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ORIGINAL PAPER

Fluctuating asymmetry of human morphometric features as a marker of developmental instability caused by adverse environmental conditions

Iwona Teul et al., Fluctuating asymmetry of human morphometric features as a marker of developmental instability

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ABSTRACT

Background: This article is an attempt to apply fluctuating asymmetry as a morphometric method of studying changes in specific structures of the right and the left side of the body to determine variables which may affect morphogenesis and, consequently, human morphology in adulthood. The main aim of this study was to use the fluctuating asymmetry level as an indicator of adverse living conditions in childhood by determining the impact of environmental components (socio-economic factors and air pollution) on the level of body asymmetry in young women and men.

Materials and methods: Data were collected from 877 students from various Polish universities, including 483 women and 394 men. Anthropometric data and questionnaire responses were recorded. As part of the surveys, respondents provided information about their place of residence, socio-economic status and lateralisation. The composite body FA (cFA) was assessed based on six bilateral features: the length of fingers II and IV of both hands, the length and width of the ear, and the length and width of the foot.

Results and Conclusions: The present study supports the hypothesis that asymmetry increases as socioeconomic status decreases and air pollution levels increase. Differences in asymmetry, depending on environmental factors, socioeconomic status (SES) and air quality, were in most cases greater in men than in women. The results confirm that variable asymmetry is a sensitive indicator of an individual's exposure to unfavorable environmental factors during ontogenesis. Moreover, the results of the conducted research suggest that environmental factors may influence the structure of the human body, and irreversible morphological alterations are the result of unfavorable conditions occurring in the early stages of biological development.

Keywords: fluctuating asymmetry, morphometric method, environmental conditions

INTRODUCTION

The study of the form and structure of organisms, as well as their individual organs and systems, has always played a salient role in anatomy. Despite the implementation of increasingly advanced methods, morphological evaluation remains a dominant tool in qualitative and quantitative description of structural traits. Each living organism has its own form, which depends on its body structure and capabilities determined by the species and the environment. In humans, we observe considerable inter-individual variation in terms of the structural features of the body, which may be of relevance in everyday clinical practice, health sciences and human biology. To a large extent, this variation results from the phenotypic plasticity of a given organism. Not only does morphometry enable us to analyse intra-individual as well as within-individual variation (as the individual grows older), but it also can be applied in developmental biology for the analysis of the ontogenetic changes in the size, proportions and spatial distribution of existing features arising from both genetic and environmental factors. Morphometry proves especially useful in the study and comparison of the growth stages, as it helps identify differences in the development of attributes at consecutive stages of life. Even in cases where morphogenesis has already been completed [31, 34, 35].

Fluctuating asymmetry (FA) is a morphometric method used in research on the course and conditions of biological development. The term refers to slight, random deviations away from perfect symmetry [27, 40]. In optimum conditions for development, FA is minimal; however, its value grows markedly if the individual develops in an adverse environment [6, 9, 20]. Since both sides of the body develop under the control of identical genome and are influenced by the same environment, fluctuating asymmetry is assumed to reflect the body's inability to inhibit processes leading to specific disorders. Given that morphology is considered one of the most conspicuous facets of the phenotype, reflecting the complex nexus between structural elements and biological functions within organs and tissues, it is asymmetry that emerges as an indicator signaling the presence of disorders. Thus, it can be regarded as a phenotypic effect of developmental instability [10, 21, 36].

FA is employed in biological and medical studies to determine exposure to adverse conditions during ontogenesis [1, 9, 19, 20, 21, 37, 39]. Based on research performed on contemporary populations it was also found that FA is correlated with health and biological condition [4, 7, 8, 9, 13, 27, 28]. The above aforementioned reveal the frequency and importance of studies on asymmetry in humans, as well as interest in this phenomenon among researchers various scientific disciplines.

There is scarcity of research on the impact of environmental factors on asymmetry in contemporary populations. Moreover, its findings are contradictory; some studies argue that there is no connection between FA and adverse conditions during ontogenesis [21, 29, 37]. Therefore, it seems justified to carry out further analyses on the phenomenon, particularly in the context of the increasingly extensive use of FA as a marker of environmental stress in human childhood and adolescence.

This article is an attempt to apply fluctuating asymmetry as a morphometric method of studying changes in specific structures of the right and the left side of the body to determine variables which may affect morphogenesis and, as a consequence, human morphology in adulthood. The purpose of this study was to use the fluctuating asymmetry level as an indicator of adverse living conditions in childhood by determining the impact of environmental conditions (socio-economic factors and air pollution) on the level of body asymmetry in young women and men.

The following hypotheses were formulated based on data available in the literature of the subject on factors modifying ontogenesis in humans [2]:

1. The fluctuating asymmetry level increases as socio-economic status (SES) decreases, and air pollution grows.
2. Due to higher eco-sensitivity of the male sex, differences in the fluctuating asymmetry levels dependent on environmental factors are higher in men than in women.

MATERIAL AND METHODS

Data were collected from 877 students at various Polish universities, including 483 women and 394 men. The age of the subjects ranged from 19 to 25 years. The study protocol was approved by the Bioethics Committee of the Jagiellonian University in Kraków. The data collection process for the study was in accordance with the ethical principles contained in the Declaration of Helsinki. Informed consent was obtained from all individual study participants [3].

Anthropometric and questionnaire information was collected. The survey included questions about place of residence, socio-economic status and lateralisation. Questions on socio-economic factors included place of residence in the following categories: village, city of up to 100,000 inhabitants and city of more than 100,000 inhabitants; mother's and father's educational attainment in the following categories: occupational, secondary, and tertiary; number of older siblings. Based on the data of the Polish Chief Inspectorate for Environmental Protection, the level of particulate matter (PM_{10}, $PM_{2.5}$), sulphur dioxide (SO_2), nitric dioxide (NO_2) and benzene (C_6H_6) at participants' residential locations during childhood and adolescence was assessed. Childhood and adolescence locations were divided into 3 categories, considering the air pollution level observed in the location for the majority (at least 10 years) of the development period of the individual. Class 1 (low air pollution level) comprised zones where annual pollutant values and the number of days per year with exceedances were below the allowable limit; Class 2 (medium air pollution level) — zones with annual values below the permissible limit, but with the number of days of exceeding the norm above the limit, and Class 3 (high air pollution level) included zones above the limit.

For each subject, the length of fingers II and IV in both hands, ear length and width, and foot length and width were measured in millimetres according to current standards applicable in anthropometry. Finger, ear and foot width measurements were taken by means of an electronic linear calliper, whereas foot length was measured by means of a conventional linear calliper.

All measurements were taken twice at a certain interval (10 to 15 minutes) by the same researcher, both on the right- and left-hand side. Mean value was calculated for measurements performed on each side; measurement error was also computed.

Statistical methods

The Shapiro–Wilk test was applied to check the normality of distribution of collected data. The distribution of the analysed variables was verified as normal. Therefore, asymmetry level variation between groups was subjected to Student’s t-test, as well as univariate and multivariate analysis of variance (ANOVA and MANOVA). A significance level of $p < 0.05$ was assumed.

RESULTS

Fluctuating asymmetry calculation

Six bilateral traits have been used to calculate FA: length of the fingers II and IV, ear length and ear width, foot length, and foot width. Body FA was calculated according to the procedure described by Palmer and Strobeck [27]. This method was also used in our previously paper [41].

First, the type of symmetry was established. A two-way mixed ANOVA showed that the measurement error was not larger than the difference between the two sides for any analyzed trait (F-ratios ranged from 1.82–2.26 with all p-values > 0.05). The effects of the interaction between factors: side and individual were statistically significant (ear length: $F = 12.40$, $p < 0.01$; ear width: $F = 13.04$, $p < 0.01$; second digit length: $F = 12.78$, $p < 0.01$; fourth digit length: $F = 12.95$, $p < 0.01$; foot wide: $F = 10.11$, $p < 0.01$, foot length: $F = 10.25$, $p < 0.01$). The measurement error in any case was not larger than the difference between the two sides. Asymmetries in all analyzed traits were normally distributed (as determined by a Shapiro–Wilk test) around a mean of zero (determined by a one sample t-test with the null hypothesis set to a mean of zero). The results of the calculations indicate a fluctuating asymmetry, not a directional asymmetry.

For each measured bilateral trait the difference between the right and left side (R–L) was calculated and the signed asymmetry was obtained. Signed asymmetry (SA) in each individual case was adjusted according to trait size by dividing each one by the average value of the trait measurements ([R+ L]/2) and the relative asymmetry was obtained. This method allows the direct comparison of asymmetries in dimensions of different size [8, 27]. Finally, for each person the arithmetic mean of relative asymmetry for all the traits was calculated and composite FA (cFA) was obtained.

Asymmetry level and socio-economics factors

Statistically significant differences in asymmetry for the entire group were found only for variables such as “mother’s educational attainment” and “number of older siblings” (Table 1).

In women, only mother's educational attainment had a meaningful effect on FA (Table 1). In men, statistically significant differences were observed depending on place of residence, mother's educational attainment and number of older siblings (Table 1).

An analysis of SES-dependent variability in asymmetry levels revealed certain tendencies, which were identical for the whole material, both in the female and the male group. Although differences arising from place of residence in the entire group were insignificant, representatives of rural population had slightly lower asymmetry levels than inhabitants of urban areas. Lower fluctuating asymmetry was associated with mother's higher educational background. A quite similar relationship was reported for "father's educational attainment". A slightly higher total asymmetry was noticed in subjects whose fathers had occupational and secondary education. As for the variable "number of older siblings", firstborn children and only children were characterised by the lowest FA (Table 2). Socio-economic differences in asymmetry levels were much smaller among female than male students (Table 2).

Asymmetry level and environmental pollution

Taking into account air quality in the subject's place of residence during childhood and adolescence, a significant relationship was detected between pollution and asymmetry levels. Total asymmetry increased together with the quantity of a given pollutant in the air (Table 3).

Similarly, all variables in women were found to have had a marked effect on fluctuating asymmetry (Table 3). All the analysed factors had a statistically significant effect on total asymmetry in male subjects (Table 4), too.

Separate results for female and male subjects show that fluctuating asymmetry levels rose along with the increasing concentration of a given pollutant. Like for socio-economic factors, vast majority of male subjects were characterised by greater variation in FA depending on pollutant levels in comparison to women. These values were equal only for the "SO_2" variable.

DISCUSSION

The present work corroborates the hypothesis that asymmetry grows with decreasing socio-economic status and increasing level of air pollution.

Sources on this subject include studies indicating the existence of a relationship between socio-economic status and asymmetry in humans. Higher socio-economic status of the family responsible for the child's development is often related to better conditions for foetal growth.

Factors such as parents' educational background, place of residence or number of older siblings have an impact on e.g. hygienic conditions, diet or access to medical care [2, 16]. It was also proved that children born to parents with lower educational attainment were more asymmetrical at birth than the children of better-educated parents [23, 41]. Other studies revealed statistically significant differences in FA depending on a number of factors such as family size, parent's educational attainment and occupation, and the number of rooms in the flat or house. Fluctuating asymmetry was influenced mostly by mother's educational attainment, followed by father's educational attainment [24, 40]. Our findings also revealed a relationship between mother's educational background and the level of fluctuating asymmetry. In comparison, father's educational attainment had a significant effect on FA only in male subjects. This presumably stems from the fact that father's educational background and the related type of occupation and exposure to harmful conditions do not directly affect the course of pregnancy. Rather, they have more to do with the family's income and ensuring the appropriate living standard. Factors which exert greater impact on FA include mother's educational attainment – associated with knowledge on disease prevention, caring for one's health during pregnancy and being committed to ensure suitable conditions for the child's early development. Results in the literature also indicate a direct link between factors related to mother's health, such as obesity or smoking and tooth asymmetry in children [12].

Unquestionably, living conditions in early childhood influence the level of fluctuating asymmetry have an effect on the level of fluctuating asymmetry. The results of the present study show that subjects living in cities have a higher FA level. This could be explained by a higher intensity of ambient noise, air pollution and light pollution. Here, however, statistically significant differences depending on place of residence were found only for men. The narrowing of the gap between living conditions in urban and rural environment is a process which we can also see in Poland and which is currently discussed in the literature of the subject [15, 16].

Another factor analysed in our research was the number of siblings. Since asymmetry develops mainly at the foetal stage, we decided to include only older siblings [12]. In the group of subjects examined in this study, significant differences in this criterion were present for the entire group and for male subjects. In both cases an increase in the number of older siblings was linked to a rise in FA level. Similar result was obtained in other study [25]. This could partly be caused by the fact that a pregnant woman's body needs time to fully recover from the previous gestation. In addition, the mother needs to take care of other children and does not have time to rest properly. Also, a high number of siblings attending pre-school or school increases the likelihood of bringing home various pathogens. All mentioned factors may affect foetal development.

Individual environmental factors pertaining to air pollution and socio-economic status are interrelated; they complement and overlap each other. In many countries, social inequalities have been levelled out by the progress of civilisation and extensive social policy measures, as manifested in the gradual disappearance of body size variation as well as asymmetry levels. However, air quality still remains a key factor modifying human development.

Other factors analysed in our study were related to atmospheric air quality. In plants and animals, asymmetry level is an index of eco-toxicity e.g. from pesticides, heavy metals, air and water pollution or elevated carbon dioxide concentration. Typically, unnatural toxins tend to increase fluctuating asymmetry [9,10]. Higher FA levels due to air pollution have been reported for plants, reptiles, birds or mammals [7, 17, 19]. To the best of our knowledge, the present study is the first one to analyse the relationship between air pollution and asymmetry levels in humans. Air pollution was found to be an important factor affecting FA. Significant differences were observed for every pollutant – both for the entire group and separately for female and male subjects. This was presumably due to their negative effect on human health and biological development: harmful substances cause modifications on cellular level, and ultimately to alterations in organs, systems and the entire body.

In our research, differences in asymmetry depending on environmental factors, SES and air quality in most cases were greater in men than in women. Many other researchers have emphasised sex-dependent variation in fluctuating asymmetry [18, 24, 26, 32, 33, 38]. It was suggested that during puberty testosterone causes facial masculinisation whilst inhibiting the function of the immune system, presumably exposing men to a greater degree of stress [25].

Similar results were obtained in the present work; in most cases lower levels of asymmetry were reported in women. However, the literature of the subject also contains studies which indicate no significant differences between the sexes or even a reverse tendency, in several or all features [4, 9, 11, 25, 38].

Literature offers no data juxtaposing asymmetry between girls and boys raised in identical environmental conditions. A key question is whether both sexes react similarly to nutritional conditions. A hypothesis commonly accepted by anthropologists, according to which male stature (from foetal life to adulthood) appears more “sensitive” to environmental factors than female stature [2], has not been consistently proved, as important dimorphic differences in conditions and lifestyle are noticeable after the prenatal period. This may be exemplified by the choice of different physical activities depending on sex and specific behaviour, e.g. boys tend to engage in injury-prone motor play more than girls do. Sex determines the development of the foetus and the child alike. It varies the size and proportions of the body. This sexual dimorphism may stem from variation in foetal origins, leading to health differences in later life [4]. It is possible that foetal origins are also related to higher eco-sensitivity in men, which could explain greater environment-dependent differences in asymmetry in men than in women.

This study has several limitations. Subjects included male and female university students, which may not be fully representative of the entire population of Poland. Individuals from very low-income families often tend to become self-reliant early on, which means that they abandon further education and start working at an early age. For this reason, future research should be conducted on a group characterized by greater diversity in terms of socioeconomic status.

CONCLUSIONS

The results of our research allowed us to validate all hypotheses formulated earlier in this article, indicating that fluctuating asymmetry may be used in morphometric studies in humans. The results we obtained confirm that fluctuating asymmetry is a sensitive indicator of an individual's exposure to adverse environmental factors during ontogenesis. Being relatively easy to measure, it may be a useful benchmark of human developmental stability. When an increase in fluctuating asymmetry is recorded and linked to a specific environmental factor, this could provide effective strategies on how to create optimum conditions for a child's development by reducing the negative impact of stress factor or, where possible, eliminating it completly. In historical populations, high asymmetry may be treated as a sign of adverse conditions.

In addition, the results of the conducted research indicate that environmental factors may affect the structure of the human body, and irreversible morphological changes in the human body are the result of unfavorable conditions occurring in the early stages of biological development. It can be assumed that factors causing morphological changes are also likely to affect functional activities, leading to a deterioration of the biological condition of the individual.

Article information and declarations

Data availability statement

The data that support the findings of this study are available on request from the corresponding author, [I.T.]. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

Ethics statement

The study protocol was approved by the Bioethics Committee of the Jagiellonian University in Kraków no 122.612047.2016. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Guidelines set by Henry et al. [3] applied. All participants gave their written consent to take part in the study.

Author contributions

Author contributions according to CRediT: Conceptualization — IT, IW,WF. Project administration — IW, IT. Methodology — IW, WF, IT. Investigation — IW, WF, IT, BS. Data curation — IW, WF, BS, IT. Formal analysis — IW, WF, IT. Visualization — IW, WF, BS. Writing (original draft) — IW, IW, WF, BS. Writing (review & editing) — IW, WF, BS, IT. Supervision — IT, IW, WF, BS.

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Conflict of interest: The authors declare no conflicting interests.

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Table 1. The result of MANOVA (main effect) with the cFA as a dependent variable and socioeconomic factors as an independent variable

Factor	Whole group		Women		Men	
	F	p	F	p	F	p
Place of living	3.02	0.081	0.95	0.388	4.82	**0.029**
Mother's education	4.69	**0.010**	3.95	**0.038**	5.24	**0.006**
Father's education	1.86	0.156	1.11	0.331	1.08	0.341
Number of older siblings	3.23	**0.040**	1.54	0.214	2.74	**0.042**

cFA (composite fluctuating asymmetry) — the total level of asymmetry for each individual (the arithmetic mean of the asymmetry for all the analyzed bilateral trait). Bold type indicates significant differences ($p < 0.05$).

Table 2. The composite fluctuating asymmetry (cFA) of participants by socioeconomic factors

SES Factor	Category	Whole group		Women		Men	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Place of living	Village	0.021	0.013	0.018	0.015	0.023	0.014
	City	0.023	0.016	0.020	0.014	0.027	0.016
Mother's education	Vocational	0.024	0.014	0.020	0.015	0.028	0.014
	Secondary	0.021	0.016	0.020	0.019	0.023	0.016
	Higher	0.020	0.014	0.017	0.017	0.022	0.016
Father's education	Vocational	0.023	0.014	0.019	0.014	0.026	0.014
	Secondary	0.023	0.017	0.021	0.016	0.026	0.016
	Higher	0.020	0.014	0.018	0.018	0.024	0.017
Number of older siblings	0	0.021	0.012	0.018	0.013	0.024	0.012
	1	0.022	0.017	0.020	0.017	0.026	0.018
	2 or more	0.025	0.018	0.022	0.018	0.028	0.019

cFA (composite fluctuating asymmetry) — the total level of asymmetry for each individual (the arithmetic mean of the asymmetry for all the analyzed bilateral trait).

Table 3. The result of MANOVA (main effect) with the cFA as a dependent variable and the level of air pollutants as an independent

Pollutant	Whole group		Women		Men	
	F	p	F	P	F	p
PM_{10}	23.50	**0.000**	24.53	**0.000**	14.02	**0.000**
$PM_{2.5}$	13.83	**0.000**	8.90	**0.000**	16.44	**0.000**
NO_2	110.44	**0.000**	41.45	**0.000**	84.21	**0.000**
SO_2	91.65	**0.000**	29.10	**0.000**	16.41	**0.000**
Benzen	3.07	**0.047**	7.01	**0.001**	21.12	**0.000**

cFA (composite fluctuating asymmetry) — the total level of asymmetry for each individual (the arithmetic mean of the asymmetry for all the analyzed bilateral trait). Bold type indicates significant differences ($p < 0.05$)

Table 4. The composite fluctuating asymmetry of participants by the level of air pollutants.

Pollutant	Pollution level	Whole group		Women		Men	
		Mean	SD	Mean	SD	Mean	SD
PM_{10}	Low	0.010	0.010	0.014	0.010	0.003	0.006
	Medium	0.019	0.012	0.016	0.012	0.023	0.010
	High	0.027	0.016	0.024	0.015	0.031	0.015
$PM_{2.5}$	Low	0.010	0.012	0.013	0.014	0.006	0.010
	Medium	0.022	0.012	0.018	0.012	0.026	0.011
	High	0.026	0.015	0.022	0.014	0.031	0.015
NO_2	Low	0.017	0.013	0.016	0.012	0.019	0.014
	Medium	0.021	0.011	0.019	0.010	0.023	0.011
	High	0.027	0.018	0.023	0.018	0.031	0.017
SO_2	Low	0.020	0.012	0.018	0.010	0.023	0.013
	Medium	0.022	0.020	0.019	0.019	0.026	0.020
	High	0.025	0.011	0.022	0.010	0.027	0.011
Benzene	Low	0.019	0.012	0.018	0.010	0.019	0.015
	Medium	0.022	0.016	0.020	0.019	0.026	0.010
	High	0.028	0.016	0.022	0.011	0.033	0.017

cFA (composite fluctuating asymmetry) — the total level of asymmetry for each individual (the arithmetic mean of the asymmetry for all the analyzed bilateral trait)