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# USE OF A BIOMETRICAL METHOD FOR PREDICTION OF BODY HEIGHT FROM THE KNOWN VALUE OF FOOT LENGTH

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The study of interrelations existing among body dimensions is an important and longtermed problem in anthropology. These interrelations can be expressed by means of the biometrical methods based on the correlation analysis.

Authors present a biometrical (mathematico-statistical) model for prediction of the values of body dimensions and test it by studying the relation between body height and foot length in the population of Czech countries of both sexes from the age of 4 years. The solution of the problem of prediction may be important not only from the point of view of the theory but also in practice. In our case some results can be obtained useful for criminalistical identification because they make possible to estimate the unknown value of body height from the known value of foot length (or the respective length of the trace). The accuracy of this prediction can be derived by our biometrical model, too.

## MATERIAL AND METHOD

The material were the results obtained by Garment Research Institute (VÚO) in Prostějov in the study of children and youth of Czech countries in 1968. 4,694 probands were measured, 2,315 boys and 2,379 girls in the age from 3 to 18 years. Six of the so-called basic dimensions were followed up: body height, weight, chest girth I, chest girth II, waist girth, hip girth. In the less part of this group (approximately 60 probands in each age category) 49 dimensions were followed up including foot length. All dimensions have been measured according to the unifited measurement program, designed and practically verified by the specialists of all participating countries (Komenda et al.). In each age category about 30 probands were from its lower part and about the same number from the upper one. Since no probands younger than 3 years and older than 18 years were measured, the age subcategories 3—3.5 years and 17.5—18 years have been eliminated.

The measurements have been carried out in the summer camps, kindergartens and children's mess-rooms by the instructed research workers of VÚO. The greater part of the children of the age from 3 to 6 years originated from Prague and Prostějov. The children of the age from 7 to 15 years were from various places in the East Moravian region and from Prague; the youth of the years 16—18 almost solely from the district Prostějov. This group of probands was adequate for the original aim of research: the requirements of the garment industry. An analysis of the results showed that the basic parameters of the group were similar to the parameters of the State-wide research carried out in 1961. From this follows that our data can be utilized in the study of other problems, too.

The measurement of body height and foot length respected the criteria generally accepted in somatometric research: body height was evaluated by an anthropometer according to Martin (dimension No 1), foot length was evaluated by means of the upper part of the anthropometer as the direct distance between the perpendiculars touching the point pternion and the point akropodion of the loaded foot (dimension No 58 according to Martin).

The results thus obtained were logically revised, all pathological cases eliminated and distributed into the age categories from 4 to 17 years, for both sexes. Statistical evaluation has been carried out separately in each age category.

We assume that such a categorization may be useful in the criminalistical practice because a trace can be accompanied by some other qualities (the sort of shoes etc.) which enable us to distinguish, if the trace corresponds to a boy or a girl and to a man or a woman, respectively.

The studied problem concerns the population of the subjects older than 4 years. Since the mean values of the body height in the age category of 17 years are almost the same as these values in the population of adults and the growth of the foot length is completed in both sexes (Klementa, 1973), this age category is taken as representative for the adult population, from the point of view of our problem.

Our method of prediction of body height, presented here, is based on the dimension length of the right foot. The differences between the length of the right and left foot vary in the range which can be considered here as negligible. When studying the foot length in 2,450 boys in the age from 14 to 20 years Klementa (1973) found that the length of the left foot makes 1 mm more in comparison with the right one. Such a difference need not be taken into account in the boot-and-shoe industry or garmet industry and both feet may be considered as having the same length. No difference between the length of the left and right foot was found when studying 1,120 girls in the age from 15 to 20 years.

The results discussed can be considered as representative for the population of Czech countries, because the initial data differ very little from the values of the body dimensions as found in 1961. This can be verified by means of the normalization index recommended by Suchý (1967) as a method for evaluation the relation of a group studied to the reference population. More detailed comparison and further characteristics of the sample can be found in the paper of Krátoška et al. (1971).

## MATHEMATICAL FORMULATION OF THE PROBLEM AND ITS SOLUTION

The problem of prediction, introduced above, can be taken mathematically as a problem how the conditional distribution of the dimension $X$ (body height) may be found in dependence of the dimension $W$ (foot length) in a population. The parameters of this population must be specified thoroughly; such a specification can influence the conclusions derived in a very essential way.

As a starting point for further considerations we assume that the dimensions $X$ and $W$ are random variables distributed according to the two-dimensional normal law, in every age category from 4 to 17 years. The same type of distribution is supposed to govern these dimensions in the population of adults. Numerical solution of the problem is carried out separately for both sexes. The methods described in the paper of Komenda et al. are used as a basis for it.

Thus, the random vector $(X, W)$ has two-dimensional normal distribution in each age category $t_\tau$, with the vector of expectations

$$(\mu_X(t_\tau),\ \mu_W(t_\tau))$$

and the covariance matrix

$$\begin{pmatrix} \sigma_{XX}(t_\tau), & \sigma_{XW}(t_\tau) \\ \sigma_{WX}(t_\tau), & \sigma_{WW}(t_\tau) \end{pmatrix} \tag{1}$$

The estimates of these parameters, i.e. averages, variances and covariances calculated from the observations, are summarized in the columns I—VI in Table 1.

From this follows the form of the conditional probability density of the dimension $X$, in each age category $t_\tau$

$$f(x/w,t_\tau) = \frac{1}{\sqrt{2\pi\sigma_{X.W}(t_\tau)}} \exp\left\{-\frac{1}{2\,\sigma_{X.W}(t_\tau)}(x - \mu_{X.w}(t_\tau))^2\right\} \tag{2}$$

where

$$\mu_{X.w}(t_\tau) = \mu_X(t_\tau) + \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)}(w - \mu_W(t_\tau)) \tag{3}$$

$$\sigma_{X.W}(t_\tau) = \sigma_{XX}(t_\tau) - \frac{\sigma_{XW}(t_\tau)^2}{\sigma_{WW}(t_\tau)} \tag{4}$$

The regression coefficients from (3) and residual variances from (4) are given in the columns VII and VIII in Table 1.

The conditional distribution of the dimension $X$, in the whole population (integrated with respect to the age) can be derived as

$$f(x/w) = \sum_\tau f(x/w,t_\tau)\, P(t_\tau/w) \tag{5}$$

where

$$P(t_\tau/w) = \frac{f(w/t_\tau)\, P(t_\tau)}{\sum_\tau f(w/t_\tau)\, P(t_\tau)}$$

is the age structure of the subpopulation defined by the condition $W = w$.

By the symbol $w_i$ the following random event will be denoted

$$w_i - \Delta_W \leqq W < w_i + \Delta_W$$

This event says that the value of the foot length of the subject randomly chosen belongs to the introduced interval.

The probability of this event can be written as

$$P(w_i/t_\tau) = \int_{w_i-\Delta_W}^{w_i+\Delta_W} f(w/t_\tau)\, dw = \tag{6}$$

$$= \Phi\left(\frac{w_i + \Delta_W - \mu_W(t_\tau)}{\sqrt{\sigma_{WW}(t_\tau)}}\right) - \Phi\left(\frac{(w_i - \Delta_W - \mu_W(t_\tau)}{\sqrt{\sigma_{WW}(t_\tau)}}\right)$$

where $f(w/t_\tau)$ means the probability density of the dimension $W$ in the age category $t_\tau$ and $\Phi(\ \ )$ is the standardized normal distribution function.

By means of the Bayes formula the inverse probability can be derived that the subject with the value of the dimension $W$ from the interval $w_i$ belongs to the age category $t_\tau$

$$P(t_\tau/w_i) = \frac{P(w_i/t_\tau)\, P(t_\tau)}{\sum_\tau P(w_i/t_\tau)\, P(t_\tau)} \tag{7}$$

In this formula, the probabilities $P(t_\tau)$, $t_\tau = 4, 5, \ldots, 17, > 17$, determine the age structure of the considered population; they can be estimated from the demographical data (see column I in Table 1).

Probability distributions (6) and (7) are given in Table 2 and Table 3, respectively. For the calculations the value $\Delta_W = 5$ mm was taken.

Obviously

$$f(x/w_i,t_\tau) = \frac{\int_{w_i-\Delta_W}^{w_i+\Delta_W} f(x/w,t_\tau)\, f(w/t_\tau)\, dw}{P(w_i/t_\tau)} \tag{8}$$

is the probability density of the dimension $X$ in the subpopulation $(w_i, t_\tau)$.

Thus, we have

$$f(x/w_i) = \sum_\tau f(x/w_i,t_\tau)\, P(t_\tau/w_i) \tag{9}$$

Mean value (expectation) of the dimension $X$ in the subpopulation $(w_i, t_\tau)$ equals then

$$\mu_{X \cdot w_i}(t_\tau) = \int_{-\infty}^{\infty} x f(x/w_i,t_\tau)\, dx =$$

$$= \frac{1}{P(w_i/t_\tau)} \int_{-\infty}^{\infty} x \int_{w_i-\Delta_W}^{w_i+\Delta_W} f(x/w,t_\tau)\, f(w/t_\tau)\, dw\, dx$$

By interchanging the order of integration we obtain

$$\mu_{X \cdot w_i}(t_\tau) =$$

$$= \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} \left[ \int_{-\infty}^{\infty} x f(x/w,t_\tau)\, dx \right] f(w/t_\tau)\, dw =$$

$$= \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} \mu_{X \cdot w}(t_\tau)\, f(w/t_\tau)\, dw$$

and, taking into account (3),

$$\mu_{X \cdot w_i}(t_\tau) =$$

$$= \mu_X(t_\tau) + \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} (\mu_{W \cdot w_i}(t_\tau) - \mu_W(t_\tau)) \quad (10)$$

where

$$\mu_{W \cdot w_i}(t_\tau) = \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} w f(w/t_\tau)\, dw \quad (11)$$

Let us substitute the distribution

$$\frac{f(w/t_\tau)}{P(w_i/t_\tau)}$$

by the rectangular one in the interval $w_i$. Then

$$\mu_{W \cdot w_i}(t_\tau) = w_i \quad (12)$$

and, simultaneously

$$\mu_{X \cdot w_i}(t_\tau) = \mu_X(t_\tau) + \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} (w_i - \mu_W(t_\tau)) \quad (13)$$

These values are summarized in Table 4.

Mean value of the whole population is expressed as follows

$$\mu_{X \cdot w_i} = \int_{-\infty}^{\infty} x f(x/w_i)\, dx =$$

$$= \int_{-\infty}^{\infty} x \sum_\tau f(x/w_i,t_\tau)\, P(t_\tau/w_i)\, dx$$

By interchanging the order of summation and integration we obtain

$$\mu_{X \cdot w_i} = \sum_\tau \left[ \int_{-\infty}^{\infty} x f(x/w_i,t_\tau)\, dx \right] P(t_\tau/w_i)$$

and finally, setting from (10) and (13), respectively,

$$\mu_{X \cdot w_i} = \sum_\tau \mu_{X \cdot w_i}(t_\tau)\, P(t_\tau/w_i) \quad (14)$$

These values are summarized in Table 4.

In a similar way, the variance of the dimension $X$ can be derived, in the subpopulation $w_i$ with respect to the dimension $W$.

The variance of the body height $X$ in this subpopulation $w_i$ and the age category $t_\tau$ is

$$\sigma_{X \cdot w_i}(t_\tau) = \int_{-\infty}^{\infty} (x - \mu_{X \cdot w_i}(t_\tau))^2 f(x/w_i,t_\tau)\, dx =$$

$$= \frac{1}{P(w_i/t_\tau)} \int_{-\infty}^{\infty} (x - \mu_{X \cdot w_i}(t_\tau))^2 \cdot$$

$$\left[ \int_{w_i-\Delta_W}^{w_i+\Delta_W} f(x/w,t_\tau)\, f(w/t_\tau)\, dw \right] dx$$

and, by interchanging the order of intergation

$$\sigma_{X \cdot w_i}(t_\tau) =$$

$$= \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} \left\{ \left[ x - \mu_X(t_\tau) - \right.\right.$$

$$\left.\left. - \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} (\mu_{W \cdot w_i}(t_\tau) - \mu_W(t_\tau)) \right]^2 f(x/w,t_\tau)\, dx \right\} \cdot$$

$$\cdot f(w/t_\tau)\, dw = \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} \left\{ \int_{-\infty}^{\infty} \left[ (x - \mu_{X \cdot w}(t_\tau)) + \right.\right.$$

$$\left.\left. + \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} (w - \mu_{W \cdot w_i}(t_\tau)) \right]^2 f(x/w,t_\tau)\, dx \right\} f(w/t_\tau)\, dw =$$

$$= \sigma_{X \cdot W}(t_\tau) + \left( \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} \right)^2 \sigma_{W \cdot w_i}(t_\tau)$$

This equals approximately

$$\sigma_{X \cdot w_i}(t_\tau) = \sigma_{X \cdot W}(t_\tau) + \left( \frac{\sigma_{XW}(t_\tau)}{\sigma_{WW}(t_\tau)} \right)^2 \frac{\Delta_W^2}{3} \quad (15)$$

(see Table 4).

In this formula

$$\sigma_{W \cdot w_i}(t_\tau) = \frac{1}{P(w_i/t_\tau)} \int_{w_i-\Delta_W}^{w_i+\Delta_W} (w - \mu_{W \cdot w_i}(t_\tau))^2 f(w/t_\tau)\, dw$$

is the variance of $W$ in the subpopulation $w_i$; the approximation introduced above has been derived under the assumption that the distribution of the dimension $W$ in this subpopulation $w_i$ can be considered as rectangular.

Further—in the subpopulation $w_i$, independently on the age—the variance of the body height $X$ can be given by the formula

$$\sigma_{X \cdot w_i} = \int_{-\infty}^{\infty} (x - \mu_{X \cdot w_i})^2 f(x/w_i)\, dx =$$

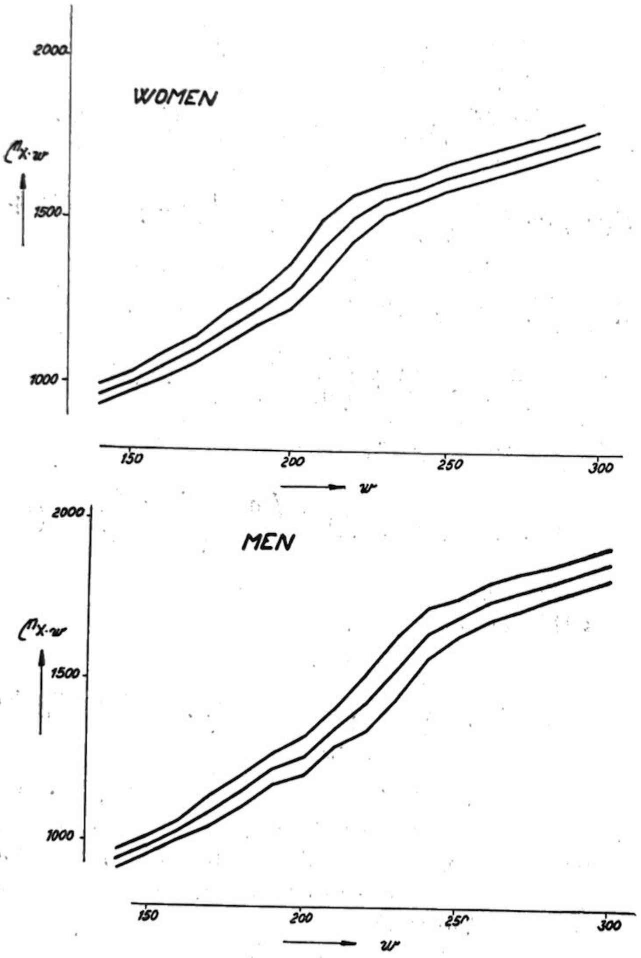
$$= \int_{-\infty}^{\infty} (x - \mu_{X \cdot w_i})^2 \sum_\tau f(x/w_i,t_\tau)\, P(t_\tau/w_i)\, dx$$

and, by interchanging the order of summation and integration,

$$\sigma_{X.w_i} = \sum_{\tau} \Big\{ \int_{-\infty}^{\infty} \big[(x - \mu_{X.w_i}(t_\tau)) + (\mu_{X.w_i}(t_\tau) - \mu_{X.w_i})\big]^2 f(x/w_i, t_\tau)\, dx \Big\} P(t_\tau/w_i) = \sum_{\tau} \sigma_{X.w_i}(t_\tau)\, P(t_\tau/w_i) + \sum_{\tau} (\mu_{X.w_i}(t_\tau) - \mu_{X.w_i})^2 P(t_\tau/w_i) \qquad (16)$$

These results are summarized in Table 4.

In the figure expected values $\mu_{X.w_i}$ of body height $X$ can be found as a function of the observed value $w_i$ of foot length (middle curve). The data on both axes are in mm. Lower and upper curves give the expected body height diminished and increased, respectively, by the value of the residual standard deviation $\sqrt{\sigma_{X.w_i}}$. The knowledge of it enables us to realize the variability of the body height in the subpopulation of the individuals having the given value of foot length (ascertained with the accuracy of 1 cm).




FIGURE

In the figure the expected values $\mu_{X.w_i}$ of body height can be ascertained from the known values $w_i$ of foot length (middle curve). The scales of both axes are denoted in mm. Upper and lower curves delimitate the range of probable variation of body height in the category $w_i$ of foot length ($\pm \sqrt{\sigma_{X.w_i}}$). This prediction concerns the population of subjects older than 4 years, of the given sex.

## RESULTS AND DISCUSSION

In the foregoing part of our paper the problem has been formulated how to predict biometrically the value of an anthropometric dimension from the known value of any other dimension. In further part of the paper the results are analyzed and evaluated.

The body height of the studied group is comparable with the values of this dimension of the boys and girls in Czech countries as observed in 1961— Krátoška et al. (1971). The compared average values differ only little, in all age categories. In 17 years the boys are 172.5 cm high, i.e. 2.3 cm more than in 1961, the girls are 162.2 cm high, i.e. they have the same height as in 1961. Comparison of these results with the averages obtained in the IIIrd Czechoslovak Spartakiade 1965 (Fetter et al., 1967) shows that the men of 18—19 years are 1 cm higher but the men of 20—24 years 0.3 cm lower and, as is generally known, older age categories have still lower average height. As far as the women concern, the situation seems to be similar. The women of 18—19 years (IIIrd Czechoslovak Spartakiade 1965) are 1.3 cm higher and the women older than 35 years are lower when compared with our results.

The investigation of the adult population (age ranging from 18 to 60 years) made by the Garment Research Institute (VÚO) during 1967 found the average body height in ČSSR to be equal 171.7 cm in men and 159.6 cm in women. The men of 18—19 years were 172.9 cm high, the men of 20—24 years were 173.5 cm high; for older age categories the average body height decreases. From all these comparisons the conclusion can be derived that the growth in body height can be taken as essentially completed in 17 years, for both sexes and that the interrelations of length dimensions studied in this age category can be applied for the adult population. This conclusion is supported by the results of Titlbach et al. (1971), too, presenting the average body height 173.6 cm in the age category from 18 to 45 years with the average age 27.2 years. Simultaneously (1968) these dimensions were investigated in German Democratic Republik in the group of the same size and according to the same design. The results were published by Greil et al. (1971). From the following table the similarity of the values of body height and of the growth dynamics can be seen immediately, for both sexes.

The observed values of foot lenght correspond in essence with the results of Šmiřák (1960) and Klementa et al. (1971) (in manuscript). In their groups linear growth of the foot length can be observed in dependence of age; this holds in the range from 7 to 15 years for boys, when the growth completes in essence (in our group one year later). As the girls concerns, Šmiřák derives the completion of the growth of foot length in 14 years (in our group there is remarkable retardation of this growth in the age range from 12 to 16 years). Nevertheless, we agree with the Šmiřák's conclusion that approximately in the middle of puberta the growth of foot length can be taken as completed, for both sexes.

| | Boys | | | | Girls | | | | Differences | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CSSR | | GDR | | CSSR | | GDR | | CSSR–GDR | |
| | Kl-Ko-Krá | | Gr-Vock | | Kl-Ko-Krá | | Gr-Vock | | | |
| | *m* | *S.D.* | *m* | *S.D.* | *m* | *S.D.* | *m* | *S.D.* | boys | girls |
| 4 | 104.7 | 4.7 | 103.5 | 3.8 | 102.9 | 4.4 | 101.3 | 5.7 | 1.2 | 1.6 |
| 5 | 109.4 | 5.8 | 110.7 | 5.0 | 109.8 | 4.8 | 109.4 | 5.2 | –1.3 | 0.4 |
| 6 | 115.7 | 5.5 | 116.1 | 4.7 | 117.2 | 4.7 | 115.1 | 4.2 | –0.4 | 2.1 |
| 7 | 122.7 | 4.8 | 121.6 | 5.4 | 121.5 | 4.9 | 122.2 | 5.9 | 1.1 | –0.7 |
| 8 | 128.4 | 5.5 | 127.2 | 5.7 | 126.9 | 5.7 | 126.1 | 6.2 | 1.2 | 0.8 |
| 9 | 133.6 | 5.6 | 133.5 | 5.9 | 131.5 | 6.0 | 131.4 | 5.6 | 0.0 | 0.1 |
| 10 | 139.1 | 6.6 | 136.6 | 5.8 | 139.4 | 6.1 | 137.2 | 6.4 | 2.5 | 2.2 |
| 11 | 143.6 | 7.0 | 140.9 | 5.4 | 144.1 | 7.4 | 141.2 | 6.6 | 2.7 | 2.9 |
| 12 | 148.1 | 7.7 | 145.9 | 7.2 | 152.4 | 6.3 | 148.3 | 7.0 | 2.2 | 4.1 |
| 13 | 152.0 | 7.7 | 153.9 | 8.1 | 157.1 | 7.0 | 154.6 | 6.2 | –1.9 | 2.5 |
| 14 | 160.7 | 9.2 | 159.6 | 8.5 | 159.2 | 6.0 | 160.0 | 7.0 | 1.1 | –0.8 |
| 15 | 165.4 | 7.1 | 166.5 | 8.0 | 160.7 | 6.2 | 160.2 | 6.9 | –1.1 | 0.5 |
| 16 | 171.5 | 7.3 | 172.1 | 8.3 | 162.1 | 5.2 | 160.8 | 6.0 | –0.6 | 1.3 |
| 17 | 175.2 | 6.1 | 172.0 | 7.4 | 162.2 | 5.9 | 162.2 | 5.9 | 3.2 | 0.0 |

Klementa (1973) concludes that the growth of the foot length completes in 15 years for girls and in 17 years for boys. The foot does not grow later, in essence. When comparing the foot length in both sexes, there are no greater differences in the age categories to the 13 years. Remarkable differences can be found in older age categories (in our group after 14 years, in Šmiřák's group after 15 years): the foot of boys is almost 2 cm longer than the foot of girls. Similar course of the curves of the length of the right and left foot demostrate Suchý et al. (in manuscript), in a group of boys from Prague (age ranging from 6 to 16 years) although authors used plantograms. In the group of Klementa (1973) the differences between boys and girls vary in the range 1.2—1.8 cm. The presented conclusions concerning the tendencies of the foot length growth are supported by Wolanski (1962) in the Polish population and by the results of Gavrilovič et al. (1971) in the Jugoslavian population.

It is of interest to compare the foot length in the age category of the men older than 17 years in our group and the groups of other authors. Our men have the foot length 26.1 cm in average, students of the Middle Industrial School in Břeclav 26.5 cm (Bednář 1952), university students (Medical Faculty) in Prague 26.0 cm (Novotný 1966), students in Olomouc 26.0 cm (left foot) and 26.2 cm (right foot), (Šmiřák 1960), university students (Faculty of Law) in Prague 26.6 cm (right foot), (Titlbach et al. 1971).

Our women have the foot length 24.2 cm, in Šmiřák's group 24.1 cm and in Novotný's group 24.1 cm.

The differences presented can be taken as negligible, which demonstrates the objectivity of the used method and the demographical comparability of the populations of various authors. This makes it possible to evaluate the interrelation of body height and foot lenght not only in younger age categories but also in the population of adult men and women.

The standard statistical characteristics of the body height and foot length are given in Table 1 for both sexes. As is obvious from the column I, we assume the percentage of the whole population be the same in any age category of children. The age category "> 17" years covers up the percentage of the adults in the whole population.

This percentual structure corresponds in main characters to the demographical situation in Czech population.

In further columns II and III average values are given of the body height $X$ and foot length $W$, respectively, in each age category.

Investigating thoroughly the dependence of both dimensions on age, we can see an analogy in the growth of both dimensions, as the boys concerns. The increments of the body height have their first maximum in 7 years, the increments of foot length in the range of 8—10 years. From this point of view there exists a retardation of 2—3 years in the growth of foot length when compared with the body height. The increment maxima are the same in puberta but the values of the foot length seem to demonstrate a completion of the foot growth in 16 years. On the contrary, the body height continues to grow (see Table 5).

With regard to this, the proportion of the foot length to the body height, i.e. the index, varies from the value 15.7 in 4—15 years to the value 14.9 in 17 years. This knowledge enables to conclude that the foot is relatively shorter in men when compared with the boys younger than 15 years. Such a conclusion is supported by the relations of the growth of body height and foot length, summarized in Table 6.

Assuming that in 17 years both dimensions completed their growth, it can be concluded that the growth in foot length precedes the growth in body height. E.g. foot length is relatively greater by 2.2 % in two years, by 4.2 % in four years, by 4.5 % in ten years and by 2.9 % in fifteen years. The data about the children younger than three years originated from the State-wide research in 1962, carried out by VÚO.

When comparing and analyzing the results obtained in the group of girls, the events discussed seem to be more expressive. The curve of increments in foot length corresponds in essence to the curve of increments in body height with the exception that the second incremental maximum can be found already in 10 years, for foot length, and only in 12 years, for body height. The index (ratio of foot length to body height) equals 15.5 in almost all age categories to 11 years and 14.8 — 14.9 in the age categories older than 13 years. It means that for adults the proportion of foot length to body height remains the same in both sexes. That is the reason why we conclude the growth of foot length precedes the growth of body height in girls, too. Such a conclusion can be demonstrated in the table of relations where foot length is relatively greater by 1.6 % in two years, by 3.1 % in four years and by 3.4 % in ten years.

The variability of body height and foot length can be evaluated by means of the auxiliary values in the columns IV—IX of Table 1. The covariances make

TAB. 1

Statistical characteristics of the body dimensions. Age sequences of variances and covariances have been adjusted by the method of moving averages; the averages of three subsequent values have been calculated, on the margins of each sequence the averages of two marginal values

| MEN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $t_\tau$ (years) | I $P(t_\tau)$ | II $\mu x(t_\tau)$ (mm) | III $\mu w(t_\tau)$ (mm) | IV $\sigma xx(t_\tau)$ (mm²) | V $\sigma ww(t_\tau)$ (mm²) | VI $\sigma xw(t_\tau)$ (mm²) | VII $\sigma x.w(t_\tau)$ (mm²) | VIII $\frac{\sigma xw(t_\tau)}{\sigma ww(t_\tau)}$ | IX $\sqrt{\sigma ww(t_\tau)}$ (mm) |
| 4 | 0.018 | 1.047 | 167 | 2.802 | 111 | 464 | 862 | 4.18 | 11 |
| 5 | 0.018 | 1.094 | 173 | 2.869 | 106 | 439 | 1.051 | 4.14 | 10 |
| 6 | 0.018 | 1.157 | 183 | 2.901 | 110 | 433 | 1.197 | 3.94 | 10 |
| 7 | 0.018 | 1.227 | 189 | 2.781 | 118 | 395 | 1.459 | 3.35 | 11 |
| 8 | 0.018 | 1.284 | 199 | 2.842 | 145 | 453 | 1.427 | 3.12 | 12 |
| 9 | 0.018 | 1.336 | 210 | 3.550 | 141 | 490 | 1.847 | 3.48 | 12 |
| 10 | 0.018 | 1.391 | 219 | 4.187 | 169 | 628 | 1.853 | 3.72 | 13 |
| 11 | 0.018 | 1.436 | 224 | 5.084 | 180 | 720 | 2.204 | 4.00 | 13 |
| 12 | 0.018 | 1.481 | 233 | 5.566 | 205 | 814 | 2.334 | 3.97 | 14 |
| 13 | 0.018 | 1.520 | 234 | 6.738 | 228 | 886 | 3.295 | 3.89 | 15 |
| 14 | 0.018 | 1.607 | 250 | 6.467 | 238 | 819 | 3.649 | 3.44 | 15 |
| 15 | 0.018 | 1.754 | 254 | 6,297 | 245 | 770 | 3.877 | 3.14 | 16 |
| 16 | 0.018 | 1.715 | 261 | 4.719 | 198 | 600 | 2.901 | 3.03 | 14 |
| 17 | 0.018 | 1.752 | 261 | 4.547 | 177 | 582 | 2.633 | 3.29 | 13 |
| >17 | 0.748 | 1.752 | 261 | 4.547 | 177 | 582 | 2.633 | 3.29 | 13 |
| **WOMEN** | | | | | | | | | |
| 4 | 0.018 | 1.029 | 161 | 2.115 | 110 | 371 | 864 | 3.37 | 10 |
| 5 | 0.018 | 1.098 | 170 | 2.134 | 106 | 359 | 918 | 3.39 | 10 |
| 6 | 0.018 | 1.172 | 184 | 2.267 | 106 | 357 | 1.065 | 3.37 | 10 |
| 7 | 0.018 | 1.215 | 187 | 2.609 | 126 | 423 | 1.189 | 3.36 | 11 |
| 8 | 0.018 | 1,269 | 197 | 3,080 | 150 | 488 | 1,492 | 3.25 | 12 |
| 9 | 0.018 | 1.315 | 203 | 3.584 | 152 | 528 | 1.750 | 3.47 | 12 |
| 10 | 0.018 | 1.394 | 216 | 4.322 | 173 | 595 | 2.276 | 3.44 | 13 |
| 11 | 0.018 | 1.441 | 223 | 4.442 | 174 | 597 | 2.394 | 3.43 | 13 |
| 12 | 0.018 | 1.524 | 231 | 4.772 | 187 | 642 | 2.568 | 3.43 | 14 |
| 13 | 0.018 | 1.571 | 234 | 4.130 | 169 | 566 | 2.234 | 3.35 | 13 |
| 14 | 0.018 | 1.592 | 236 | 4.091 | 164 | 564 | 2.151 | 3.44 | 13 |
| 15 | 0.018 | 1.607 | 238 | 3.374 | 163 | 484 | 1.949 | 2.96 | 13 |
| 16 | 0.018 | 1.621 | 242 | 3.332 | 142 | 462 | 1.829 | 3.25 | 12 |
| 17 | 0.018 | 1.622 | 242 | 3.080 | 135 | 426 | 1.736 | 3.16 | 12 |
| >17 | 0.748 | 1.622 | 242 | 3.080 | 135 | 426 | 1.736 | 3.16 | 12 |

it possible to compute the correlation coefficients and thus to estimate the interrelation of both dimensions.

The variability of foot length is minimum in 5 and 6 years for boys and in 4,5 and 6 years for girls. That is the reason why body height can be predicted in these age categories most accurately. There are 99 % of all subjects in the range: average ±3 cm. E.g., for boys of 6 years, we have approximately 68 % subjects in the range: 18.3 ± 1.0 cm, 95 % of subjects in the range: 18.3 ± 2.0 cm, and 99 % subjects in the range 18.3 ± 3.0 cm.

In the contrary, variability of foot length is maximum in 15 years for boys and in 12 years for girls. E.g., the foot of a boy of 15 years can be shorter by 3.4 cm when compared with the average value of this age category and thus be the same as a foot of an average boy of 9 years.

Further, the interrelations of foot length and some other body dimensions were investigated. There is a close-fitting relation between foot length and body height. The values of correlation coefficients vary in the range 0.6—0.8 for both sexes (see Table 7), in the followed up age categories. The correlation of foot length with some other length dimensions of lower extremity—lateral and step length—was evaluated. Somewhat narrower relation of these dimensions to the body height was found. These dimensions of applied anthropology are used in garment industry. Correlation between foot length and body weight varies in the range 0.4—0.7. As can be seen, body weight could be predicted from the known foot length, too, though with a lower reliability.

Biometrical model, introduced above, could be utilized for prediction of the expected value of any other body dimension, under the assumption that the values of some other dimension are known.

Table 2 enables us to ascertain the distribution of the probands of the given sex and age category with respect to the values of foot length.

E.g., in the population of boys of 7 years, the foot length is distributed as follows

| | | |
|---|---|---|
| 150 mm 0.1 % | 180 mm 25.7 % | 210 mm 6.5 % |
| 160 mm 1.4 % | 190 mm 35.0 % | 220 mm 0.8 % |
| 170 mm 8.7 % | 200 mm 21.7 % | 230 mm 0.1 % |

As can be seen, approximately 75—80 % of the boys or girls belong to three middle intervals, in each age category (i.e., into the range: average ±1.5 *S.D.*).

In the following table, approximate range of variability in the foot length is estimated

| Age | Range of foot length, mm | | Age | Range of foot length, mm | |
|---|---|---|---|---|---|
| | boys | girls | | boys | girls |
| 4 | 160–180 | 150–170 | 12 | 220–240 | 220–240 |
| 5 | 160–180 | 160–180 | 13 | 220–240 | 220–240 |
| 6 | 170–190 | 170–190 | 14 | 240–260 | 230–250 |
| 7 | 180–200 | 180–200 | 15 | 240–260 | 230–250 |
| 8 | 190–210 | 190–210 | 16 | 250–270 | 230–250 |
| 9 | 200–220 | 190–210 | 17 | 250–270 | 230–250 |
| 10 | 210–230 | 210–230 | 17 | 250–270 | 230–250 |
| 11 | 210–230 | 210–230 | | | |

The percentage of girls is relatively greater in the intervals of the same extent, when compared with boys. This can be explicated by higher homogeneity of the group of girls which is probably in a connection with generally known fact that the growth of body height and proportions is more continuous in girls, in the prepubertal and pubertal periods.

Further, the distribution of probands of the given sex, belonging to the given category of foot length, with respect to age, can be ascertained in Table 3. E.g., age structure of boys with the foot length equal 210 mm is as follows

| Age | % | Age | % | Age | % |
|---|---|---|---|---|---|
| 5 | 0.1 | 9 | 27.1 | 13 | 6.4 |
| 6 | 1.1 | 10 | 19.8 | 14 | 0.7 |
| 7 | 5.4 | 11 | 14.4 | 15 | 0.6 |
| 8 | 18.0 | 12 | 6.4 | 16 | 0.1 |

For each category of foot length, the set of age categories can be given, most frequently occurring in this category of foot length:

| Foot length (mm) | Most frequent age categories | |
|---|---|---|
| | boys | girls |
| 140 | 4 | 4 |
| 150 | 4 and 5 | 4 and 5 |
| 160 | 4 and 5 | 4 and 5 |
| 170 | 4,5 and 6 | 4, 5 and 6 |
| 180 | 5, 6 and 7 | 5, 6 and 7 |
| 190 | 6, 7 and 8 | 6, 7 and 8 |
| 200 | 7, 8 and 9 | 7, 8 and 9 |
| 210 | 8, 9, 10 and 11 | 9, 10 and > 17 |
| 220 | 9, 10, 11, 12 and 13 | > 17 |
| 230 | 11, 12, 13 and > 17 | > 17 |
| 240 | > 17 | > 17 |

Such an interpretation can be accepted for the age categories from 4 to 17 years. Nevertheless it cannot be taken as valid absolutely for some marginal age categories. The proportion of 4—, 5—, and 6-aged in some dimension categories is overestimated since there are no values for the younger probands in our group. On the other hand, the age category "> 17" is more wider in comparison with the others. An unbiased distribution of age can be found in the interval of foot length of 210 mm for boys and of 190 mm for girls.

Resulting solution of the problem making possible to predict the expected value of body height from the known value of foot length is summarized in Table 4 and demonstrated in the figure. By means of the tabulated values body height can be predicted in each age category from 4 to 17 eyars as well as in the category of adults. The values concerning adults (17 > years) are to be considered as most important in practice, together with the values in the last column, valid for the integral populatin covering all age categories. The values of body height are accompanied by the corresponding variances. The predicted values of body height in the age category of older than 17 years approach the more to the values in the integral population, the greateris the percentage of adults having the given foot length.

Klen (1949) proposed the following formula for prediction of body height:

body height = foot length × coefficient (dependent on age). These coefficients have been overtaken from the paper of Bertillon (without being cited by Klen).

Further, the results of Titlbach et al. (1971) can be compared with ours. These authors studied a group of adult men. For this reason, their results may be compared with our subpopulation of men older than 17 years On this place it must be noted that in practice the age of the subject who left the trace is not known, in most cases.

By means of average values in Table 4 we calculated the so-called "reconstruction" coefficients and compared them in the following table with the values of Titlbach, Bertillon and H. de Parville presented by Titlbach et al. (1971).

| Foot length (cm) | "Reconstruction" coefficients, men | | | | |
|---|---|---|---|---|---|
| | Bertillon (1889) | de Parville (1889) | Titlbach et al. (1971) | Kl-Ko-Krá adult men (>17) | Kl-Ko-Krá integral population, men |
| 22.0 | 6.840 | 7.0 | — | 7.35 | 6.51 |
| 23.0 | 6.610 | 7.0 | — | 7.17 | 6.71 |
| 24.0 | 6.505 | 7.0 | 6.90 | 7.01 | 6.87 |
| 25.0 | 6.407 | 7.0 | 6.74 | 6.86 | 6.82 |
| 26.0 | 6.328 | 7.0 | 6.59 | 6.73 | 6.72 |
| 27.0 | 6.254 | 7.0 | 6.48 | 6.60 | 6.59 |
| 28.0 | 6.120 | 7.0 | 6.39 | 6.48 | 6.48 |
| 29.0 | 6.080 | 7.0 | 6.34 | 6.37 | 6.37 |
| 30.0 | — | 7.0 | 6.34 | 6.27 | 6.27 |

We can agree with the conclusions of Titlbach et al. (1971) that the "reconstruction" coefficients of Bertillon and H. de Parville differ too much

TAB. 2

Probability distribution $P(w_i/t_r)$ of the foot length $W$ in individual age categories $t_r$. The calculations have been carried out as given in (6); the necessary characteristics were overtaken from Table 1. The values $w_i$ of foot length were given in mm. The probabilities were rounded off to one thousandth; lower values were not given here

| $t_r$ (years) | $w_i$ 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MEN** | | | | | | | | | | | | | | | | | |
| 4 | 0.021 | 0.115 | 0.291 | 0.338 | 0.183 | 0.045 | 0.005 | | | | | | | | | | |
| 5 | 0.003 | 0.033 | 0.176 | 0.367 | 0.306 | 0.101 | 0.013 | 0.001 | | | | | | | | | |
| 6 | | 0.003 | 0.033 | 0.176 | 0.367 | 0.306 | 0.101 | 0.013 | 0.001 | | | | | | | | |
| 7 | | 0.001 | 0.014 | 0.087 | 0.257 | 0.350 | 0.217 | 0.065 | 0.008 | 0.001 | | | | | | | |
| 8 | | | 0.002 | 0.021 | 0.098 | 0.250 | 0.321 | 0.217 | 0.077 | 0.014 | 0.001 | | | | | | |
| 9 | | | | 0.002 | 0.017 | 0.087 | 0.231 | 0.326 | 0.231 | 0.087 | 0.017 | 0.002 | | | | | |
| 10 | | | | | 0.004 | 0.028 | 0.108 | 0.238 | 0.299 | 0.212 | 0.088 | 0.020 | 0.003 | | | | |
| 11 | | | | | 0.001 | 0.012 | 0.059 | 0.173 | 0.287 | 0.270 | 0.144 | 0.045 | 0.008 | 0.001 | | | |
| 12 | | | | | | 0.003 | 0.020 | 0.077 | 0.184 | 0.276 | 0.245 | 0.137 | 0.047 | 0.010 | 0.001 | | |
| 13 | | | | | | 0.004 | 0.022 | 0.077 | 0.170 | 0.254 | 0.242 | 0.149 | 0.062 | 0.016 | 0.003 | | |
| 14 | | | | | | | 0.001 | 0.009 | 0.037 | 0.112 | 0.212 | 0.258 | 0.212 | 0.112 | 0.037 | 0.009 | 0.001 |
| 15 | | | | | | | 0.001 | 0.007 | 0.027 | 0.084 | 0.169 | 0.240 | 0.227 | 0.152 | 0.067 | 0.021 | 0.004 |
| 16 | | | | | | | | 0.001 | 0.004 | 0.023 | 0.084 | 0.198 | 0.274 | 0.238 | 0.129 | 0.041 | 0.008 |
| 17 | | | | | | | | | 0.003 | 0.020 | 0.086 | 0.214 | 0.299 | 0.238 | 0.107 | 0.028 | 0.005 |
| > 17 | | | | | | | | | 0.003 | 0.020 | 0.086 | 0.214 | 0.299 | 0.238 | 0.107 | 0.028 | 0.005 |
| **WOMEN** | | | | | | | | | | | | | | | | | |
| 4 | 0.050 | 0.219 | 0.381 | 0.264 | 0.073 | 0.008 | | | | | | | | | | | |
| 5 | 0.006 | 0.061 | 0.242 | 0.382 | 0.242 | 0.061 | 0.006 | | | | | | | | | | |
| 6 | | 0.002 | 0.027 | 0.155 | 0.356 | 0.324 | 0.118 | 0.017 | 0.001 | | | | | | | | |
| 7 | | 0.002 | 0.021 | 0.115 | 0.291 | 0.338 | 0.183 | 0.045 | 0.005 | | | | | | | | |
| 8 | | | 0.004 | 0.030 | 0.125 | 0.274 | 0.316 | 0.184 | 0.057 | 0.009 | 0.001 | | | | | | |
| 9 | | | 0.001 | 0.009 | 0.057 | 0.184 | 0.316 | 0.274 | 0.125 | 0.030 | 0.004 | | | | | | |
| 10 | | | | 0.001 | 0.008 | 0.044 | 0.145 | 0.270 | 0.287 | 0.173 | 0.059 | 0.012 | 0.001 | | | | |
| 11 | | | | | 0.002 | 0.014 | 0.068 | 0.184 | 0.292 | 0.261 | 0.133 | 0.039 | 0.006 | 0.001 | | | |
| 12 | | | | | 0.001 | 0.004 | 0.026 | 0.096 | 0.207 | 0.280 | 0.227 | 0.115 | 0.036 | 0.007 | 0.001 | | |
| 13 | | | | | | 0.001 | 0.012 | 0.059 | 0.173 | 0.287 | 0.270 | 0.145 | 0.044 | 0.008 | 0.001 | | |
| 14 | | | | | | 0.001 | 0.008 | 0.044 | 0.145 | 0.270 | 0.287 | 0.173 | 0.059 | 0.012 | 0.001 | | |
| 15 | | | | | | | 0.006 | 0.032 | 0.121 | 0.250 | 0.296 | 0.200 | 0.076 | 0.017 | 0.002 | | |
| 16 | | | | | | | 0.001 | 0.011 | 0.066 | 0.203 | 0.318 | 0.261 | 0.113 | 0.024 | 0.003 | | |
| 17 | | | | | | | 0.001 | 0.011 | 0.066 | 0.203 | 0.318 | 0.261 | 0.113 | 0.024 | 0.003 | | |
| > 17 | | | | | | | 0.001 | 0.011 | 0.066 | 0.203 | 0.318 | 0.261 | 0.113 | 0.024 | 0.003 | | |

TAB. 3

Age structure (distribution) $P(t_\tau/w_t)$ in individual categories $w_t$ of the foot length $W$. The calculations have been carried out as given in (7); $\Delta_W = 5$ mm. Calculated values were rounded off according the same rule as in Table 2

| $t_\tau$ (years) | $w_t$ 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MEN** | | | | | | | | | | | | | | | | | |
| 4 | 0.875 | 0.757 | 0.564 | 0.341 | 0.148 | 0.038 | 0.005 | | | | | | | | | | |
| 5 | 0.125 | 0.217 | 0.341 | 0.370 | 0.248 | 0.085 | 0.012 | 0.001 | | | | | | | | | |
| 6 | | 0.020 | 0.064 | 0.178 | 0.298 | 0.258 | 0.092 | 0.011 | 0.001 | | | | | | | | |
| 7 | | 0.007 | 0.027 | 0.088 | 0.208 | 0.295 | 0.197 | 0.054 | 0.006 | | | | | | | | |
| 8 | | | 0.004 | 0.021 | 0.079 | 0.211 | 0.292 | 0.180 | 0.053 | 0.006 | | | | | | | |
| 9 | | | | 0.002 | 0.014 | 0.073 | 0.210 | 0.271 | 0.159 | 0.040 | 0.003 | | | | | | |
| 10 | | | | | 0.003 | 0.024 | 0.098 | 0.198 | 0.206 | 0.097 | 0.018 | 0.002 | | | | | |
| 11 | | | | | 0.001 | 0.010 | 0.054 | 0.144 | 0.197 | 0.124 | 0.030 | 0.004 | 0.001 | | | | |
| 12 | | | | | | 0.003 | 0.018 | 0.064 | 0.127 | 0.126 | 0.050 | 0.013 | 0.003 | 0.001 | | | |
| 13 | | | | | | 0.003 | 0.001 | 0.064 | 0.117 | 0.116 | 0.050 | 0.015 | 0.005 | 0.002 | 0.001 | | |
| 14 | | | | | | | 0.001 | 0.007 | 0.025 | 0.051 | 0.044 | 0.025 | 0.016 | 0.011 | 0.008 | 0.007 | 0.004 |
| 15 | | | | | | | | 0.006 | 0.019 | 0.038 | 0.035 | 0.024 | 0.017 | 0.014 | 0.014 | 0.017 | 0.018 |
| 16 | | | | | | | | 0.001 | 0.003 | 0.011 | 0.017 | 0.019 | 0.020 | 0.022 | 0.027 | 0.032 | 0.035 |
| 17 | | | | | | | | | 0.002 | 0.009 | 0.018 | 0.021 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 |
| > 17 | | | | | | | | | 0.086 | 0.381 | 0.735 | 0.876 | 0.917 | 0.928 | 0.928 | 0.922 | 0.920 |
| **WOMEN** | | | | | | | | | | | | | | | | | |
| 4 | 0.893 | 0.771 | 0.564 | 0.276 | 0.063 | 0.006 | | | | | | | | | | | |
| 5 | 0.107 | 0.215 | 0.358 | 0.400 | 0.210 | 0.049 | 0.005 | | | | | | | | | | |
| 6 | | 0.007 | 0.040 | 0.162 | 0.308 | 0.259 | 0.095 | 0.010 | | | | | | | | | |
| 7 | | 0.007 | 0.031 | 0.120 | 0.252 | 0.270 | 0.147 | 0.027 | 0.001 | | | | | | | | |
| 8 | | | 0.006 | 0.031 | 0.108 | 0.219 | 0.253 | 0.109 | 0.013 | 0.001 | | | | | | | |
| 9 | | | 0.001 | 0.009 | 0.049 | 0.147 | 0.253 | 0.163 | 0.029 | 0.003 | | | | | | | |
| 10 | | | | 0.001 | 0.007 | 0.035 | 0.116 | 0.160 | 0.067 | 0.017 | 0.004 | 0.001 | | | | | |
| 11 | | | | | 0.002 | 0.011 | 0.055 | 0.109 | 0.068 | 0.025 | 0.009 | 0.003 | 0.001 | 0.001 | | | |
| 12 | | | | | 0.001 | 0.003 | 0.021 | 0.057 | 0.048 | 0.027 | 0.015 | 0.010 | 0.007 | 0.006 | 0.007 | | |
| 13 | | | | | | 0.001 | 0.010 | 0.035 | 0.040 | 0.028 | 0.018 | 0.012 | 0.009 | 0.007 | 0.007 | | |
| 14 | | | | | | | 0.006 | 0.026 | 0.034 | 0.026 | 0.019 | 0.014 | 0.011 | 0.011 | 0.007 | | |
| 15 | | | | | | | 0.005 | 0.019 | 0.028 | 0.024 | 0.020 | 0.017 | 0.015 | 0.016 | 0.015 | | |
| 16 | | | | | | | 0.001 | 0.007 | 0.015 | 0.020 | 0.021 | 0.022 | 0.022 | 0.022 | 0.022 | | |
| 17 | | | | | | | 0.001 | 0.007 | 0.015 | 0.020 | 0.021 | 0.022 | 0.022 | 0.022 | 0.022 | | |
| > 17 | | | | | | | 0.033 | 0.271 | 0.640 | 0.811 | 0.874 | 0.900 | 0.913 | 0.915 | 0.919 | 0.978 | 0.978 |

TAB. 4

Expected values $\mu_{X \, . \, w_i}(t_\tau)$ of body height in individual age categories $t_\tau$ and categories $w_i$ of foot length. The calculations have been carried out as given in (13). The variances $\sigma_{X \, . \, w_i}(t_\tau)$ in the last column have been calculated as given in (15). In the last rows of the table there are the expected values $\mu_{X . w_i}$, variances $\sigma_{X . w_i}$ and standard deviations $\sqrt{\sigma_{X . w_i}}$ of body height in the categories $w_i$ of foot length, calculated with regard to (14) and (16)

MEN

| $t_\tau$ (years) | $w_i$ 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 | 300 | $\sigma_{X . w_i}(t_\tau)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 934 | 976 | 1.018 | 1.060 | 1.101 | 1.143 | 1.185 | | | | | | | | | | | 1.008 |
| 5 | 957 | 999 | 1.040 | 1.082 | 1.123 | 1.164 | 1.206 | 1.247 | | | | | | | | | | 1.194 |
| 6 | | 1.027 | 1.066 | 1.106 | 1.145 | 1.185 | 1.224 | 1.263 | 1.303 | | | | | | | | | 1.326 |
| 7 | | 1.096 | 1.130 | 1.163 | 1,197 | 1.230 | 1.264 | 1.297 | 1.331 | 1.364 | | | | | | | | 1.552 |
| 8 | | | 1.162 | 1.194 | 1.225 | 1.256 | 1.287 | 1.318 | 1.350 | 1.381 | 1.412 | | | | | | | 1.508 |
| 9 | | | | 1.197 | 1.232 | 1.266 | 1.301 | 1.336 | 1.371 | 1.406 | 1.440 | | | | | | | 1.948 |
| 10 | | | | | 1.246 | 1.283 | 1.320 | 1.358 | 1.395 | 1.432 | 1.469 | 1.506 | | | | | | 1.968 |
| 11 | | | | | 1.260 | 1.300 | 1.340 | 1.380 | 1.420 | 1.460 | 1.500 | 1.540 | 1.580 | | | | | 2.337 |
| 12 | | | | | | 1.310 | 1.350 | 1.390 | 1.429 | 1,469 | 1.509 | 1.548 | 1.588 | 1.628 | | | | 2.465 |
| 13 | | | | | | 1.349 | 1.388 | 1.427 | 1.466 | 1.504 | 1.543 | 1.582 | 1.621 | 1.660 | 1.699 | | | 3.421 |
| 14 | | | | | | | 1.435 | 1.469 | 1.504 | 1.538 | 1.573 | 1.607 | 1.641 | 1.676 | 1.710 | 1.745 | 1.779 | 3.748 |
| 15 | | | | | | | | 1.516 | 1.547 | 1.579 | 1.610 | 1.641 | 1.673 | 1.704 | 1.736 | 1.767 | 1.798 | 3.959 |
| 16 | | | | | | | | 1.560 | 1.591 | 1.621 | 1.651 | 1.682 | 1.712 | 1.742 | 1.773 | 1.803 | 1.833 | 2.977 |
| 17 | | | | | | | | | 1.617 | 1.650 | 1.683 | 1.716 | 1.749 | 1.782 | 1.815 | 1.847 | 1.880 | 2.723 |
| > 17 | | | | | | | | | 1.617 | 1.650 | 1.683 | 1.716 | 1.749 | 1.782 | 1.815 | 1.847 | 1.880 | 2.723 |
| $\mu_{X . w_i}$ | 937 | 984 | 1.032 | 1.088 | 1.151 | 1.220 | 1.260 | 1.353 | 1.433 | 1.544 | 1.439 | 1.704 | 1.746 | 1.778 | 1.812 | 1.844 | 1.875 | |
| $\sigma_{X . w_i}$ | 1.089 | 1.195 | 1.108 | 2.287 | 2.897 | 2.987 | 3.310 | 3.468 | 7.340 | 11.114 | 6.910 | 3.979 | 3.250 | 3.043 | 2.983 | 2.991 | 2.984 | |
| $\sqrt{\sigma_{X . w_i}}$ | 33 | 35 | 33 | 48 | 54 | 55 | 58 | 58 | 86 | 105 | 83 | 63 | 57 | 55 | 55 | 55 | 55 | |

WOMEN

| $t_\tau$ (years) | $w_i$ 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 | 300 | $\sigma_{X . w_i}(t_\tau)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 958 | 992 | 1.026 | 1.059 | 1.093 | 1.127 | | | | | | | | | | | | 959 |
| 5 | 996 | 1.030 | 1.064 | 1.098 | 1.132 | 1.166 | 1.200 | | | | | | | | | | | 1.014 |
| 6 | | 1.057 | 1.091 | 1.125 | 1.159 | 1.192 | 1.226 | 1.260 | 1.293 | | | | | | | | | 1.160 |
| 7 | | 1.091 | 1.124 | 1.158 | 1.191 | 1.225 | 1.259 | 1.292 | 1.326 | | | | | | | | | 1.283 |
| 8 | | | 1.149 | 1.181 | 1.214 | 1.246 | 1.279 | 1.311 | 1.344 | 1.376 | | | | | | | | 1.580 |
| 9 | | | 1.166 | 1.200 | 1.235 | 1.270 | 1.305 | 1.339 | 1.374 | 1.409 | | | | | | | | 1.850 |
| 10 | | | | 1.236 | 1.270 | 1.305 | 1.339 | 1.373 | 1.408 | 1.442 | 1.477 | 1.511 | | | | | | 2.375 |
| 11 | | | | | 1.294 | 1.328 | 1.362 | 1.396 | 1.431 | 1.465 | 1.499 | 1.534 | 1.568 | 1.602 | | | | 2.492 |
| 12 | | | | | 1.349 | 1.383 | 1.418 | 1.452 | 1.486 | 1.521 | 1.555 | 1.589 | 1.623 | 1.658 | 1.692 | | | 2.666 |
| 13 | | | | | | 1.424 | 1.457 | 1.491 | 1.524 | 1.558 | 1.591 | 1.625 | 1.658 | 1.692 | 1.725 | | | 2.327 |
| 14 | | | | | | | 1.468 | 1.503 | 1.537 | 1.571 | 1.606 | 1.640 | 1.675 | 1.709 | 1.743 | | | 2.250 |
| 15 | | | | | | | 1.495 | 1.524 | 1.554 | 1.583 | 1.613 | 1.643 | 1.672 | 1.702 | 1.731 | | | 2.022 |
| 16 | | | | | | | 1.485 | 1.517 | 1.550 | 1.582 | 1.615 | 1.647 | 1.680 | 1.712 | 1.745 | | | 1.917 |
| 17 | | | | | | | 1.489 | 1.521 | 1.552 | 1.584 | 1.616 | 1.647 | 1.679 | 1.710 | 1.742 | 1.774 | 1.805 | 1.819 |
| > 17 | | | | | | | 1.489 | 1.521 | 1.552 | 1.584 | 1.616 | 1.647 | 1.679 | 1.710 | 1.742 | 1.774 | 1.805 | 1.819 |
| $\mu_{X . w_i}$ | 962 | 1.001 | 1.046 | 1.101 | 1.168 | 1.229 | 1.304 | 1.417 | 1.518 | 1.578 | 1.614 | 1.647 | 1.678 | 1.709 | 1.739 | 1.774 | 1.805 | |
| $\sigma_{X . w_i}$ | 1.103 | 1.296 | 1.691 | 2.359 | 2.610 | 2.786 | 5.213 | 9.012 | 5.207 | 2.795 | 2.126 | 1.947 | 1.879 | 1.869 | 1.862 | 1.819 | 1.819 | |
| $\sqrt{\sigma_{X . w_i}}$ | 33 | 36 | 41 | 49 | 51 | 53 | 72 | 94 | 72 | 53 | 46 | 44 | 43 | 43 | 43 | 43 | 43 | |

temporally and ethnically. The coefficients of Titlbach and ours are very similar although they were derived in the subpopulations distinct in age and origin.

The coefficients of both sets are most similar for higher values of foot length. They are most reliable in the application for our population and thus can be used for criminalistical practice. Existing non important discrepancies can be explicated by the differences in both sets of probands. Our set covers also younger age categories, the set of Titlbach covers men over 25 years. In applying our method in practice the results of Titlbach concerning the differences between the trace of the naked and the clothed foot can be utilized.

The size of 10 mm intervals for foot length in Tables 2, 3 and 4 is considered as suitable in practice. Body height could be evaluated also from other values of foot length, if necessary, by means of linear interpolation or by direct computation.

Practical aid for ascertaining the body height from the known foot length is Table 4. Besides this, rapid approximative information about the expected body height and its variability can be derived by means of the figure.

In Table 4, body height can be ascertained under the assumption that the subject, the trace of which has been found, is older than 4 years and that his sex is known.

The values, summarized in Table 4 have been calculated under the given assumptions according to the formula (14). The way how body height may be found in this table is as follows:

Let us suppose that from the trace found the male sex of the subject and the length 25 cm of his foot are ascertainable. At the bottom of the upper part of Table 4 the expected value of body height equal

TAB. 5

**Absolute and relative increments of body height and foot length and the proportion index of them**

| Age | BOYS | | | | | GIRLS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Increments of | | | | Index [1]) | Increments of | | | | Index [1]) |
| | body height | | foot length | | | body height | | foot length | | |
| | absol. | rel. | absol. | rel. | | absol. | rel. | absol | rel. | |
| 4 | — | — | — | — | 15.9 | — | — | — | — | 15.7 |
| 5 | 4.7 | 4.5 | 0.6 | 3.6 | 15.8 | 6.9 | 6.7 | 0.9 | 5.6 | 15.5 |
| 6 | 6.3 | 5.8 | 1.0 | 5.8 | 15.8 | 7.4 | 6.7 | 1.4 | 8.2 | 15.7 |
| 7 | 7.0 | 6.0 | 0.6 | 3.3 | 15.4 | 4.3 | 3.7 | 0.3 | 1.6 | 15.4 |
| 8 | 5.7 | 4.6 | 1.0 | 5.3 | 15.5 | 5.4 | 4.4 | 1.0 | 5.3 | 15.5 |
| 9 | 5.2 | 4.0 | 1.1 | 5.5 | 15.7 | 4.6 | 3.6 | 0.6 | 3.0 | 15.5 |
| 10 | 5.5 | 4.1 | 0.9 | 4.3 | 15.7 | 7.9 | 6.1 | 1.3 | 6.4 | 15.5 |
| 11 | 4.5 | 3.2 | 0.5 | 2.3 | 15.6 | 4.7 | 3.4 | 0.7 | 3.2 | 15.5 |
| 12 | 4.5 | 3.1 | 0.9 | 4.0 | 15.7 | 8.3 | 5.8 | 0.8 | 3.6 | 15.2 |
| 13 | 3.9 | 2.6 | 0.1 | 0.4 | 15.4 | 4.7 | 3.1 | 0.3 | 1.3 | 14.9 |
| 14 | 8.7 | 5.7 | 1.6 | 6.8 | 15.6 | 1.9 | 1.3 | 0.2 | 0.9 | 14.8 |
| 15 | 4.7 | 2.9 | 0.4 | 1.6 | 15.4 | 1.5 | 0.9 | 0.2 | 0.8 | 14.8 |
| 16 | 6.1 | 3.7 | 0.7 | 2.8 | 15.2 | 1.4 | 0.9 | 0.4 | 1.7 | 14.9 |
| 17 | 3.7 | 2.1 | 0.0 | 0.0 | 14.9 | 0.1 | 0.0 | 0.0 | 0.0 | 14.9 |

Index[1]) $= \frac{\text{foot length . 100}}{\text{body height}}$

1,705 mm can be found, in the column $w_t = 250$ mm. Besides this, the last but one row of this part of the table makes it possible to evaluate the variance, which equals 3,979 mm$^2$. From this standard deviation can be derived having 63 mm. Thus, we can conclude that the probable body height of our subject varies in the range from 1,641 mm to 1,767 mm.

If there is information about the age of the unknown subject, too, the expected value of body height can be ascertained in the upper half of Table 4, in the respective row. E.g., if it is known that the trace belongs to a boy of 12 years having the foot length of 250 mm, the expected body height can be found in the row "12" and the column "250". It equals 1,548 mm. Besides this, the variance of 2,465 mm$^2$ can be found in the last but one column of this half of the table. Standard deviation equals 50 mm.

As was to be expected, completion of the initial information by the knowledge of the age makes an estimate of the body height more precise. That is the way, in which the decrease of the variance can be interpreted.

By the same way, the expected value of body height can be ascertained from the known value of foot length, in the lower half of Table 4, if it is known the sex of the subject to be female.

In the figure, the expected value of body height (on the vertical axis) can be found for the known value of foot length (denoted on the horizontal axis); the range of probable variation is expressed by the strip.

The results of studying the interrelations existing between foot length and body height can be summarized as follows:

a) Growth rate of foot length decreases absolutely and relatively for boys and girls in the period of 6—7 years. Its maximum intensity is observable in the period of 7—10 years (relative increments equal approximately 5 %). There is a decrease in the period of 10—11 years in boys. A new increase of the growth appears again in the period of 11—14 years reaching its maximum in 14 years (absolute increments equal 1.6 cm, i.e 6.8 % relatively). No increments were observed in the period of 16—17 years. As far as the girls is concerned, the increment is maximum in 10 years (1.3 cm absolutely, i.e. 6.4 % relatively); growth proceeds significantly in the period of 10—12 years (about 3.5 %). After this, the increments stabilize themselves and vary further about 0.2—0.4 cm per year, to 16 years.

In the contrary, body height grows more intensively to the age of 7 years (about 6 %) and then the increments decrease slowly to the age of 13 years. This growth reaches its pubertal maximum (5.7 %) in coincidence with the increments of foot length. In the following period to 17 years the increment are significantly higher when compared with the foot length; the growth of this last dimension is already completed in this period. In girls, the curve of the body height increments resambles the respective curve of the foot length, with the exception that the decrease in the growth rate of foot length appears two years sooner (approximately in 14 years). We want to underline that this completion of the growth

TAB. 6

Age changes in body height and foot length

| Age | Body height (length*) cm | Foot length cm | Body height % | Foot length % | Body height % | Foot length % | Ratio of averages: foot length to body height |
|---|---|---|---|---|---|---|---|
| | **BOYS** | | | | | | |
| months: | | | | | | | |
| 3 | 57.3* | 8.4 | — | — | — | — | 14.7 |
| 12 | 74.5* | 11.2 | — | — | — | — | 15.0 |
| 24 | 84.1 | 13.1 | 48.0 | 50.2 | 100.0 | 100.0 | 15.6 |
| years: | | | | | | | |
| 4 | 104.7 | 16.7 | 59.8 | 64.0 | 124.5 | 127.5 | 16.0 |
| 10 | 139.1 | 21.9 | 79.4 | 83.9 | 165.4 | 167.2 | 15.7 |
| 15 | 165.4 | 25.4 | 94.4 | 97.3 | 196.7 | 193.9 | 15.4 |
| 17 | 175.2 | 26.1 | 100.0 | 100.0 | 208.3 | 199.2 | 14.9 |
| | **GIRLS** | | | | | | |
| months: | | | | | | | |
| 3 | 56.0* | 8.5 | — | — | — | — | 15.2 |
| 12 | 72.7* | 10.9 | — | — | — | — | 15.0 |
| 24 | 83.2 | 12.8 | 51.3 | 52.9 | 100.0 | 100.0 | 15.4 |
| years: | | | | | | | |
| 4 | 102.9 | 16.1 | 63.4 | 66.5 | 123.7 | 125.8 | 15.6 |
| 10 | 139.4 | 21.6 | 85.9 | 89.3 | 167.5 | 168.8 | 15.5 |
| 15 | 160.7 | 23.8 | 99.1 | 98.3 | 193.1 | 185.9 | 14.8 |
| 17 | 162.2 | 24.2 | 100.0 | 100.0 | 195.0 | 189.1 | 14.9 |

of foot length precedes the respective completion of the growth of body height by 2 years, in boys and girls.

b) The ratio of foot length to body height (proportion index) varies about 15.7 % for boys in the period of 4—14 years, and then decreases subsequently to the value 14.9 % for boys at the age 17. This index varies about 15.5 % for girls from 4 to 11 years, then decreases relatively rapidly and stabilizes on the value 14.9 % (the same as in boys) for girls older than 14 years. It is remarkable that the proportion of foot length to body height remains the same in both sexes, for adults.

c) Variability of foot length is higher to a certain degree in boys when compared with girls. It reaches its maximum at 13—15 years for boys and at 10—15 years for girls. Coefficients of variation are higher in foot length in comparison with body height, for both sexes.

d) The correlation of foot length and body height is relatively high, reaching the values 0.6—0.8, for both sexes. The correlation of foot length and body weight is lower, varying in the range 0.4—0.7. During the pubertal period both dimensions correlate less closely with foot lenght.

e) In the integral population (covering all age categories older than 4 years) when predicting body height from the known value of foot length three regions of foot length can be evaluated separately, for both sexes:

TAB. 7

Correlation coefficients between foot length and body height (or body weight)

| Age | BOYS | | GIRLS | |
|---|---|---|---|---|
| | Foot length to | | Foot length to | |
| | body height | body weight | body height | body weight |
| 4 | 0.82 | 0.70 | 0.79 | 0.60 |
| 5 | 0.86 | 0.77 | 0.75 | 0.68 |
| 6 | 0.73 | 0.58 | 0.73 | 0.71 |
| 7 | 0.72 | 0.67 | 0.71 | 0.61 |
| 8 | 0.64 | 0.57 | 0.76 | 0.70 |
| 9 | 0.75 | 0.65 | 0.69 | 0.45 |
| 10 | 0.70 | 0.67 | 0.71 | 0.55 |
| 11 | 0.80 | 0.68 | 0.70 | 0.75 |
| 12 | 0.75 | 0.61 | 0.66 | 0.51 |
| 13 | 0.74 | 0.47 | 0.71 | 0.65 |
| 14 | 0.67 | 0.65 | 0.67 | 0.50 |
| 15 | 0.57 | 0.41 | 0.69 | 0.42 |
| 16 | 0.60 | 0.52 | 0.57 | 0.45 |
| 17 | 0.72 | 0.52 | 0.75 | 0.63 |

In men:

1. The region 14.0—19.0 cm of foot length, where body height grows slowly, with the rate of about 5 cm per 1 cm of foot length.

2. The region 20.0—24.0 cm of foot length, where body height grows most rapidly, with the rate of about 10 cm per 1 cm of foot length.

3. The region 25.0—30.0 cm of foot length, where body height grows slowly, with the rate of about 3—4 cm per 1 cm of foot length.

These three regions are approximately the same for women, with the exception that the decrease in growth of body height (3rd region) appears at lower value of foot length, for women.

f) In practice, body height can be ascertained from the known value of foot length by means of

— Table 4, if sex of the tested subject is known or both sex and age

— the figure, if sex of the tested subject is known.

SUMMARY

Authors present biometrical method for predicting the expected value of a body dimension when the value of some other body dimension is known. This method can be utilized frequently when ergonomical problems are to be solved in designing industrial products.

In the paper general principles of the solution were applied in a situation when body height is to be predicted from the known value of foot length. The tables and figure make it possible, for Czech population of the subjects older than 4 years.

The solution of the problem is important not only theoretically; it may be interesting in criminalistical identification. As a part of this solution, accuracy of the prediction can be evaluated.

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