საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 18, №1, 2024
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 18, no. 1, 2024

Biomechanics

Pedographic Studies of Foot Deformities in Children with Cerebral Palsy and Establishment of the Analytical Relationship between the Foot Support Area and Peak Pressure

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This paper presents pedographic studies of foot deformities in children with cerebral palsy (CP) in order to choose orthotic materials for individual orthopedic insoles. As a result of the pedographic examination of the foot of a patient with CP, there have been established peak pressure areas in the plantar part of the foot and the sizes of the contact area with the supporting surface of the foot. Based on the use of mathematical research method, an analytical relationship between the foot supporting area and the peak pressure on the plantar part of the foot has been determined. This is a necessary condition in the process of choosing the right materials for individual orthopedic insoles. Research in this field is especially crucial when it comes to the health issues of the patients with CP.

orthopedic insoles, cerebral palsy, pedograph method

Cerebral palsy (CP) in children develops as a result of irreversible damage to the brain which is associated with disturbances in body posture and movements of patients. Pathological changes in muscle tone of the lower extremities in children with CP develop against the background of muscular dystonia; perinatal damage may be present to varying degrees. This is directly related to the motor disorders of the patient with CP and the limitation of activities. It is of crucial importance to define the type and severity of CP an individual has. Treatment options can include the use of therapeutic, pharmaceutical, orthopaedic, and assistive means. The approach is individual and includes the development of effective combinations of therapeutic, rehabilitation and orthopedic interventions. A timely and targeted intervention helps to partially prevent deformities and contractures of the muscles, tendons, and bones [1-6].

The national clinical practice guidelines of Georgia report that individual orthotics of patients is crucial in the process of treating cerebral palsy, which has a high degree of recommendation. Early orthosis and adjusting the size of the orthosis depending on the age of a child is of great importance. The orthosis is becoming a major component of daily life for a large number of children with CP and determines the quality of their mental and social comfort. Individual orthosis made using innovative technologies with an integrated individual orthopedic insole ensures the correction of congenital pathologies and prevention of orthopedic complications in children with CP. Insoles should be manufactured taking into account the over-pressure areas of the foot, made from a combination of materials with different degrees of hardness. The combination of insole materials is designed to increase the contact area between the deformed foot and insole, which additionally reduces the balance deficit and the patient can feel more comfortable. The combined effect of an orthosis and an insole on the patient's foot will qualitatively improve both movement dynamics and proprioception, i.e., the sense of maintaining posture and balance [7-12].

The goal of the present work is to determine the analytical relationship between the peak pressure on the plantar side of the foot and the supporting area of the foot for choosing the right materials for individual orthopedic insoles. To select materials, a pedographic study of the feet of children with CP is necessary. Based on the processing of the results obtained by means of experiment, an analytical relationship will be established between the supporting area of the foot and peak pressure on the plantar side of the foot. In the process of choosing materials, it is also necessary to determine various parameters, such as: determining the stability of the insole under various pressures and the optimal value of the relative compression of the material. The results obtained during the experiment will be studied by means of mathematical research method in order to determine the optimal value of the relative compression of a particular material of an orthopedic insole.

To solve this problem, regression analysis of matrix form was used [13-19]. Regression is a mathematical model in which the variable y linearly depends on $x_1, x_2, \ldots, x_n$ variables. The dependence of the search parameter on the factors is described in the form of a linear equation, which is given below:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots b_n x_n + e\,, \qquad (1)$$

where $b_0, b_1, b_2, \ldots, b_n$ are the coefficients of the regression equation, e is the free term of the equation (deviation).

The regression equation is checked for adequacy, as to what extent the obtained results and factors are balanced with each other. The performance of the regression equation is evaluated by the difference between y (which is obtained experimentally) and $\hat{y}$ (which is obtained by calculating the regression equation). The difference between y and $\hat{y}$ should be minimal, not above 5%.

Let's consider the method of general regression analysis in matrix form. Let us introduce the following notations:

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \qquad (2)$$

where y is a column-vector of n-dimensional matrix which consists of the independent variables obtained as a result of the experiment. In our case, the relative compression values of an individual orthopedic insole material obtained experimentally, are given in percentage.

$$x = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ - & - & - & - & - \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}, \tag{3}$$

(3) is *nx* (m+1) dimensional matrix, in which each i - row (i = 1, 2, . . . n) represents the number of i - independent variables $x_1, x_2, \ldots x_n$. In our case, the peak overpressure falls on the supporting area of the foot and the plantar part of the foot.

$$B = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_m \end{bmatrix}. \tag{4}$$

Expression **(**4) is a column-vector of (m+1)-dimensional matrix, the elements of which correspond to the free term of the linear regression equation b_0 and the coefficients $b_1, b_2, \ldots b_n$.

$$e = \begin{bmatrix} e_0 \\ e_1 \\ \vdots \\ e_n \end{bmatrix}. \tag{5}$$

Expression (5) is a column-vector of n-dimensional matrix which shows the difference between the results obtained by experiment y_i and the results obtained by regression equation $\hat{y}_i$, where:

$$\dot{y}_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \cdots + b_m x_{im} \quad (i = 1, 2, \cdots n). \tag{6}$$

Using the above designations, we can write a matrix equation:

$$e = Y - XB. \tag{7}$$

Taking into account the method of least squares, we have:

$$\sum_{i=1}^{n} e_i^2 = e^T \cdot e = (Y - XB)^T (Y - XB) \rightarrow \min, \tag{8}$$

where e^T represents the transposed matrix of the *e* matrix, i.e. $e^T = (e_1\, e_2 \ldots e_n)$.

It is proved that the mentioned minimum condition is fulfilled if we calculate the column vector B by the following formula:

$$B = \left(x^T x\right)^{-1} \cdot x^T y, \tag{9}$$

where x^T is the transposed matrix of the X matrix, and a $(x^T x)^{-1}$ represents $(x^T x)$ to the inverse matrix.

Based on the presented mathematical research method, we established an analytical relationship between the foot supporting area and the peak pressure on the plantar part of the ankle, which is a necessary condition in the selection process of individual orthopedic insole materials.

Orthopedic insoles for CP patients are manufactured individually, based on the analysis of the patient's pedogram. Therefore, only one patient's pedogram, aged 14, with body weight 56kg, is presented in the study. The patient's pedogram is illustrated in Figure.

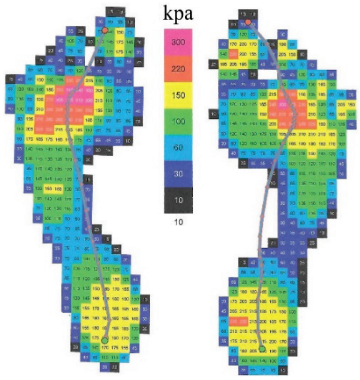

Fig. The pedogram of a patient with CP.

From the analysis of the pedogram, it is clear that the contact area (cm^2) of the patient's foot with the supporting surface is equal to: $x_1 = 155$; 152; 158. Peak pressure (kPa) is equal to: $x_2 = 330$; 152; 158. Relative compressibility parameters of insole material in percent (%) equal to y = 10.5; 12; 9.

According to the above formulas and based on the data taken from the pedogram, we made calculations, namely:

$$x = \begin{bmatrix} 1 & 155 & 330 \\ 1 & 152 & 340 \\ 1 & 158 & 325 \end{bmatrix} \quad y = \begin{bmatrix} 10,5 \\ 12 \\ 9 \end{bmatrix} \quad x^T = \begin{bmatrix} 1 & 1 & 1 \\ 155 & 152 & 158 \\ 330 & 340 & 325 \end{bmatrix}$$

$$x^T \cdot x = \begin{bmatrix} 1 & 1 & 1 \\ 155 & 152 & 158 \\ 330 & 340 & 325 \end{bmatrix} \begin{bmatrix} 1 & 155 & 330 \\ 1 & 152 & 340 \\ 1 & 158 & 325 \end{bmatrix} = \begin{bmatrix} 3 & 465 & 995 \\ 465 & 72093 & 154180 \\ 995 & 154180 & 12210358900 \end{bmatrix}$$

$$\left[x^T \cdot x\right]^{-1} = \frac{\left[x^T \cdot x\right]^*}{\left|x^T \cdot x\right|}, \tag{10}$$

where $\left[x^T \cdot x\right]^*$ is $\left[x^T \cdot x\right]$ the adjoint matrix of the matrix $\left|x^T \cdot x\right| = def\left(x^T \cdot x\right)$

$$\left[x^T x\right]^{-1} = \begin{bmatrix} 171,14 & -214,16 & 175,34 \\ -91,25 & 143,25 & 104,17 \\ 87,17 & -153,17 & 185,28 \end{bmatrix}$$

$$x^T \cdot y = \begin{bmatrix} 1 & 1 & 1 \\ 155 & 152 & 158 \\ 330 & 340 & 325 \end{bmatrix} \begin{bmatrix} 10,5 \\ 12 \\ 9 \end{bmatrix} = \begin{bmatrix} 31,5 \\ 4873,5 \\ 10470 \end{bmatrix}$$

$$B = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \left[x^T \cdot x\right]^{-1} \cdot x^T \cdot y = \begin{bmatrix} 16,3 \\ 3,14 \\ -1,53 \end{bmatrix}.$$

If we add the obtained coefficients $b_0 = 16.3$; $b_1 = 3.14$; $b_2 = - 1.53$ into the regression equation, we get the following:

$$\dot{y} = 3.14x_1 - 1.53x_2 + 16.3\,. \tag{12}$$

If we introduce the first variant of the x_1 and x_2 data into equation (12): $x_1=155$ $x2=330$, in this case we have $\dot{y} = -1.9$. In case of the second variant when $x_1=152$ and $x_2=340$, $\dot{y}_i$ will be equal, and in case of the third variant when $x_1=158$, $x_2=325$, $\dot{y}_i$ will be equal to $\dot{y} = 15,17$.

Based on the analysis of the obtained results, it is clear that the minimum difference between the experimental results (relative shrinkage of the material) and the results of the regression equation is minimal at x_1=155 cm^2 and peak pressure x_2=330 kPa. The quantities indicated represent the best option when selecting materials for an individual patient.

This work was fulfilled with the financial support of Shota Rustaveli National Science Foundation of Georgia, Grant FR № 22 - 1515.

ბიომექანიკა

ცერებრული დამბლით დაავადებული ბავშვების ტერფების პედოგრაფიული კვლევა და ანალიზური კავშირის დადგენა ტერფის საყრდენ ფართსა და პიკურ დატვირთვას შორის

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(წარმოდგენილია აკადემიის წევრის თ. ნანეიშვილის მიერ)

ნაშრომში წარმოდგენილია ცერებრული დამბლით დაავადებული ბავშვების ტერფის პედოგრაფიული კვლევები ინდივიდუალური ორთოპედიული სუპინატორების მასალების შერჩევის მიზნით. კვლევის შედეგად დადგენილია ტერფის პლანტარულ ნაწილზე პიკური დატვირთვები და ტერფის საყრდენ ზედაპირთან საკონტაქტო ფართის სიდიდეები. მათემატიკური კვლევის მეთოდის გამოყენების საფუძველზე დადგენილია ანალიზური კავშირი ტერფის საყრდენ ფართსა და ტერფის პლანტარულ ნაწილზე მოსულ პიკურ დატვირთვებს შორის, რაც წარმოადგენს აუცილებელ პირობას ინდივიდუალური ორთოპედიული სუპინატორების მასალების შერჩევის პროცესში. აღნიშნული მიმართულებით კვლევები განსაკუთრებით აქტუალურია, როდესაც საქმე ეხება ცერებრული დამბლით დაავადებული პაციენტების ჯანმრთელობის პრობლემებს.

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Received December, 2023