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ORIGINAL ARTICLE

Shape characteristics of the foot arch: Dynamics in the pregnancy period

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Abstract

OBJECTIVES: The aim is data detection and finding some load consequences generated by various mechanical or physiological changes in the interaction of the end segment of the body – the foot – and the environment.
DESIGN: Shape instability of the foot caused by e.g. loading of the foot by long-term frequency loads – walking, by extreme loads – sport, by hormonal changes – pregnancy, by aging, by pathologies, etc. The footprint surface was numerically described in 3D by means of stereo-photo-gram-metrical method – DMR digital relief model. Density of discrete points – 250–400 per one print.
SETTING: Detailed DMR was constructed by means of triangular web including contour picture with the use of Atlas program. The specified generated web is characterized by triangles with a cca 1mm side in the number of up to 4.500 elements per one footprint model.
RESULTS: The results enable us to deduce shape characteristics of DMR – the shape of the interactive boundary of the foot – the rest surface, to solve foot arch straining, to solve issues of discomfort and distribution of the pressure at the boundary of the foot – the rest surface, the shoe, etc. The gained findings can be interpreted in the field of prevention, therapy, orthopedics, podology, and enable us to come up with recommendations for the orthopedic practice and industrial use in the footwear production, etc.
THE MAIN FINDINGS: The difference between volume reductions of the space under the foot arch characterizes the level of "fall" of the arch. This criterion is independent of the foot size, and is in 3D.
CONCLUSIONS: Shape characteristics of footprints in pregnant women and in the period after childbirth were calculated on the basis of the defined criterion. The results of the group of four women tested in three periods suggest that there is no clear tendency towards the foot arch falling / increasing of the foot arch "fall" during the pregnancy period.

Introduction

Interaction between the foot (with a shoe or without) and the environment generates a great number of problems. Problems: **physiological** – dealing with general locomotion, **health** – pathology of the foot, e.g. hallux valgus, destruction of the foot arch build – change of its shape (injuries, hormonal changes e.g. in pregnancy, post-operation conditions, decalcification of the bone, change in the cartilage trophics, changes of the pressure and surface of intra-articular areas) [12], defects in the control of pressure distribution in hemipareses, diabetes, etc., **locomotion** – short-term confrontations of the foot with the rest surface or the shoe with the pressure e.g. 1900 kPa [2,3], etc., **forensic** – footprint detection and their identification, offensive and defensive use of the lower extremity – leg, etc., **structural** (characteristics of bones, cartilage, tendons, ligaments, muscles, and the other soft parts, e.g. fatty tissue, interstitial connective tissue, etc.) and their space arrangement including connections, **shape problems** in quasi-static and dynamic situations [8], **interactive** with various surfaces – division of pressures and tensions and related phenomena like changes of the shape and characteristics of coincidental elements [9,12], traumas, etc.

The important findings of the tension of materials at the boundary of the implant – the bone [5,13], and characteristics of single tissues and tissue structures [6,7] enable us to specify models of mechanical characteristics of not only tissues themselves, but also characteristics of more complex functionally complementary wholes, like e.g. the end segment of the body – the foot [12].

When identifying them, changes of the foot shape in 3D can be a guideline for model and inverse dynamic tasks. They can contribute to explanation of causes of biomechanical reactions of structural elements of the foot (e.g. osseous and articular changes). They can contribute especially to explanation of mechanical factors and dominance of their impact of biological mechanisms controlling changes of bones and connective tissues [4].

Development of 3D detection of the foot shape will lead to possibility of a non-invasive record of data, describing position changes of single structural elements of the end segment of the body – the foot.

The umbrella workflow is made up of numerical data processing and generation of mathematical, digital, and physical models enabling a broad use of gained data. Their processing enables simulation of a real observed condition or process. Thus we can solve tasks that could not be solved without the use of virtual mathematical and physical models.

Material and Methods

Pregnant women footprints were taken in early pregnancy, before the delivery, and in the period following the puerperium.

The footprint was taken by means of sinking both feet in the plastic substance Phase Plus Chromatic in the resting stance. The positive plaster cast fixed in the control frame was shot by a digital camera. Photos are processed by means of the program PhoTopoL. The data detection describing the footprint surface in 3D is performed by the stereo-photo-gram-metric method [10]. Density of the gained discrete points is 250–400 per one footprint. The created list of detailed points – their coordinates – is processed by means of the program Atlas. The generated triangular web of footprint points – triangles with the side length of cca 1 mm – (Figure 3) is adapted by the procedure of "planing". The goal of the procedure is to make the model surface smooth and flowing. Its fineness can be mathematically parameterized in advance.

Area of Interest

"Area of Interest – AI" – foot arch area that will be studied from the standpoint of the shape and its changes. It is defined geometrically by defining the space:

- by footprint boundary – in the plan in view, with a closed curve (Figure 1)
- by the plane perpendicular to the plan in view involving the front balls of the foot,
- by the plane parallel to the above defined plane in the heel area,
- by the arch area,
- by the plane defined by three footprint points positioned lowest.

In the defined space we will observe the main parameter – the fall gradient of volume differences of AI. It is defined as the difference of volumes over the planes parallel to the tangential plane **α,** gradually increasing by 2 mm up to the highest point of the arch.

AI_0	– volume of the observed space over the tangential plane **α**,
AI_{0+1}	– volume of the observed space over the plane parallel to the tangential plane **α** placed 1mm higher,
$AI_0 - AI_{0+1}$	– difference between the adjoining volumes of AI limited by plane **α** and **α** + 1.

Table 1. Summary of the calculated values – volumes under the foot arch in AI – left foot (cm³).
1 – beginning of pregnancy, 2 – end of pregnancy, 3 – end of puerperium.

h [mm]	Her1	Her2	Her3	Hom1	Hom2	Hom3	Jav1	Jav2	Jav3	Ls1	Ls2	Ls3
0 – 4	13,29	20,08	27,47	15,46	22,53	18,48	22,64	20,01	23,24	20,94	21,19	21,67
4–22 (max)	9,32	9,22	29,13	4,27	9,65	7,32	15,77	7,68	11,06	14,59	10,00	7,08
Total V	22,61	29,30	56,60	19,73	32,18	25,79	38,41	27,70	34,30	35,53	31,19	28,75

Faster decrease of volume differences means "the foot arch fallen lower" than in case of a slower decrease of these differences.

Sensitivity of the method of construction of DMR (digital model of relief) of a sunk footprint to changes of vertical coordinates, e.g. in the change of one coordinate "**z**" by 1mm in the space under the foot arch in AI, is 0.1%.

Results

The final product of the photo-gram-metrical evaluation of a sunk footprint is a realistic description of this shape in 3D (Figures 3, 4). Parameters of the digital relief model enable us to assess dynamics of changes of the footprint shape in the observed area of interest AI.

Calculations of volumes (per 2 mm – see above AREA OF INTEREST) are clearly resumed in two levels in Table 1. Category 0 – 4 mm and 4 – max. (22 mm). The maximum value of a related plane is individual in each case. This fact is apparent in graphs in Figure 6.

In case of a high foot arch, the speed of volume reduction is lower than in fallen arch at the beginning (Figure 5).

Discussion

As it is clear in the Table 1, changes of the foot arch shape in pregnancy are individual to such an extent that it will not be probably possible, even when using a statistically significant sample, to state generally if the trend of falling or rising of the arch prevails in the pregnancy period.

Generally, we can specify any section from DMT, and approximate it in 2D using a proper function A (x). A´ (x) is then a derivation of the approximative function and, at the point of the section, continuously expresses the size of the tangent directive towards the plate surface (towards the foot arch surface), thus its gradient. Consequently, it is possible to analytically assess "the fall" of the foot arch.

According to the relation of the magnitude of the supporting force of the arch in its established rise [11], in case of a more fallen foot arch, greater demands for supporting forces arise, consequently, for the forces affecting single structural elements of the foot. As we can deduce, single moments of force (muscular, ligamental) increase in relation to single bones of the foot. Intra-articular tension – forces in foot articulations – increases as well [12].

Mechanical factors have a dominant control of biological mechanisms, which control changes of bones and connective tissues – Utah paradigma [4]. These changes are a result of exertion not only in static and quasi-static regimes, but also in regimes of dynamic strain of osseous tissue [1].

The presumption is that the created model will be used not only in the discipline of orthopedics, surgery, traumatology, physiotherapy, and prothetics, but also in industrial fields – footwear production.

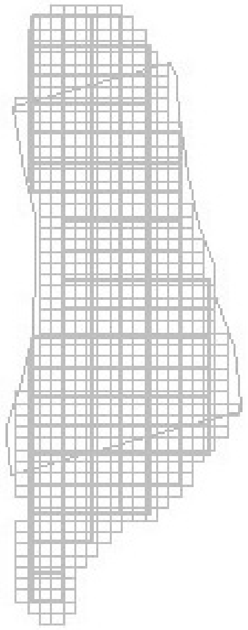

Figure 1. DMR in format GRID – plan in view AI – generally.

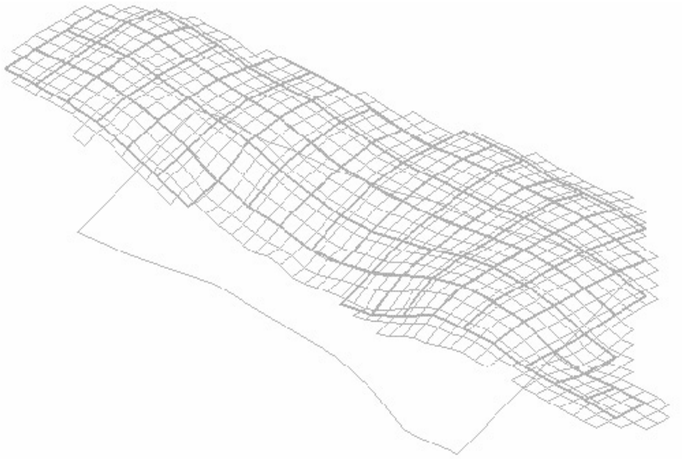

Figure 2. Perspective description of the area of interest – AI – generally.

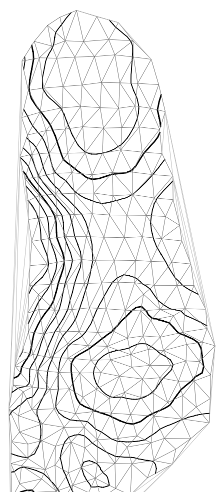

Figure 3. Generated 3D model of the footprint shape by means triangular web – in concrete terms.

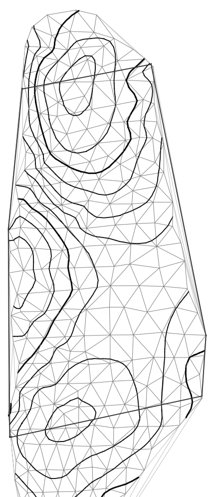

Figure 4. Definition of the area AI – in concrete terms.

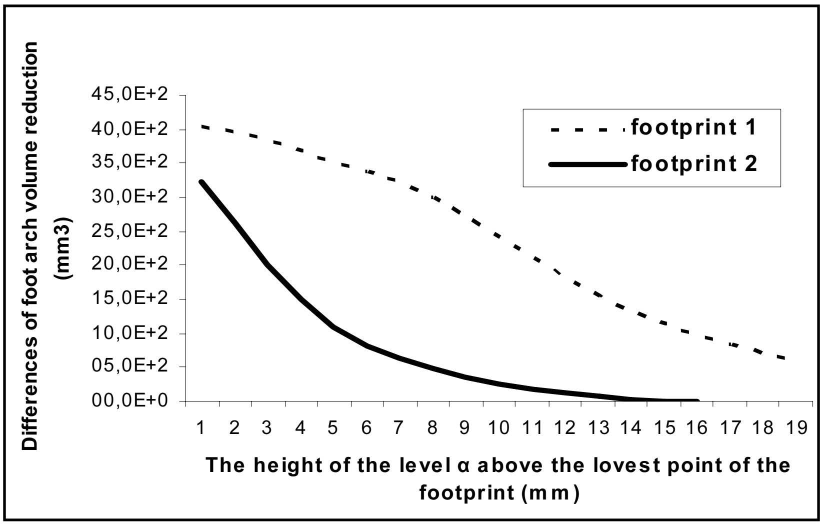

Figure 5. Difference of foot arch volume reduction – comparison of two footprints – generally. Dependence on the distance from the parallel plane to the tangential plane.

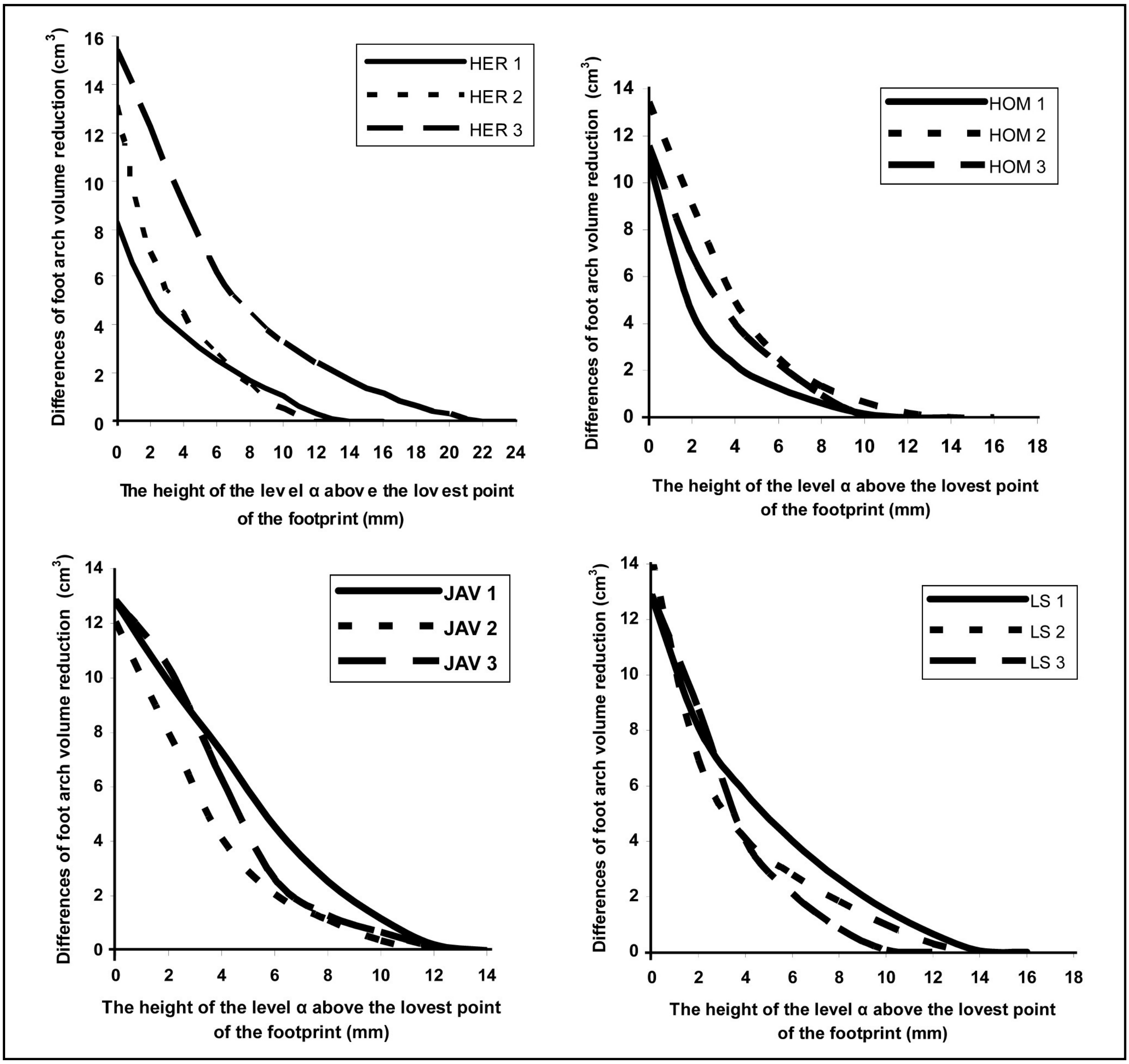

Figure 6. Difference of foot arch volume reduction. Dependence on the distance from the parallel plane to the tangential plane. The group of four pregnant women dtto Table 1.

It will be possible to use DMT of the foot for the shape reconstruction – physical model, e.g. by means of technology RAPID PROTOTYPING. It will be also possible to use the data for creation of the linear computing model of normal and tangential tension between the foot and rest surface in their interaction. Inversely, it will be possible to study the forensic issue of a person's weight decoding according to the origin of a footprint.

The main contribution of DMT is opening the opportunity for the study of the footprint in 3D in contrast with the long-standing orthopedic practice of assessing the footprint in 2D. However, the footprint in 2D significantly reduces information of the "bearer" to such an extent that this reduced information is very often useless.

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