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Stature Estimation Formulae for Indigenous North American Populations

Benjamin M. Auerbach[1,2]* and Christopher B. Ruff[3]

[1]*Department of Anthropology, The University of Tennessee—Knoxville, Knoxville, TN 37996*
[2]*Center for Archaeological Investigations, Southern Illinois University, Carbondale, IL 62901*
[3]*Center for Functional Anatomy and Evolution, Johns Hopkins University School of Medicine, Baltimore, MD 21205*

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ABSTRACT Stature estimation methods for adult indigenous humans from the Americas have generally relied on a limited number of regression equations. The available equations, however, are not broadly applicable to the diversity of the populations that lived in the New World prior to European colonization. Furthermore, some equations that have been used were originally derived from inappropriate reference samples, such as the "Mongoloid" group measured by Trotter and Gleser (Am J Phys Anthropol 16 [1958] 79-123). This study develops new stature estimation equations for long bones of the lower limb from a geographically diverse sample of North American archaeological sites. Statures were reconstructed from 967 skeletons from 75 archaeological sites using the revised Fully anatomical technique (Raxter et al., Am J Phys Anthropol 130 [2006] 374-384). Archaeological samples were grouped according to general body proportions, using relative tibia and femur length to stature as guides. On the basis of differences in these proportions, three broad groupings were identified: a high latitude "arctic" group, a general "temperate" group, and a Great Plains group. Sex-specific ordinary least squares regression formulae were developed based on femoral and tibial lengths for each of these groups. Comparisons of the new stature estimation equations with previously available equations were conducted using several archaeological test samples. In most cases, the new stature estimation equations are more precise than those previously available, and we recommend their use throughout most of North America. The equations developed by Genovés for Mesoamerican and US Southwest samples are a useful alternative for these regions. Applicability of the new equations to South American samples awaits further testing. Am J Phys Anthropol 141:190–207, 2010. © 2009 Wiley-Liss, Inc.

The estimation of adult human stature from skeletal remains has been researched for over a century (Rollet, 1888; Dwight, 1894; Pearson, 1899). As noted by Lundy (1985), two approaches have been employed in this endeavor: the "anatomical" approach, which involves the summation of superoinferior measurements of contributory skeletal elements to determine stature as directly as possible; and the "mathematical" approach, which involves the extrapolation of living stature from individual skeletal measurements by the utilization of ratios or regression analyses. The former method, most often attributed to Georges Fully (1956), has recently been reexamined in detail by Raxter et al. (2006, 2007). Relatively few studies have employed the "anatomical" approach; however, as regression formulae from a limited number of skeletal elements (that is, one or two long bones) are much easier to apply, especially in archaeological settings.

Indeed, a substantial literature has been devoted to the "mathematical" method. Researchers have developed techniques to estimate living statures from a variety of skeletal elements, including the major long bones of the limbs (e.g., Trotter, 1970), crania (e.g., Ryan and Bidmos, 2007), and other whole bones, as well as fragmentary remains (e.g., Simmons et al., 1990). The vast majority of equations have been developed for long bones of the upper and lower limbs to estimate statures of African, Asian and European populations (Trotter and Gleser, 1952, 1958; Fujii, 1960; Allbrook, 1961; Olivier, 1976; Feldesman and Lundy, 1988; de Mendonça, 2000).

In contrast, few stature estimation equations have been developed specifically for indigenous populations from the Americas. Trotter and Gleser (1958) developed the first regression formula broadly applicable to populations from the Americas, and tested it on a limited sample ($n = 8$) with some success (Table 11 in their article). They recommended in that article a preference for their "Mongoloid" formula for the estimation of statures for indigenous American populations, though this is problematic, as the sample that constituted the "Mongoloids" was a mixture of individuals of Japanese, "American Indian," Chinese, Melanesian, Micronesian, and Polynesian descent, many of whom where acknowledged to have ancestors from both these regions and Europe. Thus, preference has been shown by some archaeological researchers (e.g., Buikstra, 1976;

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*Correspondence to: Benjamin M. Auerbach, Ph.D., Department of Anthropology, 250 South Stadium Hall, The University of Tennessee, Knoxville, Tennessee 37996. E-mail: auerbach@utk.edu

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Larsen, 1984; Storey et al., 2002) for the employment of Genovés's (1967) regression formulae developed from cadavers derived from a low socioeconomic class Mexican sample, asserted to have had limited ancestral contributions from Europeans. Del Angel and Cisneros (2004) recently revised these equations, following the advice of Genovés. However, based on differences in intralimb proportions, Auerbach and Ruff (2004) concluded that the Genovés equations may not be appropriate for all indigenous populations from the Americas; samples from the arctic, for example, have limb proportions significantly different from those of populations from Mexico and the US Southwest.

Sciulli et al. (1990) attempted to address the problem of applying stature estimation equations to archaeological indigenous North Americans by developing stature estimation equations directly from Ohio River Valley skeletal remains dating to before European colonization (Late Archaic to Mississippian periods). After reconstructing stature for these individuals using the anatomical technique developed by Fully (1956), they regressed long bone lengths on the "anatomical" method stature estimations to derive formulae.[1] Fully's (1956) soft tissue correction was subsequently added to obtain "living" statures. Sciulli et al. compared results from their new equations with those developed by Trotter and Gleser (1958), Genovés (1967), and Neumann and Waldman (1967). Sciulli et al. (1990) demonstrated that the "Mongoloid-derived" Trotter and Gleser (1958) equations consistently overestimated the statures of the Ohio River Valley skeletons, a trend also observed to lesser degrees with the other equations. This was attributed to the high cormic (lower limb length relative to total stature) and crural (leg length relative to thigh length) indices of the Ohio sample relative to the samples used by previous authors. Thus, they illustrated the need for more population-specific formulae in the estimation of statures of populations from the New World.

It is worth noting that Sciulli has revisited these equations twice. Sciulli and Giesen (1993) added more skeletons to the Ohio River Valley sample used in the 1990 publication, and reconfirmed their previous conclusions concerning cormic and crural indices. Their revisions made minor changes to the coefficients and constants to their initial regression equations and, moreover, provided formulae for additional skeletal elements and their combination. More recently, Sciulli and Hetland (2007) recalculated stature estimation equations from a similar suite of skeletal elements, employing the revised Fully stature estimation method (Raxter et al., 2006). Sciulli and Hetland did not compare their revised stature equations to either the previously calculated mathematical method equations (Sciulli et al., 1990; Scuilli and Giesen, 1993) or with the other available regression equations, however.

The general dilemma that Sciulli et al. set out to address—the need for population-specific formulae for stature estimation in prehistoric populations from the Americas—still persists. Currently, only the few equations referenced above are available to researchers for estimating statures among the variety of indigenous human skeletal remains from the Americas, and it is unclear how widely applicable they are. For example, no equations currently exist for the estimation of stature for populations that lived in the Southeastern United States, the populations of the Great Plains, or for the arctic. Researchers have defaulted to using the apparently most appropriate of the available formulae, citing a "best fit" scenario, sometimes using limb proportions as a guide (e.g., Auerbach and Ruff, 2004). This is problematic, as stature estimations are prone to high amounts of error when the reference sample for equations and the estimated sample are from genetically and environmentally distinct populations (Holliday and Ruff, 1997; Konigsberg et al., 1998). As stature estimates are widely used as an indicator for stress, disease, and diet when comparing past groups (e.g., Haviland, 1967; Cohen and Armelagos, 1984; Bogin, 1999), in addition to ecological and forensic studies, appropriate stature estimation formulae are crucial.

The goal of this article is to derive "mathematical" stature estimation equations that are broadly applicable to indigenous human remains from the Americas. Statures are reconstructed using the "anatomical" method for a large sample representing a diversity of time periods and geographic regions, thus inherently incorporating variability in body proportions. These statures are then used to derive regression equations based on the major bones of the lower limb (femur and tibia). Results from these new equations are also compared with those obtained from previously published equations.

MATERIALS AND METHODS

Samples

A total of 2,621 adult skeletons from 149 North American archaeological sites were examined by B.M.A. (Auerbach, 2007a). Of the total sample, a sufficient number of elements (see below) for estimating statures using the "anatomical" method (Raxter et al., 2006) were preserved in 967 individuals (535 males, 432 females) from 75 sites. These elements include the cranium, vertebrae (second cervical to the first sacral), and at least one femur, tibia, and talus and calcaneus from the same side. The sites were divided into eleven cultural "regions" based on archaeological relationships among sites (Fagan, 2005). Site locations and region boundaries are shown in Figure 1. Small sites that are geographically and temporally proximal to each other were combined into single samples for analyses, such as several sites from the Sacramento River Valley. In the case of the single sample from the Western Plateau (the Coast Salish), they are subsumed into the Pacific Northwest region as their geographic range cannot be asserted to be representative of the Western Plateau, and their political range extended to the coast. The samples from the Prairie and Eastern Woodlands are also subdivided, with some samples incorporated into the Great Plains for the creation of stature estimation formulae (see Results for the reasoning behind this). Summary data for these sites and their regional designations are listed in Table 1.

It should be noted that skeletons from these sites are of unequal antiquity. The skeletons from Windover Pond,

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[1] Neumann and Waldman (1967) had previously attempted a similar method, measuring in situ body lengths from Mississippian and Hopewellian remains from the Dickson Mound site and developing regression equations for the long bones. However, they did not report estimation errors, and their equations remain generally unused in estimating the statures of archaeological samples.

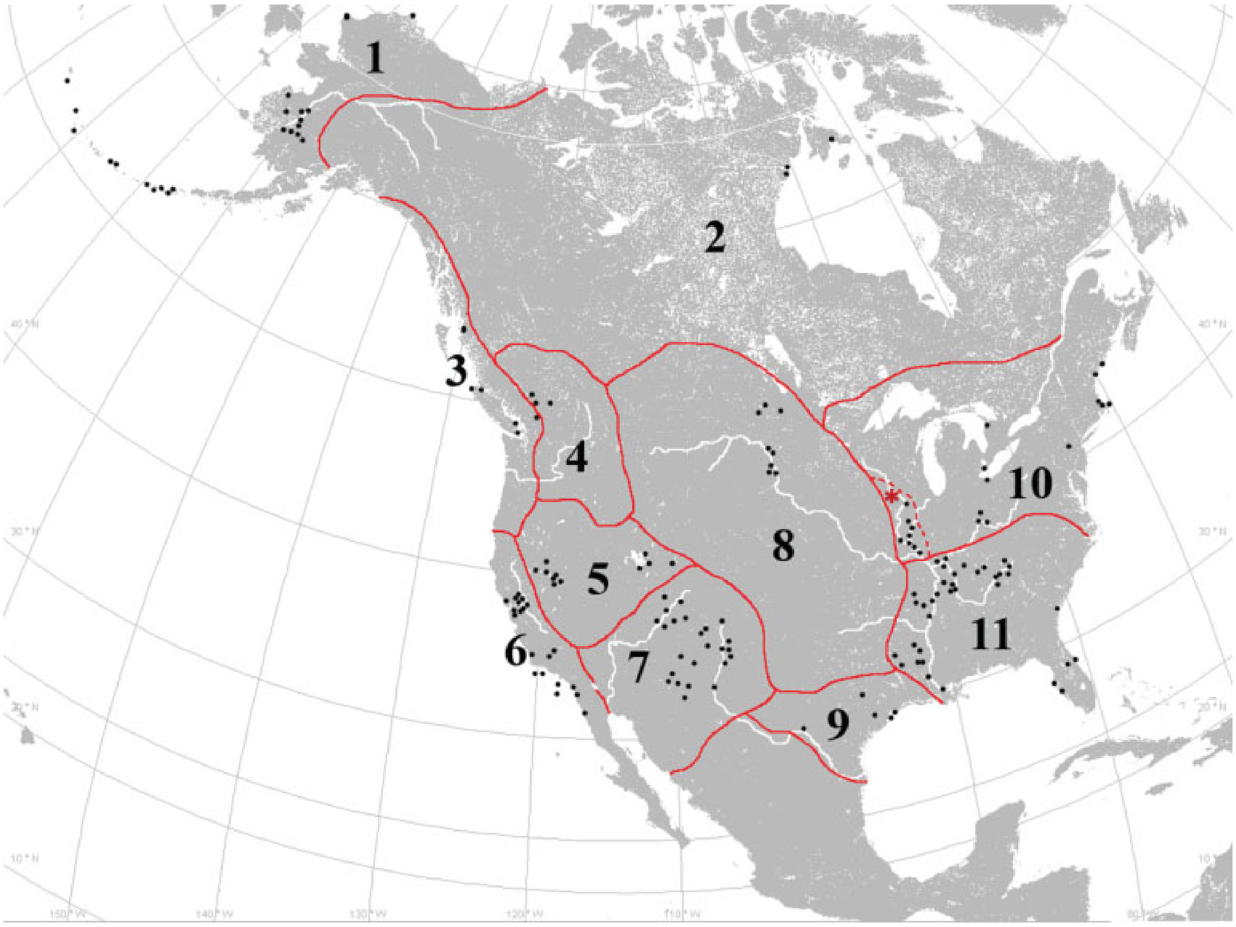

Fig. 1. Regions and sites from North America sampled. Each dot represents a single archaeological site with skeletons represented in the total sample (Table 1). Regions are based on the cultural regions designated by Fagan (2005), delineated by both natural and cultural boundaries: 1, Western Arctic; 2, Central Arctic; 3, Pacific Northwest; 4, Western Plateau; 5, Great Basin; 6, California; 7, US Southwest; 8, Great Plains; 9, Southern Great Plains; 10, Prairie and Eastern Woodlands; 11, Southeastern US; * = subregion of the Prairie and Eastern Woodlands incorporated into the Great Plains sample for analyses. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

for example, date to at least 7,000 years before present, whereas others, such as the Aleut, are from the last few centuries. Furthermore, the temporal distribution of sites among regions is not equal; samples from the arctic and the southwestern United States are limited to the last two millennia, whereas sites in California and the southeastern US represent the majority of the Holocene. In this article's analyses and groupings, we do not mean to imply that body shape and size have remained completely static within regions. Some body proportions do show temporal variation within the smaller regions shown in Figure 1; however, these changes are not consistent and only occur in morphologies not under consideration in this study, such as brachial index (Auerbach, 2007a). Aggregating temporal periods, as we do here, somewhat increases the morphological variation represented for each region, but allows for greater applicability of the new stature equations to skeletons from throughout the Holocene.

Adult status was determined by the same criteria as reported elsewhere for these data (Auerbach and Raxter, 2008), namely by complete epiphyseal closure of long bones and vertebrae. Age (in decadal increments except for young adulthood, which was split into two categories: 21–25 and 26–30 years) and sex were also determined using established methods based on the cranium and os coxae (Brooks and Suchey, 1990; Bruzek, 2002; Buckberry and Chamberlain, 2002). These techniques did not allow for age estimation beyond the age of 50; individuals over the age of 50 were collectively designated in a broad 50+ age category (constituting 5.4% of the total sample). Individuals of indeterminate sex were excluded from these analyses, along with skeletons exhibiting perceptible trauma or pathologies affecting the measurements taken on the skeleton.

Measurements

Following the protocol specified by Raxter et al. (2006), living stature was estimated from these 967 skeletons using the revised Fully stature estimation technique. In tests conducted using skeletons from the Terry Collection, this technique was demonstrated by Raxter et al. to be accurate to within 4.5 cm of the known cadaveric statures in 95% of these individuals, without directional bias. Basion-bregma height (BBH; Martin, 1928, #17)

TABLE 1. Sample composition

Site(s)[a]	Region[b]	Region number[c]	*n* (male/female)	Source[d]
Bear Creek	California	6	4 (2/2)	UCD
Blossom	California	6	16 (10/6)	PAHMA
Channel Islands	California	6	10 (3/7)	NMNH/SDMM
Cook	California	6	4 (3/1)	UCD
Ellis Landing	California	6	1 (1/0)	PAHMA
Karlo	California	6	3 (1/2)	PAHMA
Need 1	California	6	6 (4/2)	PAHMA
Ryan Mound	California	6	42 (22/20)	SJSU
Sacramento Valley[e]	California	6	14 (4/10)	NMNH/PAHMA
Western Berkeley	California	6	1 (1/0)	PAHMA
Yerba Buena	California	6	5 (4/1)	PAHMA
Kiklewait	Central Arctic	2	8 (7/1)	CMC
Sadlermiut	Central Arctic	2	36 (22/14)	CMC
Caldwell Village	Great Basin	5	3 (2/1)	UMNH
Evans	Great Basin	5	4 (1/3)	UMNH
Polley-Secrest	Great Basin	5	6 (4/2)	UMNH
Cheyenne River	Great Plains	8	15 (7/8)	NMNH
Larson	Great Plains	8	20 (9/11)	UTK
Mobridge	Great Plains	8	26 (14/12)	NMNH
Sully	Great Plains	8	12 (8/4)	NMNH
Caplen	Great Plains (Southern)	9	2 (1/1)	TARL
Loeve Fox	Great Plains (Southern)	9	9 (6/3)	TARL
Mitchell Ridge	Great Plains (Southern)	9	8 (5/3)	TARL
Kwakwaka'wakw	Pacific Northwest	3	16 (10/6)	AMNH
Nuu-chal-nulth	Pacific Northwest	3	4 (3/2)	AMNH
Prince Rupert Harbor	Pacific Northwest	3	32 (22/10)	CMC
Cape Cod Bay	Prairie and Eastern Woodland	10	9 (6/3)	HPMAE
Dickson*	Prairie and Eastern Woodland	10	37 (21/16)	ISM
Donaldson	Prairie and Eastern Woodland	10	2 (2/0)	CMC
Elizabeth*	Prairie and Eastern Woodland	10	17 (9/8)	ISM
Fort Ancient	Prairie and Eastern Woodland	10	14 (10/4)	FMNH
Kuhlman*	Prairie and Eastern Woodland	10	9 (5/4)	ISM
Libben	Prairie and Eastern Woodland	10	10 (4/6)	KSU
Madisonville	Prairie and Eastern Woodland	10	15 (8/7)	HPMAE
Maine	Prairie and Eastern Woodland	10	3 (2/1)	HPMAE
Modoc Rock Shelter*	Prairie and Eastern Woodland	10	4 (3/1)	ISM
Montague	Prairie and Eastern Woodland	10	15 (5/10)	NMNH
Averbuch	Southeastern US	11	28 (13/15)	UTK
Candy Creek	Southeastern US	11	9 (8/1)	MM
Carrier Mills	Southeastern US	11	24 (13/11)	SIUC
Cherry	Southeastern US	11	11 (9/2)	MM
Ebenezer	Southeastern US	11	4 (3/1)	MM
Eva	Southeastern US	11	22 (14/8)	MM
Hiwassee	Southeastern US	11	20 (9/11)	MM
Indian Knoll	Southeastern US	11	41 (20/21)	WOAC
Irene Mound	Southeastern US	11	10 (3/7)	NMNH
Ledford Landing	Southeastern US	11	10 (5/5)	MM
Palmer	Southeastern US	11	10 (4/6)	FLMNH
Thompson Village	Southeastern US	11	3 (2/1)	MM
Toqua	Southeastern US	11	17 (9/8)	MM
Ward Place	Southeastern US	11	3 (2/1)	NMNH
Windover Pond	Southeastern US	11	17 (11/6)	FSU
Ackmen	US Southwest	7	2 (2/0)	FMNH
Canyon del Muerto	US Southwest	7	10 (6/4)	AMNH
Carter Ranch	US Southwest	7	7 (5/2)	ASM
Chaco Canyon	US Southwest	7	10 (4/6)	UNM
Chamisal	US Southwest	7	6 (3/3)	UNM
Gallina Springs	US Southwest	7	3 (1/2)	UNM
Glen Canyon	US Southwest	7	16 (10/6)	NMNH/UMNH
Grasshopper	US Southwest	7	42 (24/18)	ASM
Hawikuh	US Southwest	7	24 (8/16)	NMNH
Kinishba	US Southwest	7	3 (1/2)	ASM
Mimbres	US Southwest	7	3 (3/0)	UNM
Paa-Ko	US Southwest	7	13 (6/7)	SDMM
Point of Pines	US Southwest	7	4 (3/1)	ASM
Pottery Mound	US Southwest	7	15 (10/5)	UNM
Puye Cliff Dwellings	US Southwest	7	12 (7/5)	NMNH
Ikogmiut	Western Arctic	1	39 (18/21)	NMNH
Kuskowagamiut	Western Arctic	1	20 (9/11)	NMNH

(continued)

TABLE 1. (Continued)

Site(s)[a]	Region[b]	Region number[c]	*n* (male/female)	Source[d]
Neo-Aleut[f]	Western Arctic	1	27 (17/10)	NMNH
Point Barrow	Western Arctic	1	12 (9/3)	NMNH
Point Hope Ipiutak	Western Arctic	1	24 (13/11)	AMNH
Point Hope Tigara	Western Arctic	1	33 (16/17)	AMNH
Pre-Aleut[f]	Western Arctic	1	13 (7/6)	NMNH
Coast Salish**	Western Plateau	4	7 (4/3)	AMNH
Total Sample			967 (535/432)	

[a] These are single archaeological sites or groups of temporally and geographically proximate burial sites.
[b] Region designations are adapted from the cultural regions specified by Fagan (2005). See Figure 1 for a map depicting these regions.
[c] Region numbers refer to areas designated in Figure 1.
[d] AMNH, American Museum of Natural History, New York City, New York; ASM, Arizona State Museum, Tucson, Arizona; CMC, Canadian Museum of Civilization, Gatineau, Québec; FLMNH, Florida Museum of Natural History, Gainesville, Florida; FMNH, Field Museum of Natural History, Chicago, Illinois; FSU, Florida State University Department of Anthropology, Tallahassee, Florida; HPMAE, Harvard Peabody Museum of Anthropology and Ethnology, Cambridge, Massachusetts; ISM, Illinois State Museum, Springfield, Illinois; KSU, Kent State University Department of Anthropology, Kent, Ohio; MM, Frank H. McClung Museum, Knoxville, Tennessee; NMNH, National Museum of Natural History (Smithsonian Institution), Washington, D.C.; PAHMA, Phoebe A. Hearst Museum of Anthropology, Berkeley, California; SDMM, San Diego Museum of Man, San Diego, California; SIUC, Southern Illinois University Department of Anthropology, Carbondale, Illinois; SJSU, San Jose State University Department of Anthropology, San Jose, California; TARL, Texas Archaeological Research Laboratory, Austin, Texas; UCD, University of California – Davis, Davis, California; UMNH, Utah Museum of Natural History, Salt Lake City, Utah; UNM, University of New Mexico, Albuquerque, New Mexico; UTK, University of Tennessee – Knoxville Department of Anthropology, Knoxville, Tennessee; WOAC, Webb Osteology and Archeology Collection, Lexington, Kentucky.
[e] Includes various mounds located along the Sacramento River, including Hicks, Herzog, and Augustine.
[f] The distinction of the Aleut into these categories follows Hrdlička's (1945) designations, though see Coltrain et al. (2006) for a revision of this grouping.
* The sites from the western margin of the Prairie and Eastern Woodland are grouped with the Great Plains samples in the construction of stature estimation equations (see main text for discussion).
** The grouped sites from the Western Plateau are combined with the Pacific Northwest in the construction of stature estimation equations (see main text for discussion).

was assessed using spreading calipers, the superoinferior maximum heights of vertebral centra (C2 to S1) were measured by Mitutoyo 150 mm digital sliding calipers with direct input to a notebook computer, and femoral bicondylar length (FBL; Martin, 1928, #2), the maximum length of the tibiae without the intercondyloid eminence ("Fully" length of the tibia, TFL; Martin, 1928, #1), and talocalcaneal height (TCH) were measured bilaterally when possible on a portable field osteometric board. Femoral maximum length (FML; Martin, 1928, #1) and tibial maximum length (TML; Martin, 1928, #1a) were also measured. These osteometric measurements are described in detail in Raxter et al. (2006) and Auerbach (2007a). All bilateral measurements were averaged to minimize the effects of bilateral directional asymmetry (Auerbach and Ruff, 2006). Repeated measurements of a subset of the total sample indicate that the measurements employed are highly accurate, with measurement errors below 1%.

In a further technical note on the technique (Raxter et al., 2007), the authors specify that the use of the regression equation for converting skeletal stature to living stature reported in the Raxter et al. (2006) article should normally include the coefficient term for age (provided in the first article). Following their recommendations, mean ages were used in place of age ranges. That is, for example, in calculating living statures, an age of "35" was used for all individuals aged between 30 and 40. Individuals in the 50+ category were given a "mean" age of 55; as only 53 individuals (5.4% of sample) are in this category, it is unlikely that the stature distributions for any group are significantly influenced even if some of the oldest individuals' statures were overestimated by using an underestimated mean age coefficient. Mean estimated living statures for all of the samples are reported in Table 2 by sex.

Missing skeletal elements are a common impediment to applying the "anatomical" stature estimation technique to archaeological specimens. However, using regressions based on preserved elements in complete skeletons, it is possible to reliably estimate some of the skeletal elements required for the revised Fully stature estimation technique without tautology [i.e., without assuming the proportions of an individual (Auerbach et al., 2005; Auerbach, 2007a)]. Such an approach was applied to estimate particular vertebral heights and talocalcaneal height, some of the most commonly missing elements. In the case of vertebral elements, only individuals missing nonconsecutive vertebrae (e.g., T1 and T3, but not T1 and T2) were used in this study, though previous studies included attempts to estimate vertebral column length from as few as the five lumbar vertebrae (Fully and Pineau, 1960), with less accuracy (Auerbach, 2007a). Missing vertebrae, except for C2, C3, C6, T2, T11, L1, and L5 could be estimated reliably by averaging the maximum heights of adjacent (superior and inferior) vertebrae. The seven vertebrae that could not be estimated by averaging adjacent vertebrae fall at the end of the (measured) vertebral column, or do not fall near the midpoint of the heights of their adjacent vertebrae. Instead, these vertebrae were estimated proportionally as percentages of the centra heights of either a superior or inferior vertebra, employing a protocol described in detail elsewhere (Auerbach, 2007a). Average absolute percent prediction errors (%PE) for all of these estimates

TABLE 2. Sample mean statures (estimated by the revised Fully method), length of the lower limb relative to stature, and crural indices, by sex

Region number	Site(s)	Sex	Mean stature (cm)	Mean relative lower limb length[a]	Mean crural index[b]
6	Bear Creek	M	172.91	49.53	84.18
		F	156.82	49.64	84.61
6	Blossom	M	169.01	48.65	85.15
		F	160.92	47.96	83.83
6	Channel Islands	M	156.36	48.95	85.26
		F	144.61	48.39	83.11
6	Cook	M	166.89	49.29	84.43
		F	159.98	49.72	83.84
6	Ellis Landing	M	162.72	47.89	85.14
		F	–	–	–
6	Karlo	M	161.02	49.05	83.53
		F	156.35	47.74	81.69
6	Need 1	M	162.01	48.84	84.86
		F	159.88	48.29	85.02
6	Ryan Mound	M	161.74	48.83	84.21
		F	152.92	48.01	84.17
6	Sacramento Valley	M	167.01	49.40	86.05
		F	155.85	48.84	83.98
6	Western Berkeley	M	164.72	48.57	81.63
		F	–	–	–
6	Yerba Buena	M	161.54	49.00	85.45
		F	157.19	50.16	85.93
2	Kiklewait	M	158.06	49.28	82.65
		F	150.55	49.20	78.01
2	Sadlermiut	M	158.74	49.22	80.22
		F	151.07	48.40	80.46
5	Caldwell Village	M	159.60	48.61	86.51
		F	141.18	47.97	83.56
5	Evans	M	162.60	48.40	85.73
		F	147.20	47.38	85.75
5	Polley-Secrest	M	159.08	47.91	86.27
		F	145.26	46.71	83.06
8	Cheyenne River	M	168.90	49.95	86.05
		F	154.03	48.48	85.07
8	Larson	M	165.22	48.94	87.07
		F	153.63	48.61	86.21
8	Mobridge	M	168.89	49.31	85.28
		F	154.76	48.39	86.12
8	Sully	M	168.04	49.37	87.42
		F	152.95	48.56	86.46
9	Caplen	M	164.13	49.87	82.57
		F	155.28	49.04	84.90
9	Loeve Fox	M	168.97	50.15	86.08
		F	155.57	49.65	85.54
9	Mitchell Ridge	M	169.43	49.77	86.31
		F	156.96	48.81	83.83
3	Kwakwaka'wakw	M	157.66	47.90	82.87
		F	149.83	47.87	82.51
3	Nuu-chal-nulth	M	146.31	48.84	80.97
		F	158.36	48.94	82.42
3	Prince Rupert Harbor	M	158.52	47.55	82.69
		F	147.85	47.32	82.13
10	Cape Cod Bay	M	167.40	49.94	84.13
		F	156.68	50.57	82.32
10	Dickson	M	168.98	49.29	84.43
		F	158.79	48.03	85.02
10	Donaldson	M	178.19	50.29	83.17
		F	–	–	–
10	Elizabeth	M	165.60	49.46	85.67
		F	159.48	48.88	84.48
10	Fort Ancient	M	167.86	48.80	85.31
		F	159.21	47.84	83.29
10	Kuhlman	M	163.23	48.79	85.71
		F	154.67	49.14	85.48
10	Libben	M	167.33	49.37	86.06
		F	156.99	49.35	84.38
10	Madisonville	M	165.29	48.69	84.59
		F	158.52	48.16	84.98
10	Maine	M	165.99	48.92	84.40

(*continued*)

TABLE 2. (Continued)

Region number	Site(s)	Sex	Mean stature (cm)	Mean relative lower limb length[a]	Mean crural index[b]
		F	157.48	49.96	85.14
10	Modoc Rock Shelter	M	171.15	50.04	85.73
		F	158.24	49.96	84.75
10	Montague	M	167.36	49.90	85.11
		F	157.26	49.10	84.81
11	Averbuch	M	169.62	49.07	84.23
		F	159.97	48.65	84.24
11	Candy Creek	M	165.89	49.17	85.48
		F	156.63	47.29	87.23
11	Carrier Mills	M	162.28	49.94	84.14
		F	153.60	49.43	84.17
11	Cherry	M	159.83	48.81	84.87
		F	150.91	48.59	84.80
11	Ebenezer	M	166.81	50.03	84.86
		F	166.13	48.85	86.64
11	Eva	M	162.19	49.08	83.76
		F	153.72	49.34	83.90
11	Hiwassee	M	168.20	49.13	84.46
		F	156.46	48.22	82.22
11	Indian Knoll	M	161.35	49.50	84.93
		F	150.22	48.66	84.36
11	Irene Mound	M	172.15	49.65	84.30
		F	155.55	48.82	83.46
11	Ledford Landing	M	165.43	49.30	84.53
		F	154.12	48.38	85.43
11	Palmer	M	161.87	49.39	83.55
		F	156.34	49.07	84.63
11	Thompson Village	M	164.07	47.79	84.02
		F	159.34	47.87	85.36
11	Toqua	M	164.37	48.69	84.16
		F	157.77	48.94	83.14
11	Ward Place	M	166.73	49.54	83.13
		F	161.19	49.75	85.73
11	Windover Pond	M	166.32	50.29	85.81
		F	154.77	49.50	84.83
7	Ackmen	M	166.65	50.59	87.21
		F	–	–	–
7	Canyon del Muerto	M	157.77	48.37	87.06
		F	153.60	49.12	85.35
7	Carter Ranch	M	160.53	48.36	86.64
		F	143.33	46.19	83.98
7	Chaco Canyon	M	169.28	49.27	85.01
		F	157.21	48.32	83.47
7	Chamisal	M	157.97	47.74	85.32
		F	144.94	47.62	83.34
7	Gallina Springs	M	154.45	48.30	86.83
		F	156.11	48.87	84.48
7	Glen Canyon	M	161.52	49.16	86.55
		F	151.06	48.98	84.33
7	Grasshopper	M	161.97	48.88	86.23
		F	151.34	48.70	85.39
7	Hawikuh	M	160.03	48.75	85.22
		F	149.79	48.31	84.53
7	Kinishba	M	167.15	50.72	86.18
		F	148.47	48.44	86.45
7	Mimbres	M	160.25	48.82	84.42
		F	–	–	–
7	Paa-Ko	M	160.47	48.81	86.16
		F	150.30	47.88	83.59
7	Point of Pines	M	163.88	48.74	86.82
		F	142.88	48.47	84.62
7	Pottery Mound	M	159.42	48.95	84.70
		F	149.35	47.95	84.05
7	Puye Cliff Dwellings	M	155.79	49.66	84.52
		F	147.85	49.07	85.60
1	Ikogmiut	M	158.17	48.30	82.30
		F	148.29	47.81	80.26
1	Kuskowagamiut	M	156.75	48.13	79.54

(*continued*)

TABLE 2. (Continued)

Region number	Site(s)	Sex	Mean stature (cm)	Mean relative lower limb length[a]	Mean crural index[b]
		F	147.51	48.62	80.77
1	Neo-Aleut	M	159.31	48.05	81.29
		F	147.18	46.81	81.42
1	Point Barrow	M	156.74	49.52	81.54
		F	149.22	48.69	83.82
1	Point Hope Ipiutak	M	154.32	48.60	81.17
		F	146.36	47.77	80.18
1	Point Hope Tigara	M	159.29	48.90	83.06
		F	147.78	48.59	82.78
1	Pre-Aleut	M	156.77	47.99	80.95
		F	149.63	46.73	81.26
4	Coast Salish	M	156.99	48.73	82.97
		F	148.45	48.68	84.12

[a] FBL + TFL (cm)/Stature (cm).
[b] TML/FBL.

range from 3.3% to 7.2%, which amount to estimation errors under 0.5 mm in all instances. Talocalcaneal heights were estimated, when missing, using femoral and tibial lengths in a multiple regression formula (Auerbach, 2007a); these equations have a 95% confidence interval of −0.13 to 0.17 mm. Cranial height cannot be reliably estimated by any other portion of the skeleton, largely because of some apparent morphometric discontinuity (or independent variance) of the cranium from postcrania (Auerbach et al., 2005, 2007b). In addition, the estimation of femoral length from tibial length, or vice versa, was not attempted, as this requires *a priori* assumptions of intralimb proportions within a population.

Stature estimation methods and statistics

Stature estimation equations from femoral and tibial lengths of individuals with anatomically derived living statures were generated in this study using linear regression methods. Living stature was estimated, rather than skeletal stature, as this was considered more useful in comparative studies; comparability in skeletal statures among human groups has not been established. Moreover, all available mathematical estimation formulae yield living stature predictions with the exception of the formulae developed by Scuilli et al., which estimate skeletal stature to which Fully's "soft tissue correction" factor is added. Most authors have developed ordinary least squares (OLS) formulae by regressing long bone lengths (x) against stature (y), followed by solving for stature. This method—classic calibration (Konigsberg et al., 1998)—works well when a sizable sample is employed and when the error in x and y is quantifiable and small. OLS regression, contrasted with reduced major axis (RMA) or major axis (MA), is appropriate when predicting y from x, so long as a number of basic statistical assumptions are met (Berry, 1993; Zar, 1996). Namely, we assume that the long bone lengths were measured with a quantifiable and minimal error, that there is no multicollinearity among the dimensions considered, that there is no heteroscedasticity in the predicted dimension (stature), and that the resultant equations will not be used to extrapolate beyond the range of the original data used to create the equations.

The use of OLS regression has one major detractor in the sample used for this study, however. As none of the skeletons had living statures that were actually known, a degree of error exists for the statures used in the development of estimation formulae. Raxter et al. (2006) reported a ±4.5 cm 95% confidence interval around stature estimations using the revised Fully technique, resulting from a combination of errors in estimating skeletal stature[2] and in correctly converting that dimension to living stature. (In short, this is random variation among individual skeleton stature estimations.) This error is not systematic (there is no systematic bias for whole samples) or correlated with either the dependent or independent variables. Furthermore, it follows that any influence of this estimation error on the error term of the living stature estimation equation devised by Raxter et al. (2006) is uncorrelated with either variable, and so does not violate any fundamental linear regression assumptions (Berry, 1993). Yet, it must be acknowledged that, although more precise than any other method available for estimating statures for populations with unknown living anthropometrics, the Fully method estimated statures used in this analysis were subject to an unknown error term within 4.5 cm of the estimation.

In estimating statures, focus is placed here on lower limb long bones as predictors over those of the upper limb. Lower limb bones are favored given their more common preservation in archaeological contexts and their direct contribution to total stature; on the basis of our archaeological skeletal sample, upper limb length has greater variance relative to stature ($r = 0.906$) than does lower limb length ($r = 0.967$), similar to findings

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[2] As no independent measurement of "skeletal stature" can be taken from individuals, unlike living stature, the amount of error in any estimation of skeletal stature cannot be calculated. Furthermore, it is worth noting that the term "skeletal stature" is a misnomer, in that the bone measurements taken as part of the anatomical method include overlaps and gaps between elements (Raxter et al., 2006), and therefore do not present a representation of the skeleton's stature were it possible to remove soft tissues and accurately rearticulate the skeleton.

reported by other researchers (Trotter and Gleser, 1952; Raxter et al., 2008). Other segments of the skeleton (e.g., vertebral column lengths or cranial height) are not considered. As noted above and previously (Auerbach, 2007b), cranial height is highly variable relative to stature (r = 0.53), and vertebral column length does not have correlation coefficients as high as those for either limb (thoracic and lumbar vertebrae, r = 0.83; total vertebral column, r = 0.85). Another (practical) reason for limiting this study to the lower limb bones is that the femur and tibia were available for all individuals whose statures had been estimated using the revised Fully technique (see above), whereas some of these individuals lacked upper limb bones. Therefore, this approach maximized the available sample size.

Previous authors (Genovés, 1967; Sciulli et al., 1990; Holiday and Ruff, 1997; Ruff et al., 2002; Auerbach and Ruff, 2004) have noted that different linear body proportions (e.g., between femoral length and stature) create a need for different stature estimation equations. We have previously argued (Auerbach and Ruff, 2004) that crural index may be used as a guide to matching appropriate estimator samples to estimated samples, as crural index may reflect the relative contribution of these elements to total stature. To examine this explicitly, the proportion of lower limb length—or the elements thereof—to stature should be undertaken, especially in ascertaining whether proportional contributions of the lower limb or its elements to stature significantly vary among populations. Indeed, there is a great range of variation in these proportions in the Americas (see Table 2), which argues that more than one set of stature estimation equations will be necessary. For these reasons, an examination of the relative length of the femur ("physiological" length), of the tibia ("Fully" length), and of the combination of these (a proxy for lower limb length) to stature were used as the primary criteria to group samples prior to developing stature estimation equations. This group assignment was obtained by comparing the residuals from a line of isometry for each of these lengths regressed against stature. (That is, sample groups with high relative proportions would have significantly more positive residuals than groups with lower relative proportions.) Significant differences among groups were determined using *post-hoc* Games-Howells tests (which do not assume equal variance among the groups compared), as homogeneity of variance in the regressed variables cannot be assumed, especially because the residuals compared are determined from a line of isometry and not a regression line.

To provide equations that are useful over relatively broad geographic regions (as opposed to site- or temporal-specific equations), while maintaining reasonably accurate estimations (based on variation in proportions), the methods adopted in this article have been to first examine geographic patterning in body proportions, and then group samples by similarity in proportions as well as geographic proximity. This approach is justified by the known ecogeographic patterning in limb proportions in the Americas (Stinson, 1990; Ruff, 1994; Weinstein, 2002; Jantz, 2006; King, 2007) that seems to relate to climate more than other environmental variables, such as subsistence (Auerbach, 2007a). In addition, this approach leads to geographic groupings that should aid future researchers in choosing the most appropriate estimation formulae for new samples.

Comparisons with other methods

Finally, to test the utility of the resultant stature estimation equations for specific archaeological sites, comparisons were carried out between stature estimations using the new equations and estimations utilizing previously available equations. The initial comparisons were made using groups from the dataset described in Table 1: sites from eastern Arizona (Grasshopper, Point of Pines, and Carter Ranch), individual sites from the Ohio River valley (Madisonville, Fort Ancient), the Neo-Aleut, the Sadlermiut, Mobridge, and Dickson sites. The Arizona samples were combined in this analysis because they date to a roughly similar time period, are geographically proximate, and are not significantly different in proportions; the same is true for the Ohio samples (Auerbach, 2007a). Although all of these samples were included among those used to develop the equations, they individually form only a small subset of the large groupings from which equations were calculated, and so the comparisons should not be tautological.

These comparisons also provide an opportunity to test and refine the exact methods used for employing the new stature estimation formulae. Specifically, appropriate equations are identified based on geographic location, and confirmed by comparing the proportions of the test sample (crural index, then relative lower limb length) against those of the reference group. By assessing the utility of this protocol, a more specific recommended procedure is developed and is presented in the Discussion.

All analyses were conducted using Microsoft Excel 2008 and Stata SE 10 for Macintosh.

RESULTS

Limb proportions and stature groupings

Groups exhibit a considerable range in statures and proportions. As shown in Table 2, male mean group statures range more than 30 cm between the shortest (the Nuu-chal-nulth, 146.31 cm) and the tallest (individuals from the Donaldson site, 178.19 cm). A slightly lower range exists among female mean group statures (141.18–166.13 cm). This scope of statures is similar to the ranges reported by Eveleth and Tanner (1976) in New World living populations. Crural indices, likewise, exhibit a great diversity, ranging from 75.69 to 90.77 for males, and 75.97 to 90.74 for females. The range of crural indices in this New World sample is almost as great as the range reported for Europe and Africa (Holliday, 1995), which are between 75.00 and 91.59 for males, and between 78.00 and 90.43 for females (calculated from Holliday's raw data; Holliday, pers. comm.). The variability in linear body proportions suggests that, to minimize estimation errors, multiple stature equations should be developed for the indigenous North American groups.

Natural log-log bivariate plots of group means for tibial length against estimated living stature are presented for males (Fig. 2a) and females (Fig. 2b), and for femur+tibia length against estimated living stature (Fig. 3a, males; Fig. 3b, females); the length of the femur alone versus stature did not produce results significantly different from the latter comparison. Reference lines in these graphs indicate isometry (plotted through the grand mean x, y). Groups with short tibiae or limb lengths relative to stature plot above the line; groups

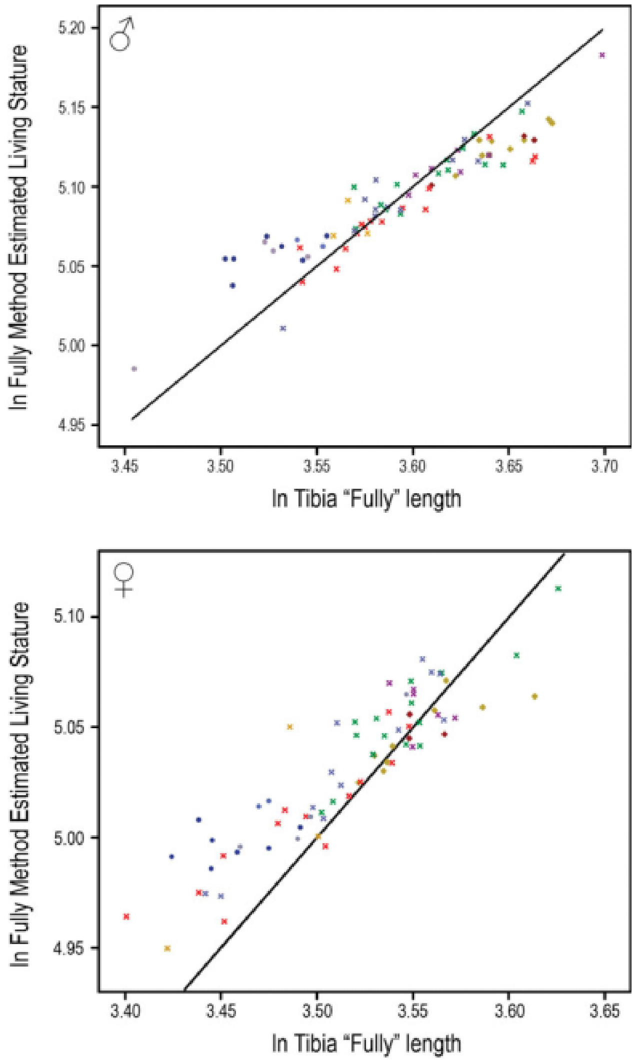


Fig. 2. Log-log plots of mean group proportions of the tibia "Fully" length to total Fully-estimated (Raxter et al., 2006) statures for males (Fig. 2a) and females (Fig. 2b). Solid lines represent isometry between tibia length and stature. Symbols represent regional designations listed on Table 1: dark blue circles, Western Arctic; light blue circles, Central Arctic; lavender circles, Pacific Northwest and Western Plateau; gold diamonds, Great Plains and Illinois River Valley; dark red diamonds, Southern Great Plains; purple x's, non-Illinois River Valley Prairie and Eastern Woodlands; orange x's, Great Basin; red x's, US Southwest; green x's, Southeastern US; blue x's, California. Visit http://web.utk.edu/∼auerbach/Pub.htm for a high-resolution version of this figure.

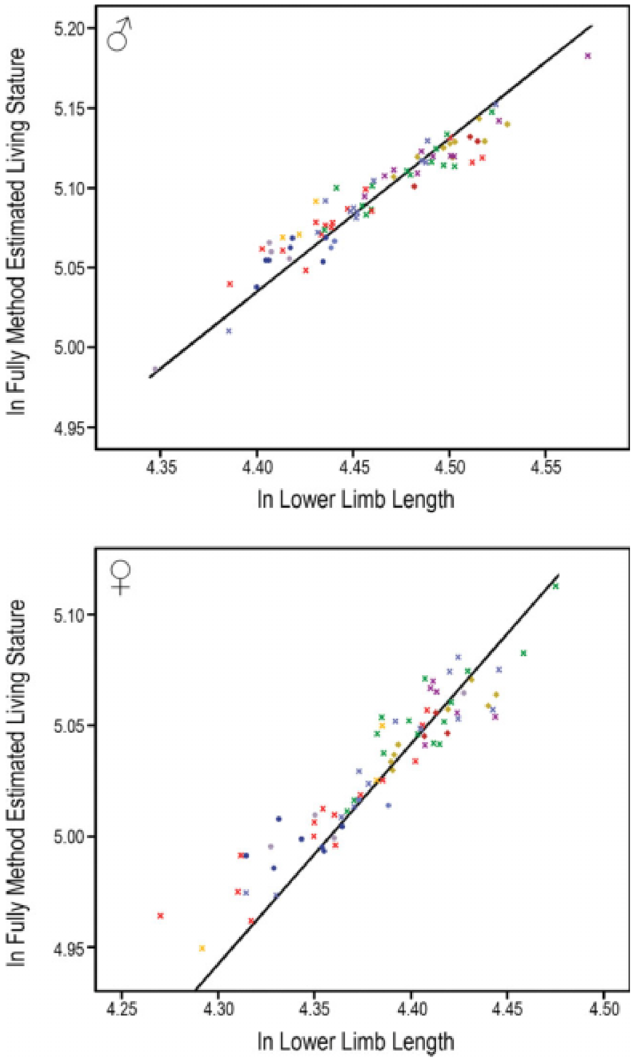
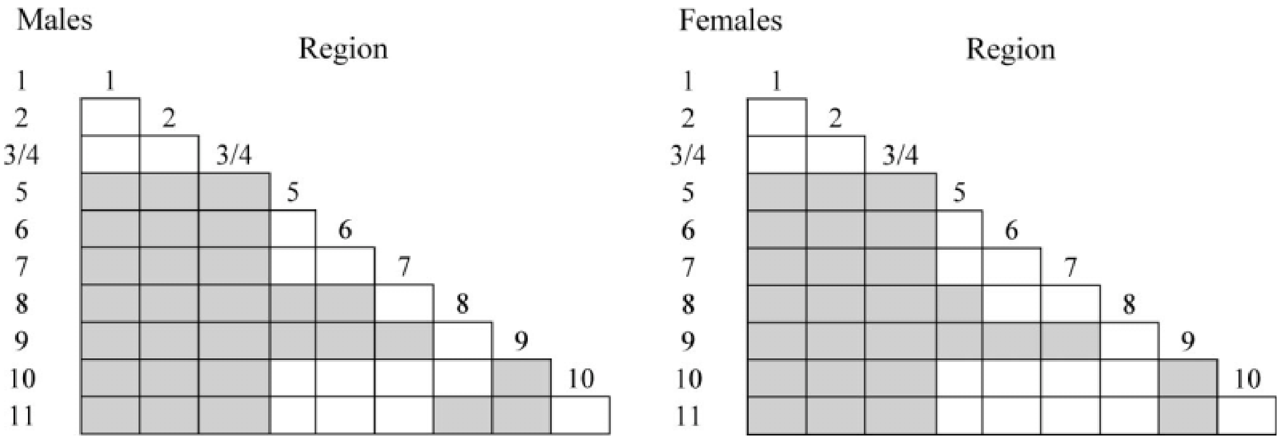


Fig. 3. Log-log plots of mean group proportions of lower limb length to total Fully-estimated (Raxter et al., 2006) statures for males (Fig. 3a) and females (Fig. 3b). Solid lines represent isometry between lower limb length and stature. Symbols represent regional designations listed on Table 1: dark blue circles, Western Arctic; light blue circles, Central Arctic; lavender circles, Pacific Northwest and Western Plateau; gold diamonds, Great Plains and Illinois River Valley; dark red diamonds, Southern Great Plains; purple x's, non-Illinois River Valley Prairie and Eastern Woodlands; orange x's, Great Basin; red x's, US Southwest; green x's, Southeastern US; blue x's, California. Visit http://web.utk.edu/∼auerbach/Pub.htm for a high-resolution version of this figure.

with longer tibia or limb lengths relative to stature plot below the line.

The plotted mean log-transformed lower limb lengths and statures in Figure 2 reveal some regional trends. Among both males and females, statures are generally lower in the arctic, Pacific Northwest and Western Plateau (Regions 1–4) than in other regions, and the majority of these samples have relatively short tibia lengths relative to their statures. Sex-specific ANOVAs with *post-hoc* Games-Howell tests comparing relative tibia length to stature between regions bears this out: samples from Regions 1 to 4 are not different from each other but are significantly different from all other regions (Table 3). Groups from the Great Plains and South Texas (Regions 8 and 9) tend to be distinct from other regions, more consistently among males (Table 3). Although not shown here, this is also true for some samples from the Prairie and Eastern Woodlands. Specifically, the four samples from the Illinois River Valley (see Table 1) have significantly higher statures and relative

TABLE 3. ANOVA Games-Howell post-hoc test results comparing regression residuals of tibial "Fully" length relative to stature among regions[a]



Males

Region	1	2	3/4	5	6	7	8	9	10
1									
2	☐								
3/4	☐	☐							
5	▨	▨	▨						
6	▨	▨	▨	☐					
7	▨	▨	▨	☐	☐				
8	▨	▨	▨	▨	▨	☐			
9	▨	▨	▨	▨	▨	▨	☐		
10	▨	▨	▨	☐	☐	☐	☐	▨	
11	▨	▨	▨	☐	☐	☐	▨	▨	☐

Females

Region	1	2	3/4	5	6	7	8	9	10
1									
2	☐								
3/4	☐	☐							
5	▨	▨	▨						
6	▨	▨	▨	☐					
7	▨	▨	▨	☐	☐				
8	▨	▨	▨	▨	☐	☐			
9	▨	▨	▨	▨	▨	▨	☐		
10	▨	▨	▨	☐	☐	☐	☐	▨	
11	▨	▨	▨	☐	☐	☐	☐	▨	☐

[a] Region numbers match the areas designated in Figure 1 and Table 1. Note that some samples from Prairie and Eastern Woodland (Region 10) have been combined with the Great Plains (Region 8) (see Results). Gray-filled boxes denote significant ($P < 0.05$) difference between regions in relative tibia length.

tibia lengths than most other samples from the Prairie and Eastern Woodlands or from the Southeastern US (Regions 10 and 11).[3] These Illinois samples, however, are not significantly different from the Plains samples in these dimensions. Because they are geographically contiguous and similar in proportions, these four western Prairie samples were grouped with the Great Plains samples for derivation of stature estimation equations. All other temperate groups generally fail to significantly differ in relative tibia lengths. These patterns are also evident (by small degrees) in comparing the mean relative tibia lengths among the regions (Table 4).

In contrast with these results, the relative length of the lower limb to estimated living stature does not delineate groups as clearly. *Post-hoc* test results from an ANOVA (not presented here) create similar groupings to those found from comparisons in relative tibia length, but do not significantly distinguish some regional groups. This is evident in Figure 3; for example, Central Arctic males' lower limb lengths relative to stature do not significantly differ from the US Southwest, Great Plains, or California. The patterns emerging from *post-hoc* comparisons among residuals for the relative lower limb length at best suggest differences between samples generally west of the Mississippi River and those mostly east of that geographic landmark; groups in the eastern half of North America tend to have relatively longer lower limbs. However, there are a number of inconsistencies in any of the resulting groupings, especially when trying to match the male pattern with the female pattern. The ambiguity in this pattern is evident by comparing mean proportions among regional groups (Table 4).

As the general patterns of variation do not match between these two proportions, they either should be considered together when grouping samples for the generation of stature estimation formulae, or one set of proportions should be given preference. Relative lower limb length does not distinguish among samples in any practically applicable pattern, as even the west-east distinction has notable exceptions. More importantly, the males and females demonstrate little correspondence in *post-hoc* tests; they produce considerably different groupings.

In the interest of using less dubious groupings and developing more generally applicable equations, then, decisions regarding regional groupings were based on the relative tibia length comparisons. This yields three general groups for stature estimation equations: (1) arctic samples, and groups from the Pacific Northwest and Western Plateau; (2) samples from the Great Plains (including the Southern Plains) and the western Prairie samples; and (3) all other samples, comprising a "general temperate" group. The general geographic distribution of these three groups is illustrated in Figure 4. (Note that the distributions have been extended to cover the entirety of regions, instead of being limited to the portions of those regions sampled in this study, to aid in the practical application of the formulae.) Indeed, the arctic, Pacific Northwest and Western Plateau samples have significantly lower ($P < 0.01$, $F = 56.95$) crural indices compared with all other regions (also see Table 6). As it has been demonstrated that the variance in tibia length contributes more to crural index variance than the femur (Holliday and Ruff, 2001; Auerbach, 2007a), this is expected. Interestingly, however, mean crural indices among samples from the Great Plains, South Texas and Illinois River Valley (the Prairie) samples do not significantly differ from the US

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[3] It should be noted that some samples from both the Prairie and Eastern Woodlands and from the Southeastern US have even higher statures and crural indices (e.g., Libben). However, these sites are geographically isolated, and excluding them from their regional samples would lead to sample-specific and non-contiguous groupings in developing stature estimation equations. As the Illinois River Valley samples largely differ from the other samples from these two regions, do not significantly differ from the Plains samples, and are geographically on the border between these two regions, their separation from the Prairie and Eastern Woodlands is justifiable.

TABLE 4. Regional mean statures and relative tibia and femur lengths for males and females

Region (Fig. 1 number)	Sex	Mean stature (cm)	Std. deviation	Mean tibia length/stature[a]	Std. deviation	Mean femur+tibia length/stature[b]	Std. deviation
Western Arctic (1)	Male	157.63	6.55	21.62	0.74	48.49	1.30
	Female	147.80	4.05	21.38	0.77	47.91	1.10
Central Arctic (2)	Male	158.75	5.63	21.86	0.62	49.25	1.03
	Female	152.35	6.91	21.56	0.64	48.58	0.98
Pacific Northwest and Western Plateau (3 and 4)	Male	157.89	4.54	21.56	0.56	47.70	0.92
	Female	149.17	4.66	21.82	0.41	47.61	1.03
Great Basin (5)	Male	159.69	5.91	22.07	0.33	47.97	0.76
	Female	148.63	6.54	21.31	0.55	47.32	0.92
California (6)	Male	163.90	6.36	22.30	0.49	48.89	0.91
	Female	153.78	5.65	21.93	0.55	48.29	0.98
US Southwest (7)	Male	160.79	5.33	22.46	0.51	48.94	1.01
	Female	150.52	5.17	22.03	0.54	48.38	0.89
Great Plains (8) and Prairie (10)	Male	168.02	4.85	22.76	0.49	49.38	0.83
	Female	153.82	3.95	22.30	0.63	48.50	1.00
Southern Great Plains (9)	Male	168.76	5.39	22.96	0.46	49.97	0.67
	Female	156.12	1.72	22.44	0.48	49.20	0.84
Eastern Woodlands (10)	Male	167.61	4.81	22.32	0.48	49.29	0.98
	Female	158.03	4.96	22.22	0.52	48.72	1.11
Southeastern US (11)	Male	164.68	6.44	22.42	0.52	49.28	0.89
	Female	155.32	5.86	22.11	0.58	48.75	0.96

[a] "Fully" tibia length (without the intercondyloid eminences).

[b] Femoral bicondylar ("physiological") length and "Fully" tibia length combined for femur+tibia.

Southwest, the Great Basin, or California. As the groups from the Great Plains were, on average, much taller than those from these other regions, the results of the residual comparisons are perhaps in part justified; these Plains groups also had among the highest crural indices in North America (Table 2), which may be in part commensurate with slight positive allometry in limb length among taller humans (Jantz and Jantz, 1999).

Stature estimation equations

As described in the Methods, sex-specific stature estimation equations were developed for each of the sample groupings by regressing lower limb bone lengths on the Fully technique estimated living statures. The resulting equations have been labeled "Arctic," "Temperate," and "Great Plains," though these labels do not necessarily reflect sample composition; the "Arctic" equations, for example, include sites from the Pacific Northwest and Western Plateau. These equations are listed in Table 5 with standard errors of the estimate (both SEE and %SEE), and the regional groups from which they are generated. In addition, the means and ranges of Fully-estimated living statures, relative lower limb lengths, and crural indices are given in Table 6 for use in corroborating the geographic groupings used to determine the application of these equations to archaeological samples; note the great overlap in these ranges for relative lower limb length, however. The specific samples used in all of the groups are not listed in the interest of brevity, though the regional groupings correspond with those defined in Table 1.

As is reported in Table 5, the precision of the new equations is quite good, with percent standard errors of the estimate between 1% and 2%. (This translates into an average standard error of estimate between 2 and 3 cm.) In all cases, femur and tibia multiple regression formulae have the best performance, followed by femur equations, with tibia formulae having the lowest precision of the three. Compared with the equations generated by previously available formulae, these equations are an improvement or are comparable in precision: Trotter and Gleser (1958) reported a SEE of ±3.80 cm for their femur equation (Table 12 in their article); the femur formulae of Genovés (1967) have SEEs of ±3.417 (males) and ±3.816 cm (females). [Sciulli and Giesen (1993) report the standard errors of the regression, and not SEEs for their analyses.] The performance of the equations among the three general regions is comparable, but it is worth noting that male equations tend to be more precise than female equations. The Arctic female equations have the lowest precision of the new formulae, but they are still at or below 2% SEE.

Comparison of new with previous equations

The accuracy and precision of living stature estimates using the new equations is compared with those of previously available equations for several small, geographically diverse samples in Table 7. Mean differences as well as standard deviations of these differences from the Fully living stature estimates are given. Both earlier and more recent versions of the Genovés (Genovés, 1967; Del Angel and Cisneros, 2004) and Sciulli (Sciulli and Giesen, 1993; Sciulli and Hetland, 2007) equations are included to provide the reader with an evaluation of the new formulae against both the established stature estimation formulae and their recent revisions. For the Genovés and Trotter and Gleser (1958) formulae, the femur-only equations were used, as these produced the lowest estimation errors in their studies. Combined femoral and tibial length was used in estimates employing the Sciulli equations. These mathematically estimated living statures were compared with the anatomically estimated living stature using paired Student's *t*-tests after assessing normality in the estimated statures' distributions using a Lilliefors test.

All three of our new sets of living stature estimation equations were applied to all of these individual samples. However, as expected, the equations from the

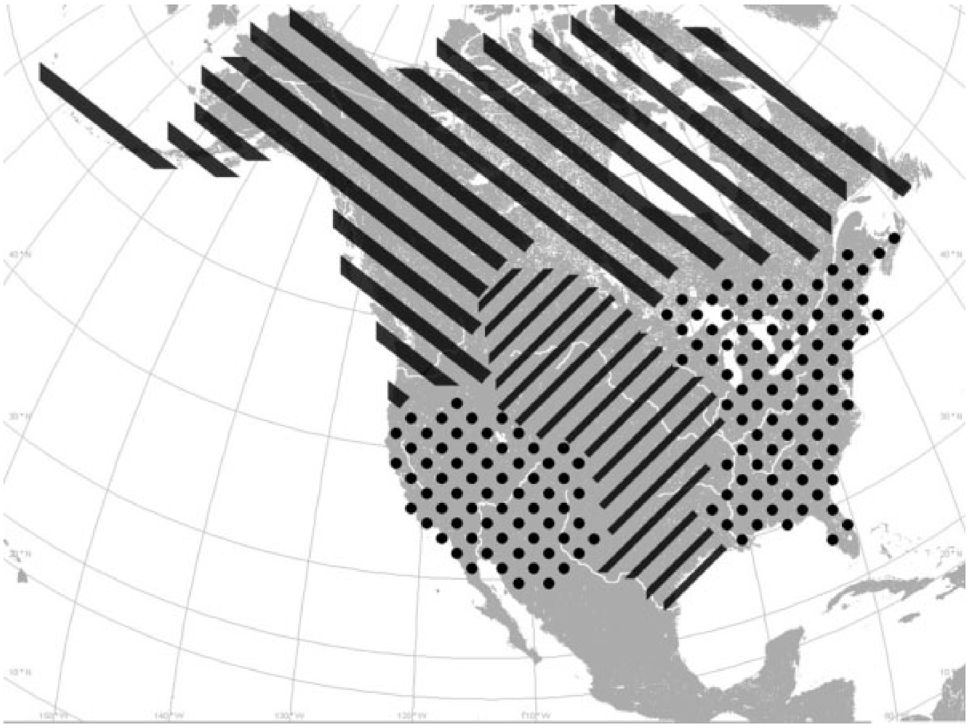

Fig. 4. General regional distributions of samples combined in generating broad stature estimation equations (Table 4): "Arctic" (left-slanting diagonal lines), "Temperate" (dots), and "Great Plains" (right-slanting diagonal lines).

matching geographic regions performed the best (shaded areas in Table 7). Limb proportions in the test samples also fell well within the ranges of their respective broader geographic groups (see Table 6), further supporting use of these equations. In almost all cases, the new mathematical stature estimation formulae from the matched geographic groups produce more accurate results (smallest mean differences) than estimates using previously available equations. The only exceptions are slightly better estimations of female statures from Dickson Mounds and Eastern Arizona by the 1967 Genovés and 2004 Del Angel and Cisneros formulae, respectively. Generally, the new equations also have the highest precision, as demonstrated by comparing their standard deviations with those of the previously available equations. New equations that use both femoral and tibial lengths generally produce the best estimates with the least dispersion around the mean. The recent revisions of Genovés' and Sciulli et al.'s formulae usually perform better than their earlier versions (the exceptions being the Mobridge and Dickson samples using the two Genovés formulae). The revised Sciulli and Hetland (2007) equations do nearly as well as the new equations in Eastern Arizona and Ohio River Valley males, but do less well among Ohio River Valley females and other samples. The Del Angel and Cisneros (2004) equations are consistently good for both Eastern Arizona males and females (more accurate than ours among females), but perform less well in other regions.

DISCUSSION

The new living stature estimation equations perform better than other equations currently available in predicting Fully estimated statures—the best available estimation of living statures—for archaeological New World indigenous populations. In the majority of the comparisons made among the equations on the samples presented in Table 7, the new femur and tibia multiple regression equations yield the most accurate (estimated mean closest to the mean Fully-estimated stature) and precise (lowest dispersion around that mean) living stature estimations. Furthermore, these new equations' guidelines for their application provide better certainty in their use for archaeological samples. For these reasons, it is recommended that the new equations should be used in place of those previously available.

On the basis of the results presented in Table 7, which simulate the practical application of these formulae, we recommend the following protocol for the application of these new stature estimation equations. It is reasonable to first identify a candidate equation based on the geography of the sample to be estimated, as demarcated in Figure 4. Comparing crural indices of the sample to be estimated with the ranges presented for each region in Table 6 further verifies the appropriateness of that geographical assignment. In the case of all of the test samples here, crural ranges were well within the ranges of the appropriate geographic reference samples (highlighted in Table 7). However, if a sample has an average crural index near or beyond the extremes of the ranges for their region, the most geographically proximate region with more similar crural indices should be chosen as a reference group for stature estimation formulae. Moreover, samples that are at or near to geographic boundaries between our three broad groups are best assigned to a stature estimation formula on the basis of both geography and proportions, namely crural index.

TABLE 5. Sex-specific stature estimation equations, listed by samples used in their calculation[a]

Regions	Samples	Sex	*n*	Femur equation	SEE (%SEE)	Tibia equation	SEE (%SEE)	Femur and tibia equation	SEE (%SEE)
Arctic (western and central) and subarctic (Pacific Northwest and Western Plateau)	All samples from Alaska (including the Aleut), British Columbia, and Nunavut	Male	157	0.225 × FBL + 62.73	2.90 (1.83%)	0.255 × TML + 69.51	2.99 (1.89%)	0.128 × FBL + 0.126 × TML + 59.86	2.62 (1.66%)
		Female	117	0.213 × FBL + 64.82	2.99 (2.01%)	0.231 × TML + 74.71	3.01 (2.03%)	0.117 × FBL + 0.120 × TML + 64.00	2.82 (1.90%)
"Temperate": California, US Southwest, Great Basin, Eastern Woodlands, Southeastern US	All samples from Arkansas, Arizona, California, Florida, Georgia, Kentucky, Louisiana, Maine, Massachusetts, Nevada, New Jersey, New Mexico, Ohio, and Tennessee	Male	287	0.254 × FBL + 52.85	2.55 (1.56%)	0.302 × TML + 51.66	2.81 (1.72%)	0.160 × FBL + 0.126 × TML + 47.11	2.35 (1.44%)
		Female	245	0.267 × FBL + 44.80	2.58 (1.68%)	0.296 × TML + 52.30	2.90 (1.89%)	0.176 × FBL + 0.117 × TML + 41.75	2.40 (1.56%)
"Great Plains": Prairie, Great Plains, Southern Great Plains	All samples from Illinois, Southern Manitoba, South Dakota, and Texas	Male	91	0.244 × FBL + 58.23	2.05 (1.22%)	0.249 × TML + 72.23	2.77 (1.65%)	0.188 × FBL + 0.076 × TML + 54.13	1.94 (1.15%)
		Female	70	0.244 × FBL + 55.85	2.58 (1.65%)	0.259 × TML + 65.10	2.97 (1.90%)	0.168 × FBL + 0.104 × TML + 50.55	2.41 (1.54%)

[a] Equations yield living stature in centimeters. FBL, femoral bicondylar length (mm); TML, tibial maximum length (mm).

Relative lower limb length may be used as an additional criterion, especially in assigning groups to the Arctic formulae, but is a less useful discriminator because it (1) has greater overlap among the regional reference samples, and, (2) may only be calculated when some statures for the test sample are able to be estimated using the Fully technique. Preference, therefore, is given to the crural index.

Importantly, the use of these estimation equations should only be undertaken when the revised Fully technique is not practical, either because of skeletal representation or time constraints. Moreover, in samples wherein a number of skeletons are eligible for anatomical stature reconstructions, it may be possible to generate novel regression equations by which to estimate statures for the remainder of the sample. As a caveat, though, researchers opting for this latter option must ensure that the reference samples are sufficiently large and representative of the sample as a whole, in terms of range of statures and possible substructuring of the population in body proportions. Except for large samples wherein these criteria are met, it is recommended that researchers use the formulae devised in this article and assess their applicability using the skeletons with anatomically estimated statures. If no satisfactory estimation equation is possible, statures should only be estimated using the revised Fully method.

As argued above, crural index is used as a proxy for the use of the relative length of the tibia to stature, the criterion by which the stature estimation formula groupings were determined. In general, for samples with low mean crural indices (<80), the "Arctic" equations are most appropriate. The delineation between the "Temperate" and "Great Plains" equations is not as clear, though the latter is best utilized in a sample in which there is a prior reason to assume that the population represented was especially tall, based on geography; namely, the groups living within the Plains were significantly taller than most other populations in North America, especially during the last millennium (Auerbach, in press). Particularly tall statures may be associated with high crural indices, as Jantz and Jantz (1999) and Sylvester et al. (2008) argued that there is slight positive allometry in tibial length. In fact, the results of the residual comparisons from lines of isometry (Figs. 2 and 3) lend support to these studies: arctic and Pacific Northwest samples, which have the lowest crural indices and well as some of the shortest statures, significantly differ from all other groups in their short tibiae. Future analyses examining allometric relationships among the contributing skeletal dimensions to stature may further clarify this trend. In addition, additional samples for assessing the applicability of the new equations to the borderline regions would be particularly useful.

The general lack of success in using relative lower limb length to distinguish groups requires further attention. In European and African samples, the relative length of the lower limb to trunk length demonstrates a strong latitudinal pattern (Holliday, 1997). On the basis of the results of this study, however, as well as Jantz et al. (in press), no such latitudinal pattern is evident in North America. However, both Jantz et al. (in press) and the results above suggest a longitudinal pattern, in which humans from the eastern half of the continent tend to have higher cormic indices (i.e., relatively longer lower limbs compared to stature) than those farther west. Note, again, that there is a great amount of

TABLE 6. Descriptive statistics for the three stature estimation groupings, by sex

		Stature		Relative Lower Limb Length[a]		Crural index[b]	
Regional grouping	Sex	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Arctic	M	158.05 (6.10)	141.32–177.58	48.77 (1.30)	45.3–52.3	81.80 (2.31)	75.69–87.13
	F	148.72 (4.94)	138.53–165.38	48.08 (1.32)	42.2–50.5	81.41 (2.15)	75.97–87.41
Temperate	M	163.61 (6.29)	146.86–184.50	49.31 (0.99)	46.3–51.9	85.06 (1.93)	79.78–89.78
	F	153.78 (5.95)	135.13–170.11	48.82 (1.00)	46.0–52.5	84.24 (1.99)	79.11–88.58
Great Plains	M	167.87 (4.88)	158.57–178.96	49.65 (0.88)	47.6–51.7	85.67 (2.17)	79.32–90.77
	F	155.95 (5.13)	146.09–171.08	48.79 (1.01)	47.0–51.4	85.51 (2.31)	80.57–90.74

[a] (Femur bicondylar length + "Fully" tibia length)/Stature.
[b] Maximum tibia length/femur bicondylar length.

variation in this pattern; relative lower limb length has considerable ranges even among the Western Arctic samples (47.99–49.52 among males; see Table 2), which tend to have low indices overall. Moreover, this is the only pattern observable in any proportions of total lower limb length in the Americas; Auerbach (2007a) found no significant geographic pattern (despite the trends reported in this study) or any correspondence between cormic index and climatic or subsistence variables. It is notable that Jantz et al. (in press) suggested that instead the trend corresponds to colonization history, assuming that the relative length of the lower limb is constrained and heritable (cf. Tanner et al., 1982). At present, however, relative lower limb length remains a less discriminating criterion than crural indices for regional groups in the application of stature estimation formulae.

It is likely that some of the variation observed in proportions among the samples is a result of group-specific perturbations arising from health insults incurred during primary growth (Saunders and Hoppa, 1993; Bogin, 1999). The effects of health and nutrition on crural indices have not been explicitly examined among living humans, though Auerbach (2007a) did not find covariation in changes in crural indices and subsistence over time in pre-Columbian North America. A few studies have indicated that significant increases occur in the relative length of the lower limbs relative to overall stature when modern human groups encounter an increase in nutrition and decrease in environmental stress (Tanner et al., 1982; Takamura et al., 1988; Bogin and Rios, 2003). However, the age and sex of individuals experiencing augmentations in health and diet has an effect on the observed impact on stature and relative lower limb length (Malina et al., 2004). As noted previously, there is some evidence that taller humans exhibit positive allometry in tibia length, though the correlation of this with the overall relative increase in lower limb length observed in the cited studies is not known, and the pattern does not become apparent except in the tallest groups. Some of the incongruity between the relative lower limb length and crural index results may stem from differential responses in these dimensions to increases (or decreases) in subsistence and stress. Research into the relationship of these indices and stature is ongoing, especially in archaeological contexts. Yet, as current evidence (Holliday, 1999; Auerbach, 2007a) suggests more stability in crural indices over time than relative lower limb length, even with changes in health and nutrition, the use of crural indices retains utility as a criterion for group affiliation in determining the utilization of stature estimation equations.

Given the range of lower limb proportions (relative lower limb length and crural indices) among the samples used to calculate the "Temperate" equations, it is arguable that they may be applied to any skeletons within that range of variation in crural indices, including samples from regions not examined in this article. As no Central or South American samples were used in the creation of stature estimation equations, however, and the variation in limb proportions among those samples have not been documented relative to the samples used in this study, it is not recommended that the new stature estimation equations be applied to Central or South American archaeological samples. Future analyses using a more diverse geographic sample from the Americas will determine if new equations should be generated, or if the new "Temperate" equations are widely appropriate.

The application of these equations to samples throughout North America is broadly supported. One additional restriction, however, is the inappropriateness of these equations for estimating the statures of especially short New World populations, as they may lie beyond the size range represented here. This is likely a rare occurrence, based on comparisons of the range of statures in this study's data set with the reported ranges of New World living statures recorded by Eveleth and Tanner (1976), though the range of living populations' statures may be a poor indicator of the range present throughout the Holocene. On the opposite end of the stature range, it is unlikely that any skeletal samples exist that represent populations taller than those found on the Great Plains (Auerbach, in press). Indeed, both the "Temperate" and "Great Plains" male equations include individuals of at least 183 cm (6 feet) in estimated stature.

Comparisons of results with those of previously available equations yield some interesting findings. One of these is the systematic underestimation of statures using the 1993 equations developed by Sciulli and colleagues, which seems to have largely been corrected in the new equations developed by Sciulli and Hetland (2007). This difference is arguably due to techniques used in determining skeletal statures from the Ohio samples employed in their papers. The earlier formulae were generated using vertebral column lengths summing measurements at the middle anterior margins of their centra, which underestimate the length of the column compared with those taken at the maximum heights along the centra margins (Raxter et al., 2006). In addition, Raxter et al. (2006) demonstrated that using the measurement of talocalcaneal height as described by Lundy (1988)-the technique cited by Sciulli et al. (1990)-also results in a significant underestimation of statures. Sciulli and Hetland (2007) cite these discrepancies as well. As both their new equations and those presented in this article were developed using the revised Fully method, it is also

TABLE 7. Performance of stature estimations (cm) using new equations and best-performing previously available equations, compared against Fully technique estimated statures

					Mean Difference (cm)[a] (Standard Deviation)													
					New "Arctic" equations			New "Temperate" equations			New "Great Plains" equations			Trotter and Gleser (1958)	Genovés (1967)	Genovés (2004 revised)	Sciulli and Giesen (1993)	Sciulli and Hetland (2007)
Sample	Sex	*N*	Mean crural index	Mean femur + tibia / stature	Femur	Tibia	Femur and tibia	Femur	Tibia	Femur and tibia	Femur	Tibia	Femur and tibia	Femur	Femur	Femur	Femur and tibia	Femur and tibia
Eastern Arizona	M	39	86.4	48.8	*−3.10 (2.6)*	*1.69 (3.1)*	−0.92 (2.6)	−0.65 (2.6)	1.12 (3.1)	−**0.06 (2.5)**	0.47 (2.6)	*2.21 (3.1)*	0.49 (2.6)	*3.23 (2.6)*	*1.75 (2.6)*	−0.65 (2.6)	*−13.6 (2.6)*	0.45 (2.6)
	F	27	85.4	48.7	−1.18 (2.3)	*2.45 (2.4)*	1.01 (2.0)	0.39 (1.9)	*2.24 (1.8)*	0.91 **(1.4)**	*2.24 (2.0)*	*2.40 (2.1)*	*2.08 (1.6)*	*8.21 (2.2)*	*3.14 (1.8)*	**0.57** (1.8)	*−12.34 (1.4)*	0.94 (1.6)
Ohio River Valley	M	22	85.0	48.9	*−4.06 (3.4)*	−1.94 (3.0)	*−2.48 (3.2)*	−1.14 (3.6)	−1.15 (3.4)	−**1.10** (3.4)	1.17 (3.5)	1.47 **(3.0)**	1.48 (3.4)	*2.15 (3.3)*	1.87 (3.4)	−1.53 (3.4)	*−14.92 (3.3)*	1.12 (3.4)
	F	17	84.4	48.0	*−5.35 (2.6)*	*−3.04 (3.0)*	*−4.01 (2.7)*	−**1.42** (2.7)	−2.64 (2.9)	−1.85 **(2.6)**	*2.90 (2.8)*	*2.82 (3.0)*	*2.77 (2.7)*	*4.54 (2.3)*	2.28 (2.6)	−2.29 (2.6)	*−16.08 (2.5)*	*3.74 (2.5)*
Neo−Aleut	M	17	81.3	48.1	−1.02 (1.8)	*−1.76 (2.2)*	−**0.58 (1.7)**	*1.42 (1.7)*	*−3.38 (2.2)*	−0.74 (1.8)	*2.55 (1.7)*	*−4.79 (2.2)*	0.91 (1.7)	*4.43 (3.7)*	*2.91 (3.6)*	0.60 (3.6)	*−15.05 (2.5)*	*−2.06 (2.43)*
	F	10	81.4	46.8	−1.05 **(1.7)**	−0.66 (1.9)	−**0.16** (1.9)	−0.45 (1.9)	*−2.85 (2.4)*	−1.87 (2.1)	1.82 (1.8)	−1.56 (2.1)	−1.21 (2.0)	*8.53 (3.0)*	*2.72 (3.2)*	1.15 (3.2)	*−15.05 (2.2)*	−2.04 (2.2)
Sadlermiut	M	22	80.2	49.2	*2.18 (2.5)*	**0.30** (2.9)	1.09 **(2.5)**	*4.96 (2.5)*	−1.36 (3.0)	*2.30 (2.5)*	*5.97 (2.5)*	*−2.98 (2.9)*	*4.04 (2.4)*	*8.63 (4.3)*	*7.29 (4.3)*	*4.89 (4.3)*	*−11.54 (3.2)*	*2.51 (3.2)*
	F	14	80.5	48.4	0.64 (3.1)	−0.53 (2.9)	**0.05** (2.6)	*2.65 (2.7)*	−1.59 (2.4)	0.89 **(2.2)**	*4.32 (2.8)*	−0.95 (2.6)	*2.16 (2.3)*	*9.91 (4.8)*	*5.17 (4.6)*	*2.61 (1.2)*	*−13.05 (3.1)*	−0.42 (3.3)
Mobridge	M	15	85.3	49.3	*−4.60 (2.2)*	−1.25 (2.2)	*−2.77 (1.9)*	−1.39 (2.2)	−1.01 (2.1)	−1.07 (1.9)	−**0.52** (2.2)	−1.07 (2.5)	−0.65 **(1.9)**	1.26 (2.2)	0.76 (2.2)	*−2.33 (2.2)*	*−15.20 (1.9)*	−1.04 (1.9)
	F	11	86.1	48.4	*−3.82 (2.8)*	0.33 (2.2)	−1.69 (2.2)	−2.00 (3.0)	0.55 **(1.8)**	−1.13 (2.3)	−0.25 (2.9)	0.47 (2.0)	−**0.09** (2.3)	*5.71 (2.8)*	0.87 (3.0)	−1.71 (3.0)	*−14.31 (2.1)*	−1.84 (2.1)
Dickson	M	21	84.4	49.3	*−4.10 (1.8)*	*−1.74 (3.2)*	*−2.72 (2.1)*	−0.81 (1.9)	−1.58 (3.6)	−0.94 (2.2)	**0.03** (1.9)	−1.32 (3.2)	−0.37 (1.9)	*1.85 (1.7)*	0.69 **(1.7)**	*−1.71 (1.7)*	*−15.07 (2.1)*	−0.91 (2.1)
	F	16	85.0	48.0	*−5.77 (2.8)*	*−2.73 (2.7)*	*−4.08 (2.4)*	*−3.43 (2.4)*	*−2.24 (2.6)*	*−2.96 (2.2)*	−1.90 (2.5)	*−2.48 (2.5)*	*−2.05 (2.2)*	*3.91 (2.7)*	−**1.46 (2.4)**	*−3.04 (2.4)*	*−16.30 (2.2)*	*−3.95 (2.3)*

[a] Mean estimated stature—mean Fully estimated stature. Mean difference between the estimated statures and Fully technique estimated statures, as well as standard deviations (SD) of the mean difference between estimates and the Fully technique estimated statures are given. Bold text indicates the smallest mean difference and smallest SD (for non-significant comparisons). Italicized text indicates estimations that are significantly different ($P < 0.01$) from the Fully estimated statures using paired *t*-tests. Shaded boxes indicate the new equations that would be recommended for the samples based on geographic location and crural index.

arguable that their similar performance is the result of a tautology. However, the Sciulli and Hetland equations were developed from a vastly different sample than the "Temperate" equations presented here.

Showing a different trend, the "Mongoloid" equation developed by Trotter and Gleser (1958) substantially overestimated statures of arctic samples. This is likely the result of higher mean statures in the sample used by Trotter and Gleser than those found among the arctic New World samples used in this study, as well as the lack of a sex-specific estimation equation for females in the Trotter and Gleser study. The underrepresentation of any indigenous populations in the generation of their equation further limits the utility of its application in determining reasonable stature estimations for high latitude (or any indigenous North American) populations.

The Genovés equations revised by del Angel and Cisneros (2004) produced stature estimations that are both accurate and precise for our test sample from Eastern Arizona. As these equations have already been applied in a number of studies of Mesoamerican skeletal samples, and given the appropriateness of Genovés' sample to estimating statures for these populations, it is recommended that the revised equations by del Angel and Cisneros (2004) continue to be used for samples from Mesoamerica, especially as no Mesoamerican samples were included in our study. In the US Southwest, however, the new "Temperate" equations are recommended on the basis of our lower mean estimation errors.

A final caveat concerns the application of these formulae in modern forensic contexts. Although these equations represent a range of morphologies for indigenous North American populations, and so should theoretically be appropriate for modern native groups, they are based on archaeological sample largely predating European colonization. Therefore, the appropriateness of these as a reference sample is uncertain, and the use of these equations should be used with caution, if at all, in these circumstances.

CONCLUSIONS

Overall, the new stature estimation equations developed in this article demonstrate wide applicability in determining the statures of indigenous populations from North America. These equations are especially useful in the estimation of statures among the indigenous groups living at high arctic latitudes and the vast majority of archaeological specimens uncovered in North America. Future analyses and additional data from South American skeletal samples will ascertain the accuracy in a wider application of these equations outside of North America.

On the basis of the presented results, the following recommendations are made for the application of these new formulae:

- The new living stature estimation equations should be used in archaeological contexts, as the reference samples for the new equations mostly predate European colonizations of North America. It is strongly discouraged that researchers employ these equations in forensic contexts.
- Following the general geographic groupings described in Table 5 and illustrated in Figure 4, appropriate equations may be identified for a sample under examination.

- As an additional check on the appropriateness of a particular set of formulae, the crural index of the sample under examination can be compared with the ranges presented in Table 6 for each general geographic grouping. If a sample departs drastically from (i.e., falls near to or beyond the range limits of) samples from that grouping, an alternate set of equations from the next closest geographical group with better matched crural indices can be used. Also, samples falling close to the geographic boundaries between groups can be placed into one or the other group on this basis.
- Relative lower limb length may be used in a way similar to crural index as a secondary criterion for group matching, but it does not discriminate as well among groups, and requires independent (i.e., anatomically based) knowledge of stature to apply.
- The revised stature estimation formulae for Sciulli (Sciulli and Hetland, 2007) and Genovés (Del Angel and Cisneros, 2004) may be employed with reasonable accuracy in the regions for which they were developed, though with slightly more error than the "Temperate" formulae demonstrated in this paper. Previous versions of these formulae, as well as the Trotter and Gleser "Mongoloid" formula, are subject to greater inaccuracy and less precision, and so are not recommended for use in future studies of indigenous North American archaeological skeletons.
- It is not recommended that these formulae be applied to samples outside the geographic range covered in this study, e.g., to South America. The revised Genovés formulae (Del Angel and Cisneros, 2004) may be appropriate for Mesoamerican samples.
- In the cases where the necessary elements are available, it is strongly recommended that stature be directly reconstructed using the revised Fully method (Raxter et al., 2006, 2007). If samples with such elements are large enough, sample-specific regression equations may be generated for individuals lacking the necessary elements for the anatomical stature estimation method.

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