BIOMECHANICAL ANALYSIS OF ANTHROPOMETRIC AND FUNCTIONAL ZONES ON HUMAN PLANTAR AT WALKING

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Abstract: The methods of representing barometric information obtained by the pressure measuring instruments of the human plantar onto the contact surface during walking have been developed. The presentation of barometric data in terms of time and phase variables along with the patterns of data elements makes grounds for analyzing independently of of the type of the barometric instrument.

1. INTRODUCTION

Biomechanics as a special branch of mechanics dealing with mechanical motion of living organisms, their separate elements and tissues is intensively developing in view of availability of numerous miniature and cheap devices enabling measurements directly on the biological objects (Mironov et al., 1999; Ihnatouski et al., 2005). The parameters of human plantar contact with a surface and characteristics of his gait are studied on the base of barometric insoles imparted a function of measuring local pressure values (Walczak et al., 2007; Sviridenok et al., 2008).

The diversity of barometric insoles and data processing systems presumes the need in adequate knowledge of their operation principles and limits of their application in both biomechanical simulation and medicinal practice (Duckworth et al., 1985; Sviridenok et al., 2005, Skvortsov, 2008).

The authors have studied in the present work a combination of techniques and a conceptual apparatus used to describe and analyze barometric data on the plantar contact with a surface in statics and dynamics. The use of mentioned in the work data abstraction extends the potentialities of biomechanical analysis together with the mathematical software independently of the type of the barometric device used.

2. METHODS USED

2.1. Instantaneous values

Definitions. During cycle T of measuring plantar pressure P^t the system may be found in any moment t (t=1,2,…, T) in one of the states characterized by a set of instantaneous pressure values p_i^t(P^t={ p_1^t, p_2^t,…, p_N^t }) transmitted from the insole sensors N and characterized by index i=1,2,…,N via direct measurements (Fig. 1). The set of instantaneous values p_i^t is a quantitative parameter that depends on man's mass (m) and a real contact area of both feet with the surface (s):

$$P^t \propto f\left(m, s, t\right) \tag{1}$$

The values of the elements of the set show pressure on the local regions and obey the additivity law.

The value of each element of the set incorporates a parasitic constituent in the form of the pressure created by pressing the insole against the plantar inside the footwear.

The considered pressure values should fit the full range from zero till the absolute maximum determined by the man's mass and the contact area of one sensor. The values of the elements in a set define the range from the minimal till the maximal value. The critical and significant levels are calculated proceeding from the range span.

The set of instantaneous pressure values is ordered according to the sensor coordinates on the insole (x_i, y_i) or by vector $\overline{r_i}$ relative to the reference point on each sensing insole. The distance between the points preset by the coordinates remain fixed at each moment.

The elements may be attached additional significance factors according to the adopted rules.

The pressure center is found by a ratio of the sum of products of the element values by the radius-vector, which depends on their coordinates, versus the sum of these values. This center specifies the point of projection onto the pressure vector plane.

The configurations of elements K_j^t with indices j=1,2,…,W ($W \le N$) turn to be associations of boundary elements chosen in terms of similarity of the values $\left(K_j^t \subset P^t\right)$. The configurations may be in the form of spots, graphic primitives or isobaric lines.

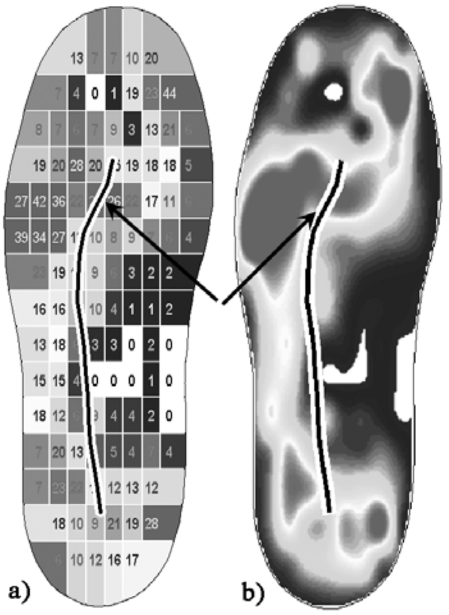

Fig. 1. 2D barograms of the left measuring insole with instant set of values (arrows show displacement trajectory of pressure center): a) numerical; b) via color gradients

Techniques. Proceeding from a disordered set of values of the elements, the statistical analysis of the values is made for two insoles separately and jointly. The analysis gives a quantitative estimation of pressure distribution values and compares them to those of the significant and critical levels. The distributions are compared for several measurements of motion of one or different men.

The ordered sets of elements serve to create a set of configurations in terms of a level or cluster analysis, providing a set of objects is given, where *X* is an *n*-dimensional space of ξ characteristics:

$$X = \{\xi_1, \xi_2, \ldots, \xi_n\}. \tag{2}$$

Partitioning into classes may be considered fully completed in case for all $X_l, X_m (l, m = 1, 2, \ldots, n; l \neq m)$ the next relation is satisfied:

$$X_l \cap X_m = 0 (\forall l, m). \tag{3}$$

Sampling X_i is a result of partitioning Π(*X*) of set *X*, where the problem consists in finding such function *f* that ensures this partitioning

$$f : X \to \prod(X). \tag{4}$$

For further analysis of their form, dimensions, statistics of values and recurrence (Vapnik et al., 1974; Cohen et al., 1993, Boykov et al., 2000), the configurations are analyzed in respect to their compliance with anatomic representations based on shift points and templates (Ihnatouski, 2000; Minchenkov, 2004).

Here are the examples of attaching significance factors to the elements:

- creation of binary maps, using which the number of elements is found that overcomes the threshold level (Ablameiko et al., 2000);
- use of contrasting multipliers enabling separate elements to impose a stronger effect on distribution images (Ablameiko et al., 2003).

2.2. Time sequences

Definitions. A combination of sets of instantaneous pressure values of a plantar recorded sequentially within the whole measuring period presents a direct barometric information about motion of a man in space (Fig. 2):

$$Z = \bigcup_{t=1}^{T} P^t. \tag{5}$$

The combination of sets consists of uninterrupted time sequences of values of the like elements of each set I^i:

$$Z = \bigcup_{i=1}^{N} I^i, \tag{6}$$

where

$$I^i = \{p_i^1, p_i^2, \ldots, p_i^T\}.$$

The minimal and maximal values of each sequence define the range of the element values. Based on the range span, the significance levels are calculated for the whole measurement cycle.

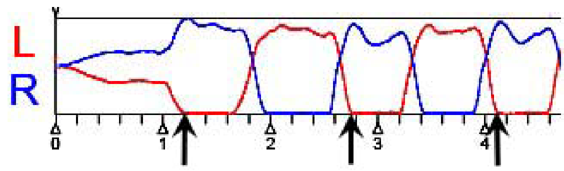

Fig. 2. A combination of a set of instant values of the left and right measuring insoles reflecting immobility during 1s and 2.5 steps within 3.5s (arrows show step limits)

Step *S* is considered to be a sequence of sets of instantaneous values of the plantar pressure constrained by reiteration of certain element configurations from the moment *t1* till *t2* (Fig. 2):

$$S = \bigcup_{t=t1}^{t2-1} P^t, \tag{7}$$

where

$$P^{t1} = \bigcup_{j=1}^{W} K_j^{t1} \equiv P^{t2} = \bigcup_{j=1}^{W} K_j^{t2}.$$

The anatomic phase of a step is a sequence of sets of instantaneous values of the plantar pressure during one step limited by the appearance of certain configurations within the frames of anatomic representations (Cappozzo, 2002; Michard, 2003).

The displacement trajectory of the pressure center presents a set of finite curves along which the pressure center moves during a half-step (Fig. 1):

$$\overline{r}_t = \frac{\sum_{i=1}^{N} p_i^t \overline{r}_i}{\sum_{i=1}^{N} p_i^t}. \tag{8}$$

The trajectory coordinates are found relative to the centers on each of two insoles similarly to those on the sensors.

Indirect values of the elements obtained for analyzing the pressure variation rate in time and along the insole length are the variations of one of the coordinates on the plane relative to the initial position of the reference point. In view of independence of the coordinates of the sensors on both insoles, the real 3D coordinates of the elements can be found only using the correction factor and probability error.

Techniques. Independent normalizing of each sequence based on the ranges obtained makes it possible to sift out the parasitic constituent of pressure values.

The statistical and frequency analyses are performed for the time sequences of the values. Proceeding from the analyses, the probability of the contact between the plantar and the surface in some local area and its contribution into the total pressure is estimated. The time sequences of the like element values of each set turn to be dependent and to find their correlation is of specific interest.

The configurations of elements formed on the base of instantaneous values are treated as existing in time objects. The life cycle of configurations is to be studied despite the fact that it is suffice to have time sequences for the values of the elements to describe qualitatively a man's motion, while for the analysis and synthesis of a model one should use associations of elements based on the ordered configurations. The phases of a step are calculated in terms of the conformity of the configurations with anatomic representations,.

When considering a step as an independent element of motion, the elements should be compared to all parameters used for describing motion as a whole.

The analysis of the trajectory gives us its spatial characteristics, namely, length and rocking in response to dimensions of a rectangle circumscribing the considered line, and the dominant displacement angle.

2.3. Phase sequences

Definitions. The anatomic phases of a step are presented as both the sequences of instantaneous value sets and the statistics of these sets.

Non-anatomic phases of a step Φ_a ($a = 1, 2, ..., A$ ($A \in \mathbf{N}$)) will be the mean values of the sequences of instantaneous value sets obtained by partitioning steps into the equal number of parts.

$$\Phi_a \bigcap P^{t_{a+1}} = \varnothing, \tag{9}$$

where

$$\Phi_a = \bigcup_{t`=t_a}^{t_{a+1}-1} P^{t`} = \bigcup_{t`=t_a}^{t_{a+1}-1} \bigcup_{j=1}^{W} K_j^{t`},$$

$$P^{t_{a+1}} = \bigcup_{j=1}^{W} K_j^{t_{a+1}}.$$

Techniques. To find motion stability, the like anatomic phases for different steps are compared. The comparison of unlike phases inside a step gives us a representation of the distinctness of their boundaries.

The analysis of the averaged values of the elements and the comparison to the parameters of time sequences is made to evaluate the stability factor within the frames of non-anatomic phase sequences.

2.4. Configurations of element's analysis

Partition of a set of sensors into groups corresponding to the anatomic zones was checked up by analyzing configurations of the elements (Lusardi et al., 2007). The variants of configurations were found from correlations of time sequences of the values of the like elements:

$$k_{i1i2} = \frac{\sum_{1}^{T}\left(p_{i1}^t - \overline{p}_{i1}\right)\left(p_{i2}^t - \overline{p}_{i2}\right)}{\sqrt{\sum_{1}^{T}\left(p_{i1}^t - \overline{p}_{i1}\right)^2}\sqrt{\sum_{1}^{T}\left(p_{i2}^t - \overline{p}_{i2}\right)^2}}. \tag{10}$$

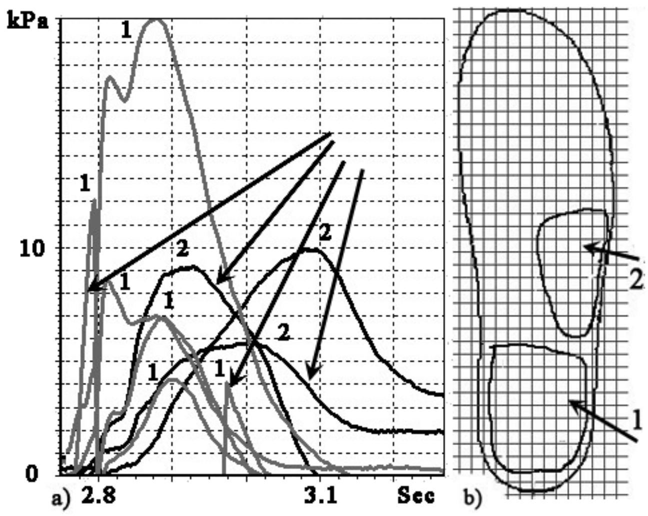

Fig. 3. Initial data: a) time sequences of the like element values joined into two groups on the right plantar per step duration (numbers of groups near lines) – arrows show removed sequences; b) groups of sensors of the right insole (the arrows show groups of sensors under study) grouping into zones based on anatomic representations

Further association of the elements into configurations takes place in provision of condition k_{ili2} tendency to a maximum with tracking association overflow. Named stages may be performed just as for the whole period of measurements so for each separate step. Time sequences of the values of the like elements joined into two groups on the right insole per one step are shown in Fig. 3a, 4a.

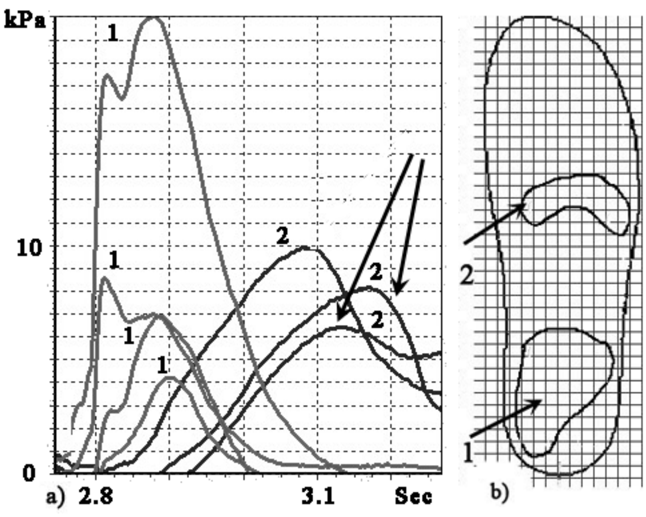

Fig. 4. Data processing results: a) time sequences of the like element values joined into two groups on the right plantar per step duration (numbers of groups near lines) – the arrow shows added sequence; b) groups of sensors of the right insole (the arrows show groups of sensors under study) configurations based on the analysis

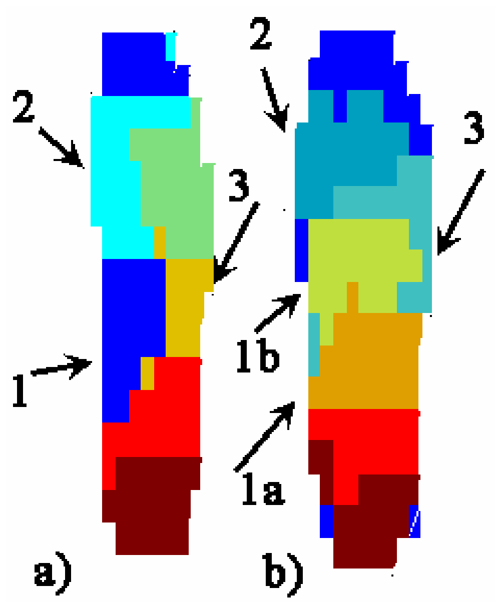

Fig. 5. Groups of sensors of the right insole configurations based on the analysis: a) diagnosis healthy; b) diagnosis Pes planovalgus

The arrows in Fig. 3,a indicate the sequences to be removed upon the analysis of the reduced groups. The sequence that was added to one of the reduced sequences is shown in Fig. 4,a by an arrow.

As it is seen from the diagrams, the analysis assists in removal of the time sequences giving imperfect agreement with the sequences of the element values that make a chief contribution into the barometric characteristics of human gait and helps to reveal and interrelate the new synchronous sequences.

The groups of sensors on the right insole are distributed over the zones according to anatomic argumentations as is shown in Fig. 3,b. Figure 4,b presents the configurations obtained on the base of the analysis, as a result of which one sensor in the zone of the heel was cancelled and the configuration of the middle chain of sensors was altered.

Above example illustrates that the basic notions used to analyze time sequences of barometric data at describing human gait should be treated with care. It would be erroneous to accept a priory the notion “zone” as anatomically substantiated and united group, since the aim of biomechanical investigations is to evaluate the anatomy and its probable pathologies using the analysis of associations of elements that incorporate both spatial and mechanical characteristics.

3. CONCLUSIONS

The analysis of barometric data aimed at describing man’s motion in space and functioning of his locomotor system proceeds from the basic conceptual pattern set forth in the present work (Ihnatouski et al., 2008). A solution is proposed for the problem of analyzing configurations of sensors of a measuring insole as to its compliance with anthropometric characteristics of patient’s plantar.

Figure 5 illustrates sets of sensors of the right insole. These configurations have been obtained from analyzing barometric data of two patients, a healthy one (Fig. 5,a) and the one affected by Pes planovalgus (Fig. 5,b).

The barogram presented in Fig. 5,a displays clearly the regions of the plantar beneath the navicular bone (1), metatarsus from the inner (2) and outer sides and the cuboidal bone (3). This image agrees with distribution of the active regions on a man’s plantar surface having healthy locomotor system, resting upon the outer side of the middle plantar at walking, while the elements of metatarsus possess certain freedom.

The barogram in Fig. 5,b of the regions (1a) and (1b) unite the areas of the plantar found between the outer and inner edges of the plantar. Such a configuration means that the pressure variations under the cuboidal and navicular bones on the contact surface are varying synchronously during walking. This fact helps to make a diagnosis of Pes planovalgus. Changes in the direction of the long axis of region (2) from the coaxial about the plantar for the perpendicular one proves that the metatarsus elements have lost their freedom and the patient is affected by a Transverse flatfoot.

It seems promising to use the modern mathematical apparatus for data processing to employ the prediction by using the database (Winter, 1991) and to conduct complex investigations on the base of uniting measuring systems for recording 3D displacements of a specific set of points on human body and barometric data (Pauk, 2005; Krupicz et al., 2008).

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