3D SCANNER APPLICATION IN THE FUNCTION OF DIGITAL FOOT ANTROPOMETRY (FootSABA 3D Foot Scanner)

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Original Scientific Paper

UDK: [572.087:611.986]:004.352.4(086.4)

Summary

The personalization of footwear in terms of dimension and shape is of the utmost importance and is nowadays considered vitally important by interdisciplinary professions (medical, footwear, ergonomics ...), since inadequately manufactured footwear inevitably results in unwanted pathological conditions of the feet. The aim of this study is to scientifically determine the application of automated 3D digitization of spatial anthropometric foot measurement in relation to the frequency of incorrectly selected footwear based on traditional methods of measurement and selection. Among the examined individuals, both male and female, it was found that more than two thirds of people wear footwear that ergonomically does not fit the basic anthropometric footwear measurements, both in width and length of their feet. There is medical evidence that wearing inappropriate footwear is closely related to pain and wounds on the feet, and that prolonged wearing leads to pathological changes of the feet, such as foot and toe deformation. In the scope of taking measures, traditional methods of determining foot morphology are not sufficient to accurately define the shape and size, in contrast to the modern approach of using 3D scanners and digital methods of measuring virtual 3D models, which enable a very accurate and quick personalization of a large amount of anthropometric data concerning foot morphology.

Keywords

Foot, 3D virtual model, 3D scanner, anthropometric measurement

1. INTRODUCTION

The application of 3D scanners for digital foot anthropometry is a potentially promising technology of the future that will meet the needs of customers in the form of individualized products. Shoe fit and comfort are among the fundamental anthropometric factors for the customer. Fashion design and construction of functional footwear is a very complex process, especially considering the attempt to meet the requirements for both functionality and esthetics, which are often diametrically opposite and mutually exclusive.

Considering that the basic input data are anthropometric measurements of customers' feet, this paper will present scientific research and analysis of measurement results obtained using traditional manual methods in comparison to recent methods of specialized 3D spatial scanning measurement systems.

Historically, the fundamental role of footwear is protection, which is an exceptionally important part of human existence. In traditional Chinese medicine, the foot is considered the second heart of the human body. In biomechanical terms, the foo controls significant and dangerous impact forces between the ground and the human body, since the foot provides the necessary contribution to the balance and stability of the musculoskeletal system. Foot problems are common, ranging from simple disorders to complex diseases and even pathological joint deformities [1].

In the average human life, human feet walk the distance equivalent to five times around the earth, but in spite of that, people give them little attention [2]. Anthropometric shape is the most important functional factor of comfort that influences the consumer's purchase decision, along with the appearance and the price [3].

2. FOOT ANATOMY

In ergonomic and biomechanical terms, a functionally healthy foot is a harmoniously coordinated mechanism consisting of bone elements, muscles and tendons.

There are three parts of the foot's bone frame: tarsus, metatarsus and phalanges. The tarsus consists of seven short spongy bones, organized in two rows. The first row consists of the cuboid, navicular, medial, intermediate and lateral cuneiform. Talus and calcaneus (heel bone) form the back row. The metatarsus consists of five short tubular bones, resembling the shape of cube and wedges. Their joint structures are connected to the structures of the phalanges. Toes consist of three elements: proximal, middle, and distal phalanges. Big toe consists only of proximal and distal phalanges, Fig. 1.

Figure 1. Foot anatomy

In biomechanical terms, the arches of the foot are the most important structural elements of the foot, which determine all its functional abilities. If the arches are properly formed at an early age, the foot performs a number of necessary biomechanical and automated functions, such as the distribution of body weight when moving, adjusting the balance of the body, mitigating impacts to the ground, i.e. the foot has an inherent ability to mitigate, accumulate and release the energy generated by the walking mechanism.

Generally, the arches of the feet function as a biomechanical amortization system, providing maximum movement comfort with minimal consequences to the body. Their damage can lead to the disruption of the entire musculoskeletal mechanism, because the body is a complex and unique unit, wherein the slightest change in any particular part can reflect directly on the whole system. For example, flat feet can cause damage to the knee, hip joints, spinal deformities, as well as disorders of function and biological position of the internal organs. These ailments occur as consequences to the inappropriate function of the foot (amortization, balance, etc.), causing the higher-level skeletal structures to assume the structural functions of lower-level skeletal elements (knee, hip joints, spine). Since the former are not biologically and inherently adapted to this type of work and load, these systems are much more vulnerable and sensitive to such daily misuse.

The longitudinal biomechanical arch of the foot is located on the inner side of the foot, within the longitudinal plantar vault. The outer longitudinal arch is formed by the mechanics of metatarsal bones, cuboid and calcaneus. The outer longitudinal arch has a supporting function in static and dynamic physical work activities. In contrast to the outer arch, the inner longitudinal arch performs a greater variety of biomechanical functions of amortization and elasticity, Figure 2.

Figure 2. Anatomy of the outer and inner longitudinal arch of the foot

The foot generally has three segmental points of biomechanical support of the metatarsal bones. For example, flat feet (flattened arch) cause anthropometric changes of these segmental points. Such changes radically affect the alteration of gait biomechanics and result in various disorders.

This specific vault-shaped design is formed and maintained by various ligaments and muscles. Ligaments play the role of passive elements, while muscles act as active entities and play an equally valuable role in the functional structure of the foot. There are three groups of muscles in the foot; the internal muscles that are responsible for the biomechanical movement of the big toe, the external muscle group for the movement of the little toe, and the central muscles involved in the creation of biomechanical movements of all toes [4].

3. DETERMINING FOOT DIMENSIONS

The traditional method of measurement is based on the determination of length and width of the shoe tread, although colloquially it would be more comprehensible to call them length and width of the footprint. In contrast to the two basic dimensions measured in traditional determination of dimensional relations of the foot within footwear construction processes, digitized 3D foot scans allow for a far greater number of measuring indicators within their acquisition methods. These indicators are not only within the range of length values, but also determine a larger number of 3D individual references of the customer.

3.1. Traditional method

In order to determine the suitability of the footwear as accurately as possible, it is necessary to determine what size(s) the customer wears, i.e. the customer's foot length and width, whereby the aggravating circumstance is the diversity of shoe mold models from different manufacturers.

As shown in Figures 3 and 4, it is necessary to measure the length and width of the feet, noting that the foot should be measured in a suitable sock (summer or winter footwear), and that both feet should be measured due to foot inequality. It is advisable to use the greater measured value in further considerations.

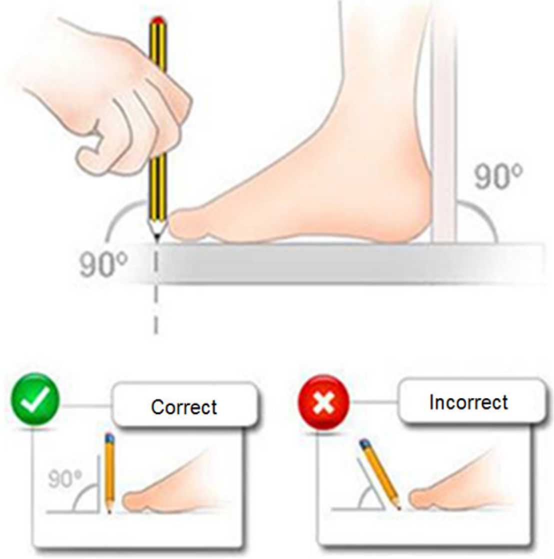

Figure 3. Traditional manual measurement of the foot [5]

According to the same principle of contouring the footprint, the width at the widest part of the foot is measured as a secondary measure in the traditional measurement procedure.

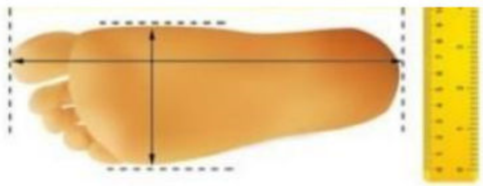

Figure 4. *Traditional length and width measurements of the foot* [5]

In addition to the length dimension, many manufacturers often designate the width of the footwear, usually for narrow, medium and wide foot.

Foot length is just the basis for determining the proper shoe size. For example, a foot length of 25.5 cm generally corresponds to size 41, but depending on the manufacturer, it may also correspond to sizes 40, 40.5, 40 2/3, 41, 41 1/3, 41.5. However, it is common for the observed foot length of 25.5 cm to correspond to e.g. size 38 in practice.

Manufacturers, especially of branded footwear, mainly put a label with numbers in different units of measurement (EUR, UK, US, JPN ...) on their products, and often the measurement expressed in cm. The Japanese measure (JPN or JP) is very useful because it is also expressed in cm. This measure of length in cm proves most reliable for determining whether a shoe fits. This measure should be at least slightly larger than the measured foot length, experientially by approximately 0.5 cm (length in cm = foot length + 0.5 cm).

Table 1 shows a comparative view of the foot length, Mondopoint, and various shoe sizes expressed in EUR, UK, US, and JP/CN. Recently, there is also the so called Mondopoint measuring system (in mm), which actually corresponds to the measure in cm and which attempts to standardize the size of the footwear according to the standard series ISO 9407: 1991 - "Shoe sizes - Mondopoint system of sizing".

It is important to emphasize that the traditional methods of taking measures, related to the associated traditional mass production and sale of the footwear, are applicable only to normal and biometrically healthy foot as the standard.

There are certainly many cases that do not fall into this category. Such cases include a more or less narrow or wide foot, a thicker foot, or a foot with some sort of congenital or acquired deformity as a result of obesity or possibly pathological diseases, which are likely to require a different, more modern and personalized approach to determine the appropriate shoe size [6].

Table 1. View of the foot length, Mondopoint, and various shoe sizes expressed in EUR, UK, US, and JP/CN

Foot [mm]	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200				
Mondopoint	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200				
EUR	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31											
UK	0	0½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13		
US	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13				
US C/Y (Athl.)	2 C	2½ C	3 C	3½ C	4 C	4½ C	5 C	5½ C	6 C	6½ C	7 C	7½ C	8 C	8½ C	9 C	9½ C	10 C	10½ C	11 C	11½ C	12 C	12½ C	13 C	13½ C	1 Y				
JP/CN	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14	14½	15	15½	16	16½	17	17½	18	18½	19	19½	20				

Foot [mm]	200	205	210	215	220	225	230	235	240	245	250	255	260	265	270	275	280	285	290	295	300	305	310	315	320				
Mondopoint	200	205	210	215	220	225	230	235	240	245	250	255	260	265	270	275	280	285	290	295	300	305	310	315	320				
EUR	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49											
UK	0	0½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14
US M	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14	14½	15
US M (Athl.)	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14				
US W (FIA)	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14	14½	15	15½	16
US W (Athl.)	3	3½	4	4½	5	5½	6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	12½	13	13½	14	14½	15				
JP/CN	20	20½	21	21½	22	22½	23	23½	24	24½	25	25½	26	26½	27	27½	28	28½	29	29½	30								

3.2. Digital 3D foot scanning

3D digital scanning technology has reached its potential in the last few years. It is used in various areas of application such as medicine, science, engineering, military, video games industry, etc. [7].

The use of 3D scanning technology to produce a digitized presentation of human anatomy parts in the future has the potential to help change the design of a wide range of products, including properly designed, constructed and manufactured footwear [8].

There are many different, technologically diverse 3D scanning software programs for the spatial digitization of different parts of the human body. Analysis of a large number of studies of 3D scanning capabilities for foot modeling showed that 3D scans are highly reliable and scientifically reproducible [9].

Designing footwear as a three-dimensional customized, but often non-personalized product is an extremely complex process, given the diametrically opposed demands of comfort and fashion trends.

Digitized 3D technologies, whether by the use of 3D photogrammetric methods, 3D structured light scanning, or laser scanning, ultimately enable the following (Figure 5):

1. 3D foot scanning,
2. Designing of 3D foot model,
3. Converting to 3D coordinate point cloud of foot model,
4. Comparison of derived 3D digitized foot model with the real scanned foot,
5. Footwear design and
6. Different options for the production of custom or more demanding footwear.

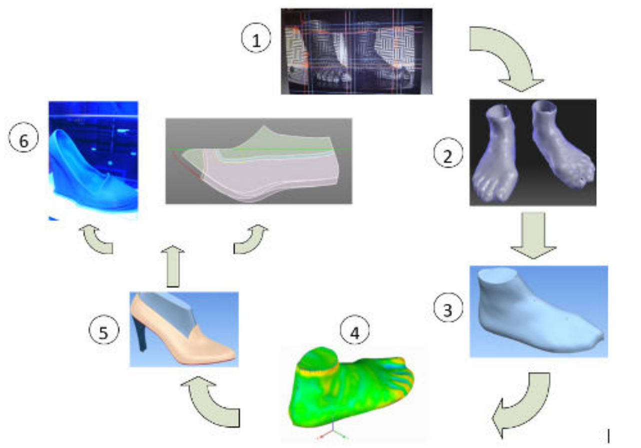

Figure 5. *Digitized process of 3D foot scanning, footwear construction and manufacturing*

Figure 6 shows the following processes: setup of a recent measurement scanning system (a), calibration using deterministic photogrammetric calibration panels (b, c), scanning of measurement entities (d, e), which in this case features simultaneous scanning of both feet, and finally the final virtualization of the derived 3D computer spatial model of feet imaging (f) [3].

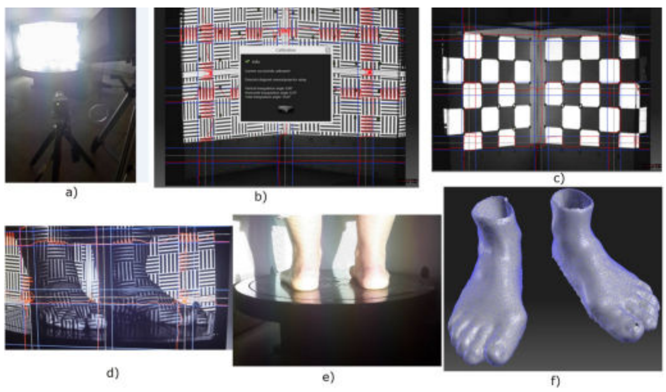

Figure 6. *Scanning process; a) Setup, (b, c) Calibration, (d, e) Acquisition, and f) Virtualization of the scan*

As of recently in use as a part of comprehensive diagnostics of anthropometric and biomedical foot conditions, the cost effective, highly accurate and practical tools *Foot*SABA 3D foot scanner with *SABALab* and the 3D scanning system developed by PolyU are shown in Figure 7.

Figure 7. 3D foot scanner with measurement and visualization display [10]

Within reversible engineering processes, especially in 3D scanning, there will always be imperfect results when recording data. Even the most advanced commercial 3D scanning systems produced by software engineers are making tremendous efforts to enable the systems to conduct an advanced digital 3D analysis of collected data; additional specialized computer programs for analysis are hence often used for a thorough 3D analysis and manipulation of acquired spatial measurements and data, e.g. Geomagic Studio ™ [11].

4. EXPERIMENTAL WORK

The digital *3D Foot Capture and Measurement System* "*Foot*SABA" by Ph.D. Sarajko Baksa is intended for spatial 3D foot scanning for the purpose of creating virtual 3D models. The result of digital anthropometric measurement is a three-dimensional virtual coordinate point cloud, which represents a measured body, specifically on examples of scanned individuals in order of magnitude: 1,387 spatial polygons, 3,241 spatial boundary lengths and 931 spatial coordinate vertices, Figure 8.

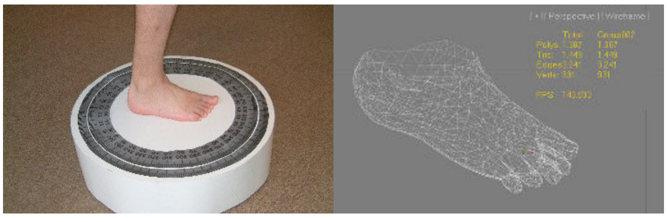

Figure 8. *"FootSABA" process of scanning and virtualization analysis of a 3D scanned model*

The traditional manual measurement was carried out by methods that are generally accepted and commonly and professionally applied on daily basis for determining foot dimensions, in accordance with the instructions shown in Figures 3 and 4. The measurement was carried out with anthropometric measuring tools for determining plane dimensions.

In both types of measurements, primarily anthropometric measurements were taken on both systems to conduct an advanced digital 3D analysis of collected data; additional specialized computer programs for analysis are hence often used for a thorough 3D analysis and manipulation of acquired spatial measurements and data, e.g. Geomagic Studio ™ [11].

Table 2 summarizes the results of 30 measured individuals, using the traditional manual and recent 3D digitized computational method for measuring dimensions of foot length and width.

Table 2. Table of the summary measurement results

Anthropometric measurement	Anthropometric entity	Measurement	
		Traditional manual method	Recent 3D computer measurement
Foot length (cm)	Left foot	26.71	26.69
	Right foot	26.64	26.61
Foot width (cm)	Left foot	10.35	10.31
	Right foot	10.25	10.27

5. DISCUSSION AND CONCLUSIONS

This research also established the well-known fact that there is a significant difference between the data on the sewn declaration (label) found on the footwear and the real - measured condition of the footwear size.

It is recommended to measure the length and width of both feet using traditional method of length measuring system such as e.g. measuring tapes when shopping for footwear. The purchase should be made in accordance with dimensions that are measured on a larger foot, since feet are generally of different anthropometric sizes. With regard to the even better fit of the footwear, it is recommended to measure the length of the inner footprint as well as the length of the (removed) shoe insert, since these are also elements that significantly contribute to shoe comfort and fitting.

Even if all of the abovementioned parameters are taken into account, this does not necessarily mean that the footwear will be appropriate and fitting in terms of anthropological differences, not only in length between feet but also in width, as well as in significant spatial dimensional differences of individual segmental sections. In practice, even people with medically healthy feet often find it difficult or impossible to find appropriate and well-fitting footwear. The common case is that the length of their left foot corresponds to size 42, and the length of their right foot corresponds to size 43; or in other case, the length of their foot corresponds to the size 43, and the width of that same foot corresponds to 44.

Given the uniform set of measured dimensions examined within this work and the expertise of the person who conducted the measurements, the scattering of the results is relatively small, but nonetheless, the difference between the anthropometric measurements of the left and right feet is clearly noticeable, as well as the precision of the 3D system.

With regard to the development of automated and digital systems for the spatial imaging of 3D footprints, there is no longer a need to choose between diametrically opposite features: attractive and fashionable footwear or ergonomically fit, anthropometrically individualized and appropriate footwear. It is now possible to have both, using recent 3D anthropometric scanners (e.g. *Foot*SABA).

Regarding the extremely large number of spatial anthropometric points resulting from the 3D measurement in comparison with two traditional methods, the anthropometric foot scanner 3D *Foot*SABA achieves an increase in analysis and modeling resolution of an incredible 150,000% solely within the domain of e.g. plane measurements with more than 3,000 accurate spatial boundary length data.

6. LITERATURE

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Acknowledgements

This paper describes the results of research being carried out within the project "Centar održivog razvoja"/"Center of sustainable development", cofinanced by the European regional development fund and implemented within Operational Programme Competitiveness and Cohesion 2014 – 2020, based on the call "Investing in Organizational Reform and Infrastructure in the Research, Development and Innovation Sector".