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ARTICLE

Investigating crossed-symmetry pattern in children from the past: questions related to the lower limb bones

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ABSTRACT In biological anthropology, bilateral asymmetry in living adult samples is a well-studied field. During the last decade, researchers have become more interested in its developmental characteristics in individuals of both living and past populations. It is still the upper limb that gets attention, as handedness and its effects on the bones via biomechanical loading is an obvious and easily measurable marker of bilateral asymmetry. The majority of the population exhibit right bias in the measurements of the upper limb bones and the lower limb behaves the opposite due to its performance in weight-bearing. This pattern is called crossed-symmetry. Despite its marked role in posture, examining the emergence of lower limb bone asymmetry during growth has not been well-researched. To add more information to this field, the present study investigated the developmental pattern of lower limb bone bilateral asymmetry in medieval Hungarian children from one of the country's biggest anthropological collections.

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Introduction

The asymmetry of the human body attracted the interest of many disciplines. The number of related studies in anatomy, neurology, evolutionary biology and in anthropology has risen in the last decades. Van Valen (1962) defined the types of asymmetry and introduced a concept that, with modern statistical additions, is still used in asymmetry studies (Sládek et al. 2018). According to his interpretation, directional asymmetry occurs whenever there is a greater development of a feature on one side of the planes of symmetry than on the other, while in the case of antisymmetry, asymmetry is normally present but it is variable which side has greater development. Finally, fluctuating asymmetry, without consistent directionality, is defined as the result of developmental noises.

Besides its genetically determined features, limb-bone directional asymmetry is linked to mechanical loading, and hence, reflects the physical activity patterns of past (and present) human populations (Steele 2000a). Right-biased directional asymmetry of the upper limb in recent human populations has been amply described in literature - thanks to handedness being a good marker and offering behavioural explanations for this functional asymmetry (for a detailed literature review see Scharoun and Bryden 2014). There are also numerous fundamental studies on skeletal remains of past human populations (Ruff et al. 1993; Trinkaus et al. 1994; Auerbach and Ruff 2006), which indicate that it is the humerus that shows the most marked directional asymmetry, followed by the radius and the ulna, with a significant shift to the right side. The diameter of the diaphysis and its cross-sectional measurements are significant dimensions, while length-measurements are less marked. Nevertheless, these studies are usually limited to adult skeletal samples, so we have less data on the developmental background of limb-bone directional asymmetry. Reviewing the work done in the last decades on upper limb bones of children demonstrates that directional asymmetry develops gradually during growth as a consequence of mechanical loading on the bones (Steele and Mays 1995; Blackburn 2011; Waxenbaum and Sirak 2016; Fogl et al. 2022).

Directional asymmetry of the lower limb is less pronounced than that of the upper limb. The dominant leg has the role of mobilization or manipulation, while the non-dominant leg has a stabilizing and supportive function for upkeeping posture (preferred and non-preferred lower limbs, respectively, see Gabbard and Iteya 1996; Sadeghi et al. 2000). Humans are usually right-footed for mobilization and left-footed for stabilization regardless of their handedness (Macho 1991; Sadeghi et al. 2000; Čuk et al. 2001). Therefore, the functional asymmetries of the upper and the lower limb result in a crossed-symmetry pattern, which was first defined by Schaeffer (1928), who characterized it as having larger dimensions of the lower limb bones on the opposite side of the dominant upper limb. As 90% of human populations are right-handed (the right arm is the dominant arm), crossed-symmetry manifests itself in larger dimensions of the bones of the left leg due to its stabilizing function. Existing literature of skeletal crossed-symmetry provides very few data about its developmental background, as most studies focus on adult skeletons (Ruff and Jones 1981; Čuk et al. 2001; Plochocki 2004; Auerbach and Ruff 2006; Tur 2014; Treffner and Kirchengast 2020). These studies confirm the presence of a crossed-symmetry pattern in diaphyseal breadth and in some cases in length measurements and show that the lower limbs demonstrate much weaker directional bias than the upper limbs.

To gain an insight into the emergence of lower limb asymmetry, one must understand the development of gross and fine motor skills in children. During the stages of locomotor development (from lifting their chins from the floor through sitting, crawling, toddling and all the way to independent walking), loading of the lower limbs grows intensely, causing changes in musculature and in femoral cross-sectional geometry as well (Swan et al. 2020). Regarding fine motor skills, the results of studies on living children indicate that the majority of them establish foot preference by approximately the age of 5 and after that there is a significant shift to right-sidedness during late childhood (Gabbard et al. 1991; Gabbard and Iteya 1996). From a skeletal perspective, this also suggests that the non-dominant, weight-bearing leg in most cases is the left leg.

In the present study, the development of skeletal lower limb asymmetry in length and diaphyseal breadth of the femur and the tibia during childhood was investigated, considering fine and gross motor skills and bipedal gait. Based on the literature, we expected femoral and tibial dimensions to be larger on the left side in older age groups, but with a lower degree of asymmetry than was present on the upper limb in the same population.

Materials and methods

Sample and data collection

The sample consisted of 225 paired femora for length measurement, 224 paired femora for diameter measurement, and 168 paired tibiae for diameter and length measurement of nonadult individuals from one of the largest archaeological burial sites from the 14th-15th century AD in Bátmonostor-Pusztafalu, Hungary. The site was reported to be an agricultural centre in the medieval period. Individuals for this study were selected according to the following complex criteria: (1) for age estimation, they had to have detectable tooth eruption, which meant the presence of a complete left or right upper or lower jaw; (2) to exclude abnormal development, only non-pathological, paired lower limb bones were selected; (3) to reduce measurement errors, bones with any stage of epiphyseal union were excluded; (4) only full-term foetuses were included as they fit better into the normal developmental pattern than peers that died in-utero (Steele 2000b).

Age estimation and age groups

For age estimation, dental eruption was used according to Ubelaker (1978). The term “nonadult” used in this study is in accordance with the classification of Knussman and Martin (1988) and covers the age range from around the time of birth through Infantia I, Infantia II and up to the Juvenile category. Sex estimation was not within the scope of this study due to the lack of an accurate estimating method for nonadult skeletons (Hoppa and Fitzgerald 1999; Scheuer and Black 2004).

Supported by previous research (Swan et al. 2020), the sample was divided into four age groups that were defined based on the development of fine and gross motor skills in children (Oláh 2008).

Group 1 marks the age range from 0.5 years to 1 year. During this period children become capable of sitting without support, they begin crawling and by the end of their first year they can stand with support. These milestones signal the beginning of the loading of the femur.

Group 2 represents the locomotor and postural changes that occur between the ages of 1 and 2 years, when children walk independently with flexed hip and knee, and still have an immature gait. They also display the first signs of hand and foot preference during play and while eating.

Group 3 includes the period between 2 and 4 years, which is a transition toward mature gait: children are quicker and more balanced in walking and running. The shift to the right lateral preference is also marked both in handedness and footedness, meaning that the functional difference (mobilizing vs. stabilizing) is highly present in the lower limb at this stage.

Finally, from 4 to 8 years of age, children attain mature bipedal gait and their lateral preferences are fixed, although these still require further refinement. In this last class – group 4 – we extended the upper age threshold to 15 years, assuming that children’s role in medieval centuries was adult-like, as they had to contribute to their family’s living by doing working (Ariés 1987). Depending on the type of activity and their foot preference, they loaded their lower limbs dissimilarly which could contribute to the bilateral asymmetry of the lower limb bones.

Measurements

Measurements were obtained from the bones of the lower limb according to Fazekas and Kósa (1978), and Martin and Saller (1957) by using a verified anthropometric toolkit with millimetre-scales (GPM). Maximum length of the diaphysis of the femora and tibiae were taken with a standard osteometric board on both sides from their proximal-most to their distal-most point. Maximum diameter of the diaphysis was also determined. The midpoint of the diaphysis was identified on the osteometric board, then the bone was rotated with one hand to obtain the maximum diameter with sliding calipers.

Data analysis

Standardized asymmetry was calculated with the equation below (Van Valen 1962; Sládek et al. 2018):

$$SA = (R - L)/((R + L)/2) \times 100$$

where R indicates right-side measurement and L indicates left side measurement. This formula considers both the direction and magnitude of asymmetry. Deviation to the right side is expressed with a positive value and deviation to the left side with a negative value. Zero or near to zero values indicate the absence of directional asymmetry. The magnitude of asymmetry is irrespective of direction and is indicated by the absolute values.

Chi^2 tests were used to compare the frequency of bones with zero and positive/negative values of SA, and also the frequency of the SA for the left and right side, in every age group. A Fisher exact test was carried out in cases where the frequency was less than or equal to five for one category. Analysis of variance (ANOVA) was used to compare the SA values for the different age groups (including 0 values). The absolute SA values for all measurements were averaged in each age group. Pearson's product-moment correlation was applied to test the correlations between the age categories and the averaged SA values (when not 0). R Statistical Environment (R Core Team 2019) was used to carry out the statistical analyses. The 'cor.test', 'chisq.test' and 'fisher.test' functions were used to perform the correlations, Chi^2 and Fisher analyses respectively. The 'aov' function from the Stats package was used to carry out the ANOVA. The SA values were included as dependent variables, while the age groups were entered as explanatory factors in the models. When performing ANOVA analyses, post hoc sequential comparisons among factor levels were carried out using the 'TukeyHSD' (Stats package) function. In order to meet the requirement of normality and homogeneity of variances, the variables were log-transformed prior to the analyses when necessary.

Results

Taking the data of all age groups together, we found asymmetry in 67% of femur length, 46% of femur diameter, 70% of tibia length, and 51% of tibia diameter measurements. Considering the age groups separately, a significantly higher frequency of asymmetry vs. absence of asymmetry was observed in the length of the femur, in the third (3-4 years) and fourth (4-15 years) age groups. In the diameter of the femur, this was seen only in the third age group (pSA values in Table 1). If present, the frequency of femur length asymmetry was significant in favour of the right limb in the first age group, whereas in the third age group it was found to favour the left limb (pDA values in Table 1). In the other age categories, asymmetry of femur length was spread evenly between the right and left limbs, and this was true of the diameter of the femur in all age categories. Asymmetry was significantly more frequent than absence of asymmetry also in the length of tibia in the fourth age group (4-15 years, Table 1). The frequency of asymmetry of length and diameter of the tibiae was evenly distributed between the right and left limbs (Table 1).

The percentage of cases with greater left- and right-side length measurements was also calculated to determine the age when nonadults would shift to left-side asymmetry (Table 2.).

The difference in standardized asymmetry among age groups was significant in the length ($F = 5.69$, $p < 0.001$; Fig. 1A) and diameter ($F = 3.61$, $p = 0.01$; Fig. 1B) of the femur. An apparently significant difference in the length of tibiae among age groups ($F = 2.75$, $p = 0.045$) proved not to be significant after the pairwise comparisons ($-0.44 < \text{diff} < 1.26$, $p > 0.11$). In the diameter of the tibiae, there were no significant difference ($F = 0.74$, $p = 0.53$) among the age groups.

Our results showed significant differences in the length of the femur between the first and third, first and fourth and third and fourth age groups (Table 3., Fig. 1A). Femur diameter was significantly different between age groups 1-3 and 1-4 (Table 3., Fig. 1B).

In respect of the magnitude of asymmetry, quantified by the SA values, the age groups were highly negatively correlated with the length (Pearson $r = -0.63$, $t = -3.06$, $N = 16$, $p = 0.008$) and diameter ($r = -0.78$, $t = -4.72$, $N = 16$, $p < 0.001$) of the femur, and with the diameter of the tibia ($r = -0.98$, $t = -16.02$, $N = 14$, $p < 0.001$), but showed no correlation with the tibial length ($r = -0.3$, $t = -1.18$, $N = 16$, $p = 0.26$). Thus, the magnitude of asymmetry decreased markedly with age in the examined measurements of lower limb bones, except in the length of the tibia.

Table 1. The frequency of directional asymmetry within age groups. SA: number of pairs with standardized asymmetry values, 0SA: number of pairs with zero standardized asymmetry values, L: asymmetry for the left side, R: asymmetry for the right side. LFEM: length of the femur, DFEM: diameter of the femur, LTIB: length of the tibia, DTIB: diameter of the tibia. P values (p) represent the differences in the frequency (zero values of SA vs. presence of directional asymmetry, left vs. right asymmetry). Significant p values are in bold font. Group 1 = 0.5-1 years, group 2 = 1-2 years, group 3 = 2-4 years, group 4 = 4-15 years.

	Age group	Total	SA	0SA	*pSA*	L	R	*pDA*
LFEM	**1**	18	8	10	0.92	0	8	**0.02**
	2	17	9	8	1	5	4	1
	3	45	33	12	**0.01**	28	5	**0.001**
	4	145	100	45	**>0.001**	52	48	0.84
	Sum	225	150	75		85	65	
	%		66.66	33.33		56.66	43.33	
DFEM	1	17	8	9	1	1	7	0.18
	2	17	10	7	0.77	4	6	0.71
	3	45	13	32	**0.031**	8	5	0.73
	4	145	71	74	0.92	39	32	0.59
	Sum	224	102	122		52	50	
	%		45.53	54.46		50.98	49.01	
LTIB	1	13	6	7	1	3	3	1
	2	8	5	3	0.68	0	5	0.1
	3	33	19	14	0.62	7	12	0.51
	4	114	88	26	**>0.001**	52	36	0.21
	Sum	168	118	50		62	56	
	%		70.23	29.76		52.54	47.45	
DTIB	1	13	3	10	0.17	0	3	0.46
	2	8	1	7	0.18	0	1	1
	3	33	15	18	0.83	7	8	1
	4	114	67	47	0.16	34	33	1
	Sum	168	86	82		41	45	
	%		51.19	48.80		47.67	52.32	

Table 2. The percentage of cases with greater left- and right-side measurements. Calculation excludes cases with equal left and right measurements. LFEM: length of the femur, DFEM: diameter of the femur, LTIB: length of the tibia, DTIB: diameter of the tibia. Higher percentages on the left side are in bold font. Group 1 = 0.5-1 years, group 2 = 1-2 years, group 3 = 2-4 years, group 4 = 4-15 years.

	Age group	L%>	R%>
LFEM	1	0.00	100.00
	2	**55.55**	44.44
	3	**84.84**	15.15
	4	**52.00**	48.00
DFEM	1	12.5	87.5
	2	40.00	60.00
	3	**61.53**	38.46
	4	**54.92**	45.07
LTIB	1	50.00	50.00
	2	0.00	100.00
	3	36.84	63.15
	4	**59.09**	40.90
DTIB	1	0.00	100.00
	2	0.00	100.00
	3	46.66	53.33
	4	**50.74**	49.25

Discussion

In this study, the development of lower limb bone directional asymmetry in diameter and length measurements of the femur and the tibia was studied.

Based on the distribution of symmetrical and asymmetrical bones, both the two bones (femur vs. tibia) and the two measurements (length vs. diameter) behaved differently in different age groups. In early childhood (2-4 years, group 3), femoral length showed a stronger asymmetry than tibial length, whereas femoral diameter was predominantly symmetric. However, in other age groups, the distribution of symmetrical and asymmetrical measurements of the femora and tibiae were even (Table 1). These differences may be explained by the effect of the mechanical forces acting on the femur during preambulatory and ambulatory phases of development (Swan et al 2020). As for the frequency of directional asymmetry, femoral length of 0,5-1-year-old infants showed a pronounced shift to the right side, followed by a shift to the left side which finally became even in older age groups (Table 2). This progress may be the reflection of the different biomechanical loading patterns that act on the lower limbs unevenly during infancy and which become even in older age groups when bipedalism reaches its adult-like characteristics.

Side predominance of femoral length shifted remarkably to the left side in 2-4-year-old children, whereas there was a quite even distribution between left and right side in the diameter of the femur and measurements of the tibia. In addition to the transition from immature to mature bipedal gait (Swan et al 2020), right-side preference is also present at the age of 2-4 years (Gabbard et al 1991; Gabbard and Iteya 1996) and contributes to the functional differences that arise in the lower limb.

On the other hand, femoral diameter displayed a smoother shift to the left side reaching its completion in older children (4-15 years). This was coherent with the outcomes of examining the magnitude of asymmetry, which decreased sharply with age both in femoral length and diameter. The background of this observation could be the demands of bipedal locomotion, which reduce asymmetry in the lower limb bones (Waxenbaum and Sirak 2016; Plochocki 2004).

Table 3. Comparison of the directional asymmetry between age groups of the different bones: LFEM: length of the femur, DFEM: diameter of the femur, LTIB: length of tibia. Significant p values are in bold font. Group 1 = 0.5-1 years, group 2 = 1-2 years, group 3 = 2-4 years, group 4 = 4-15 years. Due to the lack of differences among age groups, the results regarding the diameter of the tibia (DTIB) are not shown separately.

	Age group	L%>	R%>
LFEM	1 - 2	0.44 (-1.04, 1.17)	0.24
	1 - 3	**0.77 (-1.27, -0.27)**	**>0.001**
	1 - 4	**0.44 (-0.89, 0.002)**	**0.005**
	2 - 3	0.33 (-0.84, 0.18)	0.33
	2 - 4	0.005 (-0.46, 0.45)	0.99
	3 - 4	**0.33 (0.02, 0.63)**	**0.03**
DFEM	1 - 2	2.61 (-6.82, 1.59)	0.38
	1 - 3	**3.99 (-7.48, -0.49)**	**0.02**
	1 - 4	**3.78 (-6.92, -0.63)**	**0.01**
	2 - 3	1.38 (-4.87, 2.11)	0.74
	2 - 4	1.17 (-4.31, 1.98)	0.77
	3 - 4	0.21 (-1.88, 2.3)	0.99
LTIB	1 - 2	1.26 (-0.19, 2.72)	0.11
	1 - 3	0.84 (-0.22, 1.9)	0.17
	1 - 4	0.39 (-0.55, 1.35)	0.69
	2 - 3	0.42 (-1.7, 0.85)	0.83
	2 - 4	0.86 (-2.05, 0.32)	0.24
	3 - 4	0.44 (-1.08, 0.2)	0.29

Our findings indicate that, compared with the upper limb bones, directional asymmetry of the lower limb bones is both more variable (Auerbach and Ruff 2006) and less marked (Trinkaus et al. 1994; Plochocki 2004). The functional differences between the lower extremities originate from the limb preference and the supportive and weight bearing function of the non-preferred leg. The patterns of the biomechanical loading of the lower limbs change unevenly during infancy and only become consistent at the stage when bipedalism is adult-like. For the further refinement of mature bipedalism and gait, the direction of the loading continues to change (Swan et al. 2020). These individual but at the same time interconnected influences are reflected in different changes in the various measurements of the lower limb bones, causing a noise in the data that is not present in the upper limb bones, i.e. in the right-sided world.

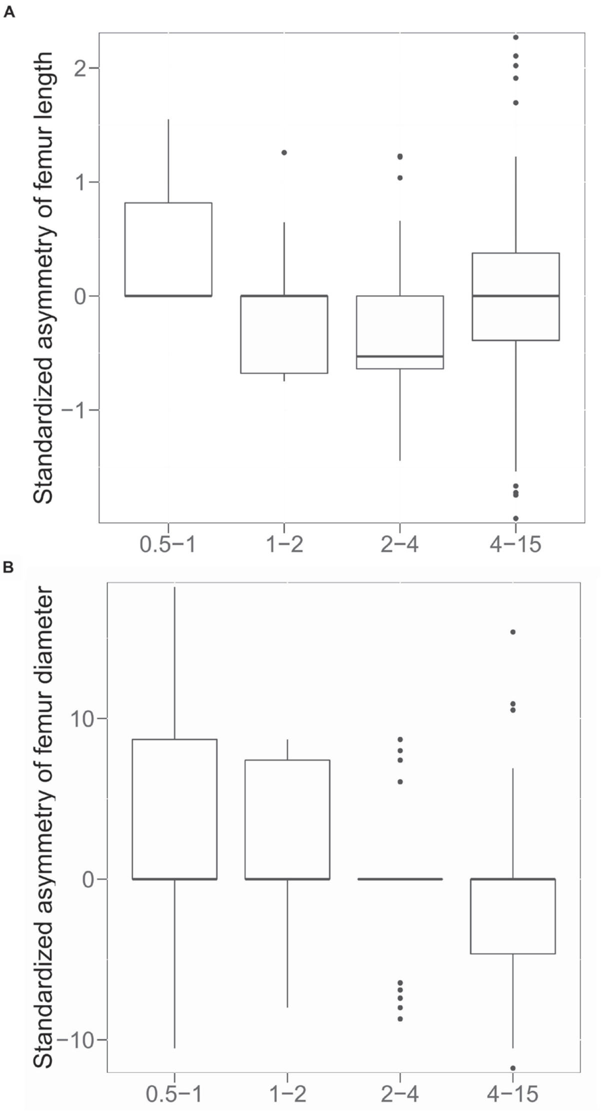

Fig. 1A-B: The differences in the directional asymmetry of the length (A) and diameter (B) of the femur between age groups.

In conclusion, the results of our study add new data and contribute to the better understanding of the development of skeletal asymmetry of the lower limbs. The age groups applied in our examination have been proved to be useful, as they allow further comparison of skeletal remains from different sites and from different geographical or chronological contexts. In the future, it would be interesting to use diaphyseal cross-sectional imaging to analyse directional asymmetry in different diaphyseal regions.

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