2 (group) by 3 (age) ANOVA with vertical direction LyE values as the dependent variable. The age effect was significant ($F[2, 46] = 17.53$, $p < 0.01$), while the group effect and group by age interaction were not (see Figure 2a).

For follow-up analysis, we tested for linear and quadratic trends within the three age groups. For the DS group, the quadratic trend test was significant ($p < 0.01$) while the linear trend test was not. Pairwise comparisons revealed that preadolescents had higher vertical direction LyE values than new walkers or adults ($p < 0.01$ for all). For the TD group, the quadratic trend test was again significant ($p < 0.01$) while the linear trend test was not. Follow-up pairwise comparisons revealed that preadolescents had higher vertical direction LyE values than new walkers and adults ($p < 0.01$ for all).

We used a similar a 2 (group) by 2 (age) ANOVA for differences in LyE values in the anterior-posterior direction. This analysis did not include the new walkers, whose anterior-posterior direction data failed surrogation analysis. The group effect was significant ($F[1, 34] = 14.44$, $p < 0.01$), as was the age effect ($F[1, 34] = 18.92$, $p < 0.01$). The group by age interaction was not significant (see Figure 2b). Inspection of means for the group effect revealed higher LyE values in the anterior-posterior direction for the group with DS, while the age effect showed higher LyE values in preadolescents compared to adults.

For follow-up analysis, we tested for a linear trend within the two age groups. We found a significant linear trend ($p = 0.01$) for the DS group, reflecting lower anterior-posterior LyE values in adults than preadolescents. Follow-up in the TD group also revealed a significant linear trend ($p = 0.04$), again reflecting lower anterior-posterior LyE values in adults than preadolescents.

<<insert Figure 2 approximately here>>

ApEn: Regularity of Pattern of Successive Step Lengths and Widths

To test for differences in step length ApEn values, we used a 2 (group) by 3 (age) ANOVA. The age effect was significant ($F[2, 49] = 9.37$, $p < 0.01$), while the group effect and group by age interaction were not (see Figure 3a). Inspection of means revealed an inverted “U” shape with highest values in preadolescents.

For follow-up analysis, we tested for linear and quadratic trends within the three age groups. Follow-up analysis for the DS group showed significant linear ($p = 0.03$) and quadratic ($p = 0.05$) trends. Pairwise comparisons revealed that the DS new walkers had significantly smaller ApEn step length values than the DS preadolescent ($p = 0.01$) or adults ($p = 0.01$) while the quadratic trend indicated higher values in the preadolescents than younger or older participants. For the TD group, the quadratic trend was significant ($p = 0.02$) and the linear trend was not, indicating higher values in preadolescents and lower values in older and younger participants.

To test for differences in ApEn of step width values, we used a 2 (group) by 3 (age) ANOVA. The age effect was significant ($F[2, 49] = 15.23$, $p < 0.01$), while the group effect and group by age interaction were not (see Figure 3b). Inspection of the means revealed an inverted "U" shape with highest values in preadolescents.

For follow-up analysis, we tested for linear and quadratic trends within the three age groups. For the DS group, follow-up analyses showed significant linear and quadratic trends ($p < 0.01$ for both) indicating higher ApEn values for preadolescents, lower values for adults and lowest values for new walkers. We obtained a significant quadratic trend ($p = 0.01$) but not linear trend for the TD group, demonstrating higher ApEn values for preadolescents and lower values for adults and new walkers.

<<insert Figure 3 approximately here>>

DISCUSSION

Within the higher amount of gait variability persons with DS consistently demonstrate compared to their peers with TD across the lifespan, we show here that they also experience an inverted "U"-shaped developmental trajectory in their *patterns* of variability across age. Overall, our results of higher LyE values indicating less stability and higher ApEn values indicating less regularity for preadolescents suggests they may be more adaptable in their gait patterns at this point than as new walkers or by 35 years and beyond. That is, at either end of their years of gait experience their patterns of variability are relatively more stable and regular, thus rendering their gait potentially less adaptable to changes in task or environmental conditions. From a clinical perspective, this suggests that physical therapists may be able to intervene to improve gait performance, specifically patterns of variability related to stability and regularity, in new walkers and adults with DS. Additionally, although amount of gait variability may not change with intervention, LyE and ApEn values could be used to quantify changes in patterns of gait variability in response to intervention. We provide here a baseline description of mean LyE and ApEn values for patterns of stability and regularity of gait variability observed across the lifespan in persons with DS.

Preadolescents with DS demonstrate closer to optimal walking performance compared to their younger and older peers with DS; they are able to produce more continuous walking strides than new walkers and prefer to walk faster than adults. Previous researchers have described preadolescents with DS as being in one of the most consistent periods in their lives as they have had at least 6 years of walking practice accompanied by steady physical growth.[17] Because preadolescents demonstrate closer to optimal walking performance than their younger and older peers, our interpretation of the values obtained is that their LyE and ApEn values are also at their peak and that they have learned to use their variability to adapt as well as possible during locomotion. Thus, for future research and application, preadolescents' LyE and ApEn values may represent the best possible values and their younger and older peers' lower values represent walking patterns that are less adaptable as a result of *too much* stability and regularity in the pattern. This is in contrast to our hypotheses that their younger and older peers would have higher values representative of walking patterns that are less adaptable as a result of *too little* stability and regularity in the pattern. Theoretically, extreme values may be on either side of the ideal value, and understanding where they are should begin to influence physical therapy interventions as we discover more. For example, a treadmill walking intervention at a constant speed may decrease amount of gait variability and promote more stable and more regular patterns of variability while walking at different and changing speeds may increase amount of gait variability and promote less stable and less regular patterns of variability. Interventions designed to promote practice with increased or decreased amounts and more or less stable and regular patterns of movement variability, as needed, should help patients learn better adaptive use of variability.

One can, however, only interpret LyE and ApEn values in a relative way, on a continuum as compared to similar data collected and analyzed in the same manner. With the algorithms used in the software we applied to our data the LyE values lie on a continuum from 0 to 0.5. A periodic sine wave, with no divergence from one trajectory to the next, produces a LyE value of 0. A random signal, with maximal divergence, produces an LyE value of 0.5. Our results showed LyE values ranging from approximately 0.15 to 0.20, indicating that divergence in participants' knee trajectories was closer to the periodic end of the continuum. Occasions where participants with DS had higher LyE values than their peers with TD reflected more divergence in their movement trajectories. In our data, because both young and older groups were lower, ideal values for LyE appeared to be around 0.20, indicating a more ideal balance between stability and adaptability of performance. This value, however, would not necessarily be the ideal for a different population or for any other gait parameter of interest, such as ankle or center of mass motion.

ApEn values exist on a continuum of 0 to 2. Complete regularity of pattern produces an ApEn value of 0, while complete irregularity and lack of a pattern is represented by an ApEn value of 2. Our participants' ApEn values ranged from approximately 0.12 to 0.48, indicating that step widths and lengths were closer to the regular pattern end of the continuum. This is not unexpected, as consecutive walking steps represent a more periodic and regular pattern as compared to variables such as center of pressure sway. For step length and width, preadolescents demonstrated higher ApEn values than their older and younger peers, indicating less regularity of pattern across successive steps and more adaptability of behavior. In our data, ideal values for ApEn appeared to be around 0.48, a balance between regularity and adaptability of performance. As with our LyE results, this is not an ideal value that would necessarily apply in a different population or to any other variable of interest.

Our results here show that patterns of gait variability are different across the lifespan within the group of persons with DS, and suggest that preadolescents in both groups are able to use higher amounts of variability in an adaptive way compared to their younger and older peers. The nonlinear measures, for the most part, reflected lifespan differences and did not reflect overall differences between the DS and TD groups. The lack of group differences in ApEn and vertical direction LyE values may be related to statistical analysis characteristics. The power to statistically demonstrate differences between groups decreased when the much larger age effects were included in the same analysis. In a study with similar dependent variables and only one age group, 8-10-year olds, group differences in LyE and ApEn of lower extremity segmental angles were observed. Results indicated statistically higher LyE and ApEn values indicating less stability and less regularity in patterns of lower extremity segmental angles for children with DS when compared to their peers with TD.[19] Our group means in this study for vertical direction LyE and ApEn step length are consistent in direction with results from this previous study.[19] It is, however, difficult to compare the actual LyE and ApEn values we obtained to those of other studies, as different parameters used lead to different values of LyE and ApEn. Despite slightly different analysis techniques and/or dependent variables, our data do appear to be in similar range as results from other studies of treadmill walking in various populations. Buzzi and Ulrich obtained LyE values ranging from 0.12 to 0.2 and ApEn values of 0.22 to 0.52 for lower extremity segmental angles of children with DS and TD.[19] Jordan and colleagues calculated LyE values of around 0.1 at the ankle near the walk-run transition speed in healthy adult females.[37] Stergiou and colleagues obtained LyE values around 0.10-0.12 and ApEn near 0.20 to 0.26 from the knee flexion/extension angle from participants with and ACL-deficient and contralaterally-intact knee.[38,39]

CONCLUSIONS

Overall our work suggests that, given their inherent neurophysiological constraints, persons with DS control their gait in a way that is functional for them. The quality of this solution, however, varies with age, as the stability and regularity of their patterns of gait variability are different across the lifespan. Preadolescents are typically at a performance peak for their lifespan, with the nonlinear measures LyE and ApEn suggesting that they are more adaptable in their walking patterns than younger and older age groups. New walkers may have difficulty adapting because they lack experience with this skill. By 35 years of age and beyond, adaptability of adults' gait may diminish due to a decline in their amount of walking or a hesitation to challenge themselves during locomotion. These results suggests that physical therapists may be able to intervene to improve gait performance, specifically patterns of variability related to stability and regularity, in new walkers and adults with DS. The strategy might be to provide practice with less stable and less regular patterns of variability using perturbations of speed or terrain to promote adaptive use of gait variability. This strategy assumes that practice will lead to improved performance despite the presence of hypotonia, high ligamentous laxity and reduced capacity to produce muscle force. Our findings hint improved performance may be possible, though, as these factors are present across the lifespan yet preadolescents with DS demonstrate different patterns of variability compared to their younger and older peers.

LIMITATIONS

We are limited in our ability to make claims about how gait variability patterns change for a person across the lifespan as our data are cross-sectional as opposed to longitudinal. Our interpretation of gait as more adaptable is also limited as we used a treadmill to collect data and did not test adaptability of gait to external manipulations. We do, however, believe that our context is an appropriate paradigm to lay a foundation of data. Nonlinear analyses are better applied to longer bouts of continuous walking and using a treadmill allowed us to obtain long, continuous walking trials from preadolescents and adults. Toddlers, however, are only able to produce 7 or 8 continuous walking strides on a treadmill at this point in developmental time, leading to shorter data sets than are typically used when performing nonlinear analyses. For these reasons, our ability to apply nonlinear analyses to new walker data was limited [See Smith, Stergiou and Ulrich for discussion of potential confounding effect of application of LyE to short new walker data sets[35]]. We also appreciate the need for software development to allow clinicians to collect and analyze data without using research laboratory resources and for correlation of nonlinear measures with clinical rating scales of body structure and function, activity and participation.

FIGURE CAPTIONS

Figure 1. Lyapunov Exponent (LyE) calculation visual analogy, using data from consecutive stride cycles of the knee marker of an adult participant with Down syndrome (DS). 1a is the knee marker vertical position time series, 1b shows 3 strides extracted from the time series (1a) and overlaid and 1c demonstrates a magnified version of an isolated segment of the state space to show the divergence between neighboring trajectories.

Figure 2. Vertical (2a) and anterior-posterior (2b) direction Lyapunov Exponent (LyE) values for participants with Down syndrome (DS) and typical development (TD). Age groups are as follows: NW = new walkers, PA = preadolescents, A = adults.

Figure 3. Approximate Entropy (ApEn) of step length (3a) and step width (3b) for participants with Down syndrome (DS) and typical development (TD). Age groups are as follows: NW = new walkers, PA = preadolescents, A = adults.

REFERENCES

1. Darling WG, Cooke JD, Brown SH. Control of simple arm movements in elderly humans. *Neurobiol Aging.* 1989;10:149-57.
2. Panzer VP, Bandinelli S, Hallett M. Biomechanical assessment of quiet standing and changes associated with aging. *Arch Phys Med Rehabil.* 1995;76:151-7.
3. Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Srikanth VK. Ageing and gait variability--a population-based study of older people. *Age Ageing.* 39:191-7.
4. Owings TM, Grabiner MD. Variability of step kinematics in young and older adults. *Gait Posture.* 2004;20:26-9.
5. Grabiner PC, Biswas ST, Grabiner MD. Age-related changes in spatial and temporal gait variables. *Arch Phys Med Rehabil.* 2001;82:31-5.
6. Menz HB, Lord SR, Fitzpatrick RC. Age-related differences in walking stability. *Age Ageing.* 2003;32:137-42.
7. Buzzi UH, Stergiou N, Kurz MJ, Hageman PA, Heidel J. Nonlinear dynamics indicates aging affects variability during gait. *Clin Biomech.* 2003;18:435-43.
8. Galica AM, Kang HG, Priplata AA, et al. Subsensory vibrations to the feet reduce gait variability in elderly fallers. *Gait Posture.* 2009;30:383-7.
9. Sosnoff JJ, Voudrie SJ. Practice and age-related loss of adaptability in sensorimotor performance. *J Mot Behav.* 2009;41:137-46.
10. Kornatz KW, Christou EA, Enoka RM. Practice reduces motor unit discharge variability in a hand muscle and improves manual dexterity in old adults. *J Appl Physiol.* 2005;98:2072-80.
11. Hausdorff JM, Nelson ME, Kaliton D, et al. Etiology and modification of gait instability in older adults: A randomized controlled trial of exercise. *J Appl Physiol.* 2001;90:2117-29.
12. Brach JS, Berlin JE, VanSwearingen JM, Newman AB, Studenski SA. Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. *J Neuroeng Rehab.* 2005;2:21.
13. Harbourne RT, Stergiou N. Movement variability and the use of nonlinear tools: Principles to guide physical therapist practice. *Phys Ther.* 2009;89:267-82.
14. Stergiou N, Harbourne R, Cavanaugh J. Optimal movement variability: A new theoretical perspective for neurologic physical therapy. *J Neurol Phys Ther.* 2006;30:120-9.
15. Fetters L. Perspective on variability in the development of human action. *Phys Ther.* 2010;90:1860-7.
16. Smith BA, Kubo M, Black DP, Holt KG, Ulrich BD. Effect of practice on a novel task--walking on a treadmill: Preadolescents with and without Down syndrome. *Phys Ther.* 2007;87:766-77.
17. Ulrich BD, Haehl V, Buzzi UH, Kubo M, Holt KG. Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Hum Mov Sci.* 2004;23:133-56.
18. Smith BA, Ulrich BD. Early onset of stabilizing strategies for gait and obstacles: Older adults with Down syndrome. *Gait Posture.* 2008;28:448-55.
19. Buzzi UH, Ulrich BD. Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control.* 2004;8:241-54.

20. Black DP, Chang CL, Kubo M, Holt KG, Ulrich BD. Developmental trajectory of dynamic resource utilization during walking: Toddlers with and without Down syndrome. *Hum Mov Sci.* 2009;28:141-54.
21. Latash ML, Anson GJ. Synergies in health and disease: Relations to adaptive changes in motor coordination. *Phys Ther.* 2006;86:1151-60.
22. Black DP, Smith BA, Wu J, Ulrich BD. Uncontrolled manifold analysis of segmental angle variability during walking: Preadolescents with and without Down syndrome. *Exp Brain Res.* 2007;183:511-21.
23. Smith BA, Ashton-Miller JA, Ulrich BD. Gait adaptations in response to perturbations in adults with Down syndrome. *Gait Posture.* 2010;32:6.
24. Brach JS, Studenski SA, Perera S, VanSwearingen JM, Newman AB. Gait variability and the risk of incident mobility disability in community-dwelling older adults. *J Gerontol A Biol Sci Med Sci.* 2007;62:983-8.
25. Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Arch Phys Med Rehab.* 2001;82:1050-6.
26. Barak Y, Wagenaar RC, Holt KG. Gait characteristics of elderly people with a history of falls: A dynamic approach. *Phys Ther.* 2006;86:1501-10.
27. Maki BE. Gait changes in older adults: Predictors of falls or indicators of fear. *J Am Geriatr Soc.* 1997;45:313-20.
28. Alton F, Baldey L, Caplan S, Morrissey LC. A kinematic comparison of overground and treadmill walking. *Clin Biomech.* 1998;13:434-40.
29. Berg K, Wood-Dauphinee S, Williams JI, Gayton D. Measuring balance in the elderly: Preliminary development of an instrument. *Physiother Can.* 1989;41:304-11.
30. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: Validation of an instrument. *Can J Public Health.* 1992;83 Suppl 2:S7-11.
31. Hausdorff JM. Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. *Hum Mov Sci.* 2007;26:555-89.
32. Ohgi S, Morita S, Loo KK, Mizuike C. Time series analysis of spontaneous upper-extremity movements of premature infants with brain injuries. *Phys Ther.* 2008;88:1022-33.
33. Dusing SC, Kyvelidou A, Mercer VS, Stergiou N. Infants born preterm exhibit different patterns of center-of-pressure movement than infants born at full term. *Phys Ther.* 2009;89:1354-62.
34. Stergiou N. Innovative analyses of human movement. Champaign, IL: Human Kinetics; 2004.
35. Smith BA, Stergiou N, Ulrich BD. Lyapunov exponent and surrogation analysis of patterns of variability: Profiles in new walkers with and without Down syndrome. *Motor Control.* 2010;14:16.
36. Sprott JC, Rowlands G. Chaos data analyzer. New York: American Institute of Physics; 1992.
37. Jordan K, Challis JH, Cusumano JP, Newell KM. Stability and the time-dependent structure of gait variability in walking and running. *Hum Mov Sci.* 2009;28:113-28.
38. Stergiou N, Moraiti C, Giakas G, Ristanis S, Georgoulis AD. The effect of the walking speed on the stability of the anterior cruciate ligament deficient knee. *Clin Biomech.* 2004;19:957-63.

39. Georgoulis AD, Moraiti C, Ristanis S, Stergiou N. A novel approach to measure variability in the anterior cruciate ligament deficient knee during walking: The use of the approximate entropy in orthopaedics. *J Clin Monit Comput.* 2006;20:11-8.