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Age-related changes in spatiotemporal characteristics of gait accompany ongoing lower limb linear growth in late childhood and early adolescence

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ABSTRACT

Walking gait is generally held to reach maturity, including walking at adult-like velocities, by 7–8 years of age. Lower limb length, however, is a major determinant of gait, and continues to increase until 13–15 years of age. This study used a sample from the Fels Longitudinal Study (ages 8–30 years) to test the hypothesis that walking with adult-like velocity on immature lower limbs results in the retention of immature gait characteristics during late childhood and early adolescence. There was no relationship between walking velocity and age in this sample, whereas the lower limb continued to grow, reaching maturity at 13.2 years in females and 15.6 years in males. Piecewise linear mixed models regression analysis revealed significant age-related trends in normalized cadence, initial double support time, single support time, base of support, and normalized step length in both sexes. Each trend reached its own, variable-specific age at maturity, after which the gait variables' relationships with age reached plateaus and did not differ significantly from zero. Offsets in ages at maturity occurred among the gait variables, and between the gait variables and lower limb length. The sexes also differed in their patterns of maturation. Generally, however, immature walkers of both sexes took more frequent and relatively longer steps than did mature walkers. These results support the hypothesis that maturational changes in gait accompany ongoing lower limb growth, with implications for diagnosing, preventing, and treating movement-related disorders and injuries during late childhood and early adolescence.

1. Introduction

Maturation of spatiotemporal gait properties occurs in stages across childhood alongside neural and musculoskeletal growth and development. Neurological control of the primary determinants of mature gait is established as early as 4 years old [1], after which children tend to walk at adult velocities [2]. Adult-like walking velocities in young children, however, are out of harmony with the still-immature lower limb, which lengthens considerably during childhood. Accordingly, gait parameters continue to change and mature as the lower limb grows.

Gait is commonly considered to reach maturity by ages 7–8 years [2–4] according to five criteria: duration of single-limb stance, walking velocity, cadence, step length, and the ratio of pelvic span to ankle spread (or *base of support*) [5]. There is, however, a substantial temporal offset between ages 7 and 8 years and the cessation of lower limb linear growth (abbreviated below as *lower limb maturity*), which continues until roughly 13 years old in girls and 15 years old in boys [6], just after peak growth velocity occurs. Given close relationships between adult lower limb length and gait characteristics [7], it seems reasonable that walking with adult-like velocity on immature lower limbs should involve the retention of immature gait patterns during late childhood and early adolescence. Existing evidence suggests that ankle and foot kinematics remain immature at 7 years old [8–10], and that spatiotemporal variables differ from the adult condition up to 11–13 years of age [11–13]. Still, few studies have examined gait across the age range during which the lower limb matures [10,14,15], whereas most studies have not [2–5,8,11–13,16]. None of these studies has evaluated the specific relationship between age-related changes in spatiotemporal gait parameters and continued lower limb growth during late childhood and early adolescence.

Here, using a sample from the Fels Longitudinal Study, we test the hypothesis that spatiotemporal aspects of gait undergo

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age-related changes as long as adult-like absolute walking velocities are coupled with immature lower limbs. More specifically, we test whether normalized gait parameters [17,18] exhibit significant relationships with age prior to lower limb maturity, after which the slopes reach plateaus and do not differ from zero. To test this hypothesis, we determine age at lower limb maturity in each sex, and evaluate trends in lower limb length and spatiotemporal gait variables by testing for significant age-related slopes that reach mature plateaus. Where such patterns do exist, age at maturity for each gait variable is compared to that of the lower limb. We also test the secondary hypothesis that the sexes differ in ages at maturity and rates of change in lower limb length and gait.

2. Methods

2.1. Participants and data screening

The sample is a subset of participants in the Fels Longitudinal Study, the world's longest-running longitudinal study of human growth and development [19]. Participants are primarily of European descent and generally live in or near southwest Ohio. All participants in the sample were considered normal and healthy, and were not selected for any disease or gait-related trait. All procedures were approved by the Institutional Review Board at Wright State University, and participants provided informed consent before testing.

A total of 528 observations of walking gait were collected on 246 individual participants (128 females, 118 males) between the (rounded) ages of 8 and 30 years. Each individual had 1–6 independent observations (median = 2). The minimum age was chosen because gait is well-characterized in children younger than 8 years old. The maximum age was selected so as to include enough adults to establish accurate estimates of mature gait parameters. Participants were excluded for prescription shoe inserts; chronic musculoskeletal conditions; toe-walking; lower limb, pelvic, or vertebral skeletal injury $\leq$5 years prior to testing; lower limb, pelvic, or back soft tissue injury $\leq$1 year prior to testing; obesity (affects gait [20,21]): children, body mass index (BMI) $\geq$95th percentile [22]; adults, BMI $\geq$30.0.

2.2. Data collection and processing

Data collection occurred at the Lifespan Health Research Center (LHRC), Wright State University Boonshoft School of Medicine. Anthropometric measurements, taken using standard methods [23,24] on barefoot participants wearing light clothing, included stature (to nearest 0.1 cm; stadiometer), body weight (to nearest 0.1 kg; scale), sitting height (to nearest 0.1 cm; stadiometer and chair), and bicristal breadth (to nearest 0.1 cm; sliding caliper, Holtain, Ltd.). Body mass index (BMI) was calculated as kg/m^2. Lower limb length (cm) was calculated as stature – sitting height.

For walking tests, participants wore socks and walked at self-selected normal velocity along a 15 m walkway in the LHRC's Motion Analysis Laboratory. The laboratory is equipped with six high-speed cameras (Motion Analysis Corp., Santa Rosa, CA) directed at the walkway and synchronized with three embedded force plates (two AMTI OR6-7-1000, Advanced Mechanical Technology, Inc., Watertown, MA; one Kistler Type 9281B11, Kistler Instruments, Winterthur, Switzerland). Cameras captured the movement of external passive reflective markers placed on each participant at major joints and body segments according to the Helen Hayes Marker System [25]. Several trials were recorded and the best three trials (clean force plate strikes for both feet, high-fidelity marker recognition) were entered into OrthoTrak software (Motion Analysis Corp., Santa Rosa, CA) to extract forward velocity (cm/s); cadence (steps/min); percent of the gait cycle spent in initial double support and single support; step width (cm); and step length (cm). For each variable, participant averages across three trials were used in the analysis.

2.3. Statistical analysis

All analyses were performed using SAS version 9.2 (SAS Inc., Cary, NC, USA), and were two-sided with $\alpha = 0.05$ as the significance level. Sexes were analyzed separately. Gait variables were normalized by expressing temporal measures as percentages of a single gait cycle, adjusting spatial measures for lower limb length, and calculating base of support by dividing bicristal breath by step width [5,17,18]. These transformations removed the effects of lower limb length as a confounder of age effects, since, at any age, lower limb length influences raw values of gait parameters. Age was thus a proxy for degree of lower limb maturity, so that gait parameters could be compared between different maturational stages on a per-unit-of-lower-limb-length basis. We did not, however, normalize forward velocity, because our hypothesis specifically predicts that similarities in *absolute* velocity between immature and mature walkers, coupled with lower limb immaturity in the former, underlie differences in gait.

Descriptive statistics were computed for each variable and normality of distributions was assessed using the Shapiro–Wilk test. Rather than analyzing left and right limbs separately, participant-specific average values of both limbs were calculated for each variable. Prior to averaging, left and right limbs were compared (paired-sample *t*-test or Wilcoxon signed rank sum test, depending on distribution), with no significant asymmetry in any variable except for step length (females: $P = 0.04$; males: $P < 0.01$). The step length asymmetries, however, were not particularly meaningful, since they were $\leq$1% of sex-specific single-leg means (females: right = 0.845, left = 0.839; males: right=0.824, left=0.815). Thus the average of left and right step lengths was used, consistent with the other variables. For all variables, differences in means between age groups (defined below) and between sexes were assessed using two-sample *t*-tests.

Piecewise linear mixed models regression, fit using SAS PROC NLMIXED, was used to determine ages at lower limb length and gait variable maturity. The procedure estimated rates of change in lower limb length and gait variables, and the ages at which these rates became zero, providing an empirically based estimation of the ages at which lower limb length and each gait parameter stabilized. Slopes after the ages at maturity were assumed to be zero; that is, it was assumed that lower limb length and gait parameters attained adult levels at a given age and then remained constant (within the age range of the sample). To check this assumption, the model was first allowed to include non-zero slopes before and after plateau ages. None of the post-maturity slopes, however, were significantly or meaningfully different from zero, validating our assumption. In contrast to other variables, the rate of change in forward velocity did not differ between childhood and adulthood: thus a simple linear fit was sufficient and obviated piecewise regression for forward velocity. As an iterative procedure, PROC NLMIXED relies on user-supplied starting values; a range of starting values was used to check the sensitivity of the analysis, and the results did not change.

3. Results

Sample characteristics for each sex subdivided by estimated ages at lower limb maturity are shown in Table 1. Sexes differed significantly ($P \leq 0.05$) for mean age at lower limb maturity: 13.2 ± 0.1 years in females; 15.6 ± 0.1 years in males. Numerous