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Mechanical and tribological properties of the TiB_2 coating deposited by HiPIMS method

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Keywords: HiPIMS, TiB_2 coating, hardness, Young´s modulus, coefficient of friction.
Abstract: In the article, the authors briefly describe the high power impulse magnetron sputtering (HiPIMS) method. This method is briefly characterized in the article. Authors researched the mechanical and tribological properties of the TiB_2 coating deposited by the HiPIMS method on a steel substrate on an industrial machine. They were measured: hardness 25 GPa, Young's modulus 240 GPa, adhesion HF1, thickness 4.1 µm and coefficient of friction 0.7.

1 Introduction

Titanium is used as a transition thin coating to ensure the desired adhesion [1]. By adding nitrogen, its hardness increases and is used as a protective TiN thin coating of cutting tools [2]. By adding boron to Ti, we obtain a TiB_2 coating whose hardness is higher than that of the TiN coating [3-7]. The TiB_2 coating can be deposited by CVD method [3,4], PVD method by evaporation [5-7], RF sputtering [8-17], HiPIMS methods [18-20]. Often, the properties of TiB_2 coatings are doped with elements [21-22].

JI CHENG DING et al. [21] deposited a HiPIMS TiB_2 coating of approx. 1.5 µm thick at a frequency of 80 Hz, a pressure of 0.7 Pa, the deposition time was 120 min., the deposition temperature was 200 °C They reached a hardness of 26 GPa and a Young's modulus of 198 GPa.

ZHANG T.F. et al. [18] deposited a HiPIMS TiB_2 coating for 120 min. at a pressure in the vacuum chamber of 0.4 Pa, a temperature of 300 °C and 300 °C, a bias of 0 to 200 V and a distance from the magnetron of 12 cm. They achieved the following properties: the thickness of the coating was approx. 2 µm at both deposition temperatures, the hardness was from 20 GPa to 53 GPa (300 °C) and 17.5 GPa to 46 GPa (200 °C).

The HiPIMS method is an improved PVD sputtering method. It consists in the fact that the DC voltage during magnetron sputtering is rectified by interruption (Figure 1) [19]. The DC generator charges the capacitor bank of the pulse unit. The energy stored in the capacitors is dissipated into the plasma in pulses of precisely defined width and frequency using ultra-fast switches. The charging voltage of a capacitor bank typically ranges from several hundred V to several kV. The accumulated energy is released in pulses of a defined width and frequency in the range of several µs using transistors located between the capacitors and the cathode with switching capability, which enables the deposition of a coating with a denser structure, with higher hardness and resistance to wear.

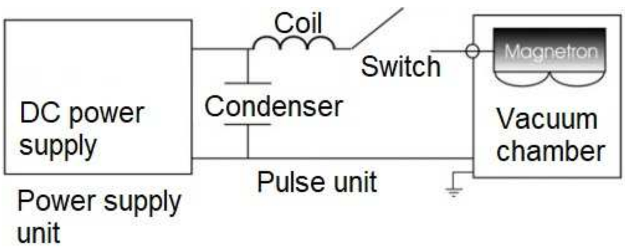

Figure 1 HiPIMS power supply architecture diagram [19]

The article is focused on the research of the mechanical and tribological properties of the TiB_2 coating deposited by the HiPIMS method and their comparison with published results in foreign scientific journals. The achieved results will serve to select the frequency and impulse width for further research on the TiB_2 HiPIMS coating to obtain higher hardness and a lower coefficient of friction.

2 Methodology

To evaluate the thickness of the coating, adhesion and coefficient of friction and wear, steel samples were used, which had the shape of a cylinder with dimensions d=22 mm and h=4 mm (Fig. 2), the material of the samples is steel (according to STN EN 19 830), whose chemical composition is (at.%): C - 0.8%; Mn - 0.45%; Si - 0.45%; Cr - 4.15%; W - 6.60%; Mo - 4.95% and V - 1.9%.

A TiB2 coating deposited by High Power Impulse Magnetron Sputtering (HiPIMS) on a CC800 device from Camecon, SRN (Figure 3) was used. Four Ti40B60 targets were used, which had dimensions of approx. 500x180 mm. The vacuum chamber of the device is 720 mm wide, 940 mm high and 920 mm deep, its volume is approx. 600 dm^3. Deposition of the TiB_2 coating took 3 hours and 55 minutes. The working gas Ar was used with a flow rate from 380 to 570 cm^3/min. During the deposition process, four Ti40B60 targets (magnetrons 1, 2 and 5, 6 - Figure 2) were used, which were arranged around the perimeter of the vacuum chamber opposite each other. In the center of the vacuum chamber, a table rotated with a planetary movement of the samples (Figure 3). The power of each HiPIMS magnetron was 4.5 kW, voltage 550 V and current 21 A. The sample table rotated at 0.5 revolutions per minute, the bias was -60 V.

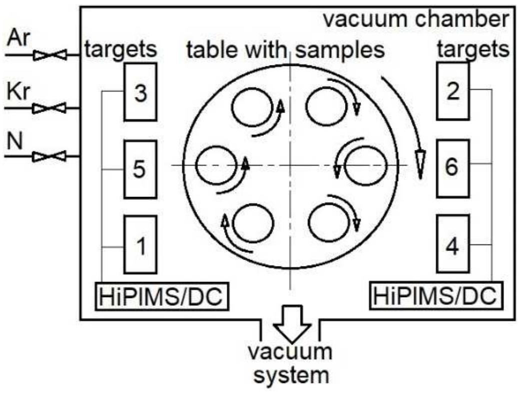

Figure 2 CC800 HiPIMS device, schematic

Figure 3 Samples in the preparation in a vacuum chamber

The properties were evaluated:

- *Thickness* – using the Kalotest method. The Swiss Calotest device from CSM Instruments was used. The parameters of the test were: the steel ball had a diameter of 15 mm, the grinding time of the calota was 300 s, and the speed of rotation of the ball was 900 revolutions/min. Struers sanding paste with a sanding grain diameter of 0.5 to 1.0 µm was used. A Japanese OLYMPUS - MX51 optical microscope was used to measure the diameters of the skull.
- *Adhesion* – was evaluated using the Mercedes test method according to the VDI 3198 standard. The puncture was made with a diamond Rockwell indenter in the shape of a cone with an angle of 120°, which gripped the top of the indenter. The injection evaluation was performed using a Japanese OLYMPUS - MX51 optical microscope.
- *Hardness and Young's modulus* – They were performed by the indentation method on a Bruker HYSITRON TI 950 TriboIndenter, with a maximum loading force of 10,000 µN. The puncture was performed with a diamond Berkovich indenter in the shape of a triangular pyramid. The maximum loading force was less than 2 N.
- *Friction coefficient* – a Pin-on-disk test was used with a linear path of the counter piece (steel ball with a diameter of 4 mm), length of the path 10 mm, speed of the counter piece 10 mm/s; test duration 7200 s; the counterweight loading force was 5 N.

3 Results and discussion

The thickness of the TiB_2 coating was measured to be 4.1 µm (Figure 4) (frequency 800 Hz, pulse width 50 µs), which is 100% more than that measured by ZHANG T.F. et al. [18], who measured the thickness of the TiB_2 coating approx. 2 µm and 300% more than THORNBERG J. et al. [23] measured a thickness of only 1 µm.

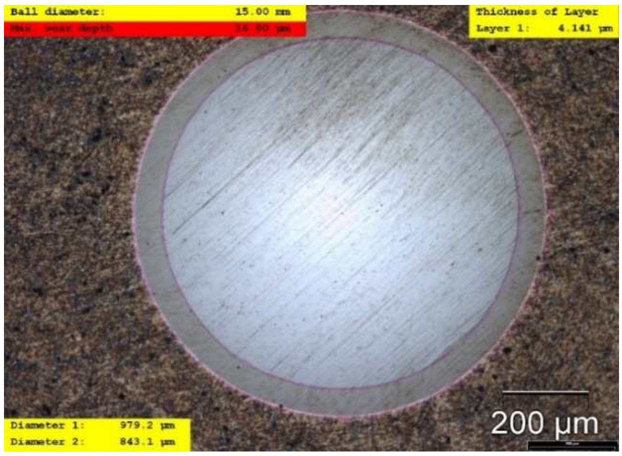

Figure 2 Calota TiB_2 coating deposited at a frequency of 800 Hz and a pulse width of 50

A view of the surface of the evaluated coating (Figure 5) shows a columnar structure with a primer of grains from 1 μm to 5 μm and gaps (voids) of 1 μm size are visible. The chemical composition of the TiB_2 coating is shown in Figure 6.

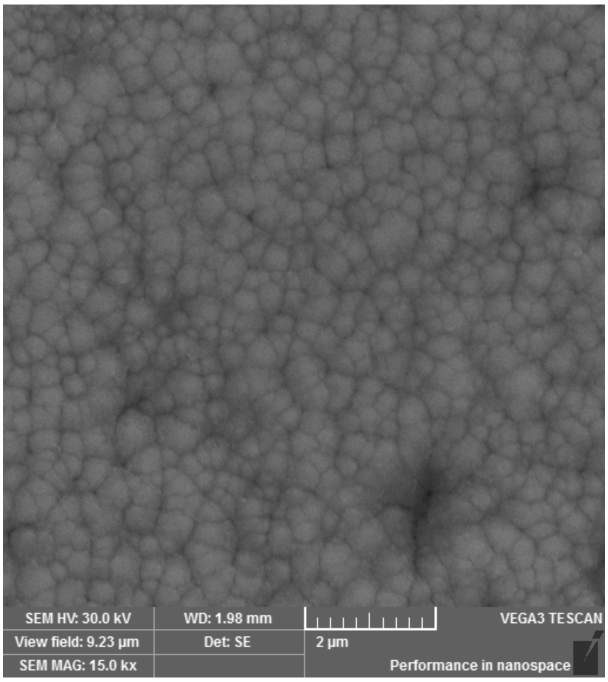

Figure 3 View of the TiB2 coating surface, SEM

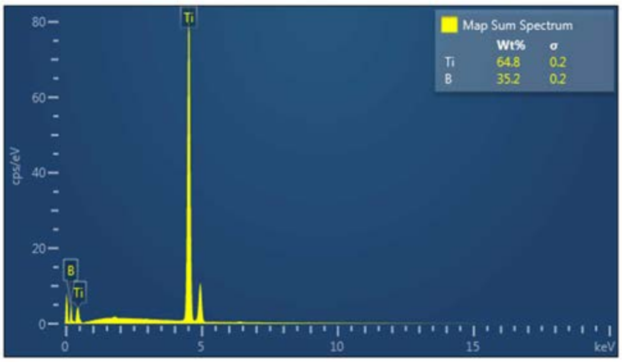

Figure 4 Chemical composition of TiB2 coating, EDS

A hardness of 25 GPa was measured, which is 20% less than ZHANG et al. [18], (29 GPa at 300 °C, bias 50 V). Young's modulus was approx. 240 GPa, which is comparable to Nedfors et al. [24] (approx. 480 GPa, 600 Hz and 1000 Hz, bias -60 V) by 40% less. Adhesion evaluated by the Mercedes test according to the VDI scale (Figure 7) reached grade HF 1 (Figure 8).

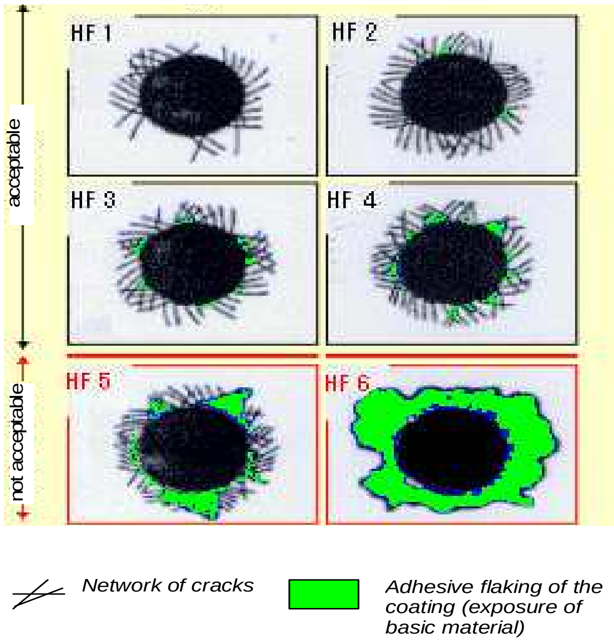

Figure 7 Mercedes test scale" HF1-HF 4 - satisfactory, HF4-HF6 - unsatisfactory adhesion [25]

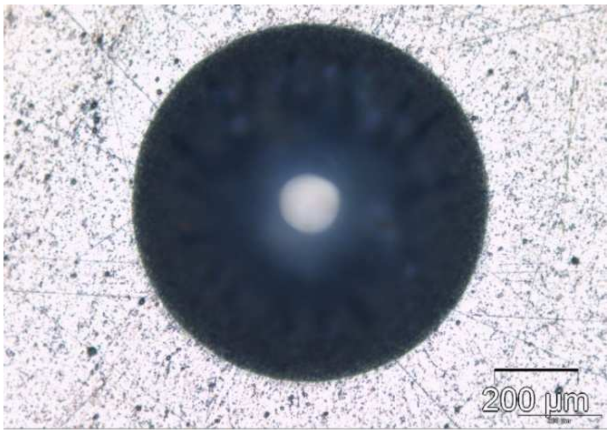

Figure 8 Adhesion of TiB_2 coating deposited at a freqency of 4000 Hz and a pulse length of 50 μs, grade HF1

The coefficient of friction after 2 hours reached a value of 0.7 (Figure 9), which is standard for the hardness of the evaluated coating of 25 GPa and the hardness of the counter piece (steel ball), because it was worn gradually, which increased the contact area. The rapid wear of the ball occurred after the first tens of seconds, when the coefficient of friction increased sharply to a value of 0.65 and then gradually increased to a value of 0.4. After a period of 5000 s, it rose to a final value of 0.7, which did not change until the end of the test (7200 s).

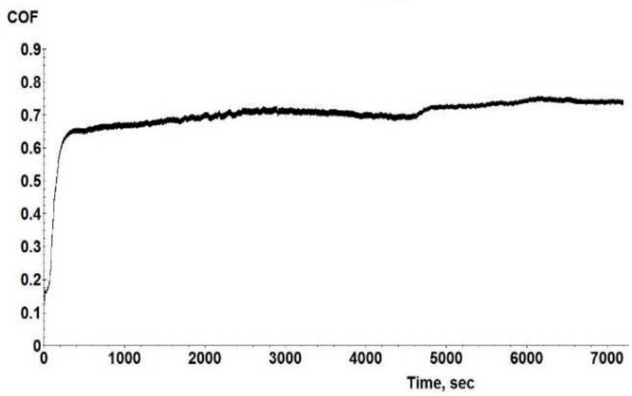

Figure 9 Dependence of the friction coefficient on time, TiB_2 coating deposited at a frequency of 4000 Hz and a pulse width of 50 μs

4 Conclusions

A TiB_2 layer was deposited on the steel substrate, where:

- a thickness of 4.1 μm was measured,
- the evaluated coating has a dense columnar structure, which corresponds to a hardness of 25 GPa and a Young's modulus of 240 GPa,
- adhesion reached grade HF1,
- the coefficient of friction was 0.7.

Based on the above, it can be concluded that the evaluated coating is suitable for industrial use for coating cutting tools.

Further research will focus on the influence of technological parameters such as frequency and width of impulse on the thickness, hardness, Young´s modulus and coefficient of friction of the TiB_2 coating deposited using progressive HiPIMS method.

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Case study of using KEPServerEX software as a connection tool between Tecnomatix Plant Simulation and a real device
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Case study of using KEPServerEX software as a connection tool between Tecnomatix Plant Simulation and a real device

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Keywords: KEPServerEX, Tecnomatix Plant Simulation, PLC, CNC, OPC UA.
Abstract: The article focuses on the processing of simulation models, covering their creation methods and exploring the possibilities of collaboration. The author utilized the Tecnomatix Plant Simulation program developed by Siemens to design a visual representation of a production line and provided a detailed description of the steps involved in its creation. To achieve the objectives of the thesis, the author employed KEPServerEX, a software solution enabling the connection and communication between the Tecnomatix Plant Simulation program and the Programmable Logic Controller (PLC). This integration allowed for the successful connection of a CNC device, establishing communication and collaboration with the Plant Simulation program. In summary, the thesis project employed the Tecnomatix Plant Simulation program to create a comprehensive visualization of a production line. The integration of KEPServerEX facilitated seamless communication between the simulation software and the PLC, enabling effective cooperation with a CNC device.

1 Introduction

The process of simulation in the production sphere is a method that allows you to model, analyze and test production processes in a virtual environment. In this way, it is possible to predict and optimize the behavior of real production systems and identify areas where efficiency, productivity, and economy can be improved.

The manufacturing simulation process includes the following steps (Figure 1):

- **Data collection**: At the beginning, it is necessary to collect relevant data about the production process, including data about equipment, workstations, material flow, cycle time, work procedures, and other relevant parameters.
- **Creation of a model**: Based on the collected data, it is necessary to create a model of the production system. This model can be created using a software simulation tool such as Tecnomatix Plant Simulation. The model includes various elements such as equipment, machines, workstations, conveyor belts, storage areas, and other relevant components [1].
- **Defining parameters and scenarios**: After creating the model, it is necessary to define the parameters and scenarios for the simulation. This includes setting equipment parameters, time constraints, material flow, work procedures, and other factors affecting the production process.
- **Simulation**: After defining the parameters, the simulation can be started. The simulation simulates the movement of material, work procedures, time constraints, and other aspects of the production process. During the simulation, it is possible to monitor system performance, identify bottlenecks, analyze material flow, and collect data on production results.
- **Analysis of results**: After the simulation is finished, the results are analyzed. In this way, it is possible to identify areas with insufficient efficiency, long cycles, equipment overload, or other problems. Based on the analysis, it is possible to propose improvements to the production process and optimize it.
- **Optimization**: Based on the analysis of the simulation results, it is possible to design and test different scenarios and improvements to the production process. These improvements may include process optimization, reallocation of equipment, changes in material flow, increased workstation capacity, and other adjustments that will help improve production efficiency, productivity, and profitability.
- **Verification and implementation**: After designing the optimal changes, it is necessary to verify their effectiveness and implement them in a real production

environment. This may include testing new procedures, adapting equipment, training staff, and other steps necessary to implement the changes.

- **Monitoring and updating**: After implementing changes, it is important to monitor and evaluate the results of the new production process. If new challenges or opportunities for improvement emerge, the model needs to be updated and the simulation run again for verification and optimization [2].

The process of simulation in the manufacturing sphere allows manufacturing companies to gain a better understanding of their processes, identify areas for improvement, and test different scenarios without having to make expensive and time-consuming physical changes to manufacturing systems. In this way, more efficient production, better use of resources, and an increase in the overall competitiveness of the production company are achieved.

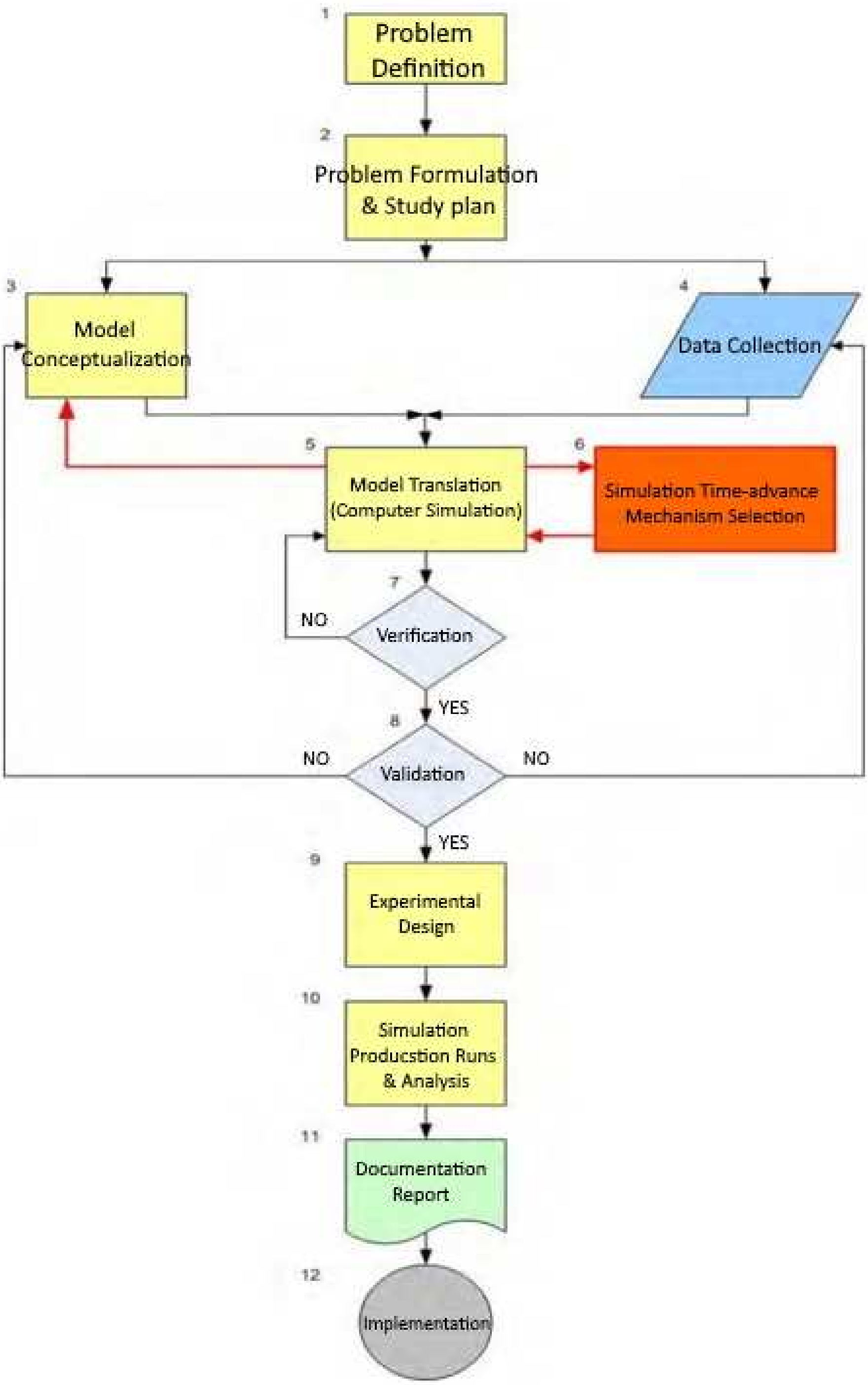


Figure 1 Steps in a simulation study [3]

The Tecnomatix Plant Simulation program offers advanced capabilities for 3D modeling and visualization. It allows users to create and visualize models in 3D using built-in libraries or external CAD data. The program supports the JT data format for efficient 3D modeling and utilizes Siemens direct model technology, ensuring realistic visualization of large-scale simulation models without sacrificing simulation accuracy and analysis.

One of the architectural advantages of Tecnomatix Plant Simulation is its support for encapsulation, inheritance, and hierarchy. This enables users to effectively manage, comprehend, and maintain complex simulations that involve intricate details, surpassing the capabilities of traditional simulation tools.

The modeling approach in Tecnomatix Plant Simulation involves using objects within objects and models within models, structured in a hierarchical manner. By utilizing libraries, users can store and maintain various objects, and any changes made to these library items are automatically applied to all instances throughout the simulation. This ensures consistency and simplifies the configuration process, allowing users to easily adapt library items to meet the specific requirements of their simulations.

In times of increasing cost and time pressures in production along with ongoing globalization, logistics has become a key factor in the success of a company. The need to deliver on time and in sequence, introduce lean manufacturing principles, plan, and build new sustainable production facilities, and manage global production networks requires objective decision criteria to help management evaluate and compare alternative approaches. Plant Simulation helps to create digital models of logistics systems so companies can explore system characteristics and optimize their performance. The digital model not only enables users to run experiments and what-if scenarios without disturbing an existing production system but it can be used in the planning process long before the real system is installed. Extensive analysis tools, statistics, and charts let users evaluate different manufacturing scenarios and make fast, reliable decisions in the early stages of production planning [4].

KEPServerEX is a software solution developed by Kepware Technologies, which is now part of PTC. It functions as a communication server specifically designed for industrial automation systems. Its primary purpose is to facilitate seamless communication and data exchange between various devices and software applications within industrial environments.

One of the key features of KEPServerEX is its ability to establish communication with a wide range of devices and support multiple network protocols commonly used in industrial settings. It can interface with devices such as Programmable Logic Controllers (PLCs), Remote Terminal Units (RTUs), Distributed Control Systems (DCS), and Computer Numerical Control (CNC) machines. Furthermore, it supports protocols like OPC (OLE for Process Control), MQTT (Message Queuing Telemetry Transport), Modbus, SNMP (Simple Network Management Protocol), Siemens S7, Allen-Bradley, and numerous others commonly employed in industrial automation (Figure 2).

KEPServerEX acts as a versatile communication server that enables efficient and reliable data exchange between different industrial devices and software applications. It supports a wide range of protocols and devices, making it a valuable tool in integrating and coordinating industrial automation systems [6].

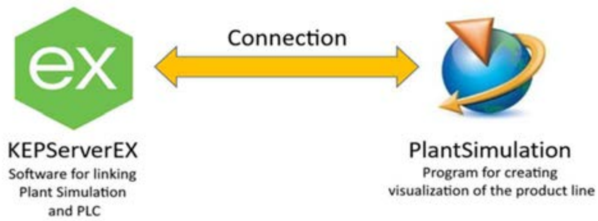


Figure 2 Communication medium (KEPServerEX) with Tecnomatix Plant Simulation

2 Case study in the TestBed 4.0 laboratory

First of all, after opening the KEPServerEX program, we click on "Project" in the menu on the left and create a "New Channel". After creating a "New Channel", the option "Select the type of channel to be created" will appear and we will select the option "Simulator" (Figure 3).

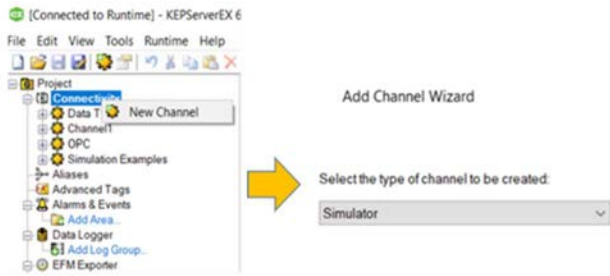


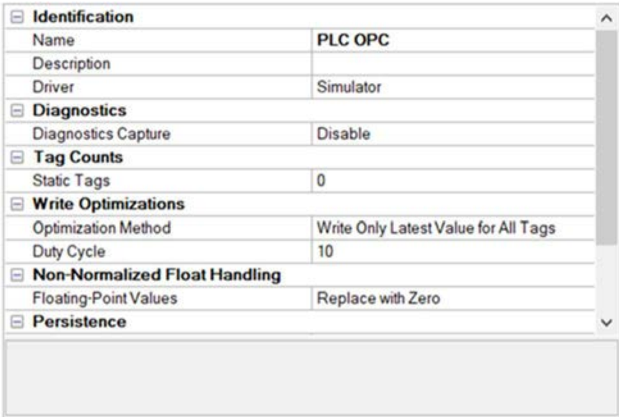
Figure 3 Creating a "New Channel"

The subsequent stage involves providing a name for the object and specifying its identity. This step requires entering the name of the object.

While configuring specific program options, it is crucial to determine the approach for handling invalid floating-point numbers when transmitting data to the client. The default setting is "Replace with Zero", which replaces any invalid floating-point numbers with zero [7].

Furthermore, the option for Item Persistence needs to be adjusted to "Disable". This setting disables the persistence feature for the item, indicating that the item's state will not be preserved between system restarts or power cycles.

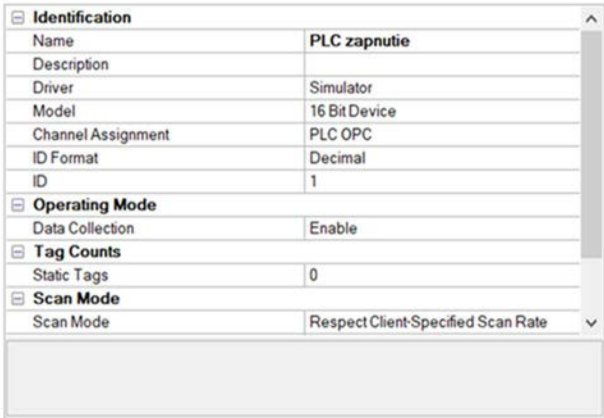
The final step in the settings options is defining the address where the information will be stored. This involves specifying the location or destination where the data will be stored for retrieval or further processing. A summary of the settings is shown in Figure 4.



Identification	
Name	**PLC OPC**
Description	
Driver	Simulator
Diagnostics	
Diagnostics Capture	Disable
Tag Counts	
Static Tags	0
Write Optimizations	
Optimization Method	Write Only Latest Value for All Tags
Duty Cycle	10
Non-Normalized Float Handling	
Floating-Point Values	Replace with Zero
Persistence	

Figure 4 Summary of set values and names

After creating a "New Channel", to which we set the name PLC OPC, click on this "channel" and create a "Device". Subsequently, it is necessary to set the specific device type, input format, and method (Figure 5).



Identification	
Name	**PLC zapnutie**
Description	
Driver	Simulator
Model	16 Bit Device
Channel Assignment	PLC OPC
ID Format	Decimal
ID	1
Operating Mode	
Data Collection	Enable
Tag Counts	
Static Tags	0
Scan Mode	
Scan Mode	Respect Client-Specified Scan Rate

Figure 5 Summary of set values and names

In the next step, we opened the production line in the Tecnomatix PlantSimulation program and assigned one of the production processes from the "Toolbox" in the "Information Flow" section called "OPC UA".

The use of "OPC UA" allows us to connect the PlantSimulation program and KepServerEX, enabling communication between these programs. After adding "OPC UA" to the production program, we right-clicked on the KepServerEX program and selected the option "OPC UA Configuration" (Figure 6).

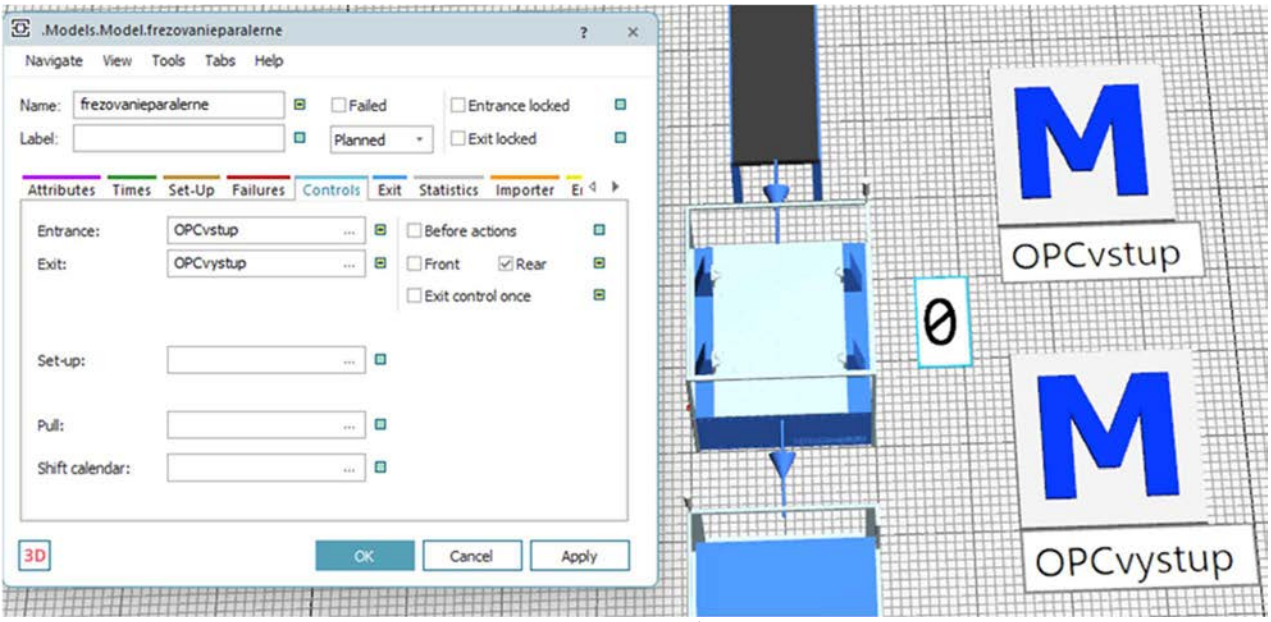


Figure 6 Allocation of methods

The "milling in parallel" process in the simulation will only be activated and the associated "CNC device" will be turned on if all four parts specified in the input arrive simultaneously. This condition ensures that the process starts only when all the necessary components are present [8].

Furthermore, the simulation involves a PLC (Programmable Logic Controller) that establishes a signal connection between the Tecnomatix Plant Simulation program and the physical CNC model. This enables the simulation to interact with and control the real CNC machine based on the defined conditions and inputs (Figure 7).

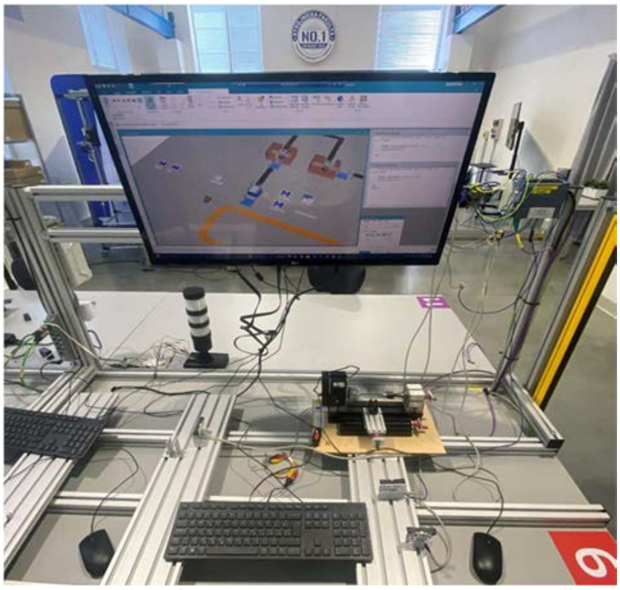


Figure 7 Means for the implementation and connection of the simulation with the real environment

3 Conclusions

The objective of the project was to model and simulate production processes in collaboration with TestBed 4.0 laboratory technologies. To achieve this, the Tecnomatix Plant Simulation program from Siemens was utilized to create a visual representation of a custom production line. The setup of the entire production line was then described in a step-by-step manner.

In the TestBed 4.0 laboratory, efforts were focused on establishing a connection between the Plant Simulation program and the Programmable Logic Controller (PLC) using KEPServerEX. This involved creating a server using KEPServerEX and establishing communication between it and the Tecnomatix Plant Simulation program to facilitate data transfer and communication. This integration allowed the project to achieve its goal of connecting Plant Simulation with the PLC, as well as integrating CNC equipment into the system.

The outcome of this work is a functional link between the simulation environment and the real-world production setting. This connection adds value to the simulation environment by showcasing its capabilities in a practical context, thereby bridging the gap between simulation and reality.

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Photogrammetric 3D digitization of the human head

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Keywords: photogrammetry, measurement, walk-around method, head digitization.
Abstract: The paper deals with the use of photogrammetry in the digitization of living objects, specifically it is focused on creating a 3D model of the human head by the walk-around method with the using 1 camera. The RealityCapture software (CapturingReality, Slovakia) was used to create the digital model, the output of which is a head model with a realistic texture with sufficient details. Using the GOM Suite 2019 software (Carl Zeiss, Germany), selected anthropometric measurements of the model were carried out before comparing them with those obtained using traditional measurement of a living subject, which we considered the reference. According to the results, the obtained head model contains sufficient details (face surface, texture). The results show that the values obtained from the 3D model differ from the reference values from 0.1 to 1.8 mm with average value 0.637 mm and standard deviation 0.471 mm. The differences between physical measurement and 3D model are lower than 2 mm. Photogrammetry is applicable for field of anthropometry, medicine, technical orthopedy and other, because the results of measurement do not differ significantly from the reference measurements.

1 Introduction

It is possible to digitalize humans or human body parts for various reasons, for example, for use in medical training and education process (anatomical models) [1]; defects or deformities detection, in the orthopedics (disease diagnosis, monitoring of treatment), creation of orthopedic-prosthetic devices (materials for orthoses, prostheses) [2-7]; anthropometry (human morphometric parameters) [8] and others. The current trend of digitization offers various possibilities how to obtain a 3D digital model. These methods can be structured light scanning, triangulation laser scanning, photogrammetry and more. Photogrammetry is the applied science of using photographs to represent an object in 3D (three-dimensional reconstruction of an object in digital or graphic form), which combines the advantages of photographs, videos, and computerized models while avoiding most of their drawbacks. The basis of photogrammetry is the image, which is, under certain conditions, the exact central projection of the photographed image. In photogrammetry, 2D photographs of an object are taken at varying angles and then overlaid using computer software to generate a 3D reconstruction. The software is used to identify common points between images taken at differing angles and then to overlay the images by matching their common points [1]. This method can be used as an alternative to conventional 3D scanners.

Photogrammetry offers several advantages for creating digital 3D models. First, this process is relatively inexpensive and available to the public, with mobile phone and freeware solutions being sufficient. Second, photogrammetry creates authentic models by generating 3D images from digital photographs. This authenticity surpasses most computer models, which often simplify fine anatomical features. Third, photogrammetry does not damage physical models, nor rely on grayscale or cross-section data to create 3D models. Finally, photogrammetric models are digital and can therefore be distributed indefinitely and do not degrade over time [1].

The following basic rules must be observed when taking photos for photogrammetry:

1. Focusing and zooming - It is recommended to use a fixed focus lens, zoom lenses are less stable than fixed focal length lenses. If a zoom lens is used a constant focal length must be maintained.
2. Lighting - Affects shutter speed and ISO value. In the case of lower light intensity, it is advisable to increase it with artificial lighting. Proper lighting reduces noise and reduces the time it takes to take a picture. It is recommended not to use the flash due to inhomogeneous light distribution, possible reflection on the surface of the subject and the formation of shadows [10].
3. White Balance - White balance ensures accurate interpretation of the object's surface by correcting the chromaticity temperature of the light.

4. Photo Overlap - It is recommended that adjacent photos overlap by 20 to 50% to correct for optical system errors and identify tie points.
5. Shooting distance - depends on the dimensions of the subject and the lens used.
6. Scanning method.

The size, shape, color and surface of the object have a significant effect on the sensing and the result of the reconstruction. The size of the subject affects the shooting distance and the lens used. The amount of detail (fragmentation of the object's surface, chamfers, rounding, holes of different diameters and depths, etc.) affects the number of images needed to digitize the object. The color and surface place the requirements on the lighting of the object and a sufficient contrast with the background must be ensured.

In addition to the light intensity and the background also affects the shooting. It is suitable to provide a one-color and contrasting background (most often green).

Compared to acquisition of inanimate objects, capturing a 3D image of a human head is more critical; in fact, it is necessary to "freeze motion", that is, to avoid the breathing and movement effects. If images are captured at different moments, errors may occur due to large movements (change of head position) or minor movements (muscle activity, change of skin or hair surface) [11, 12]. Also, the head area is the part that is rich in hair (hair, tertiary hair), which can cause additional problems in modeling.

The aim of the paper is to determine the suitability of photogrammetry for human head scanning and to determine the accuracy of scanning using the methodology and equipment for its subsequent use to obtain anthropometric data for other applications, e.g., technical orthopedics, education, medicine, etc. This article demonstrates the entire process of creating a 3D model through photogrammetry using only 1 camera by the walk-around method, highlighting the economic relevance of this method of creating 3D models.

2 Methodology of experiment

The experiment was carried out on a living object, which was a young Caucasian woman who was acquainted with the conditions of the experiment and signed an informed consent. The experiment procedures involved non risk to participant therefore research ethics committee approval was not necessary. The object of measurement was the human head, the facial area and the brain part of the head. This area of the human body has been chosen for its wide range of sizes, textures, shapes and contours. The position of the subject's head during capturing is oriented in the Frankfurt horizontal. The subject's face without any make-up during the experiment and relaxed without significant facial expressions, the view is forward. The hair was adjusted so that it did not cover the face and so that the hairline and the ear were visible. Before scanning, it is recommended to remove from the scanned area all objects (jewelry, glasses, etc.) that could affect the scanning, data processing and evaluation.

A Canon EOS 70D digital SLR camera (Japan) with a Canon EF 50mm f1 / 4 USM lens (Japan) with a fixed focus was used to capture the subject. RealityCapture software (CapturingReality, Slovakia) was used to process the images and generate the 3D model. The measurement of the model created by photogrammetry was performed in GOM Inspect 2019 software (Carl Zeiss, Germany) certified by PTB and NIST. The physical object was measured with a Somet caliper (Czech Republic).

Capturing was performed outdoors with natural lighting (bright sunny day) and without artificial additional lighting. When taking craniofacial parameters, the subject sat on a 45 cm high chair and the position of his head was oriented in the Frankfurt horizontal. Due to the shape of the object and its texture, control points were placed on the irises of the eyes (Figure 1). The face parts were photographed after the moment of person blinked. Throughout the shooting were used ISO 100, f8 aperture, and a shutter speed of 1/80.

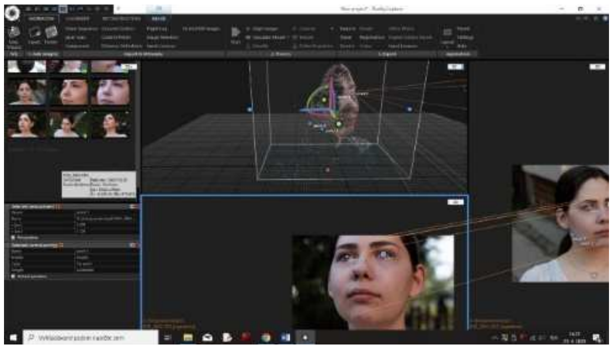

Figure 1 Checkpoints located on the irises of eyes

The person was photographed using the object walk-around method (Figure 2). To ensure stability, the camera was placed on a tripod. The images were created in three levels. In each level, 4 images with a spacing of approximately 90° were taken around the circumference of the imaginary circle. In the first level, the axis of the camera was horizontal to the ground and the camera was at head level at a height of 120 cm. In the second level, the camera was 145 cm high and the camera axis was rotated 30° downwards. In the third level, the camera was 95 cm from the ground and the camera axis was moved 30° upwards. At the same time, the approximate distance of the camera to approximately 100 cm from the subject was maintained. In this way, 12 photographs of the head were taken. In order to capture the details, 6 more photos were taken, which focused on the ear area and more complex removable areas of the neck and chin.

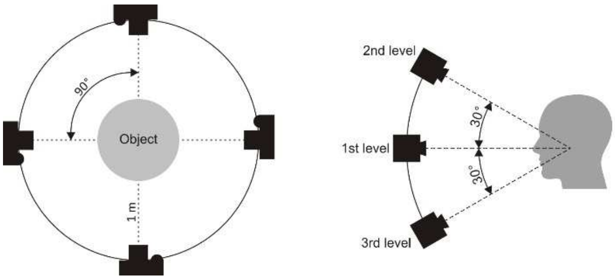

Figure 2 Head scanning scheme, top view and side view

2.1 Processing of acquired images

All acquired images were processed and visually evaluated in RealityCapture software, the resulting models were exported to *.obj format for measuring dimensions in GOM Suite.

The resulting model was created from 6,211,995 triangles and 3,106,561 vertices. Figure 3 on the left shows the non-textured STL head model in GOM Suite and the textured head model in RealityCapture. Different orientations of the used software are visible, in GOM Suite obtained surface is visible after merging individual images, in RealityCapture the surface structure is suppressed by the texture of the object.

Figure 3 Display of STL model in GOM (left) and model in RealityCapture software (right)

When creating a textured model in RealityCapture software, there are visible hair reconstruction problems (Figure 4 left), which the software cannot process as very thin objects. Other problematic parts of the model were the chin and neck area, where holes in the model were created due to insufficient number of overlapping points (Figure 4 right). Other problems in the model are in the neck area, which were caused by incorrect alignment of the photos.

Figure 4 Surface defects in hair, chin and neck

In the GOM Suite software, minor defects can be seen all over the surface of the model without texture, resulting from the insufficient number of images and from the errors caused by composing photos or by calculating the geometry (filling the holes) when exporting from RealityCapture software. These errors are reflected in the uneven surface, mainly in the cheeks, chin and neck.

2.2 Dimensional analysis

On the basis of the obtained scan was created coordinate system, while the basic conditions for maintaining the position of the head were observed.

Measures of selected anthropometric head parameters (Figure 5) (ear length and width, eye length, internal corners distance, head width, lower jaw width, head height, nose width and height) as reference measures were obtained manually using caliper to verify the accuracy of the scan. Manual measurements were performed three times after that arithmetic average were calculated. The model dimensions were taken using the GOM Suite 2019 software. Surface points were placed on the locations of individual anthropometric points using the "Surface Point" function. The direct distance between the individual points was measured using the "2-Point Distance" function (eg nose width, distance of the inner corners of the eyes), the other distances were measured in the direction of the individual axes and recorded in the table. Obtained values from physical measurements were compared with the values taken from the photogrammetric model.

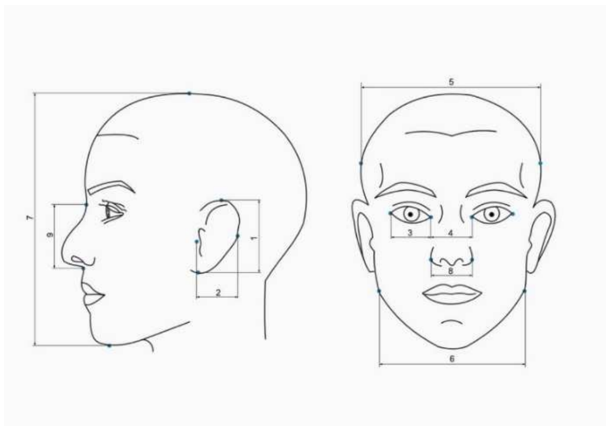

Figure 5 Selected anthropometric measures of the head

3 Results and discussion

Table 1 shows the differences between the physical object (reference model) and the 3D model. The differences are calculated as subtraction of dimensions measured on 3D model and dimensions measured manually.

Table 1 Matrix of length

	Measured dimension	Difference (mm)	
		Right	Left
1	Ear length	0.102	0.516
2	Ear width	0.278	0.456
3	Eye length	0.232	–0.259
4	Intercanthal distance	0.468	
5	Head width	0.835	
6	Mandibular width	–0.951	
7	Head height	1.813	
8	Nose width	–0.820	
9	Nose height	0.924	

The results show that the values obtained from the 3D model differ from the reference values from 0.1 to 1.8 mm. The difference between the values takes on a positive and a negative sign, so it is not possible to claim that the model is neither reduced nor enlarged. Minor deviations came out on the right side of face, the left side is affected by the reconstruction of the surface, where the surrounding hair caused the surface to deform. Dimensions at head width and height could be affected by hair, nose width and height, lower jaw width could be affected by soft tissues or inaccurate identification of anthropometric points.

A 3D model of the head was produced using the walk-around method, which presents the disadvantage of increasing labor-intensiveness, since photo equipment must be moved around while maintaining the distance between it and the object. In this way, the object remains stationary, considerably reducing the risk of movement, but it increases the capturing time, that can lead to possibility of increasing the movement risk. To achieve higher quality and resolution of the model and textures, the object could be rotated. By rotating the subject (for example, sitting on a swivel chair), the risk of the subject moving is increased, but the capturing time decreases. However, this is a more expensive solution, as it requires a monochrome background, tripod, turntable and additional lighting.

In practice, the traditional method of direct measurement of anthropometric parameters is still the most used. Measurements done by direct method are simple, noninvasive, and do not require expensive equipment [10]. Certainly, a benefit of this technique is the possibility of palpating individual anthropometric points, but soft tissue compression can cause deviations as well. Inconvenience, time consumption, and experience are disadvantages. On the other hand, measuring with software has the advantage of being non-contact, it nevertheless requires experience, and its major disadvantage is the more challenging measurement of anthropometric points. There is a partial solution in the form of manual palpation and labeling on the skin, which is then followed by scanning.

To improve the connection of the images, it is advantageous to use morphological features on the face (checkpoints). A checkpoint is chosen according to the morphology of the face and the unique identification points. Studies often use the pupil as reference points. In the case of a darker iris, their identification is complicated. For this reason, irises have been chosen as reference points for our purposes. The disadvantage of choosing pupils or irises is their response to environmental stimuli (movement). The solution would be to choose these points on the facial skin.

The control of mimic movements and breathing is essential when scanning the head, as they can significantly affect the composition of individual images. The biggest problem is capturing and then creating a model from an area with hair, because defects on the model and textures occur in these places. The solution could be to fix the hair with a hat or hair net.

Based on 3D scanning experiences of children's faces photogrammetry is more suitable method for scanning children since the flash is not used because of sufficient lighting and child does not respond to flicker as it is at most 3D scanners. Additionally, this scan does not take place in a dark closed environment like some 3D full-body scanners. The above information indicates the suitability of this method for people with various diseases, where the use of 3D scanners is limiting.

4 Conclusion

The living object model provided an effective interpretation of the surface and texture of the subject's face.

The data were processed in the RealityCapture software, where the images were combined into one object. The 3D model with texture was created and the data was exported for measurement in the GOM Suite. Empty areas were showed during processing, due to low number of images (12 photos). For this reason. another 6 images were taken from the problem areas. filling in the empty areas and improving the quality of the details. In order to improve the composition of the images, the irises of the eyes have been designated as control points, but it is necessary to ensure their stability by focusing on the selected point.

An anthropometric map was used to measure dimensions in the GOM Suite program. According to the results, the largest deviation is 1.8 mm compared to the manual measurement.

The differences between manual measurement and the measurement made on the 3D model may be related to soft tissue compression during manual measurement, as well as the ambiguous determination of anthropometric points on the model. There is less than 2 mm difference between the measurements, which is sufficient for most possible uses.

Based on the experience of creating a model using photogrammetry and the results of measurements, photogrammetry appears to be an effective tool for digitizing living objects and performing measurements on the model, provided that the conditions and optimization of imaging are observed. As a bonus, the person can have their eyes open when being photographed, thus capturing the color of their iris. The output model is sufficiently detailed and the obtained surface texture allows the model to be utilized for numerous purposes (medicine, criminology, anthropology, technical orthopedics and others).

The photogrammetric method can be used to scan various parts of the body. However, when it comes to shooting larger areas or the entire figure, the required equipment becomes quite complex.

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Repeatability and reproducibility of hydrogel 3D bioprinting

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Keywords: 3D bioprinting, biomaterial, printability, shape fidelity, extrudability.
Abstract: The study presents the basic terms of three-dimensional bioprinting and physical, chemical, and biological properties affecting the printability of hydrogel biomaterials. It deals with the principle of evaluating the quality of three-dimensional bioprinting. The goal was to design a procedural algorithm to analyze prints produced by extrusion 3D bioprinting critically. Forty-one cylindrical scaffolds were created experimentally from the same material and under varying printing parameters. The settings of the most plausible sample compared to the CAD design were used to 3D bioprint ten cylindrical samples. Analysis of measurement system (ASM) with three operators was used for evaluation. The results showed that the printability measurement system is conditionally suitable. At the same time, the methodology for evaluating the shape similarity of samples through macroscopic pore classification requires re-evaluation and further experiments.

1 Introduction

Three-dimensional (3D) bioprinting is a multidisciplinary field of science, enabling the creation of heterogeneous objects and complex biological structures based on a digital CAD model through additive manufacturing processes [1]. Thanks to the high level of structure and composition control, it has the potential to solve a diverse demand in medical research and practice, including applications in testing cosmetics, drugs, or therapy. At the same time, its primary and long-term goal is the development of fully functional organ and tissue substitutes. Current applications include bioprinting of skin, ear, and cartilage, research in the cardiovascular and gastrointestinal areas, nephrology, etc. [1,2].

We divide 3D bioprinting into cellular and non-cellular based on the printing material. [1, 3] In the cellular method, the cells are always incorporated into the printing material, i.e., bio-ink. The printing of hydrogel scaffolds replacing intercellular mass (ECM) imitating organic microstructure is mainly used here. The advantage is the spatially controlled placement of cells in a defined 3D microenvironment [4]. Cells can be, e.g., encapsulated and printed simultaneously with the scaffold. [5] By the term scaffold, we mean supporting structures made of synthetic or natural materials on which cells with the potential to replace damaged tissue can be grown [4-6]. In bio-ink, supervision over factors threatening cell viability is essential. There is another approach, without a scaffold, mimicking embryonic development. In acellular printing, the term biomaterial is used to produce objects, e.g., scaffolds. The most common are hydrogels.

Much attention is focused on formulating knowledge and principles regarding hydrogel bioprinting, and a consensus is being sought between print quality assessment criteria. The terms discussed are printability, continuous extrudability, print accuracy, precision, microstructure, and structural integrity [5].

The fundamental factor is printability, which characterizes the term evaluating the difference between the designed (CAD) and the printed construction [3]. It includes the mechanical properties of the ink, allowing it to pass through the nozzle (rheology) [4] and the application of individual layers (extrudability) to each other, according to a pre-planned code (g-code). This term includes the entire process from the programming phase (CAD design, choice of ink, slicing, g-code) through creating the construct (printing parameters, cross-linking, etc.). At the same time, the shape fidelity of the object is also influenced by the type of bioprinter and, in addition to the material's rheological properties, the shape and diameter of the nozzles [4]. The difference between the design and the created object may be due to the printed bio-inks extrudability and the printed constructs' structural malleability and stability [5]. Shape fidelity is the degree to which the 3D printed structure matches the size and spatial location of the original CAD model in terms of geometry.

Additive manufacturing based on hydrogels is challenging in terms of the variable physicochemical behavior of the printing material. Considering the problematic 3D bioprinting, the presented study aims to propose a general procedural algorithm applicable when introducing a new biomaterial for the critical analysis of prints.

2 Methodology

Tools: Cellink BIO X bioprinter; biomaterial Start Cellink; cartridge 3ml; conical nozzle 22G; SolidWorks (CAD); Slic3r (G-code); SW CorelDraw (vector graphics editor), ruler; camera (iPhone 14 Pro) with tripod, laboratory slides.

The measurement was carried out in one day at the average temperature of the environment in the laboratory (T≈23.5°C). The used Start Cellink biomaterial has a storage temperature of up to 25°C.

2.1 3D bioprinter and biomaterial

Cellink BIO X is a bioprinter based on pneumatic extrusion with an integrated compressor, UV-C germicidal lamps, a HEPA H14 double filter system, three print heads (hotends) with integrated heating elements with a thermistor, proximity sensor, cooling, and others.

CELLINK START Biomaterial* (Polybutylene succinate (PBS; polytetramethylene succinate; Polypropylene oxide) is a thermoplastic polymer resin (polyester). Biodegradable resin. It is a water-soluble gel that supports cell-laden constructs, bio-inks with poor shape fidelity and constructs with porosity along all three axes. For use as bioink in 3D Bioprinting, cell encapsulation and delivery, tissue engineering and regenerative medicine, biomedical devices, drug delivery for research. Not for human use, for research only.

3D model, a simple cylindrical scaffold with a diameter of 10 mm, a height of 3 mm, 20% rectilinear filling pattern.

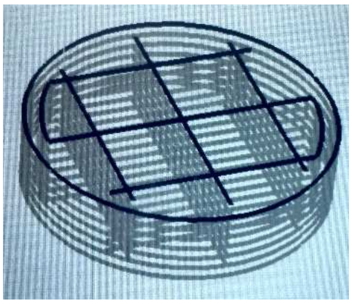

Figure 1 Visualization of cutting a 3D model in SW Cellink BioX

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2.2 Procedure Algorithm of Print Evaluation

Goal: Creation of a print protocol [7,8] for a specified sample 3D model and biomaterial. (1) Forty-one cylindrical scaffolds were printed. Each with different print settings. Experimentally, pressure (25-45 kPa), temperature (30-32 °C), and speed (16-20 mm/s) were varied. (2) Selection of the best print based on macroscopic observation of extrudability and conformation. (3) Repeatability: 3D bioprinting of ten samples with the same print settings. (4) Imaging of the created scaffolds (n=10) from a predefined perpendicular distance to the top surface of the object (TOP). (5) Measurement System Analysis (MSA).

2.3 Procedure Algorithm of Print Evaluation

The aim is to assess the extrusion and acceptability of the measurement system in terms of repeatability and reproducibility (R&R). The samples were evaluated by three operators (h=3). Ten models (j = 10) were produced for testing, all under the same printing parameters. Each operator evaluated each piece twice (k=2) using pre-agreed measurement templates for the assessed indicators. The data obtained during the patient survey were first processed using descriptive statistics. In the tables, the absolute abundance (n) is always indicated, which indicates the number of samples from the total number of samples in the examined set, and the relative abundance (%), which indicates the relative number of samples and the total extent of the set represents 100% [9,10]. Descriptive data analysis was followed by data analysis using inductive statistics methods. Working hypotheses were established, the validity of which was verified by the Shapiro-Wilk Test. Both tests verify the null hypothesis H0, which states that there is no statistically significant dependence or difference between the obtained and expected values. For each null hypothesis H0, there is an alternative hypothesis H1, which, on the contrary, claims that there is some statistically significant (significant) dependence, or difference, between the obtained and expected values. The result of both tests is the p value, the so-called p-value. If the p-value is less than the significance level α, i.e. $p < \alpha$, we say that it is possible to reject the null hypothesis H0 [9,10]. This means that there is some statistically significant dependence between the obtained and expected values, or a difference that could not be caused by chance. In case $p > \alpha$, we say that we cannot reject the null hypothesis H0. This means that there is no statistically significant (significant) dependence or difference between the obtained and expected values. The significance level α in these tests represents the probability (error rate) with which we reject the null hypothesis even if it is true. The α

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value was set at 0.05, i.e. 5%. Data pieces of information obtained from the prints are quantitative.The measurement system characteristics were calculated based on the obtained data, such as linearity, accuracy, stability, R&R, and discrimination.

Acceptability of the measurement system:

- R&R < 10% is fully compliant
- R&R = 10%– 30% conditionally acceptable
- R&R > 30% is not satisfactory and needs improvement.

3 Results and discussion

Printability, see Figure 1. Using the B-spline in the CorelDRAW graphics software, the outline of the first and bottom layers was made, which were then dimensionally compared with the CAD design. A six-level rating scale in the interval <0 was used to evaluate the printability of the print; 6>, where 0-unusable, 1-very bad, 2-bad, 3- average, 4-good, 5- very good, 6- consistent with CAD design.

The Shapiro-Wilk test showed a significant departure from normality, W(30) = .91, p = .015, see Figure 3.

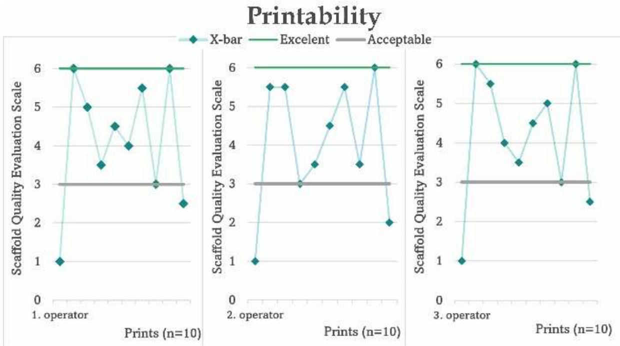
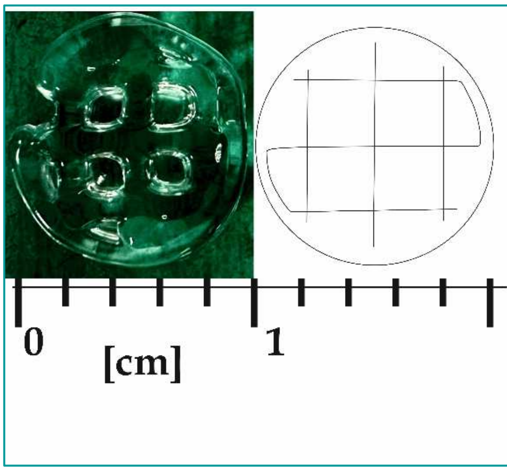


Figure 2 Printability Rating



X-bar	
Mean	4,067
Standard Error	0,290
Median	4,250
Mode	6
Standard Deviation	1,591
Sample Variance	2,530
Kurtosis	-0,736
Skewness	-0,502
Range	5
Minimum	1
Maximum	6
Sum	122
Count	30

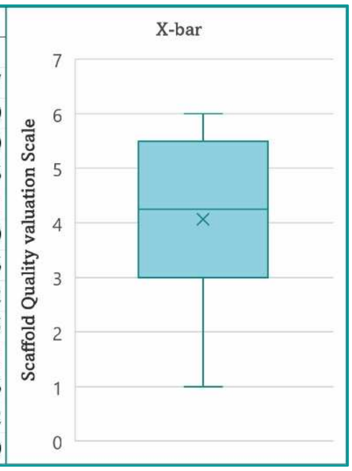
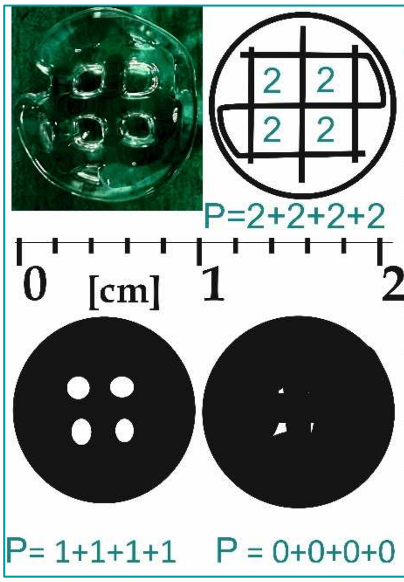


Figure 3 Printability rating



X-bar_porosity	
Mean	6,167
Standard Error	0,413
Median	7,250
Mode	8
Standard Deviation	2,264
Sample Variance	5,126
Kurtosis	0,514
Skewness	-1,267
Range	7
Minimum	1
Maximum	8
Sum	185
Count	30

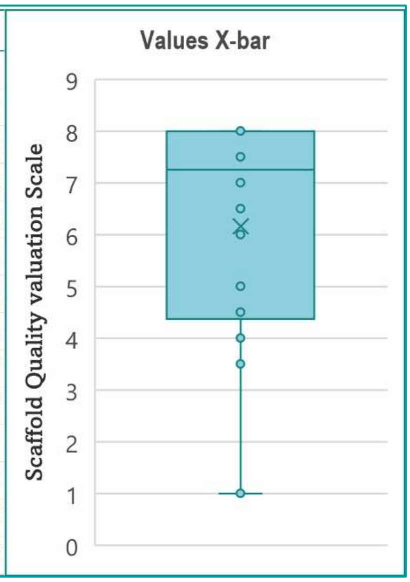


Figure 4: Evaluation of shape similarity

Evaluation of the shape similarity, see Figure 4-5. A three-level evaluation scale in the interval <0 was used to evaluate the shape of the printout with the CAD design; 2>, where 0-unusable, 1-average, 2-very good. The evaluation of one pore was defined by the difference of the bottom surface and the last top surface of the pore. Each was traced with the b-spline vector function in SW CorelDRAW. Four central pores were scored on each print.

The Shapiro-Wilk test showed a significant departure from normality, $W(30) = .78$, $p < .001$, see Figure 4.

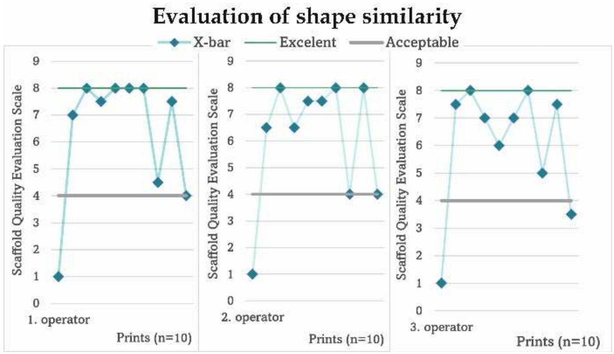


Figure 5 Evaluation of shape similarity

4 Discussion

Macroscopic observation of the internal structure, focusing on the spatial shape and the presence of visible pores, pointed out the problematic reading of the result. According to previous studies, the printability of hydrogel materials depends on rheological properties such as viscosity, shear stress or slip limit, as well as on the crosslinking process. Viscosity [3,11,12], i.e. the resistance of the fluid to flow during the application of stresses, or as the ratio of shear stress to shear rate, can be identified as the main factor affecting printability, print accuracy and shape fidelity. The viscosity of hydrogel inks can be influenced by temperature, molecular interactions and the molecular weight or concentration of the polymer [3]. In order to determine the exact parameters of 3D bioprinting and crosslinking of hydrogels, it would be interesting in the future to continuously monitor the temperature in the room and at the same time verify the viscosity of the biomaterial. Alternatively, look for other connections causing deformation of the structure of the printout.

5 Conclusions

The main goal of the study was the compilation of a procedure algorithm for the introduction of new materials and the evaluation of the set measurement system. The results pointed to the fact that, despite the same conditions, 20% of the prints did not reach the required external dimensions according to the set pattern (uniform cylinder 10x3 mm). Statistical analysis calculated the percentage of total variability for R&R extrudability of 29.5%, i.e., the measurement system is conditionally suitable. The R&R shape similarity evaluation was 41.4%, which means that it is necessary to revise the methodology for evaluating the similarity of samples.

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Methodology of CAD design and CAM production of transtibial prosthetic sockets

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Keywords: prosthetic socket, transtibial socket, CAD/CAM, 3D scanning, Fused Deposition Modeling.
Abstract: The digitization of the design process of lower limb prosthetic sockets seems to be necessary. Using modern CAD procedures and CAM technologies, it is possible to produce functional, individual prosthetic aids that bring many benefits compared to commonly used methods. However, the disadvantage of using CAD/CAM procedures can be the input costs for production technology and software. The aim of this research is to propose a low-cost solution for individual transtibial socket design and production. Modern methods and technologies like 3D scanning, CAD design and additive manufacturing have been applied. As a result, a transtibial stump positive and custom socket design methodology is proposed. In conclusions a total value of a custom transtibial socket design and production was calculated.

1 Introduction

The current trend in various areas of medicine and rehabilitation is the digitization of measurement and production processes using software applications. In the field of prosthetics and orthotics in the Slovak Republic, however, conventional methods of designing and manufacturing lower limb prosthesis sockets still prevail. Despite the significant progress in medicine, the number of amputations performed has a constantly increasing tendency, while the number of amputee patients in Europe is expected to increase from the current number of 750-850 thousand to 3,5-4 million individuals over the next 15 years. Among the most common indications that lead to this rapid increase in planned amputations of the lower limbs are diseases such as diabetes mellitus, ischemic disease of the lower limbs, cancer and amputations as a result of trauma. The number of amputations due to civilizational diseases will continue to increase due to the aging of the population. Approximately 70-80% of amputees are older than 50 years, and in 75-80% of cases, amputations of the lower limbs are involved [1,2].

For these reasons, digitization of the design process of lower limb prosthesis sockets seems to be necessary. Using modern CAD (Computer Aided Design) procedures and CAM (Computer Aided Manufacturing) technologies, it is possible to produce functional, individual prosthetic aids that bring many benefits compared to commonly used methods [3-7]. The main advantages are lower costs for the production of prosthetic devices and a fast, non-contact and wasteless device development process [8]. However, the disadvantage of using CAD/CAM procedures can be the input costs for production technology and software, which can be discouraging for CPOs (certified Prosthetist Orthotist) and O&P (Orthotic and Prosthetic) companies from lower income countries like Slovakia.

The aim of this research is to present the use of the freely available CAD software Meshmixer (Autodesk Inc., San Francisco, U.S.A.) for the design of individual transtibial sockets of lower limb prostheses, which are suitable for production through the low-cost FDM (Fused Deposition Modeling) additive manufacturing technology.

2 Methodology

The design of an individual transtibial socket of the lower limb prosthesis in Meshmixer software consists of 2 steps:

1. Editing of the obtained 3D scan of the stump and creation of an individual positive.
2. Design and creation of a 3D model of the transtibial socket.

2.1 *Editing of the obtained 3D scan of the stump and creation of a virtual positive*

A low-cost handheld optical 3D scanner Creality CR-SCAN 01 (Creality 3D Technology Co., Ltd., Shenzhen, China) is used to acquire the positives. The resolution of the device must be sufficient for use in the field of prosthetics and orthotics [9-11]. With the help of a 3D scanner, the topography of the place of interest is obtained, in this case it is the area of the stump on the lower limb. Some types of 3D scanners can also record the texture (color) of the scanned surface, according to which we can divide the methodology into:

a. Creation of an individual positive without texture,
b. Creation of an individual positive with texture.

Before the actual scanning, it is advisable to wrap the area of interest with food foil in order to create a stump surface with overall surface compression. If it is a scan with a 3D scanner capable of recording texture, it is possible to mark the cutting line of the proposed socket and compression and relieved places on the foil-wrapped stump with a marker. It is also possible to highlight sensitive or painful areas. These sketches on will be helpful in creating an individual positive.

Correct positioning of the given segment is important during scanning. The positioning of the subject depends on the type of scanned stump. When scanning the transtibial stump of the lower limb, it is necessary for the scanned subject to sit and have the segment of the given limb in extension. Subsequently, a scan is performed in the transverse plane of the segment in order to capture the surface of the residual part of the limb. Emphasis is also placed on the distal end.

The obtained 3D scan of the stump of the residual limb, exported in the correct format, is further modified in a suitable CAD software. This 3D scan model is used to create a virtual positive of the stump on which the CAD socket of the prosthesis is designed.

2.1.1 Creating an individual positive without texture

First of all, it is necessary to remove artifacts and unnecessary areas of the obtained 3D scan model (Figure 1-1). Subsequently, the reduction is applied to the given model:

1. 3-5% in the transverse plane (XY plane) for the entire 3D model.
2. 5% to the distal end (approx. 5-7 cm long) longitudinally to the axis of the bone.

After performing the reduction, it is necessary to generate loadable and relieved places (Figure 1-2). A negative extrusion of -3 mm is applied to generate load-bearing areas and a positive extrusion of +1,5 mm is applied to unloaded areas (Figure 1-3). It is important that the borders of these places have smooth transitions to the undeformed zones of the positive (Figure 1-4). Finally, it is possible to make a superstructure on the dorsal side of the positive (Figure 1-5), which is positioned individually according to the shape of the positive. After the final inspection and final smoothening of the details, it is possible to start designing the 3D model of the socket (Figure 1-6).

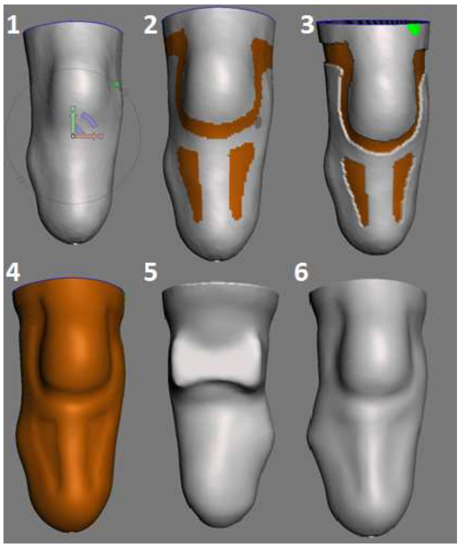

Figure 1 Editing of the obtained 3D scan of the stump and creation of a virtual positive

2.1.2 Creating an individual positive with texture

First of all, it is necessary to remove artifacts and unnecessary areas of the obtained 3D scan model. Subsequently, the reduction is applied to the given model:

1. 3-5% in the transverse plane (XY plane) for the entire 3D model
2. 5% to the distal end (approx. 5-7 cm long) longitudinally to the axis of the bone

After the reduction is done, it is necessary to generate the loaded and unloaded places using the sketches captured on the 3D models of the scan (Figure 2-1). Negative extrusion with a value of -3 mm is applied to the load-bearing areas and positive extrusion with a value of +1,5 mm for relieved areas (Figure 2-2). It is important that the borders of these places have smooth transitions to the undeformed zones of the positive (Figure 2-3). After the final inspection and final smoothening of the details, it is possible to start designing the 3D model of the socket.

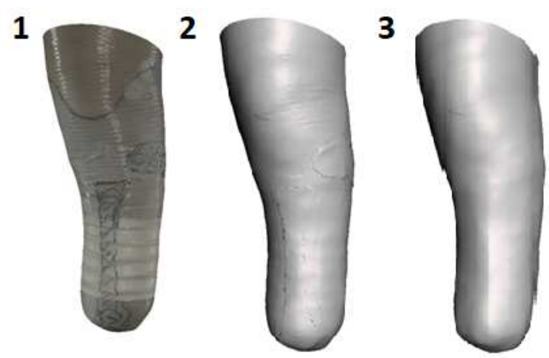

Figure 2 Creation of a virtual positive from a scan 3Dmodel with texture

2.2 Design and creation of a 3D model of the transtibial socket

Design of an individual transtibial socket can be made by 2 methods, according to the method of virtual positive creation. These methods are:

1. Design and creation of a 3D model of a transtibial socket from a positive without texture.
2. Design and creation of a 3D model of a transtibial socket from a positive with texture.

2.2.1 Design and creation of a 3D model of a transtibial socket from a positive without texture

The process of creating a transtibial CAD socket from a positive without texture (Figure 3) consists of 5 steps:

1. Sketch of the cutting line of the socket and marking of the inner surface of the socket.
2. Formation of the inner surface of the socket (extraction of the obtained inner surface of the socket from the virtual positive by a distance of 0 mm).
3. Creation of a 3D model of the socket and separation of the 3D model of the socket from the positive (displacement of the obtained surface by a value of +3 mm).
4. Creating a hole for the valve (inner diameter of the hole = 10 mm, outer diameter of the hole = 13 mm).
5. Surface smoothing and final inspection.

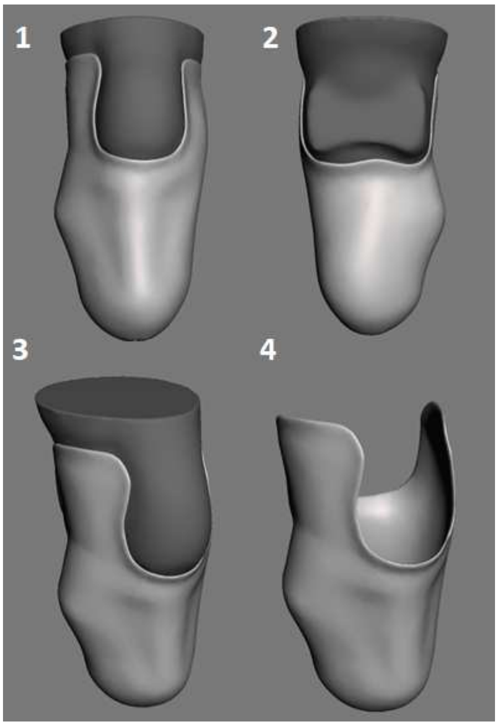

Figure 3 3D model of the transtibial socket (1 – front view, 2 – rear view, 3 – side view, 4 – side view without positive)

2.2.2 Design and creation of a 3D model of a transtibial socket from a positive with texture

The process of creating a transtibial CAD socket from a positive with texture (Figure 4) consists of 5 steps:

1. Sketch of the cutting line of the socket and marking of the inner surface of the socket according to the sketch on the positive.
2. Formation of the inner surface of the socket (extraction of the obtained inner surface of the socket from the virtual positive by a distance of 0 mm).
3. Creation of a 3D model of the socket and separation of the 3D model of the socket from the positive (displacement of the obtained surface by a value of +3 mm).
4. Creating a hole for the valve (inner diameter of the hole = 10 mm, outer diameter of the hole = 13 mm).
5. Surface smoothing and final inspection.

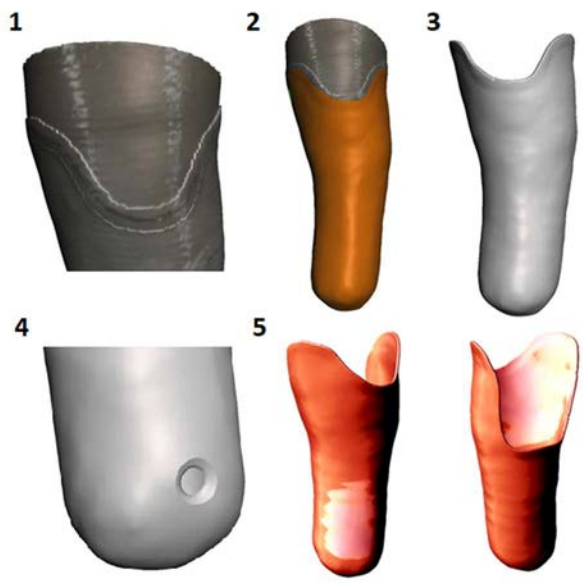

Figure 4 The process of creating a transtibial CAD socket from a positive with texture

2.3 Additive manufacturing of a transtibial CAD socket

The preparation of CAD models for additive manufacturing consists in uploading the model to the software intended for setting individual parameters of 3D printing. The choice of software depends on the additive manufacturing technology used. Since prosthetic sockets are designed for production using FDM technology, suitable software for setting printing parameters is, for example, freely available PrusaSlicer (Prusa Research, Prague, Czech Republic).

In the first step, it is necessary to choose the type of printer used for the production of the 3D model, the printing accuracy setting, the type of filament used for the production of the object and the density of the filling of the object being produced. After establishing these basic conditions, it is necessary to import a 3D model into the software interface. After importing the model, it is necessary to check and possibly overwrite the print settings. These can be set manually, or preset software parameters for the given material can be selected. The printing parameters change depending on the material used.

After choosing the printer, filament and printing parameters, it is necessary to correctly position the 3D model of the prosthetic socket. This type of model is oriented in a way that the axis of the model is perpendicular to the working platform of the printer (Figure 5).

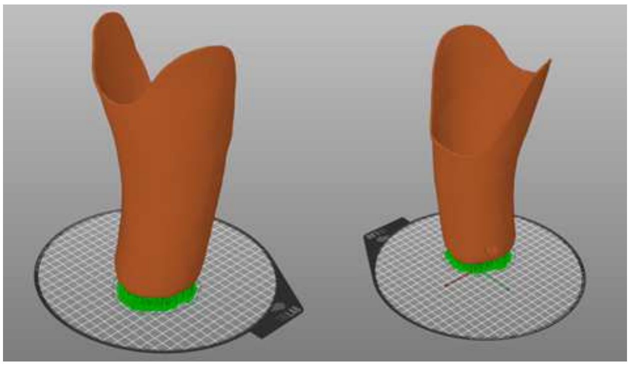

Figure 5 Correct positioning of the 3D model of the socket on the work platform of the FDM printer

3 Results and discussion

Since the data acquired while 3D scanning is used to design prosthetic devices, it is ideal to scan at the lowest possible frequency (minimum 3 fps) to avoid random errors during scanning and to reduce the amount of data acquired. The disadvantage is that these scanners are connected to the PC with cables. Therefore, it is recommended to have free space around the scanned subject for movement and manipulation of the scanner. It is advisable to perform a scan of the area of interest on the 1st attempt, which removes the random surface deformation of the 3D model during subsequent merging of multiple scans. For beginners, it is not recommended to interrupt the scan (by pausing) in order to avoid manual merging of the scans in the software, where the scans could be misaligned.

The parameters set in the individual transtibial CAD socket design methodology is stated based on the experience of CPOs in COP, s.r.o. company in Kosice, Slovakia. These parameters can vary depending on the specific subject, for which the socket is being designed for.

The individual positive of the transtibial lower limb stump creation methodology can be used not only as a basis for CAD socket design, but also for stump positive production using CNC (Computerized Numerical Control) milling machines. Using this technology it is possible to combine modern and traditional way of socket production.

Correct positioning of models on the 3D printer's virtual work platform is very important in terms of printing efficiency and output quality. Depending on how the model is positioned, the support structure is generated and the orientation of the layers is also determined. From that point of view, it is important to position the socket model so that no support structures are created on the contact surfaces of the models. Support structures can affect the quality of the surface in these places, which can deform the shape of the contact surface and thus negatively affect the overall quality of the model. However, the orientation of the layering is important in terms of the strength and quality of the model's surface. Since the possibility of breakage must still be taken into account between the individual layers, it is important to position the aids in such a way that cracks do not appear on the aid after the action of external forces (mainly bending). Layering also affects the local surface quality of the models. Since with FDM 3D printing, the accuracy is higher in the X and Y axes, the surface of the model is more accurate on surfaces oriented horizontally to the work platform.

When positioning the prosthetic socket model, it is important to orient the model so that the axis of the model is perpendicular to the working platform of the printer. In that case, no supporting structures will be generated on the inner surface of the socket, and due to the orientation of the layering, the contact surface will be of better quality. Since in the additive manufacturing of the prosthetic socket it is important that the surface quality is the greatest on the inner surface, it is important to position the model so that its distal end is in contact with the working platform and the socket walls are oriented perpendicular to it. In this way, no support structure is generated on the inner surface of the socket. With this positioning, due to the orientation of the layers, there will be no weak spots for bending, thus preventing the occurrence of cracks.

A total value of a transtibial CAD socket has been calculated, since the goal was to propose a low-cost solution for custom transtibial socket design and production using modern approaches. A total of 7 individual transtibial sockets have been designed by the proposed CAD socket design methodology. Data regarding the material and time consumption of designing and manufacturing these CAD sockets have been used to calculate and average value of a single transtibial CAD socket (Table 1).

The value of a 3D scan is around 50 euros for 1 hour, while the 3D scanning process of the lower limb does not exceed this length. Work with data, adjustment of the virtual positive and the design of the transtibial socket can be evaluated as a CAD modeling service, the value of which is usually in the range of 30-40 euros per hour. The design of the transtibial socket using the proposed methodology can be created in 1 hour, in a complicated case in 2 hours.

From this evaluation we can state that the value of a 3D scan and CAD design of a transtibial socket can be set at

80-120 euros, depending on the condition of the subject, for which the CAD socket is being made.

The price calculation using FDM technology was done with a setting of 100% density of the model filling with an activated support structure on the work platform. Materials selected for calculation:

a. PLA Prusament (27.99 euros per kg),
b. PETG Prusament (22.49 euros per kg).

Table 1 Individual transtibial socket material and time consumption by FDM production

Socket	Material weight [g]	Material lenght [m]	Time of production [hh:mm]
S1	206.59	69.27	23:36
S2	420.97	141.14	52:35
S3	296.25	99.33	35:24
S4	239.88	80.43	28:42
S5	234.20	78.52	28:21
S6	331.56	111.17	43:50
S7	279.68	93.77	35:17
Average	**289.59**	**96.23**	**35:23**

The approximate value of the material needed for transtibial socket production using FDM technology is 6.50 euros when using PETG (Polyethylene terephthalate glycol) material and 8 euros when using PLA (Polylactic acid) material. To this value, it is necessary to add the value of the preparation of the 3D printer, which is normally 3.50 euros per hour. Preparation can take 1-2 hours (max. 7 euros).

The final value is calculated by adding the maximum determined value of the CAD design to the average value by selected type of production using selected materials (Table 2).

Table 2 Total value of a transtibial CAD socket manufactured using FDM technology

Technology-Material	Design [euro]	Manufacturing [euro]	**Total [euro]**
FDM-PLA	120	15.00	**135.00**
FDM-PETG	120	13.50	**133.50**

4 Conclusions

From the statistical point of view the digitization of the design process of lower limb prosthesis sockets seems to be necessary. Using low-cost 3D scanning and CAD/CAM technology it is possible to design and produce individual transtibial sockets. As a result, a transtibial stump positive and custom CAD socket design methodology is proposed. From the calculation that has been made we can state a total value of a transtibial CAD socket design and production using low-cost CAD/CAM solutions. This value is important for CPOs or O&P companies for considering using the proposed methodology in their practice.

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