Chapter 43
Leg Length and Anthropometric Applications: Effects on Health and Disease

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Abstract Decomposing stature into its major components is proving to be a useful strategy to assess the antecedents of disease, morbidity and death in adulthood. Human leg length (foot + tibia + femur), sitting height (trunk length + head length) and their proportions (e.g. leg length in proportion to stature, and the sitting height ratio [sitting height/stature × 100], among others) are used as epidemiological markers of risk for overweight (fatness), coronary heart disease, diabetes and certain cancers. There is also wide support for the use of relative leg length as an indicator of the quality of the environment for growth during infancy, childhood and the juvenile years of development. Human beings follow a cephalo-caudal gradient of growth, the pattern of growth common to all mammals. A special feature of the human pattern is that between birth and puberty the legs grow relatively faster than other post-cranial body segments. For groups of children and youth, short stature due to relatively short legs (i.e. a high sitting height ratio) is generally a marker of an adverse environment. The development of human body proportions is the product of environmental x genomic interactions, although few if any specific genes are known. The short stature homeobox-containing gene (SHOX) is the first genomic region that may be relevant to human body proportions. For example, one of the SHOX related disorders is Turner syndrome. However, in most cases research has been showing that environment is a more powerful force to shape leg length and body proportions than genes.

Abbreviations

BMI	Body mass index
BP	Blood pressure
BW	Birth weight
F	Female(s)
FEV	Forced expiratory volume
FVC	Forced vital capacity

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H	Height
hr	hour(s)
KH	Knee height
KHR	Knee height ratio = KH/H × 100
IH	Iliac height
LL	Leg length
MRC	Medical Research Council
M	Male(s)
M&F	Males and females
NHANES	National Health and Nutrition Examination Survey
RSLL	Relative subischial leg length = H-SH/H × 100
SES	Socioeconomic status
SH	Sitting height
SHR	Sitting height ratio = SH/H × 100
SLL	Subischial leg length
TL	Thigh length

43.1 Introduction

Leg length has been widely used in biomedical sciences as an indicator of general health, socioeconomic status and propensity for disease. For many years, it was also wrongly used as a racial marker (Bogin et al. 2001; Bogin 2008; Frisancho et al. 2001). However, the concept of 'leg length' has different meanings for different authors, and there is more than one single measurement for leg length. Table 43.1 lists a few key facts about the role of leg length in human biology and evolution.

Table 43.1 Key facts about the role of leg length in human biology and evolution

1. Human beings are distinguished from the non-human primates by several anatomical features and among these are proportions of the arms and legs relative to total body length. The living apes have arms that are longer than their legs, which reflects their adaptations for brachiation (arm swinging). Bipedal fossil hominins of the species *Ardipithecus*, *Australopithecus* and *Homo habilis*, dating from about 4.5 to 1.6 million years ago (MYA) were similar to apes in body proportions, or had long arms in proportion to their legs. Since the evolution of *Homo erectus*, about 1.8 MYA, human ancestors have had essentially modern body proportions.
2. Leg length must approximate 50% of total stature to achieve the lower limits of the biomechanical efficiency of the adult human striding bipedal gait. In modern humans, this happens at the end of the childhood life history stage, which occurs at about 7.0 years of age. By adulthood, human species-specific body proportions allow for not only the bipedal striding gait, but also for long-distance running, which may have been important for hunting and survival to our ancestors.
3. Relatively long legs in modern humans and in human ancestors allows for more efficient thermoregulation in a tropical savannah environment, which was the birthplace of humanity. Long legs allow for greater body surface area for the cooling of the body by evaporation of sweat.
4. Long legs, which allow for human bipedalism, free the hands for carrying objects and infants, for technological manipulation, for gesticulation and communication, and for the type of social–emotional contact that is one of the hallmarks of humanity.

43.2 Leg Length Defined

In principle, leg length (LL) is the length of the femur plus the tibia, and possibly the height of the foot from the tibia-talus articulation to the ground. In a living human being, these lengths are difficult to measure. Consequently, LL is often defined by easier to measure dimensions, such as iliac height (IH) and subischial leg length (SLL). It is also possible to estimate LL via the combination of thigh length (TL) and knee height (KH). Some studies employ only one of these measures as the indicator of LL.

Each of these measurements can be transformed into ratios, generally in relation to total stature (see entry on stature) and sitting height (SH), to give indications of body proportions. In this entry, we will discuss the sitting height ratio (SHR), relative subischial leg length (RSLL) and the knee height ratio (KHR).

43.3 Population Variation in Body Proportions

For many years, there has been the perception that body proportions are genetically determined, immutable and, therefore, a good indicator of 'racial' markers (Eveleth and Tanner 1976, 1990). It is true that, on an average, Native Australians and people of sub-Sahara African origin have the longest leg length in proportion to total stature, followed by people of European ancestry, and those of Asian ancestry (including Native Americans). There is, however, considerable overlap in the range of both absolute and relative leg length values between these general geographic groups (Fig. 43.1).

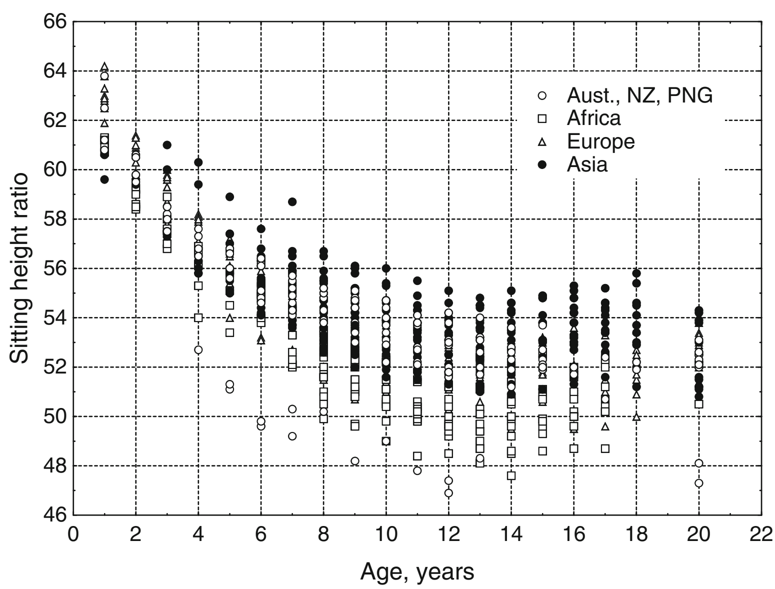

Fig. 43.1 Relative leg length as measured by the sitting height ratio by age for the four geographic groups defined by Eveleth and Tanner (1976, 1990). Age 20 years includes data for adults over the age of 18 years. (From Bogin et al. 2001)

Additionally, socioeconomic factors explain as much of the variation in leg length as does geographic origin or so-called ‘race’ (Bogin et al. 2001, 2002).

Moreover, leg length and body proportions are plastic, meaning that these phenotypic properties of the human body change in response to external (environmental) factors. Studies conducted in Japan (Kondo and Eto 1975; Tanner et al. 1982; Ohyama et al. 1987) show that environmental improvements in nutrition (mainly the inclusion of milk in the Japanese diet), health and general socioeconomic status are powerful modifiers of body proportions, resulting in longer legs in proportion to total stature in most cases. Between 1957 and 1977, the Japanese population showed a strong positive secular trend in height, and all the increase in height was due to the increase in leg length, with very little increase due to changes in trunk length (sitting height). Bogin et al. (2002) found even greater plasticity in the children of Maya families emigrating from Guatemala to the USA. The Maya families migrated due to precarious conditions in Guatemala, including hunger, poverty and civil war. In the new North American environment, the living conditions improved considerably in terms of basic health care and vaccination, education and availability of clean drinking water. Maya children and adults in Guatemala are typically of very short stature, with disproportionately short legs. Maya-American children experienced a 10–11 cm increase in stature over their Guatemalan living age mates across the ages from 5 to 12 years, and 70% of this increase was due to leg growth. These studies show how body proportions are sensitive to the quality of the environment.

43.4 The Usefulness of Leg Length

The biological and clinical usefulness of LL is based on the cephalo-caudal gradient in growth of all mammals, including humans. The ontogenetic development of human body shape is similar in all human populations, as shown in Fig. 43.2. During the foetal, infant and childhood stages of life, the brain grows faster than the body (Scammon and Calkins 1929). At birth, head length is approximately one-quarter of the total body length, whereas, at 25 years of age, the head is only approximately one-eighth of the total length. There are also proportional changes in the length of the limbs, which become longer relative to the total body length during the years of growth (Scammon 1930). Leitch (1951) was the first medical researcher to propose that a ratio of LL to total stature could be a good indicator of the nutritional history and general health in the early life of an individual. Leitch (p. 145) wrote, ‘… it would be expected on general principles that children continuously underfed would grow into underdeveloped adults…with normal or nearly normal size head, moderately retarded trunk and relatively short legs.’ Leitch found that improved nutrition during infancy and childhood did result in a greater increase in LL than in total height or weight.

A general principle of growth is that those body parts growing the fastest will be most affected by a shortage of nutrients, infections, parasites, physical or emotional traumas and other adverse conditions. The legs, especially the tibia, grow faster relative to other body segments from birth to about the age of 9 years. Relatively short LL in adolescents and adults, therefore, is likely to be due to adversity during infancy and childhood. The alterations in body proportions described by Leitch, and in the studies of Japanese and Maya, are likely due to competition between body segments, such as trunk versus limbs, and between organs and limbs, for the limited nutrients available during growth (Bogin et al. 2001, 2002).

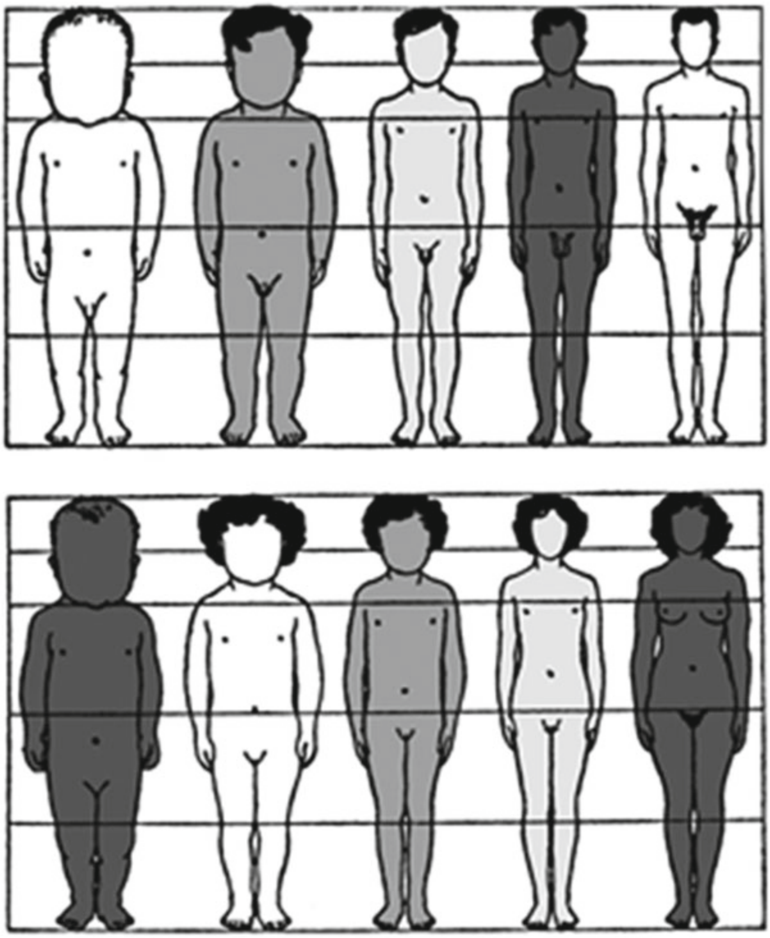

Fig. 43.2 Changes in body proportion during human growth after birth. Ages for each profile are, from left to right, newborn, 2 years, 6 years, 12 years, 25 years. The hair style and shading of the cartoon silhouettes are for artistic purposes and is not meant to imply any ethnic, eco-geographical, or "racial" phenotypic characteristics of the human species [provided courtesy of Dr. J. V. Basmajian]

43.5 Leg Length and Human Health

Table 43.2 summarises several studies that show how leg length and body proportion ratios are powerful indicators of the quality of the environment, and of the plasticity of the human body. The table refers to only a few studies. The table is not a systematic review, and is meant to provide examples of the range of studies available. What is important to note is that regardless of the specific leg measure taken (e.g. IH, SLL, TL and KH), or ratio calculated (SHR, RSLL and KHR), the longer LL is associated with better environments, better nutrition, higher SES and better general physical and psychological health, overall.

Lawlor et al. (2003) present the hypothesis that maternal leg length is associated with birthweight and later health of her infants, meaning that the shorter the maternal leg length, the lower the birthweight of the infant. In turn, low birthweight individuals have increased risk of cardiovascular diseases, among others, as adults. Li et al. (2007) found that taller childhood stature better predicts longer adult leg length than trunk length. Moreover, socioeconomic adversity in childhood

Table 43.2 Summary of studies employing measures of leg length in relation to early life living conditions and health

Measure of leg length	Sample sizes	Sample	Results	Source
IH	Total: 2,209 M: 1,062 F: 1,147	2–14 years Extracted from The Boyd Orr Survey. Children from 1,343 working class families in England and Scotland, measured between 1937 and 1939	M and F: Positive association with length of breastfeeding, decreasing numbers of children in the household and increasing household income. Overall, the individual components of stature mostly associated with childhood environment was leg length (measured as IH) and foot length (not in the scope of this entry).	Whitley et al. (2008)
	Total: 916 M: 376 F: 540	65+ years' inhabitants of Kwangju, South Korea, assessed in 2003.	Shorter limb length is associated with markers of lower early life socioeconomic status and is associated with dementia later in life, especially in women.	Kim et al. (2008)
SLL	Total: 2,338 M: 1,040 F: 1,298	30–59 years (United Kingdom)	M and F: Inverse association with systolic BP, diastolic BP, total cholesterol and fibrinogen. Direct association with FEV, FVC, BW and BMI.	Gunnell et al. (2003)
	Total: 10,308 M: 6,895 F: 3,413	35–55 years (London)	M and F: Strong inverse association with pulse pressure and systolic BP. Strong positive association with lower total/HDL cholesterol ratio, triglycerides and 2-hr glucose M: Strong inverse association with total cholesterol. F: Strong inverse association with diastolic BP.	Ferrie et al. (2006)
	Total: 3,262	Longitudinal study, births from 3–9 March 1946. Twenty-one assessment occasions between birth and 53 years. MRC National Survey of Health & Development (United Kingdom)	M and F: Positive association with mother's and father's height, BW. SLL greater among individuals from the non-manual social class and among individuals who were breastfed.	Wadsworth et al. (2002)
	Total: 5,900	The 1958 British Birth Cohort. Participants assessed at birth and at ages 7, 11, 16, 23, 32, 42 and 45 years.	Adult SLL is associated with parental height and birth weight. Taller prepubertal stature is associated with higher SLL. Maternal smoking during pregnancy resulted in lower adult SLL. Overall, adult SLL is related to a greater extent than trunk length to early life factors and prepubertal height.	Li et al. (2007)
KH	Total: 50 M: 27 F: 23	Infants grouped by gestation time at birth: <28 weeks, 28–31 weeks, 32–36 weeks, >36 weeks. Births occurred in 2004–2005, in the neonatal intensive care, Christchurch, New Zealand.	Changes in KH (using a kneemometer) correlate very well with changes in weight. If gain in weight is achieved, normal linear growth may be assumed. Because of this, kneemometry is not a useful addition to routine measurements of growth in the neonatal unit.	Dixon et al. (2008)

SHR	Total: 2,985 M: 1,465 F: 1,520	2–17 years Mexican Americans (NHANES III, USA)	M and F: Individuals with relatively shorter legs in proportion to total stature are poorer than longer legged individuals (poverty assessed by Poverty Income Ratio)	Frisancho et al. (2001)
	Total: 1,472 M: 747 F: 707	6–13 years, Oaxaca, Southern Mexico Urban settings in 1972: Total:409, M:218, F:173 Rural settings in 1978: Total:363, M:179, F:184 Urban settings in 2000: Total:339, M:173, F:166 Rural settings in 2000: Total:361, M:177, F:184	Positive time trend in leg length from 1972 to 2000 both in rural and urban settings	Malina et al. (2008)
	Total: 2003 M: 2003 F: 0	7–16 years. Two cross-sectional surveys among school aged boys from Kolkata, India. 1982–1983 ($n = 816$) 1999–2002 ($n = 1187$)	Positive time trend in relative leg length. Boys measured in 1999–2002 had relatively longer legs in proportion to total stature than their counterparts in 1983–1983.	Dasgupta et al. (2008)
	Total: 1995 M:977 F: 1018	5–12 years. Maya migrants to the USA in 1992 ($n = 211$), Maya migrants to the USA in 2000 ($n = 431$) and Maya in Guatemala in 1998 ($n = 1353$)	Leg length is a sensitive indicator of the quality of the environment. Maya children in the USA show relatively longer legs in proportion to stature than their counterparts in Guatemala. By 2000, Maya migrants to the USA were 11.54 cm taller and 6.83 cm longer-legged than Maya children in Guatemala.	Bogin et al. (2002)
RSLL	Total: 273	Intergenerational sample Parents' generation: Total:165, M:80, F:85 Offspring generation: Total:108, M:49, F:59 From Auckland and Taipei	Is an effective marker of intergenerational changes	Floyd (2008)
KHR	Total: 273	Intergenerational sample Parents' generation: Total:165, M:80, F:85 Offspring generation: Total:108, M:49, F:59 From Auckland and Taipei	Is an effective marker of intergenerational changes. Lower leg growth, as represented by KHR is similar to changes in overall leg length as regards sensitivity to environmental change.	Floyd (2008)

is associated with shorter adult leg length and stature. These two studies are examples of how early life environments, in combination with an intergenerational component, mainly through matrilineal lines, shape body size and proportion.

There are complications in the relationship between LL, health, SES and better environments for growth. One such complication is noted by Schooling et al. (2008a, b), in an analysis of a cross-sectional sample of 9,998 Chinese people aged at least 50 years, and measured in 2005–2006. Sitting height and height were measured and leg length estimated as height-sitting height (SLL). The growth environment for the 50+ year-old adults was estimated via a questionnaire asking about own education, father's occupation, parental literacy and parental possessions. The authors find that leg length and height, but not sitting height, vary with some childhood conditions. Participants with two literate parents, who owned more possessions, have longer legs. The participants' level of education and their father's occupation have no effect on height or leg length, but higher scores for these variables do associate with an earlier age at menarche. The authors explain that earlier menarche for girls, and earlier puberty for boys, will terminate growth at an earlier age. This may explain why higher SES, as measured by education and father's occupation, did not associate with longer LL.

Another complication is noted by Padez et al. (2009), who analyzed the growth status of Mozambique adolescents. The sample comprised 690 boys and 727 girls, aged between 9 and 17 years, from the capital city of Maputo. The sample is divided between those living in the centre of Maputo (higher SES) and those living in the slums on the periphery of the city. Height, weight and sitting height were measured, and the sitting height ratio was calculated. The hypothesis that relative leg length is more sensitive than total stature as an indicator of environmental quality is not uniformly confirmed. Overall, mean stature is greater for the centre group than for the slum group, but relative leg length as measured by the sitting height ratio does not differ. Compared with African-American references (NHANES II), all the girls from the centre group, 9–14-year-old slum girls, all slum boys and the oldest centre boys show relatively shorter legs. These findings show that, within the Mozambique sample, relative leg length is not sensitive enough to distinguish the quality of the living environment between the centre of Maputo (regular housing and higher SES) and the slums in the periphery. A reason for this is that Mozambique was a colony of Portugal until 1975. Civil unrest and warfare characterised the late Colonial period and the post-independence period, until a peace settlement was concluded in 1992. It is possible that all socio-economic status groups within the country, exposed to the war, suffered sufficiently to reduce relative leg length, especially when compared with the better-off African-American reference sample.

43.6 Applications to Other Areas of Health and Disease

The development of human body proportions has a likely genomic basis, although few, if any specific genes are known. *Hox* and homeobox genes are known to regulate the growth of body segments (Mark et al. 1997), and these genes are shared across all taxa. The short stature homeobox-containing gene (SHOX) is the first genomic region that may be relevant to human body proportions. 'SHOX, located on the distal ends of the X and Y chromosomes, encodes a homeodomain transcription factor responsible for a significant proportion of long-bone growth' (Blum et al. 2007, p. 219). One SHOX-related disorder is Turner syndrome (45, XO karyotype), which results in approximately 20 cm deficit in expected stature. Some studies find that legs are disproportionately affected (Neufeld et al. 1978; Ogata et al. 2002), but other studies find no disproportion

(Hughes et al. 1986). Specific candidate genes for body shape are known from some non-human mammals, especially livestock in which body proportions have considerable economic value (Quignon et al. 2009).

Leg length discrepancy (LLD), one leg shorter than the other, poses biomechanical impediments, may predispose people to a variety of musculoskeletal and psychological disorders and may require surgical correction (Gurney 2002). There are several causes for LLD, including *coxa vara*, dislocation of the hip, hemiatrophy or hemihyperatrophy as well as deformities due to rickets or other metabolic diseases. Early and accurate measurement may detect such discrepancy and allow treatment before the period of growth has been completed, when it is easier to correct.

Congenital adrenal hyperplasia (CAH) due to 21-hydroxylase deficiency is associated with alterations in body size, composition and proportion. CAH impairs limb growth, especially of the leg, hand and foot. Medical intervention can improve leg growth, especially if the intervention occurs before puberty.

43.7 Practical Methods and Techniques

We define several measurements and ratios of leg length, their anthropometric applications and their biocultural associations with health and disease. We present a brief description of the anthropometric methods required to obtain these measures of leg length. More details of the methods may be found in Lohman et al. (1988) and the NHANES anthropometric manual (http://www.cdc.gov/nchs/data/nhanes/nhanes3/cdrom/NCHS/MANUALS/ANTHRO.PDF).

Table 43.3 shows the usefulness of leg length measurements and ratios in terms of ease of accurate collection, comparison to reference data, as an indicator of body proportions, as an indicator of nutritional status and ease of accurate calculation or interpretation. From all the ratios presented, only the SHR has population-based- and statistically valid reference values (Frisancho 2008).

43.7.1 Iliac height

This is the distance between the summit of the iliac crest and the floor (see Fig. 43.3). The iliac crest is sometimes difficult to find, especially in overweight people. It also may cause ethical concerns as it requires extensive palpation at the hip level to find the landmark required to perform the measurement accurately. There are no reference data available. IH does not easily provide a good indication of body proportions because, by itself, it does not standardise against height or sitting height. This means that comparisons between individuals do not take into account their total stature. Also, as an indicator of nutritional status, it does not provide ready and easy interpretation.

43.7.2 Subischial Leg Length (SLL)

SLL is the distance from the inferior border of the ischium to the floor when the participant is in the standing position. In practice, the border of the ischium is very difficult to locate, and poses serious

Table 43.3 Usefulness of leg length measurements and ratios in terms of ease of assessment, comparison with reference data, as an indicator of body proportions, as an indicator of nutritional status and ease of calculation of the ratio and/or interpretation of the value

	Ease of accurate collection	Comparison with reference data	As an indicator of body proportions	As an indicator of nutritional status	Ease of accurate calculation and/or interpretation
Iliac height	4	4	3	3	4
Subischial leg length	1	4	3	3	3
Thigh length	3	1	3	3	4
Knee height	1	1	2	3	2
Sitting height ratio	1	1	2	1	3
Relative subischial leg length	1	4	2	2	3
Knee height ratio	1	4	2	2	3

1 excellent; *2* good; *3* difficult; *4* very difficult

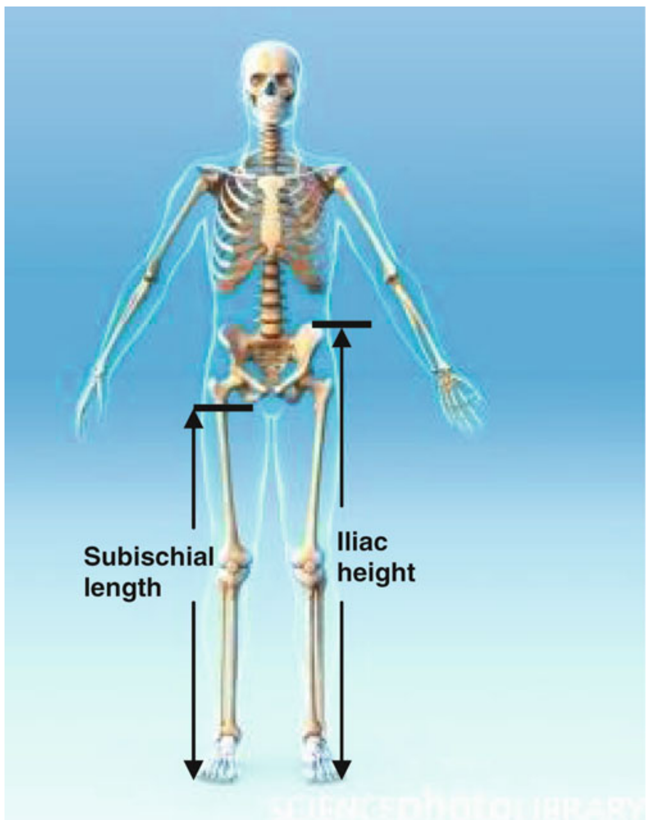

Fig. 43.3 Landmarks for the measurement of iliac height (IH) and subischial leg length (SLL). (Credit: ROGER HARRIS/SCIENCE PHOTO LIBRARY)

ethical concerns (see Fig. 43.3). Therefore, it is a common practice to estimate SLL as the difference between stature and sitting height (see Fig. 43.6). There are no reference data available. It is not a good indicator of body proportions because SLL is dependent on sitting height and it may underestimate leg length values, especially if the participants have high levels of gluteo-femoral subcutaneous fat

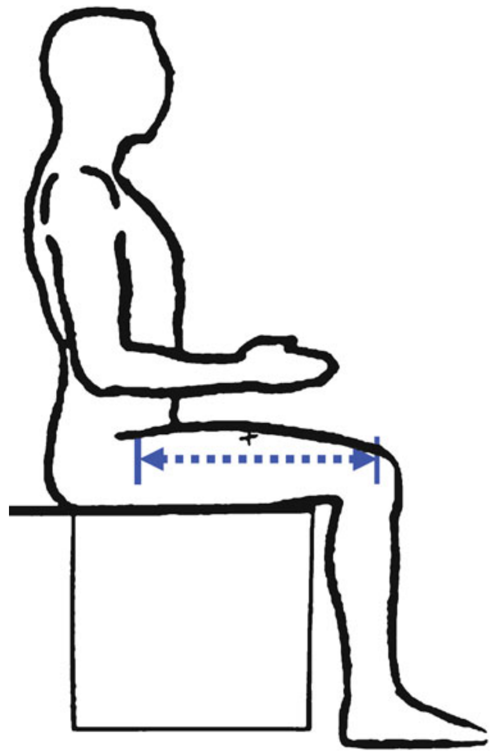

Fig. 43.4 Landmarks and correct body position for the assessment of thigh length

(Bogin and Varela-Silva 2008). Also, it does not take into account the total stature of the individual. As an indicator of nutritional status, it does not provide ready and easy interpretation.

43.7.3 Thigh length (TL)

This is the distance between the hip and the knee. Because in living humans, it is difficult to locate these joints, TL is measured from the midpoint of the inguinal ligament to the proximal edge of the patella (see Fig. 43.4). In overweight or obese people with excessive abdominal subcutaneous fat, it may be difficult to find the inguinal ligament. Also, palpation around the inguinal ligaments may cause ethical concerns. Reference data proposed by Frisancho (2008) are available. TL does not easily provide a good indication of body proportions because, by itself, it does not standardise against height, sitting height or knee height. As an indicator of nutritional status, it does not provide ready and easy interpretation.

43.7.4 Knee Height (KH)

Knee height is the distance between the anterior surface of the thigh (above the condyles of the femur and about 4 cm above the patella) and the floor (see Fig. 43.5). Knee height is regularly used in paediatric assessments, and correlates well with weight during the first month of postnatal life (Dixon et al. 2008). It is relatively easy to collect and does not pose as many ethical concerns as the

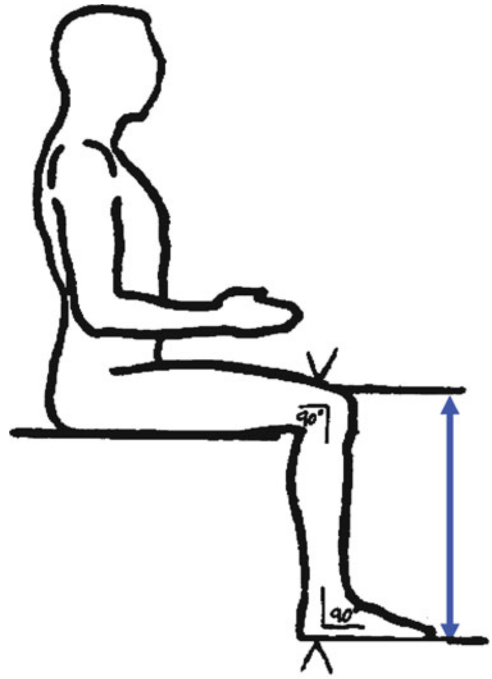

Fig. 43.5 Landmarks and correct body position for the assessment of knee height

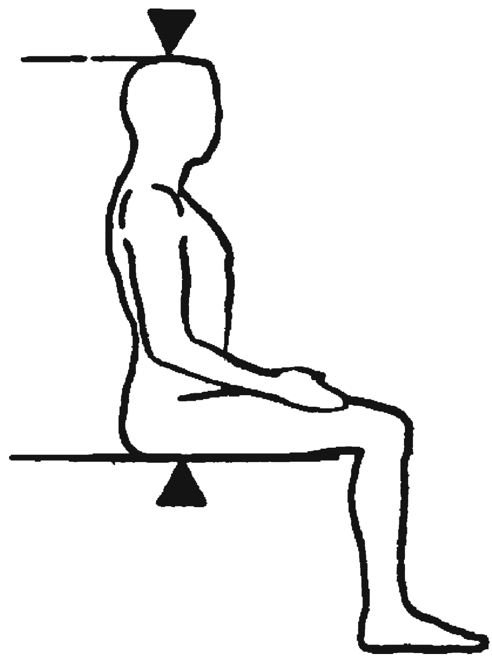

Fig. 43.6 Landmarks and correct body position for the assessment of sitting height

measurements mentioned above. There are reference data proposed by Frisancho (2008). It is a relatively good indicator of body proportions because the tibia grows at the fastest rate and for the longest amount of time relative to the femur and skeleton of the trunk. As an indicator of nutritional status, it does not provide ready and easy interpretation.

43.7.5 Sitting Height Ratio (SHR)

SHR is calculated as SH/H × 100. It defines the percentage of total stature that is comprised by head and trunk (see Fig. 43.6 for details on sitting height measurements). The remaining portion of the body will be the length of the legs. The lower the SHR, the relatively longer the legs are. The ease of accurate collection is high and there are international references (Frisancho 2008) that allow the comparison of any values and the conversion of SHR raw data into percentiles and *z*-scores. SHR is a good indicator of body proportions because it allows individuals with different heights to be compared in terms of the percentage of the body that is composed by the relative length of legs. However, because it is sitting height dependent, this measure can be overestimated in individuals with high levels of gluteo-femoral fat, therefore underestimating the relative contribution of the lower limb to total stature (Bogin and Varela-Silva 2008). It is a good indicator of nutritional status because it allows the classification of the individuals into different degrees of leg stunting, based on the *z*-scores calculated from the references.

43.7.6 Relative Subischial Leg Length (RSLL)

RSLL is calculated as H-SH/H × 100. It defines the percentage of total stature that is comprised by the legs. The lower the RSLL, the shorter are the legs. The ease of accurate collection is high. There are no international reference values. Similar to SHR, RSLL is a good indicator of body proportions because it allows individuals with different heights to be compared in terms of the percentage of the body that is composed by the relative length of legs. However, because it is sitting height dependent, this measure can be overestimated in individuals with high levels of gluteo-femoral fat, therefore underestimating the relative contribution of the lower limb to total stature (Bogin and Varela-Silva 2008). RSLL requires a more difficult computation of values of stature and sitting height than does the SHR.

43.7.7 Knee Height Ratio (KHR)

KHR is calculated as KH/H × 100. It defines the percentage of total stature that is comprised by the lower segment of the leg (tibia + foot height). The higher the KHR, the longer is the leg segment. The ease of accurate collection is high but there are no international reference values. KHR is a relatively good indicator of body proportions because it allows individuals with different heights to be compared in terms of the percentage of the body that is composed by the relative length of legs.

Summary Points

For groups of people:

- Leg length is generally associated with the quality of the environment for human growth and development.
- Longer legs, especially long legs relative to total stature, indicate better quality environments.
- Leg length and body proportions do vary between the major geographic regions of the world, but are not ‘racial’ markers.

- Leg length and body proportions may be useful in the diagnosis of genetic, endocrine and metabolic disorders.
- Different ways of measuring leg length (e.g. IH, SLL, TL and KH) make comparison among studies difficult – if one wishes to compare raw data. However, regardless of what measurement is taken, the overall results are similar, in a sense that longer legs generally show better health status overall and better early life environments.

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