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BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 17, no. 2, 2023

Biomechanics

Foot Deformities in Children with Cerebral Palsy and Individual Orthopedic Insoles for Locally Over-Pressured Areas

Merab Shalamberidze* and Malvina Tatvidze**

*Department of Design and Technology, Akaki Tsereteli State University, Kutaisi, Georgia
**Department of Chemical and Environmental Technologies, Akaki Tsereteli State University, Kutaisi, Georgia

(Presented by Academy Member Elguja Medzmariashvili)

The paper highlights the design processes of individual orthopedic insoles for children with cerebral palsy considering locally over-pressured areas. A total of 12 patients with cerebral palsy were included in the study. The examination of the patients' feet was performed by the pedograph method. The geometric shapes of the over-pressure areas of the plantar part of the foot were recorded on pedograms by curved lines. The description of the curved lines was conducted by means of the integral curves of the solutions to Dirichlet singular boundary differential equations. The ethylene-vinyl acetate copolymers of different degrees of hardness were used to manufacture the individual orthopedic insoles. The individual orthopedic insoles were produced on a computer numerical control milling machine considering the locally over-pressured areas of the foot. *© 2023 Bull. Georg. Natl. Acad. Sci.*

orthopedic insoles, cerebral palsy, pedograph method, plantar pressure

Cerebral palsy (CP) in children is a group of disorders that affect their abilities to move and maintain posture throughout life. Cerebral palsy develops as a result of irreversible damage to the brain and can happen before birth, during birth or within the first years of child's life. The disease affects the child's ability to control his muscles, which is manifested by motor disorders, namely: paralysis, a decrease or increase in muscle tone.

According to the World Center for Disease Control and Prevention (CDC), cerebral palsy is the most common cause of motor disability in children. Recent studies show that the frequency ranges from 1 to 4 per 1000 children. Around 18 million people worldwide suffer from cerebral palsy. Cerebral palsy treatment includes physical therapy, medication, orthopedic and assistive devices. The approach is individual and includes the development of an effective combination of medical, rehabilitation and orthopedic interventions. Timely and targeted intervention provides partial prevention of musculo-tendinous and skeletal deformities and contractures [1].

It should be noted that in the process of treating cerebral palsy, orthopedic means have a high degree of recommendation [2-6]. In Georgia, patients and their parents, as well as pediatricians and orthopedic traumatologists, raise the question of the demand for individual orthopedic devices. Studies in this area are particularly urgent, because orthoses are currently manufactured in Georgia using outdated technologies and do not meet specific needs of a particular patient. Orthoses made in this way usually cannot ensure the correct position of the lower limb. In addition, the foot is placed on the non-relief and rigid surface of the orthosis, which causes pain and discomfort. Skin maceration, bruises, calluses and other pathological changes develop in the locally over-pressured areas in the plantar part of the foot, which cause movement problems for children with CP. Children frequently refuse to wear such orthoses.

On the basis of the above-mentioned facts, it is necessary to provide orthoses with individual orthopedic insoles considering over-pressured areas in the plantar part of the foot, which will be made of polymer composite materials with different degrees of hardness [7-13].

Based on the global nature of the issue, the purpose of this work is to study the foot in children diagnosed with CP and protect against associated complications. To achieve this goal, a pedographic study of the feet of patients with CP was carried out using a pedograph Emed – 25 at/D manufactured by the Novel company (Munich, Germany). Based on the individual data of a patient, we designed orthopedic insoles considering locally over-pressure areas.

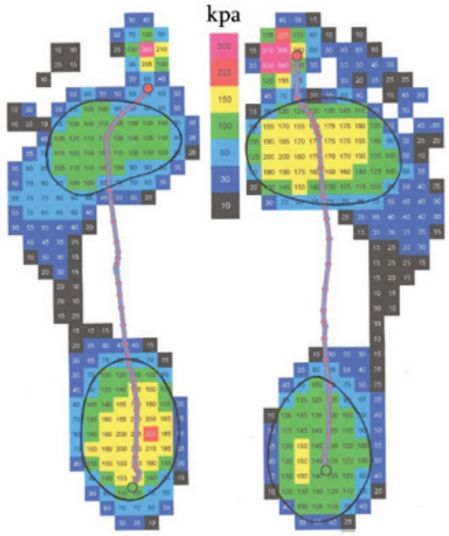

Fig. 1. The pedogram of a patient with CP

Fig. 1 illustrates a pedogram of a child with CP, aged 9 years, weighing 28 kg. It can be seen from the pedogram that the local pressure on the over-pressured areas of the plantar part of the foot in a child with CP fluctuates within 150-315 kPa, which significantly exceeds the norm. The analysis of the pedogram shows that the patient has a deformed foot (valgus deformity of the foot), the main pressure falls on the areas of the heel and metatarsophalangeal (MTP) joints of the foot plantar surface. The areas marked by curved lines on the pedogram represent the locally over-pressured areas.

An important novelty of the research consists in the fact that the description of the geometric shapes of the locally over-pressured areas of patients' pedograms was described by means of integral curves of the solutions to Dirichlet singular boundary differential equations. Application of the mentioned method makes it possible to describe the geometric shapes of the curves of the locally over-pressured areas of individual orthopedic insoles with great accuracy [14-16].

Below is the Dirichlet singular boundary differential equation:

$$u''(t)+\frac{a}{t}u'(t)-\frac{a}{t^2}u(t)=f\left(t,u(t),u'(t)\right) \quad (1)$$

$$u(t)=0,\ u'(t)=0, \quad (2)$$

where $a\in(-\infty;1), f$ satisfies the local Carathéodor condition for a set, $[0,t]\times D,\ D=(0;+\infty)\times R.$

The solution of the problem (1) - (2) is presented in the form of equations (3) and (4):

$$u(t)=\frac{t^3}{2}-\frac{1}{3}ct^{-2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2} \tag{3}$$

$$u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t-\frac{t^2}{2}+\frac{t^4}{6}. \tag{4}$$

By means of the integral curves of the solutions of equations (3) and (4), a description of the geometric shapes of the curves of the locally over-pressured areas on the pedograms was made. Fig. 2 shows a complex geometric shape of a locally over-pressured area of the plantar side of the right foot's MTP area taken from the pedogram (Fig. 1).

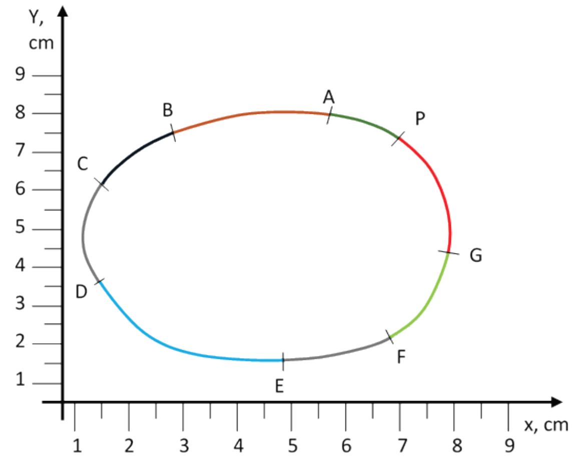

Fig. 2. The curve's shape of the locally over-pressured area in the right foot's MTP.

The curve shown in Fig. 2, was preliminary divided into eight parts to describe its shape. Each numbered section was described using the integral curves of the solutions to differential equations given below. Nine parts of the integral curves identically corresponding to the geometric shapes of the curve on the over-pressured area of the right foot's MTP were chosen, particularly the following:

1. AB curve corresponds to that part of the solution to equation $u(t)=\frac{t^3}{2}-\frac{1}{3}c\frac{1}{t^2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2}$, for which $c=5$ and corresponds to the set of [-5.1; -2.3]×[-1.3; 0.1];
2. BC curve corresponds to that part of the solution to equation $u(t)=\frac{t^3}{2}-\frac{1}{3}c\frac{1}{t^2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2}$, for which $c=2$ and corresponds to the set of [-2.4; -1.5]×[-5.1; -1.9];
3. CD curve corresponds to that part of the solution to equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which $c=1$ and corresponds to the set of [-0.08; -1] × [2.7, -0.3];
4. DE curve corresponds to that part of the solution to equation

$u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which $c=0$ and corresponds to the set of [1; 0.01] × [2.4; 4.8];

5. EF curve corresponds to that part of the solution to equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which $c=3$ and corresponds to the set of [-1.7; 3.6] × [6.8; -0.6];
6. FG curve corresponds to that part of the solution to equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which $c=5$ and corresponds to the set of [-1.1; 0.5] × [3.2; -0.4];
7. GP curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which $c=5$ and corresponds to the set of [2.5; 1.9] × [-1.1; 1.8];
8. PA curve corresponds to that part of the solution to equation $u(t)=\frac{t^3}{2}-\frac{1}{3}c\frac{1}{t^2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2}$, for which $c=5$ and corresponds to the set of [0.5; -1.1] × [0.3; -4.1].

Based on the above-mentioned mathematical algorithm, the software was developed to describe the curve sections. By rotating and parallel transferring of these sections, the entire geometric shape of the curves was assembled to represent the locally over-pressured areas on the MTP area of the right foot's plantar surface which is an exact analogue of the curve's shape shown in Fig. 2.

Fig. 3 llustrates a curve of complex geometric shape of a locally over-pressured region in the heel area of the right foot taken from the pedogram (Fig. 1).

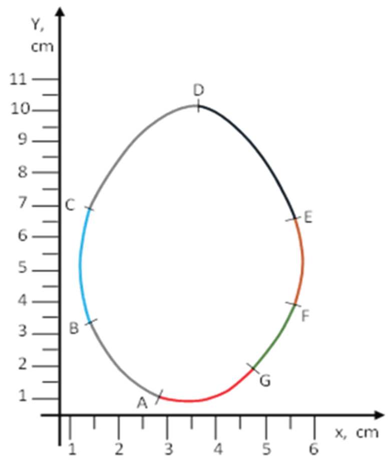

Fig. 3. The curve's shape of the locally over-pressured area in the right foot's heel area.

To describe the shape of the mentioned curve it was preliminary divided into seven parts. Each numbered section was described using the integral curves of the solutions to differential equations given below. There were chosen seven parts of the integral curves identically corresponding to the geometric shapes of the curves of over-pressured area in the right foot's heel, particularly the following:

1. AB curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which c=0 and corresponds to the set of [1.4; 0.15]× [2; 2.3];
2. BC curve corresponds to that part of the solution of equation $u(t)-\frac{t^{\partial}}{2}-\frac{1}{3}c\frac{1}{t^2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2}$, for which c=0 and corresponds to the set of [-3.1; -2.4]×[-1.2; 0.8];
3. CD curve corresponds to that part of the solution of equation $u(t)-\frac{t^{\partial}}{2}-\frac{1}{3}c\frac{1}{t^2}-\left(1-\frac{1}{3}c\right)t+\frac{1}{2}$, for which c=3 and corresponds to the set of [-6.9; -2.5]×[-1.1; -1];
4. DE curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which c=2 and corresponds to the set of [-1.4; 1.7]× [-2.4; 5.7];
5. EF curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which c=5 and corresponds to the set of [2.5; 1.8]× [-1.4; -1.3];
6. FG curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which c=1 and corresponds to the set of [3; -0.4]× [-0.7; 1.4];
7. GA curve corresponds to that part of the solution of equation $u(t)=\left(-\frac{1}{3}-\frac{1}{3}c\right)t+\frac{1}{3}c\frac{1}{t^2}+\frac{2}{3}t+\frac{t^2}{2}+\frac{t^4}{6}$, for which c=5 and corresponds to the set of [4.8; -0.6]× [-0.7; 0.3].

Also, in this case, the mathematical algorithm and the mentioned software were used to construct the curve of the corresponding geometric shape to represent the locally over-pressured area, which is an exact match to the shape of the curve shown in Fig. 3.

In the same way, complex geometric shapes of the over-pressured areas of the heel of the left foot and MTP area shown in Fig. 1 are constructed.

The complex geometrical shapes presented in Figs. 2 and 3 were produced on a computer-controlled machine (Ped-Cad, Germany) using the soft material – EVA polymer – with the hardness of 20 Shore A, and the main frame of the insole was made with the EVA polymer, the hardness of which was 35 Shore A. Further, the milled parts of the locally over-pressured areas were preliminarily inserted into the main frame of the insole. Finally, the complete insole was manufactured on the milling machine (Ped-Cad) simultaneously taking into account the locally over-pressured areas.

Thus, based on the pedographic study of the patients with cerebral palsy, the locally over-pressured areas of the plantar side of the foot were identified and shaped by curves. The curves of complex geometric shapes of the over-pressured areas were described on each patient's pedogram by the integral curves of the solutions to Dirichlet singular boundary differential equations with great accuracy. Based on the mathematical algorithm, the software package was developed to describe the above curves. Individual orthopedic insoles were manufactured on a CNC-controlled milling machine taking into account the locally over-pressured areas. It provides improved quality of patient care and prevention of foot injuries. Research in this direction is of topical importance, especially when it concerns children with cerebral palsy.

ბიომექანიკა

ცერებრული დამბლით დაავადებულ ბავშვთა ტერფების დეფორმაციები და ინდივიდუალური ორთოპედიული სუპინატორები ლოკალურად გადატვირთული უბნებისთვის

მ. შალამბერიძე* და მ. თათვიძე**

**აკაკი წერეთლის სახელმწიფო უნივერსიტეტი, დიზაინისა და ტექნოლოგიის დეპარტამენტი, ქუთაისი, საქართველო*
***აკაკი წერეთლის სახელმწიფო უნივერსიტეტი, ქიმიური და გარემოსდაცვითი ტექნოლოგიების დეპარტამენტი, ქუთაისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის ე. მემმარიაშვილის მიერ)

ნაშრომში აღწერილია ცერებრული დამბლით დაავადებული ბავშვებისათვის ინდივიდუალური ორთოპედიული სუპინატორების პროექტირების პროცესები ლოკალურად გადატვირთული უბნების გათვალისწინებით. კვლევაში ჩართული იყო ცერებრული დამბლით დაავადებული 12 პაციენტი. მათი ტერფების კვლევას ვაწარმოებდით პედოგრაფიული მეთოდით. პედოგრამებზე ვარეგისტრირებდით ტერფის პლანტარული ნაწილის გადატვირთული უბნების გეომეტრიულ ფორმებს მრუდი წირების საშუალებით. აღნიშნული წირების აღწერას ვაწარმოებდით დირიხლეს სინგულარული სასაზღვრო ამოცანის ამონახსნების ინტეგრალური წირების საშუალებით. ინდივიდუალური ორთოპედიული სუპინატორების დასამზადებლად გამოყენებული იყო სხვადასხვა სიმაგრის ეთილენ-ვინილაცეტატის თანაპოლიმერები. პროგრამული მართვის ჩარხზე დამზადებული იყო ინდივიდუალური ორთოპედიული სუპინატორები ტერფის გადატვირთულ უბნებზე მოსული დატვირთვების გათვალისწინებით.

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Received March, 2023