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PREFACE

The success of many national and international conferences in the field of computational mechanics resulted in an initiative of National Associations of Computational Mechanics of the South-East European countries to organize South-East European Conference on Computational Mechanics (SEECCM).
The first one was held in Kragujevac, Serbia in 2006; the second one at the island of Rhodes, Greece in 2009 and the third one at the island of Kos, Greece in 2013. Previous three SEECCM conferences were extremelly successful and had a profound impact on the goals of the regional and world community of scientists to invent and apply computational methods in accordance with the continuously increasing demands in science, technology and medicine.
This year, following the path of tradition, the conference again took place in Kragujevac, Serbia on July 3rd-4th. The conference was organized by the *Serbian Society for Computational Mechanics*, *Bioengineering Research and Development Centar BioIRC* and *Faculty of Engineering, University of Kragujevac in Serbia*. Over 166 authors participated in the SEECCM 2017 Conference with more than 60 papers. The scientific field of papers mainly included the areas of computational mechanics, computational chemistry and applied biomedical engineering sciences.
The papers which fulfilled the reviewers' criteria were selected as the most significant ones and are included into this *Book of Proceedings* thematically divided into seven areas:

1. Mechanics
2. Biomechanics
3. Numerical Methods
4. Finite element modeling
5. Data mining
6. Computational Chemistry
7. Computational Biology

We firmly believe that the papers selected for the Proceedings reflect current trends and innovations in the field of computational mechanics and represent an outstanding base for all parties interested in this domain.
We would like to use this opportunity to thank one more time all the authors and keynote speakers who contributed to the quality of SEECCM2017 conference and the *Book of Proceedings* with hope that the tradition that we have built together will continue.
We would also like to express our deep appreciation to institutions who provided support – European Community on Computational Methods in Applied Sciences (ECCOMAS), Serbian Academy of Sciences and Arts and the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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Framework for Creation of Customized Shape of the Shoe Insole

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Abstract

Foot is the body part which is in constant contact with the ground. Since the foot has to adjust to the ground and transfer body weight properly, it is very susceptible to injuries and deformities. One of the most common deformities is flat foot that implies fallen arches. These deformities have influence on non-amenity during walking and on irregular body weight transfer. In order to return foot mechanics in normal acting, it is necessary to wear corrective insoles. This study presents the methodology aiming at speeding up the customized insole manufacturing process through creation of the so-called "digital chain". Patients with flat foot leave footprint in polyurethane foam, which is later scanned and transferred into digital model. Selecting the appropriate points of the acquired scanned image data set defines input parameters for creating a spatial insole shape. These parameters, consequently, define boundary spatial curves, which in turn rule the insole's free form shape. This is the basis for upgrading and setting up the initial shape with corrective elements.

Keywords: Reverse engineering, NURBS, flat foot, insole

1. Introduction

Human foot is a very complex structure which consists of bones, muscles, ligaments and synovial joints. Since the foot is the only body component that is in contact with the ground, tasks to be fulfilled are related to balance and stability during standing and walking, adjustment to movement to the center of gravity, adaptation to all types and configurations of the ground, and so on. Due to its functions and tasks, foot is a very vulnerable component susceptible to the deformation development. For years, numerous researchers have dealt with foot complex functionalities using in vivo experiments and computer simulations studies (Leardini et al. 2007, Loncher et al. 2013).

The size and shape of the foot vary between age groups, population, sexes, and so on. These foot characteristics are caused by lifestyle, nationality and type of shoes, among others (Domjanic et al. 2015, Razeghi et al. 2002). Based on the clinical investigation so far, it is concluded that the main reason for the foot variability is related to the medial lateral arch (Razeghi et al. 2002). Variation of foot arches can result with deformity. The most common foot deformity is flat foot.

Flat foot deformities are directly associated with the height of the foot arches. This deformity is progressive. Patient with this deformity can feel nonconformity or pain during longer walk. Non-treatment of the flat foot can lead to arthritis, rigidity and ankle valgus (Han et al. 2011, Sadeghi- Demneh et al. 2015).

More detailed information related to the foot deformity can be obtained using 3D computer models generated upon noninvasively (mostly optically) acquired foot images. This leads to the importance of using reverse engineering techniques. For example, Hieu et al. (2010) indicated to the reverse engineering importance in the medical sciences in order to understand, control and manipulate the shapes and geometry of the anatomical structures. It is possible to gather computer models of the anatomical structures for analysis and simulations, or physical objects for replacing damaged anatomical structures by applying reverse engineering techniques and advanced mathematical descriptions of the objects.

Nowadays, there are various technical aids and techniques for determination of the foot deformities. Thus, in order to determine connection between footprint and loads in the calcaneal area, Wibowo et al. (2017) were aligning two scans for loaded and unloaded foot. They used data gathered from 3D optical scanner for unloaded foot and data gathered from foot plantar scanner for loaded foot. Data were suitable for processing within the MATLAB environment and AutoCAD software.

The purpose of this study is to show a methodology for automatic generation of the individual spatial shape of the insole curve by using footprint point cloud and through applying mathematical formulations of the advanced curves, such as non-uniform rational basis splines (NURBS).

2. Methodology and methods

2.1 Foot anatomy

Complexity of the foot anatomy is related to controlling mechanism complexity of the foot movement. Connection between the foot and the rest of the body is provided by articulated surface between proximal ends of the tibia and fibula and talus. The foot consists of three regions: rearfoot, midfoot and forefoot (Fig.1) (Dawe et al. 2011, DeMars et al. 2008).

Complete understanding of the rearfoot biomechanics implies knowledge of the foot basic anatomy. Rearfoot is the part of the foot which consists of talus and calcaneus. Calcaneus provides connection between the foot and the ground. During walking, distribution of the forces is carried out in this part of the foot – from vertical to horizontal position and vice versa. Since this is a complex kinematic process, it is necessary that tibiotalar, subtalar and distal tibiofibular joints act together such as one bone with soft tissue structures (Snedeker et al. 2012).

The midfoot has the vital role in the stability of the whole foot. This part of the foot consists of the following bones: navicular, cuboid and cuneiform (medial, lateral, intermediate). There is a minimal movement in the joints built of the mentioned bones. In the midfoot, two basic characteristics can affect the stability, first is the “Roman arch” and the second is the metaphyseal-diaphyseal junction (Pearce et al. 2010).

The most mobile region in the foot is the forefoot. This region consists of five metatarsal bones and 14 phalanges. Hallux consists of two, and rest of the fingers of three phalanges (Dawe et al. 2011, DeMars et al. 2008).

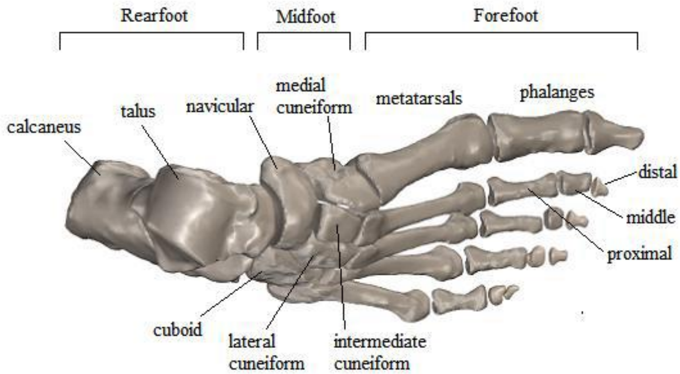

Fig. 1. Bones of the foot (DeMars et al. 2008)

Foot shape is formed by arches. These arches have multiple roles, meaning that they should provide impact absorption and store mechanical energy by reduction of the loads amplitude, and also to increase efficiency. Also, they should prevent compression of the specific plantar regions where muscles, nerves and blood vessels are stored. Ligaments and muscles hold foot arches. There are three arches: lateral longitudinal, medial longitudinal and transversal arch. The first arch consists of calcaneus, medial cuboid, and the forth and the fifth metatarsal. The second arch consists of calcaneus, talus, navicular, the three cuneiforms, and the first, second and third metatarsals. The third arch consists of cuboid, cuneiforms and the five metatarsal bases (Fig. 2) (DeMars et al. 2008).

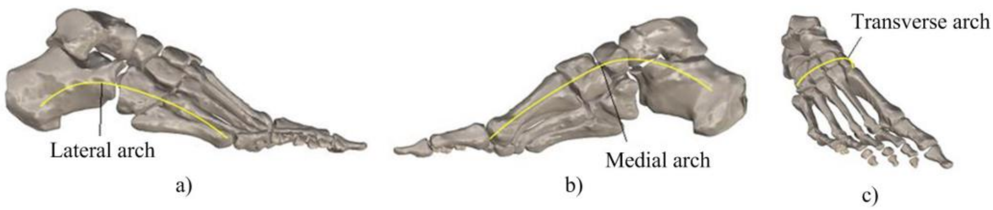

Fig. 2. Arches of the foot (DeMars et al. 2008)

Mentioned arches make one spatial arch. Loads are properly distributed over this arch and it has three supporting points:

- The posterior support point (heel bone tubercle),
- The front medial support point (head of the first metatarsal bone), and
- The front lateral support point (head of the fifth metatarsal bone).

Balance reduction of the foot structures at any region leads to foot insufficiency, and when bone changes start, it leads to foot deformations. First it leads to the changes in the arches position and loads distribution. According to pronation, foot can be classified into three groups (Cote et al. 2005, DeMars et al. 2008) (Table 1):

- Pronated foot,
- Supinated foot, and
- Neutral foot.

The first foot category is flat foot. In this foot type, internal rolling occurs and the weight is concentrated on the internal side of the foot. Arches lose on their height and they become flat. Because of this foot deformation, it is possible to report pain in the foot, knee, back and neck. It is necessary to use insoles which will return neutral position of the foot. Besides that, straight shaped shoes or motion controlled shoes are recommended in order to avoid internal rolling and provide maximal support in the foot. Insoles or shoes can have medial post or rollbar in order to provide proper movement of the foot.

Foot type		Alignment	Shoe type
Footprint	Profile view		
			
High arch		Supination	Cushioning shoe
			
Normal arch		Neutral	Stability shoe
			
Flat foot		Pronation	Motion control shoe

Table 1. Foot and shoe types

The next foot category is supinated foot. In this foot type, weight is concentrated on the external edges of the foot. Patients with this deformity have increased arches. Footprint is characterized by the thin lateral line which connects front (fingers) and the rear (heel) end of the foot. High arch compensation is provided by wearing curved shape shoes. Also, thicker insoles are recommended in order to execute foot loads relief on the internal side, and consequently provide better impact absorption.

The most common foot type is neutral. Basic characteristic of this type is proper weight distribution along the foot axis which implies on the arch height. In this case, the curve is 3/4 width of the footprint and connects the front and rear end of the foot. By using semi-curved insoles or shoes, a complete stability and softness is provided.

2.2 Patients

In this study, 10 participants with rigid deformity of the flat foot were involved. In this type of the flat foot, a structural anomaly exists, with valgus deformity on the rear end and with supination on the front end of the foot. It can be the consequence of the irregular bone growth. In this situation, the ligaments and joint capsules are shortened. Based on clinical examination (inspection and functional examination of the foot), one clinician gave the diagnosis. A technician took a footprint from participants in the memory foam with a slight pressure on the foot.

2.3 Object scanning

In order to produce customized insoles, memory foam footprints were scanned (Fig. 3) by mobile 3D scanner Artec Spider (https://www.artec3d.com/). This scanner is based on blue light technology. It has remarkable characteristics for scanning small objects in high resolution with steady precision and possibility of scanning textures. Good characteristics of the scanner are reflected in the possibility of scanning objects with complex geometry, sharp edges, etc. These are very suitable for use in the fields of reverse engineering, quality control, product design and manufacturing. Data accusation speed is 1,000,000 points/sec, 3D resolution is up to 0.1mm, and precision of the 3D points is up to 0.03mm.

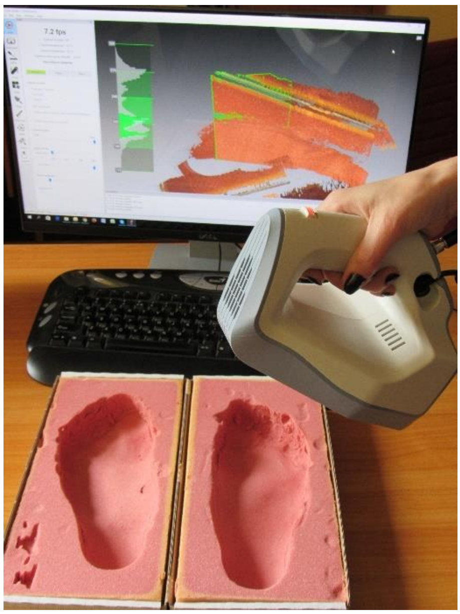

Fig. 3. Footprint scanning

In order to obtain data with better quality and precision, it is desirable that scanning object is stationary and the distance between scanning object and scanner is around 250mm. Overlapping of the scanning sequences is provided by slight moving of the scanner around the object.

After object scanning from all desired angles and after creating sufficient scanning sequences, it is possible to create a 3D object. Getting a 3D object implies next steps:

- Data revision and editing – after scanning it is possible to erase unnecessary sequences or objects from scene, translate, rotate or scaling, etc;

- Scan alignment – when quality of scanning sequences is not in the satisfactory limits, respectively when software for data processing has not enough information about relevant sequences positions, it is necessary manually adjustment;
- Global data registration – after scan alignments in the appropriate position related to one coordinate system, it is necessary to send information to a software about relative position between two scans;
- Data fusion – 3D model creating process based on discrete model;
- Final 3D model editing – possible models' errors corrections caused by scanning or fusion;
- Texture editing; and
- Export in ASCII format.

2.4 Determining insole spatial curve

ASCII format serves for storing in one coordinate system the point cloud, i.e. the vector structure where every point has its spatial coordinates - xyz. Coordinates are related to outer surfaces of the scanning object.

In order to form the outer insole contour, which has to be individualized, it is necessary to select appropriate points on the point cloud of the scanned footprint.

Using acquired points cloud and programmable environment MATLAB (https://www.mathworks.com/products/matlab.html), we created insole spatial shape using NURBS (Non-Uniform Rational B - Splines) curve. These curves are the essential entities of the CAD systems functionality because of their adaptability.

NURBS curves are parametric curves, and their definition is as follows (Kaarna A 2008):

$$C(u) = \frac{\sum_{i=0}^{n} w_i P_i N_{i,p}(u)}{\sum_{i=0}^{n} w_i N_{i,p}(u)},\ a \le u \le b, \tag{1}$$

where are

$N_{i,k(u)}$ – basic functions defined as:

$$N_{i,p} = \begin{Bmatrix} 1 & if\ u_i \le u < u_{i+1} \\ 0 & otherwise \end{Bmatrix}, \tag{2}$$

$$N_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u), \tag{3}$$

u_i – elements of non-uniform and non-periodic knot vector: $U = \{u_0, ..., u_m\}$,

P_i – control points,

w_i – weights,

p – degree of the polynomial curve,

$n+1$ – an amount of the control points P_i,

$m+1$ – length of the knot vector U, $m=n+p+1$.

3. Results

Imported footprint points cloud does not require additional processing because basic preparations are completed in the Artec Studio 11, accompanying Artec Spider scanner software. Footprint points cloud ideally fit to the real object. Algorithm for spatial curve shape generation is shown in Fig. 4.

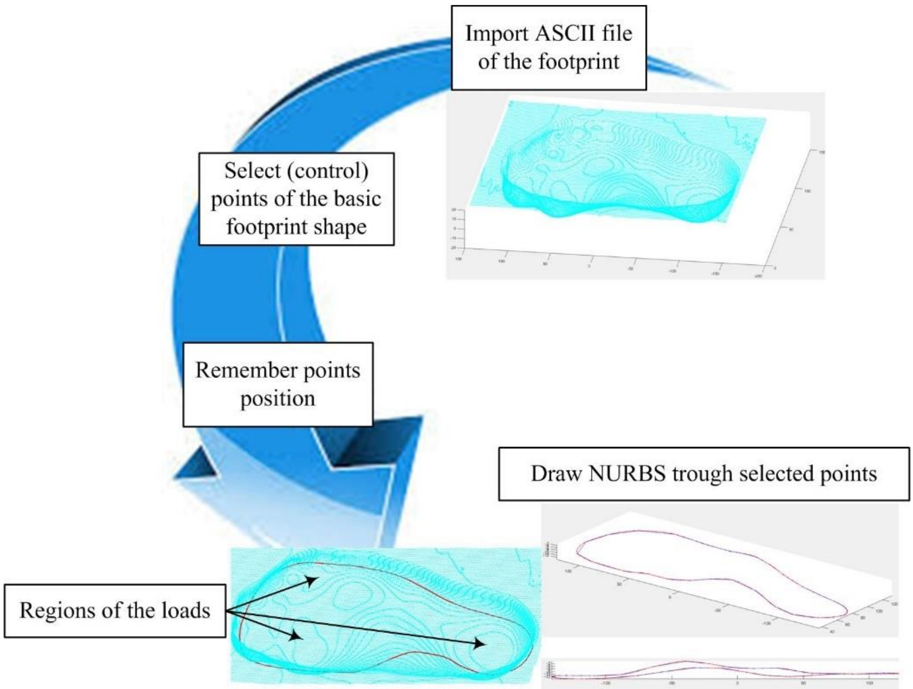

Fig. 4. Algorithm of the spatial curve generation

What is obvious in the points cloud of the scanned object, unlike the physical model of the footprint, are the spatial regions of the loads, which can be indicators for placing corrective elements under clinician supervising. In other words, it is possible to identify which foot region is the most exposed during walking, and according to that regions set up corrective elements or create insole shape which will provide a certain relief of some regions.

Since the basic regions of the foot (rearfoot, midfoot, forefoot) can be clearly perceived, selection of the control points is very easy. The application stores coordinates of the selected points. In the next step, selected coordinates are input parameters for spatial curve definition of the individualized insole. Obtained curve can be filled with free form surface and correction elements can be set in cooperation with a clinician. Finally, an individualized physical insole model can be produced.

4. Discussion

Since pronated feet, e.g. flat feet, may induce many unpleasant problems to patients, wearing corrective insoles can significantly affect everyday activities (Karimi et al. 2013, Hunt et al. 2017).

Guided by global trends, we are defining a methodology for creating specific patient insoles. Although specialized software for insoles individualization can be found (Germani et al. 2012, Daiva et al. 2013), we strive to adjust methodology proposed in this study to the needs of the technology design and manufacture within the concept of “digital chain”, through integration of anthropometric data with advanced digital technologies. Similarly, Zequera et al. (2007) suggested method for integration of computer assisted design using knowledge based system and production of therapeutic insoles using CAD/CAM system.

In the context of our method, creation and manipulation with spatial shapes involves the use of the NURBS curves. Engineering objects are described by using free form curves and surfaces because of their smoothness and well behaviour. With input data, resulting shape of the curve/surface is controlled (Dube et al. 2013, Milusheva et al. 2006). For customized shoes creation, Xiong et al. 2010. used model of scanned foot and adapted form of the shoe according to the feet selecting defined parameters using advanced mathematical formulations.

Personalized products require patient specific data. These data appear in different forms (such as medical images), but for our methodology geometric form of the footprint acquired by 3D optical scanner was necessary. With development of reverse engineering and CAD/CAM/CNC technologies, optimal design and manufacturing of the orthotic aids are greatly simplified and progressed (Milusheva et al. 2006, Rout et al. 2010). Mandolini et al. (2015) in their study pointed out the benefits of virtual prototyping approach development for insoles production. The proposed approach is based on synthesis of 3D scanners, specialized CAD software for insole design, CAM system and CNC milling machine. The main contribution of their approach is related to geometric procedure for creating complex insole shapes.

Automation of the insole spatial shape generation is done in MATLAB using its functionalities of concurrent control of geometrical shapes and data (Azariadis et al. 2010).

5. Conclusion

The methodology proposed in this study shows integration of anthropometric data with advanced digital technologies. Using this methodology, it is possible to produce precise customized insoles in the fast way. The approach indicates the importance of creating complex insole shapes through 3D scanning and points cloud application for NURBS creation. In this way, the insole creation process can speed up significantly.

Further research is directed to the implementation of the iterative closest point algorithm for insole spatial curve registration, as well as to the implementation of fuzzy logic algorithm for contour detection and automatic placing of the corrective elements.

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