Brief Communication: The Application of Knemometry to Measure Childhood Short-Term Growth Among the Indigenous Shuar of Ecuador

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ABSTRACT

Objectives: Knemometry, the precise measurement of lower leg (LL) length, suggests that childhood short-term (e.g., weekly) growth is a dynamic, nonlinear process. However, owing to the large size and complexity of the traditional knemometer device, previous study of short-term growth among children has been restricted predominantly to clinical settings in industrialized Western nations. The aim of the present study is to address this limitation and promote broader understandings of global variation in childhood development by: (1) describing a custom-built portable knemometer and assessing its performance in the field; and (2) demonstrating the potential application of such a device by characterizing childhood short-term LL growth among the indigenous Shuar of Amazonian Ecuador.
Materials and Methods: Mixed-longitudinal LL length data were collected weekly from 336 Shuar children age 5–12 years old using the custom portable knemometer (n = 1,145 total observations). Device performance and Shuar short-term LL growth were explored using linear mixed effects models and descriptive statistics.
Results: The portable knemometer performed well across a range of participant characteristics and possesses a low technical error of measurement of 0.18 mm. Shuar childhood LL growth averages 0.47 mm/week (SD = 0.75 mm/week), but exhibits large between- and within-individual variation.
Discussion: Knemometry can be reliably performed in the field, providing a means for evaluating childhood short-term growth among genetically and ecologically diverse populations. Preliminary findings suggest that Shuar weekly LL growth is comparable in mean magnitude but likely more variable than reported for healthy Western children. Future work will further explore these patterns. Am J Phys Anthropol 160:353–357, 2016.

Research over the past several decades has demonstrated that individual growth during childhood is a variable, nonlinear process when evaluated over short-term (e.g., daily or weekly) intervals (Hermanussen, 1998; Lampl et al., 1992). This discovery has presented new avenues for understanding the biological mechanisms regulating linear bone growth (Hermanussen et al., 1986; Lampl and Johnson, 2011) and has led to increasingly detailed models regarding the evolutionary implications of plasticity in human development (Lampl and Thompson, 2007). Much of this pioneering work has involved the use of knemometry, a highly reproducible method for monitoring the anatomically stable length of the lower leg (LL) using a device called a "knemometer" (Valk et al., 1983a; Hermanussen, 1988). Large and stationary in design, the traditional knemometer possesses a technical error of measurement (TEM) of 0.09–0.19 mm and is capable of detecting subtle changes in LL length with high confidence (Valk et al., 1983a; Wales and Milner, 1987; Hermanussen, 1988; Gelander et al., 1994). Although knemometry has now been applied to study multiple facets of human short-term growth (Hermanussen, 1998; Wolthers, 2010), the size and complexity of the traditional device has limited its use among children predominantly to clinical settings in developed Western nations. This methodological limitation, resulting in a dearth of short-term growth data from genetically and ecologically diverse human populations, considerably restricts nuanced understandings of global variation in childhood growth and underlying developmental biology.

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Recognizing the potential value of field-friendly knemometry for anthropologists, public health researchers, and others interested in variation in childhood growth, the objectives of the present study are twofold: First, to describe a custom-built portable knemometer and assess its performance under remote field conditions; Second, to demonstrate the usefulness and application of such a device by investigating the basic characteristics of childhood short-term LL growth among the small-scale, indigenous Shuar of Amazonian Ecuador.

MATERIALS AND METHODS

Study population

Detailed ethnographic and ecological information for the Shuar are available elsewhere (Karsten, 1935; Rubenstein, 2001). The Shuar are a large indigenous population of ≈ 40,000–110,000 individuals inhabiting the neotropical Amazonas region of southeastern Ecuador. Traditionally subsistence forager-horticulturalists, recent development of infrastructure in some regions of Shuar territory has resulted in increased contact with outsiders and varying degrees of integration into the wider market economy (Liebert et al., 2013; Lu, 2007). Many communities now possess schools, electricity, running water, and other modern features. Despite these changes, however, diet among the Shuar remains generally poor and group members, particularly children, continue to face a heavy burden of infectious disease (Blackwell et al., 2010; Cepon-Robins et al., 2014; Liebert et al., 2013). Physical growth at the population level is characterized by rates of childhood stunting of ≈ 40% but low incidence of underweight and wasting, a pattern typical of other indigenous Amazonians (Blackwell et al., 2009; Urlacher et al., 2016).

Data collection

Data were collected as part of the ongoing Shuar Health and Life History Project (http://www.bonesandbehavior.org/shuar) between August 2011 and May 2013. A total of 336 Shuar children (N = 176 females and 160 males) between the ages of 5–12 years (μ = 8.8 years, SD = 2.2 years) were recruited from four rural communities for participation in the present study. All children in the target age range who were present at the time of enrollment were invited to participate (participation rate = 97.7%). A short medical history was taken, and children were found to be generally healthy and not currently using medication. No physical examination was performed. Parental consent and child assent were obtained for all participants. Research approval was obtained from village leaders, the Federación Interprovincial de Centros Shuar, and the Institutional Review Boards of the University of Oregon and Harvard University.

Measurements of height, weight, and LL length were obtained from each participant weekly (when possible) over a three-week study period, providing a maximum of four observations per individual. Height and weight were measured following conventional methods (Lohman et al., 1988), and body mass index (BMI) was calculated. Lower leg length was measured using a custom portable knemometer designed for use in the field (Fig. 1). Modified from the designs of Valk et al. (1983a) and Davies et al. (1996), the device consists of three main components: (1) a lightweight aluminum (80/20® Inc., Columbia City, IN) frame holding a fixed footplate; (2) a waterproof, high-precision digital caliper (Mitutoyo America Corporation ABSOLUTE 552, Aurora, IL) attached to a counter-weighted polymethylmethacrylate plateau; and (3) a sliding chair operating on low-friction bearings at the base of the frame. Built-in bubble levels on the frame and caliper are used to ensure that the device is level before use. Daily calibration is performed using a steel bar of known length. To make an estimate of LL length, a child sits upright in the chair with their buttocks and spine against the back rest and places their bare right foot in a metal guide on the footplate. A small amount of talc is applied to the bare right knee to minimize friction, and the plateau is lowered to rest gently on the knee. The operator, ensuring with light pressure that foot and leg positioning remain constant, then slides the chair back and forth along the track until a stable (i.e., maximum) reading of LL length is obtained visually on the caliper's digital display. The device does not require participant training or personalized settings.

Fig. 1. The custom portable knemometer, based on modification of the designs of Valk et al. (1983a) and Davies et al. (1996). The instrument weighs approximately 12 pounds. To facilitate portability, the measuring caliper and chair back may be folded down to access a carrying handle. The device may be completely disassembled and reconstructed from individual components for long-distance travel.

At each measurement occasion, four estimates of LL length were made (to the nearest 0.01 mm), with children standing and walking several steps between each estimate. The most divergent of the four estimates was discarded, and the mean of the remaining series of three provided a final measurement of LL length (Wales and Milner, 1987; Agertoft and Pedersen, 2010). SSU performed all knemometric measurements in a semiprivate setting, blind to participant recordings on previous weeks and following daily device calibration and assignment of a random baseline measure. To limit the influence of error associated with diurnal variation in LL length (Valk et al., 1983b), participants were measured during the same 30 min period of the day on all occasions, stood for 5–10 min prior to measurement, and were excluded if reporting vigorous physical activity within the previous two hours (Hermanussen, 1988). The knemometer was disassembled into individual components to facilitate long-distance travel and was reconstructed upon arrival in each of the four participating communities.

Data analysis

The performance of the portable knemometer was evaluated using the complete dataset of LL length measurements ($n = 1{,}145$ total observations). Device TEM was calculated as the mean standard deviation of all independent series of three LL length estimates (McCammon, 1970; Hermanussen, 1988). To assess the potential influence of participant characteristics and device reconstruction on measurement precision, a linear mixed effects model was constructed with the standard deviation of independent series of LL length estimates as the dependent variable, participant sex, age, BMI, and community of residence (a proxy for device reconstruction) as fixed factors, and a random participant term. *Post hoc* multiple pairwise comparisons and one-way analysis of variance (ANOVA) were performed to evaluate the main effect of community of residence on measurement precision.

Shuar LL growth over 1-, 2-, and 3-week intervals was defined and calculated conventionally as the difference in measured LL length between two observations (Wolthers, 2010). Growth over all intervals was considered significant if the observed value was greater than or equal to two times estimated device TEM (Cameron, 2013). Random effects ANOVA was performed to calculate an intraclass correlation coefficient (ICC) to describe between- and within-individual variance components in repeated measures 1-week growth. All statistical analyses were performed in R 3.0.3 (http://www.cran.us.r-project.org/).

RESULTS

The TEM of the knemometer was calculated as 0.18 mm (95% CI = 0.176–0.189 mm), translating to 95% confidence in the ability of the device to detect LL length differences of $\geq$ 0.36 mm. Standard deviation in independent series of LL length estimates (i.e., measurement precision) was not significantly related to participant sex, age, or BMI (Table 1; all $p > 0.05$) and did not differ significantly by community of residence or, therefore, device reconstruction ($F_{1,3} = 1.987$, $p = 0.116$).

Descriptive statistics for Shuar short-term LL growth are provided in Table 2. Growth over 1-, 2-, and 3-week intervals was found to average 0.47 mm (SD = 0.75 mm), 0.91 mm (SD = 0.87 mm), and 1.30 mm (SD = 1.05 mm), respectively. Given the TEM of the portable knemometer, growth was detected at a level of significance in 51.0% of 1-week observations, 71.9% of 2-week observations, and 82.3% of 3-week observations.

TABLE 1. Linear mixed effects model investigating the impact of participant characteristics and community of residence (a proxy for device reconstruction) on the precision of portable knemometer lower leg length estimates (mm)

Fixed effect	B	SE	P-value
Sex (female)	0.004	0.007	0.562
Age (years)	0.001	0.002	0.602
BMI (kg/m^2)	0.004	0.003	0.189
Community 1	0.011	0.008	0.067
Community 2	0.008	0.012	0.502
Community 3	−0.001	.009	0.990
Community 4[a]	–	–	–

BMI = body mass index.
[a] Community main effect is not significant in post hoc analysis ($P = 0.116$; see "Results").

DISCUSSION

To our knowledge, this study is the first to evaluate the performance of a childhood knemometer in the field. Results suggest that the custom portable device operates with a TEM of 0.18 mm in remote Amazonia, precision falling within the upper range observed with the traditional knemometer in clinical settings (TEM = 0.09–0.19 mm; Valk et al., 1983a; Wales and Milner, 1987; Hermanussen, 1988; Gelander et al., 1994) and superior to that previously reported for another custom device with more limited portability (TEM = 0.27 mm; Davies et al., 1996). Furthermore, the performance of the portable knemometer was not significantly influenced by participant sex, age, BMI, or community of residence (a proxy for instrument reconstruction) in this relatively large sample of children. These findings suggest device capability to robustly detect childhood LL growth of $\geq$ 0.36 mm in the field following well-validated research protocols developed for the traditional knemometer.

To demonstrate the application and potential usefulness of portable knemometry among small-scale populations, we have provided preliminary short-term growth data obtained from the Amazonian Shuar. The portable knemometer detected significant growth in the majority of 1-, 2-, and 3-week observations in this sample of children. Although reference values for childhood short-term LL growth have not been published, mean weekly growth rates observed among the Shuar (0.43–0.47 mm/week) are comparable to values of 0.4–0.6 mm/week widely reported in knemometric studies of healthy Western children at similar ages (Valk et al., 1983a; Wales and Milner, 1987; Gelander et al., 1994). Notably, however, variation in Shuar weekly LL growth appears to be greater than previously documented in studies of Western children following similar observation periods and analytical techniques. Standard deviation in Shuar mean 1-week growth (SD = 0.75 mm/week) is, for example, $\approx$ 20% greater than reported for healthy Dutch children (SD = 0.63 mm/week) in one of the most comparable existing studies (Valk et al., 1983a). Although suggestive, additional data are needed to determine if variation in Shuar short-term LL growth is

TABLE 2. Descriptive statistics for Shuar short-term lower leg growth

Measure	N	Mean (SD) (mm)	Mean 95% CI (mm)	Range (mm)	ICC	N with significant growth[a] (% of total N)
1-week growth	335	0.47 (0.75)	0.40–0.56	−0.67–2.71	0.485	171 (51.0%)
2-week growth	192	0.91 (0.87)	0.78–1.03	−0.74–3.40	–	138 (71.9%)
3-week growth	203	1.30 (1.05)	1.15–1.44	−0.51–5.57	–	167 (82.3%)

N = number of observations; CI = confidence interval; ICC = intraclass correlation coefficient.
[a] Growth is detected at significance when $\geq$ 0.36 mm (see "Results").

indeed significantly larger than observed among Western children. As indicated by an ICC value of 0.485 for 1-week LL growth measures, large variance in Shuar short-term growth is distributed remarkably evenly, with 48.5% of total variance existing between and 51.5% of total variance existing within individuals.

The advantages and limitations of knemometry for monitoring short-term growth have been thoroughly reviewed (Hermanussen, 1998; Hermanussen et al., 1988; Wolthers, 2010). However, we note several lines of evidence supporting the results of the present study. First, all knemometry was performed by a single observer following well-validated protocols designed to minimize bias and error associated with diurnal variation in child LL length. Second, Shuar mean short-term LL growth far exceeds knemometer TEM and associated statistical lower limit of detection. Third, Shuar mean weekly growth rates are stable across 1- to 3-week intervals, suggesting little influence of interval length or magnitude of growth on estimation error. Finally, potentially confounding biological factors, such as weight and soft tissue dynamics, have been found elsewhere to have minimal impact on the knemometric assessment of growth among prepubescent children (Hermanussen, 1988; Ahmed et al., 1996).

A limitation of this paper is that our validation has not directly compared the performance of the custom portable knemometer to that of the traditional knemometer device. Although such a comparison would be useful, we note that the portable instrument is intended to provide an approach for performing knemometry in formerly unfeasible field settings, not as a replacement for the traditional knemometer in clinical contexts. Recognizing this, the TEM of the portable knemometer suggests reliability appropriate for fieldwork investigating childhood linear growth over periods as short as one week. In comparison, conventional field assessments of stature or knee height typically require periods of several months to reliably monitor growth (Rogerson et al., 1998; Hogan, 1999; Ulijaszek and Kerr, 1999).

Knemometry is a novel method for the study of childhood development, providing a means for documenting and investigating potentially important variation in short-term growth that is otherwise masked by the traditional assessment of stature or knee height. The findings of the present study demonstrate that knemometry may be reliably performed in the field, expanding the scope of short-term growth research into diverse genetic and ecological contexts. Initial data presented here for the Shuar suggest that childhood short-term LL growth in this Amazonian population is comparable in mean magnitude but likely more variable than observed among healthy Western children. While specific factors are unclear, environmental influences (e.g., nutrition and infectious/parasitic disease burden) may explain much of this short-term variation in growth. Future application of knemometry among small-scale populations should further investigate patterns of short-term growth, with particular focus on exploring possibly significant relationships with primary environmental factors, long-term development, and health.

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