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Article

Low-Cost Method for 3D Body Measurement Based on Photogrammetry Using Smartphone

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Abstract: This paper is focused on the possibilities of data collection via photogrammetry methods, using smartphone cameras and post-processing. The aim of this paper is to refer to progressive technologies that are part of smartphone devices, which bring more performance and variability of usage year by year. The theoretical part starts with looking to the past, describing problems of measurements and solutions invented by famous mathematicians, which we use nowadays. The following section deals with the background of measuring the human body and photogrammetry. The next section is about measuring and using calibration methods. The results section presents the architecture design of the system and a visual representation of how the application works. The result of processing a 3D person is a data object with measurements in real world metric units with minimum deviation. The conclusion is that we created our own low-cost method for 3D body measurement which partially or completely removes the shortcomings that were identified during the review of similar solutions. Our method is based on the use of open-source libraries, the use of a single smartphone mobile device and the creation of a true 3D human body model.

Keywords: 3d measurement; photogrammetry; posenet; tensor flow; meshroom; neural networks

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1. Introduction

The process of taking measurements of various human body parts, such as the waist, hips, and shoulders, to name a few, is known as anthropometric measurement extraction. Medical science [1,2], clothes design [3], virtual try-on [4], internet shopping [5], and many other fields rely on these measurements [6]. Traditionally, anthropometric data collection has been done manually with a measuring tape by a trained operator [7,8]. This method, on the other hand, is time-consuming and costly, and its correctness is dependent on the operator's knowledge. Because of these factors, it can only be used for online tasks. Human beings may now be scanned using 3D scanning technology [9]. The captured scans, on the other hand, are frequently fragmentary and noisy. With the rapid advancement of scanning technology, various researchers have worked to develop contact-free automatic methods for extracting anthropometric data from noisy and partial scans. Data is one of the most important factors determining the performance of such approaches.

Comparison and competitiveness have been natural qualities of the human mentality since ancient times. Whether it is competition in business, sport or ordinary life, the human mind sometimes needs to perceive competition in order to gain enough motivation to make a full effort and thus achieve its goals. This phenomenon can also be sensed in the case of overtaking in the development of intelligent devices such as smartphones, where flagships are overtaken by ever higher quality and more progressive technologies.

The first smartphone is considered to be the Simon phone from IBM, when in 1994 they included the control of basic operations via a touch screen and the use of basic applications such as a calculator, calendar, mail, and so forth. Since then, technologies have moved to a far different level. Today, we have the ability to use a variety of applications and powerful hardware with excellent quality of performance, that is increased year by year. In the case of this progression and acceleration, software developers are able to always bring some new ideas to mobile applications, especially thanks to many kinds of data-input sensors and quickly improving cameras. Apple introduced a LIDAR sensor in their smartphone, the iPhone 12 Pro, which is a big deal for applications that are used for the measurement 3D objects or augmented reality. How can we deal with information like this?

Imagine that we can collect detailed data of the human body via smartphone camera. Thanks to these data, we can proceed according to the principles and knowledge of anthropology and the scientific field of anthropometry, and thus create a relatively simple method of performing measurements of the human body. Anthropometric measurements have a huge benefit, especially in medicine and sports but also in industries such as tailoring and fashion design. In medicine, thanks to this methodology, doctors can examine the differences and the development of a patient's diagnosis with special features of their body and thus improve the quality of treatment. In the field of sports, it is possible to examine the genetic predisposition of an individual and then it is possible to predict in what type of sport his type of figure can excel. Shopping for clothes online is very popular and convenient nowadays, but it also brings with it problems with estimating the right size.

The aim of the research is an application that will allow the user to perform measurements of the human body and will create the opportunity to generate a 3D model of their body based on images from the camera stream. These data are represented in a mobile application, which also includes the CMS application for user and data management.

2. Background of Anthropology, Anthropometry and Photogrammetry

This section provides explanations of basic concepts.

Anthropology is characterized by Echaudemaison as a broad set of disciplines that are related to man. It specifically includes disciplines such as biology, philosophy, economics and pedagogy, but also archeology, sociology and theology [10]. In practice, anthropology is used mainly as applied anthropology, thanks to the use of knowledge of human science, especially in sports, criminology (forensic anthropology) and industry. Thus, a person can be included in a suitable work process because of his natural physical and mental characteristics, in a place where he could best apply himself in human society as an individual [11].

Anthropometry is the study of the measurement of the human body. In its most basic form, anthropometry is used to help scientists and anthropologists understand physical variations between humans. Anthropometry is useful for a wide range of applications and provides some basis for human measurements. In modern times, anthropometrics have had more practical applications, especially in the field of genetic research and workplace ergonomics. Anthropometry also provides insight into the study of human fossils and can help paleontologists to better understand developmental processes.

Typical body measurements used in anthropometrics include height, weight, BMI, waist to hip ratio, and body fat percentage. By studying the differences in these measurements in humans, scientists can assess risk factors for a variety of diseases [12].

Anthropometry has a very accurate system of measuring and observing the human body and its parts. This is facilitated by the points located on the body, which are covered only by the skin and not by muscle or fat. Thanks to the exact data obtained in this way, it is widely used in various areas such as medicine (development and growth, nutritional status), architecture, criminology, sport, industrial design, the textile industry and the gaming industry.

Photogrammetry is a scientific discipline that deals with determining the position, shape and dimensions of objects and phenomena in their photographic images. It is an optical measuring method, and therefore the measurement is made on the measuring images, not directly on the object. It is a modern mapping method that has many advantages, such as:

- the measurement takes place without contact with the object;
- information about the object is obtained at the moment of taking the picture, (ensures the measurement of objects that are shape-changing and moving);
- the mapping is performed outside the space of the object;
- the measured object can be in any state of matter and in any size (microscopically small or extremely large);
- changing phenomena can be detected over time and during its measurement [13].

Nowadays, the trend is of a transition from photogrammetric image to electronic image creation via digital sensors such as CCD. Their importance has increased with the development of computer capacity and the production of special equipment for digitizing analogue photogrammetric images (scanners), as well as digital cameras for online digital image processing. At the same time, various digital image processing methods or photogrammetric algorithms have been developed, which ultimately paved the way for digital photogrammetry applications [14].

3. Related Works

Nowadays, the use of photogrammetry can be found in many fields of science and practice. It is necessary to discuss those areas that are related to the topic of the article.

3.1. Photogrammetry in Biology and Medicine

In orthodontics, multimodal imaging, including 3D modalities, is increasingly being used as a diagnostic tool and, more importantly, for the design of intraoral appliances, where geometric precision is critical. Laser scanners and other precise 3D imaging systems are costly and inconvenient, limiting their application in medical practice. Photogrammetry, which converts 2D images or video recordings into 3D imagery, is a less expensive and more convenient option, as it uses common consumer cameras instead of specialized equipment. The purpose of this research [15] is to see to what degree and in what situations this technology can be a good substitute for a 3D scanner.

Precise measurements of human body surface geometric parameters are critical for a wide range of applications, including medical, identification, clothing design and production, and so forth. In most circumstances, it is more convenient to take measurements from a 3D model rather than a real subject. A photogrammetric technique for precise 3D reconstruction of the human body is proposed in this paper [16]. A series of CCD cameras, a frame grabber, and a structural light projector are among the hardware components of the designed system. Older original Windows XP software allows you to scan the surface of the human body, build a textured 3D model, and perform certain measurements. The 3D models created are accurate in scale and texture, providing dependable data for processing.

An interesting system for scanning the human body has been introduced in [17]. Although it is presented as a cheap solution, up to 100 cameras are needed, so it is not really very low cost.

Anatomical teaching based on cadavers is supplemented by a variety of pedagogical resources, ranging from creative diagrams to photographs and videos to three-dimensional (3D) models. Many of these supplements, on the other hand, either simplify the genuine anatomy or have limited usage and dissemination. By producing interactive, authentic digital models of cadaveric specimens using photogrammetry, which overlaps 2-dimensional (2D) pictures to produce digital 3D models, such flaws are addressed. In this exploratory pilot project [18], they created digital 3D models of eight dissected regional anatomy specimens using a photogrammetric setup and rendering software provided by an outside group. The photogrammetrically created anatomical models were true to their original specimens and accurate.

Reference [19] presents the deep-learning-based approach for automatic contact-less anthropometric measurement extraction (AM-DL). To learn local features from point clouds at multiple scales, a novel module called multiscale EdgeConv is proposed. Multiscale EdgeConv can be directly integrated with other neural networks for a variety of tasks, such as point cloud classification. This module is used to create an encoder–decoder architecture that learns how to deform a template model to fit a given scan. On the deformed template model, the measurement values are then computed. Twenty-seven female and 25 male subjects were scanned using a photogrammetry-based scanner and measured by an experienced tailor to evaluate the proposed method. The proposed method outperforms state-of-the-art methods and performs sufficiently close to a professional tailor, according to experimental results on the synthetic ModelNet40 dataset and on real scans.

In Reference [20], the authors created a system that combines close range photogrammetry and a neural gas network to recognize diseases based on their outward symptoms. Furthermore, the use of the neural gas network and the ability to perform local and general organ examinations improve diagnosis accuracy. In this system, the diagnosis of foot disease has been used as a case study. The findings revealed that, when compared to previous methods for modeling the human body, the neural gas network has a higher degree of flexibility and provides a better approximation. In addition, the precision with which the 3D model of the object is reconstructed is useful in the diagnosis process and has an impact on the system's intelligence level. Finally, the results of the implemented system revealed that the disease had been correctly diagnosed in five feet of the patients. In addition, the disease's location was correctly identified in four cases.

Using two-dimensional images automatically acquires anthropometric dimensions, providing a convenient, effective, and low-cost method for measuring anthropometric parameters. The user's background and posture are severely limited in existing methods, and the anthropometric dimensions obtained using the ellipsoid model are insufficiently accurate. The work [21] proposes a new method for measuring anthropometric dimensions based on this observation. This method combines the deep learning method with the deeplabv3 and openpose frameworks, and instead of using the ellipsoid model, it uses the contour matching method to obtain anthropometric dimensions. Experiments show that our method is capable of dealing with complex background and posture issues while also improving accuracy.

A pose can be calculated from a single or numerous frames, in a single (monocular) or multi-view (stereo) arrangement, and for a single or multiple individuals in the scene. In paper [22], an overview of traditional and deep learning-based 3D pose estimation algorithms is presented. Relevant evaluation measures, pose parametrizations, body models, and 3D human pose datasets are also highlighted. A review of current pose estimate results is presented and there is a brief discussion of open issues and recommendations for future research.

3.2. Photogrammetry in Fashion

The goal of Reference [23] is to investigate the 3D Body scanning mobile application Nettelo in order to assess the mechanism, precision, and level of acceptance of the application for mass-customization of clothes. To determine the answers of Pakistani consumers, a mixed-methods approach (both quantitative and qualitative) was used. Participants' reactions were analyzed using try-on bespoke clothing made from digital measurements acquired from a 3D body scanning smartphone application.

The authors of [24] describe a patent-pending smartphone-based photogrammetric method for analyzing cranial deformation. The technology enables the automatic creation of newborn head three-dimensional (3D) models. It is non-invasive, low-cost, and easy to use even if you do not know anything about photogrammetry. A smartphone app, a coded cap that is attached to the infant's head, and processing software that generates 3D models make up the offered tool. Data collection is simple and can be done during a typical clinical appointment. While the program gathers data around the infant's head, the patient is handled by an adult. The method is similar to video recording, and the app will help you through it.

In order to develop a "Real Avatar", Reference [25] introduced a Raspberry Pi Zero W-based 360-degree full body shooting/3D scanning system kit. The term "Real Avatar" refers to a photo-realistic 3D Humanoid Avatar. The configuration, flow, and functioning of the system, as well as the resulting 3D scanned model, are all shown in this publication. The authors utilized the photogrammetry software RealityCapture on a Microsoft Azure virtual machine with an NVIDIA GPU to build the mesh and texture. The authors also provide a quick overview of the VRM format, which is a 3D Humanoid Avatar format with the potential to be used in a variety of VR/AR apps and platforms.

The authors of [26] propose a novel smartphone-based body size measurement method that does not require any additional objects of known size as a reference when acquiring a subject's body image with a smartphone. The novelty of this proposed method is that it uses body proportions and machine learning techniques to acquire measurement positions, and it performs a 3D reconstruction of the body using measurements obtained from two silhouette images. The proposed method is used to measure male and female body sizes (waist, lower hip, and thigh circumferences) in order to find well-fitting pants. The experimental results show that the proposed method estimates the waist, lower hip, and thigh circumferences with an average accuracy of 95.59 percent.

Reference [27] describes a novel approach for creating an in-home virtual dressing room for garment fitting by combining individualized 3D body model reconstruction with garment fitting simulation. This method emphasizes and builds a relational link between the enormous scatter spots on the 3D generic model. Starting with a limited collection of anthropometric interlinked ordered intrinsic control points existing on the silhouette of the generic model's projections, corresponding control points on two canonical images of the person are found automatically, importing similar saliency between the two sets. A loop subdivision procedure is used to establish additional equivalent saliencies between the projected locations from the generic model and the canonical images. This method can also be used to create a virtual fitting system for online businesses, as well as for apparel design and tailored garment simulation. The method is convenient, straightforward, and efficient, and it involves no user participation other than snapping two photographs using a camera or smartphone.

3.3. Summary of Related Works

Based on an in-depth review of the literature, it can be stated that the 3D body scanning and modeling systems are aimed at medical applications and fashion applications. The results of the survey showed that there are different approaches to the problems of 3D human body modeling. The common approach is morphing a generic 3D model based on two (front and side view) 2D images based on selected measurement places (e.g., waist, hips, thighs etc.). A limitation of this approach is that images of people should be in the same posture or articulation as the generic model and that the measurements of body proportions, shape and curvatures is only a form of approximation, where details of body composition (like fat or muscles) are lost. There are also approaches that utilize several dozen monocular cameras in a solid rig, and therefore such a solution is non-portable. Some methods use commercial 3D photogrammetry modelling software. This inspired and encouraged us to create our own low-cost method for 3D body measurement which partially or completely removes the above-mentioned shortcomings. Our method will be based on the use of open-source libraries, the use of a single smartphone mobile device, and the creation of a true 3D human body model.

4. Concept of the Developed Application

The concept behind this application is to use a mobile device to capture the human body and extract measured data. With professional equipment such as multiple cameras around a human it can be easy and achievable to obtain a human 3D model. However, this approach can be fairly expensive. With the use of mobile devices, which we already have, it can be more accessible. Additionally, with Tensorflow ready-made models, it is possible to obtain measurement data of the human body.

This concept can be described based on the points in Figure 1.

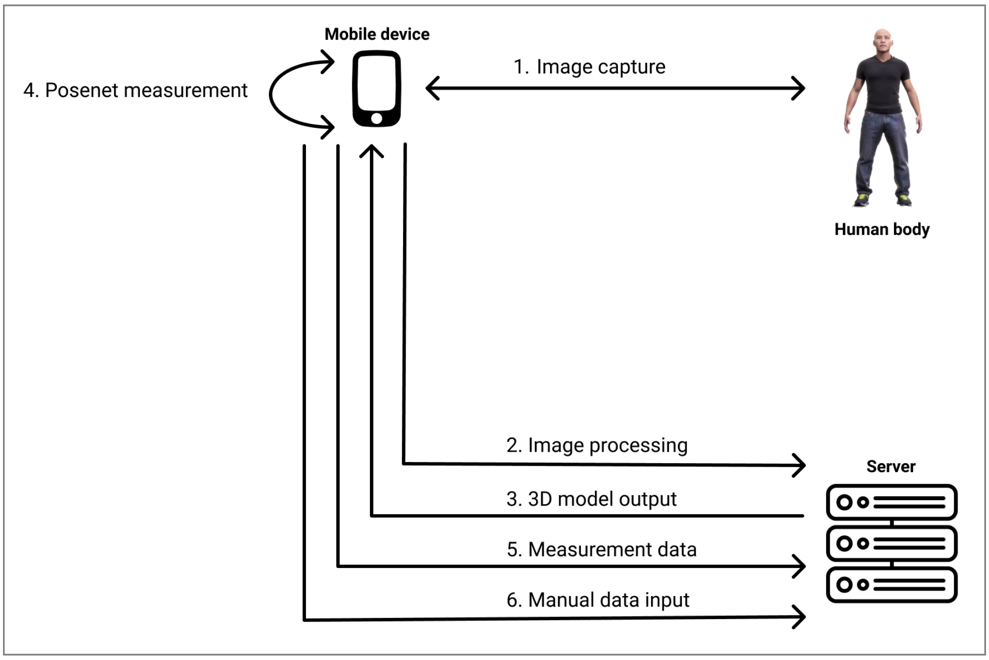

Figure 1. Concept of the application to capture human keypoints measurement data.

1. Image capture
   Mobile application scanner can be used in two modes: image avatar and image scan. In image avatar mode we need to take multiple images around human, which will be sent to the server for processing. In the image scan mode we can see live measurement data and save them to the server.
2. Image processing
   After images were uploaded successfully to the server, it can be processed by Meshroom server instance to obtain a 3D image model.
3. 3D model output
   Human 3D model can be visualized inside mobile application.
4. PoseNet measurement
   With Tensorflow.js PoseNet estimation we can track human keypoints of a body realtime on mobile device.
5. Measurement data
   After capturing pose, the data will be sent to the server.
6. Manual data input
   With manual data input we can set basic information about the user, such as height, which is currently needed for accurate computation of the measurements.

5. Measuring Methods

The initial state of making our application, named Vitruviani, was to conduct robust research of possible solutions of the described problems. The essence of the application idea was measuring human body parts with a smartphone camera. That means that some OpenCV algorithms and artificial intelligence were more than necessary. There are two parallel processes—the process of body measurement and the process of creating a 3D avatar. The aim of this chapter is the measurement process, so let us take a closer look at the problematic areas.

5.1. Pose Estimation

Pose estimation is the task of using an ML model to estimate the pose of a person from an image or a video by estimating the spatial locations of key body keypoints.

It is based on computer vision techniques that can detect a human body in images or videos. It needs to be known that pose estimation only estimates where the key body keypoints are, and does not recognize who is in that image.

Models for this measurement process take images from the camera as input data and outputs the information about keypoints of the body. Detected keypoints are indexed by ID of the body part with a confidence number between 0.0 and 1.0. That number indicates the probability that a certain keypoint exists in that position [28].

For this task, the PoseNet by TensorFlow was chosen. It has very good results for recognizing key points of the body in terms of accuracy and speed of execution on a mobile device [29].

PoseNet

PoseNet provides state-of-the-art models for real-time pose detection. This package provides pre-trained models, where you can choose based on preferences—model speed vs. model accuracy. Since the Vitruviani application solves measurement processes and thus requires maximum accuracy, the ResNet50 model was chosen, which is slower but is the most accurate one [29,30].

As you can see in Figure 2, this model is able to detect up to 17 keypoints.

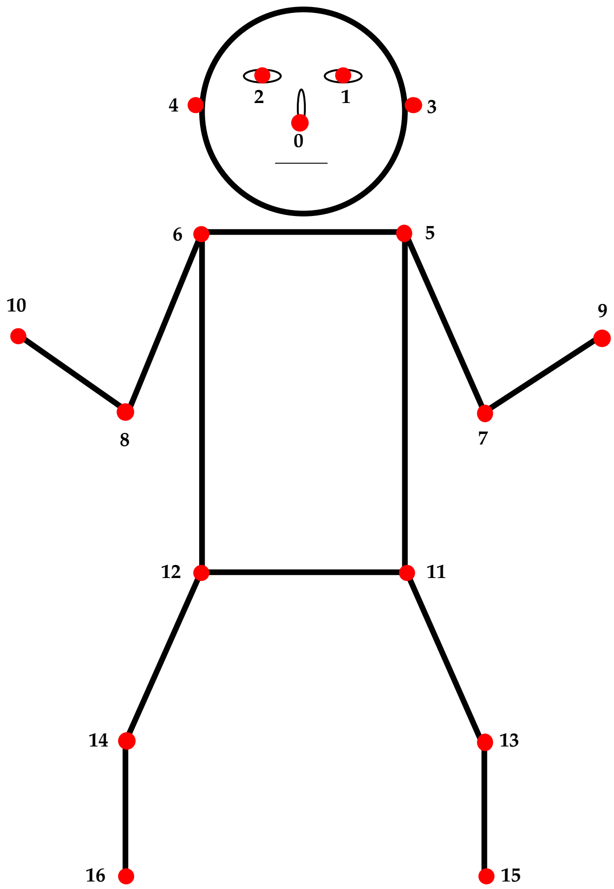

Figure 2. COCO Keypoints: Used in MoveNet and PoseNet.

PoseNet model is used with TensorFlow.js package on mobile device.

5.2. First Calibration Ideas

The biggest blocker that had to be solved was camera calibration. More simply, this means converting pixel metrics to real world metric units, such as centimeters. The first solution attempt was to calculate it via camera specifications such as focal length, number of pixels, and so forth. However, from a mathematical point of view, this solution could not be implemented, because to measure the object, it would be necessary to know its distance from the camera, which would significantly increase the difficulty of the measurement process for the user.

The second attempt was using BodyPix net by Tensorflow. This network allows the contouring of the human body so it would be possible to make a conversion of centimeters from the registration form to a specific height of the measured person. Unfortunately, there were discrepancies in the use of BodyPix, which made it impossible to use this solution.

5.3. Final Calibration and Calculations

The final solution of the calibration is that the measured person must stand in the process of scanning the body so that his height covers the vertical dimension of the camera preview in mobile application. It means that height of the person must be filled in the profile before the scan. The accuracy of the measurement result therefore depends on the dexterity of the scanned person, so care must be taken to ensure that the top of the head ends exactly at the upper edge of the preview and the foot is in the lower edge of the preview.

After a successful scan, PoseNet returns the position of the joints (consider point A and point B), where it is possible to calculate their distance in pixels using the Euclidean distance theorem. Subsequently, it is possible to perform the conversion into real world metric units using the following calculations ((1)–(4)).

Equation (1) computes `pixel_size_in_cm`, which is the value of a pixel in centimeters. It is computed by dividing `human_height` captured from user settings and `vertical_preview_in_pixels` which can be variable based on the mobile screen size (also evaluated in pixels on current mobile phone).

$$pixel\_size\_in\_cm = \frac{human\_height}{vertical\_preview\_in\_pixels}. \tag{1}$$

With the result of Equation (1), `X_cm` and `Y_cm` can be calculated, which are generated points on the body.

$$X_{cm} = \sqrt{(A_x - B_x)^2} * pixel\_size\_in\_cm \tag{2}$$

$$Y_{cm} = \sqrt{(A_y - B_y)^2} * pixel\_size\_in\_cm. \tag{3}$$

In the last Equation (4), the distance between two points on the body is computed in centimeters.

$$distance\_in\_cm = \sqrt{(X_{cm})^2 + (Y_{cm})^2}. \tag{4}$$

6. 3D Model Meshing

To create a 3D model, various types of software were tested. RealityCapture software achieved the best results in terms of the quality of the resulting model, but unfortunately did not provide an open-source license.

For the Vitruviani project, it was essential that the reconstruction software was open-source, and thus the only suitable candidate was the Meshroom software. Meshroom also works as a classic desktop application. Its results can be seen in the Figure 3, but above all it is possible to access its source code directly and thus start the process via commands. The server-side application takes care of starting the Meshroom processes.

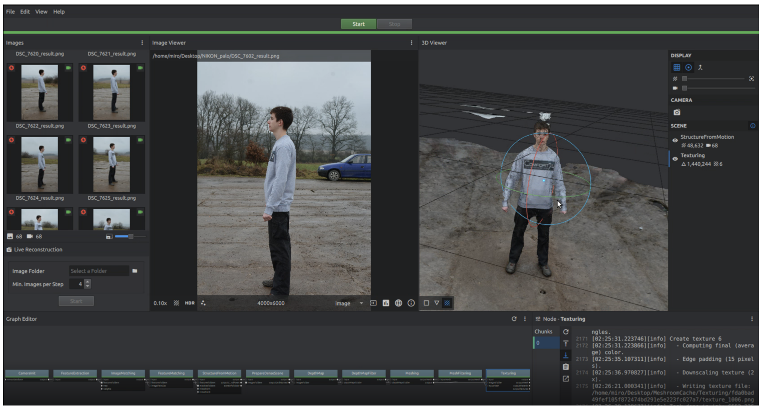

Figure 3. Meshroom–human model meshing.

7. Implementation

The implementation is divided into multiple layers. The whole system will be described in its individual sections: server and mobile app.

7.1. Server with Database

As we can see in Figure 4, on the server side we have the PotstgreSQL database and the Laravel application.

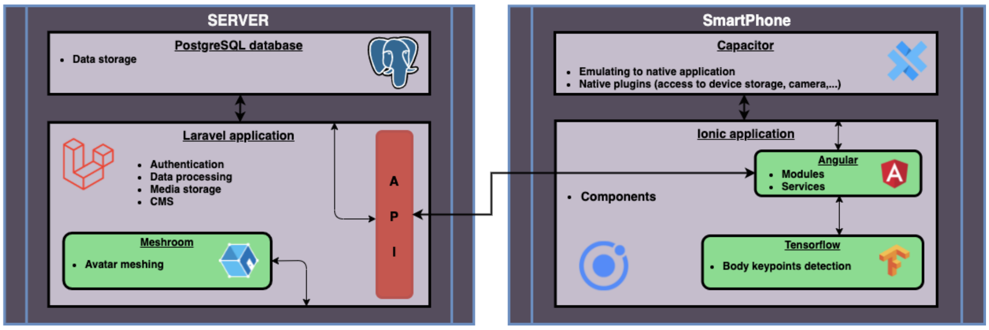

Figure 4. Architecture of the system.

In the beginning of a backend application development it is necessary to analyze which type of data will be stored and how they will be represented. It is good to create some database scheme to better understand relations between some tables, their cardinality and attributes. In the case of Vitruviani, the initial state of the project analysis suggested the PostgreSQL database as the best idea. The main reason for this decision was the possibility of using the JSONB database attribute type. This data type is represented the same way as the basic JSON data type (which is also included in the ordinary MySQL database), but the major practical difference is one of efficiency. The json data type is stored as an exact copy of the input (like raw text). That means a higher difficulty of processing, because it must be reparsed on each execution, while JSONB data are stored in a decomposed binary object. The binary format is a little bit slower to store, but much faster to read, since no reparsing is needed. So, during the analysis table attributes such as translations and measurements were looked for, and it was concluded that there will be more "read" query requests than insertions. JSONB also supports table indexing, which can be a significant advantage for improving database performance and query time.

The application server is also responsible for handling authentication and API requests from mobile applications.

On the server side, there is also the Meshroom application, which is responsible for 3D model generation from multiple images (360 view).

7.2. Mobile App

A mobile application was created with an Ionic framework which simplifies mobile app development. Thanks to this framework it is possible to create an app for Android and iOS with one codebase (HTML, CSS, TypeScript, Capacitor).

In the following pictures you can see the process inside the application. Figure 5 shows a profile page with the important input field height. It is part of the computation of other body parts' measurements.

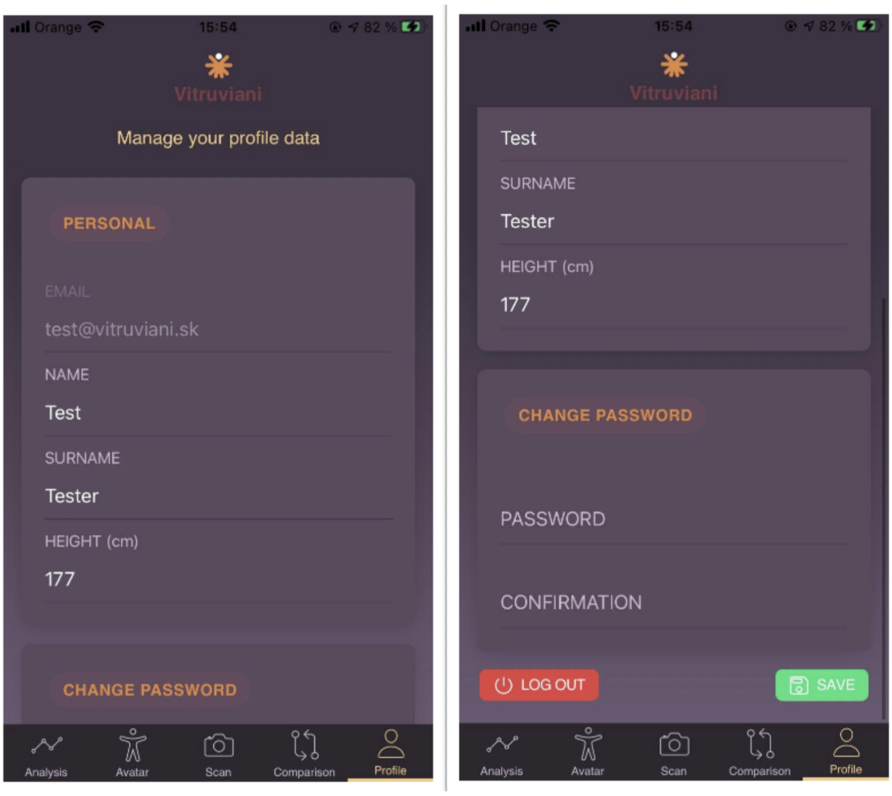

Figure 5. Profile page.

In Figure 6 we can see a sample Analysis page, where there is an image about how the measurements works.

The following Figure 7 shows the page Avatar, where the user can be scanned or where the final 3D scan can be seen. It works by capturing multiple images of a person with the mobile phone. It has to be mentioned that you have to take between 30 to 40 images of the person from different angles to get enough pictures for Meshroom, which runs on the server side.

The source files are sent to the server with Meshroom which generates a 3D model output. Unfortunately, this part is not always stable and sometimes the 3D output can be very noisy. For future exploration in could be interesting to use video instead of multiple pictures.

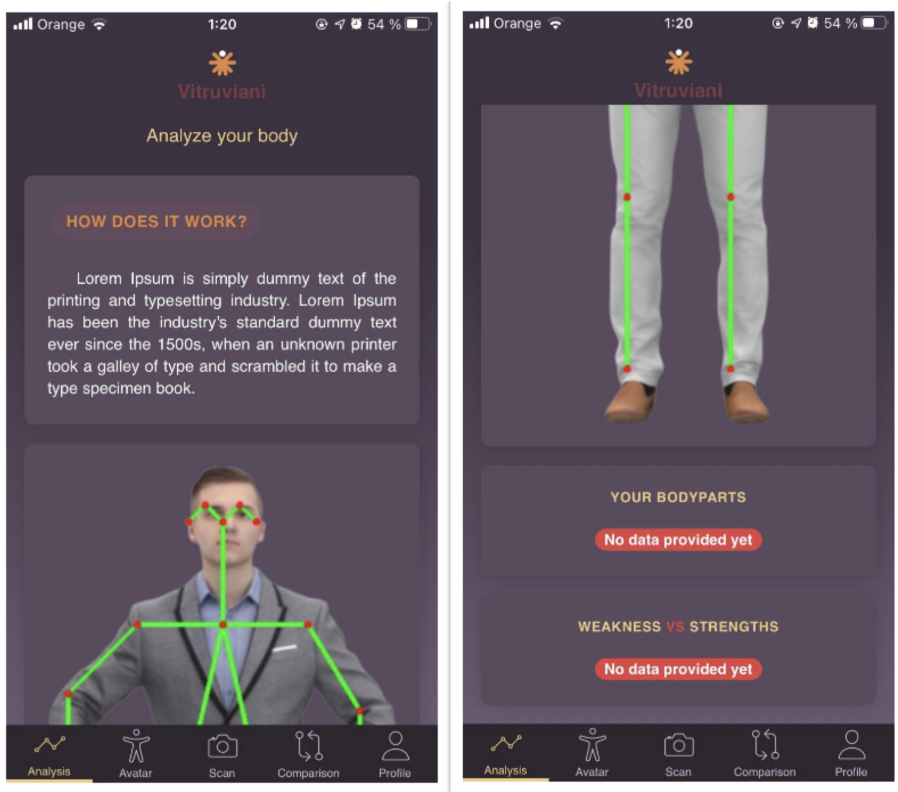

Figure 6. Sample analysis page of the user.

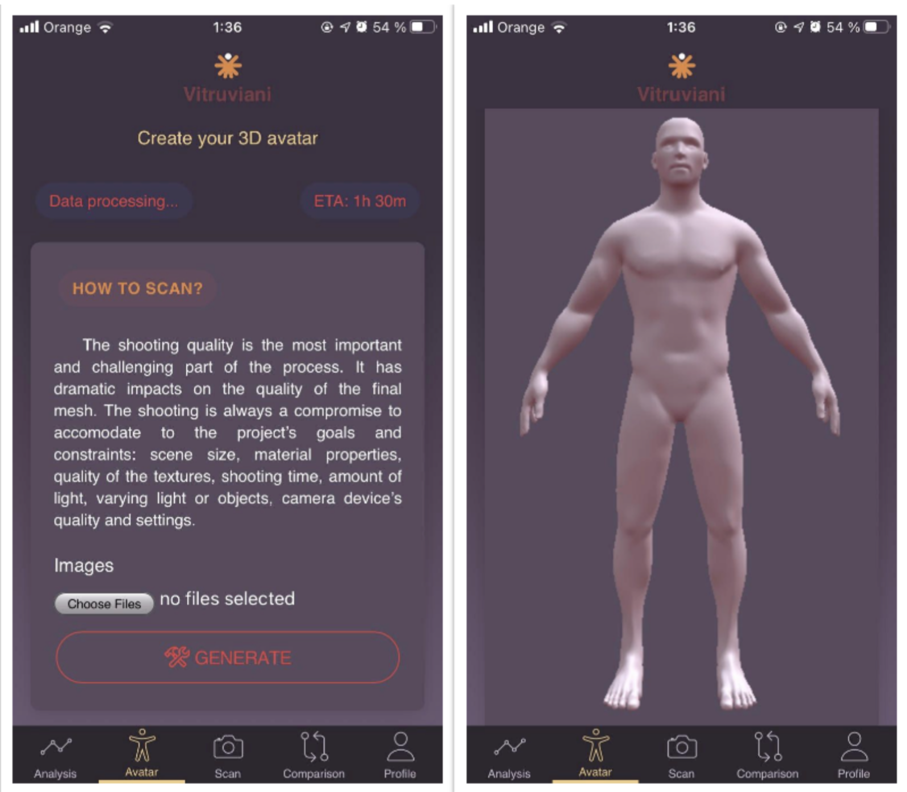

Figure 7. Avatar page with process of generating vs. viewing avatar.

Figure 8 shows the Scan page which is a real time video scanner. After detecting the person it automatically shows pose estimation lines with measurements in centimeters. Note that the person in the picture must be in the exact position, where the feet are on the bottom edge of the frame and the head is at the top edge of the frame. Thanks to that, we can obtain the most accurate measurements.

After stabilization of the person's movement in Figure 8, we can click on the camera image to take a snapshot and also save all the measurement information. After processing in the mobile application, all the measurements are shown in Figure 9.

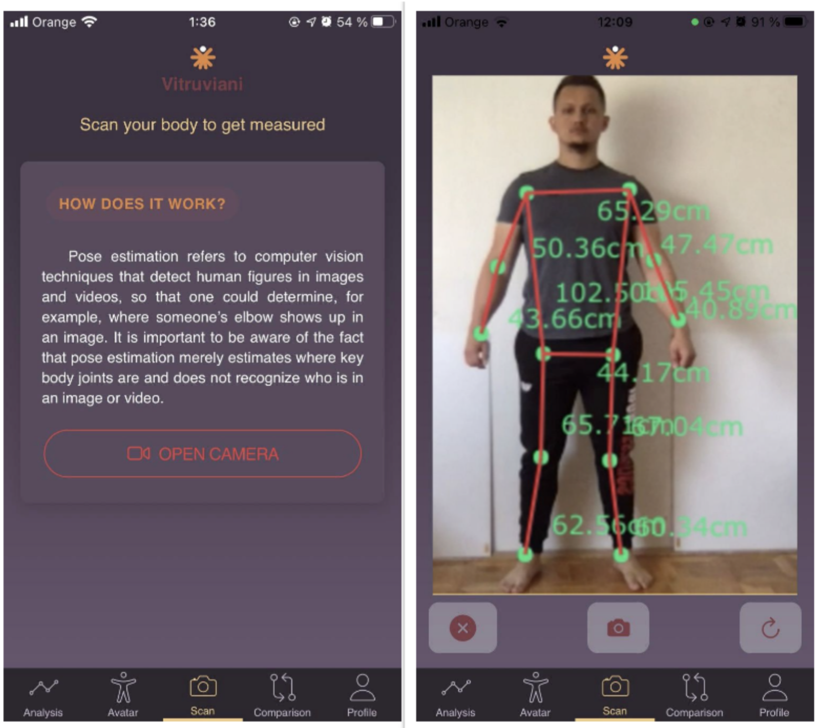

Figure 8. Measurement capture page vs. visualization page of keypoints.

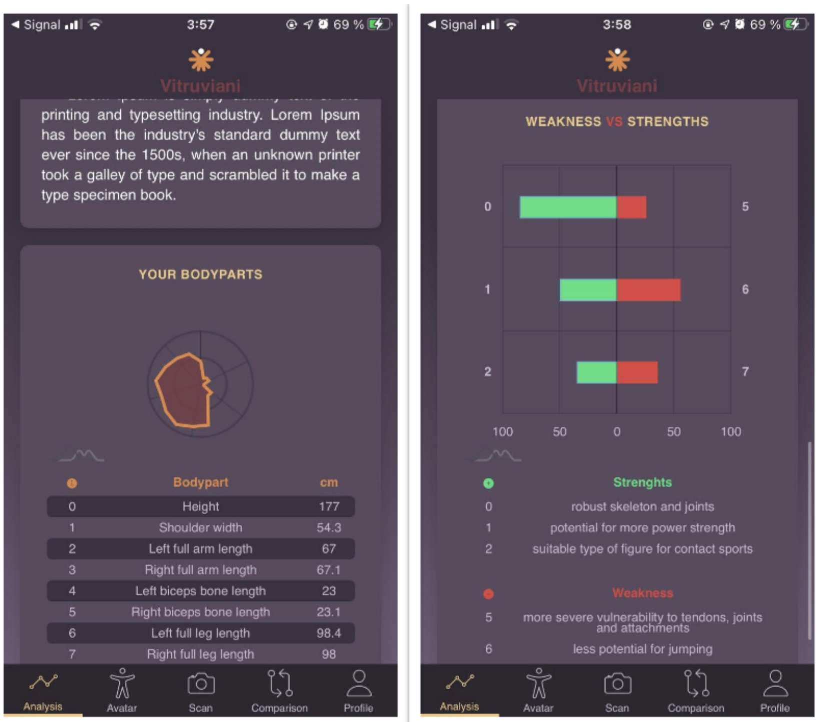

Figure 9. Basic analysis page of the scanned user.

8. Experimental Results

The numerical results of the measurements are available in Tables 1 and 2. We were comparing measurements of key points of the body between automatic measurement (mobile application) and manual measurement with ordinary length meters. It can be seen that there is some deviation between measurements of around 1 to 3 centimetres. Such a deviation can occur for several reasons: One of them may be an inaccurate manual measurement of a body part or the measurement was performed individually with several persons. This measurement is routinely performed by a person who has knowledge of anthropometry and can accurately target these values. Another reason for the deviation may be caused by the human subtly wriggling.

Table 1. Automatic measurements of the keypoints.

Key Points	Person 1	Person 2	Person 3	Person 4
shoulder joints (6–>5)	37 cm	40 cm	46 cm	44 cm
upper arm (5–>7)	31 cm	31 cm	32 cm	32 cm
forearm (7–>9)	25 cm	30 cm	31 cm	25 cm
shoulder to hip (5–>11)	45 cm	48 cm	55 cm	50 cm
hip joints (12–>11)	33 cm	36 cm	36 cm	31 cm
tigh bone (11–>13)	47 cm	41 cm	39 cm	47 cm
shin bone (13–>15)	39 cm	39 cm	45 cm	43 cm

Table 2. Manual measurements of the keypoints.

Key Points	Person 1	Person 2	Person 3	Person 4
shoulder joints (6–>5)	36 cm	39 cm	45 cm	42 cm
upper arm (5–>7)	30 cm	30 cm	35 cm	31 cm
forearm (7–>9)	24 cm	29 cm	28 cm	25 cm
shoulder to hip (5–>11)	46 cm	50 cm	57 cm	50 cm
hip joints (12–>11)	30 cm	35 cm	35 cm	33 cm
tigh bone (11–>13)	46 cm	40 cm	41 cm	45 cm
shin bone (13–>15)	38 cm	41 cm	43 cm	45 cm

Mean and standard deviation of the measurements can be found in Table 3.
The mean can be calculated using Equation (5).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}. \tag{5}$$

The standard deviation can be calculated using Equation (6).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}. \tag{6}$$

Table 3. Deviations of measurement.

Key Points	Person 1	Person 2	Person 3	Person 4	Mean	Std. Deviation
shoulder joints (6–>5)	−1 cm	−1 cm	−1 cm	−2 cm	−1.25 cm	0.5 cm
upper arm (5–>7)	−1 cm	−1 cm	3 cm	−1 cm	0 cm	2 cm
forearm (7–>9)	−1 cm	−1 cm	−3 cm	0 cm	−1.25 cm	1.26 cm
shoulder to hip (5–>11)	1 cm	2 cm	2 cm	0 cm	1.25 cm	0.96 cm
hip joints (12–>11)	−3 cm	−1 cm	−1 cm	2 cm	−0.75 cm	2.06 cm
tigh bone (11–>13)	1 cm	−1 cm	2 cm	−2 cm	0 cm	1.83 cm
shin bone (13–>15)	−1 cm	2 cm	−2 cm	2 cm	0.25 cm	2.06 cm

9. Conclusions

The topic of this paper was to focus on the possibilities of data collection using a smartphone camera, its subsequent processing and the creation of an original application. Among the main objectives of the work was to point out the possibilities of creating a human 3D model, measuring the human body parts and the subsequent use of these data samples.

Based on a thorough analysis of the literature, it is possible to conclude that 3D body scanning and modeling systems are primarily directed at medical applications and, especially, fashion applications. According to the survey results, there are several approaches to the issues of 3D human body modeling. The standard strategy is to morph a general 3D model based on two (front and side view) 2D photos depending on specified measurement points (e.g., waist, hips, thighs, etc.). A disadvantage of this technique is that human photographs must be in the same posture or aligned as the generic model, and measurements of body frame, shape, and curvatures are simple approximations, with lost nuances of body composition (such as fat or muscles).

There are additional techniques that use numerous number monocular cameras in a solid setup, making such a system immobile. Some techniques require the use of commercial 3D photogrammetry modeling tools.

This motivated and inspired us to develop our own low-cost method and implementation for human 3D modeling that partially or totally eliminates the drawbacks listed above. Our solution relies on open-source libraries, a single smartphone mobile device, and the construction of a realistic 3D human body model.

In the initial phase of the project, it was necessary to conduct research on the possibility of implementing functional requirements. It was found that there are a few ideas on how to implement the measurement process, but not all could be applied to the case of this application and it was necessary to design a measurement process with currently available technologies. In addition to the measurement process, it was necessary to solve the process of the reconstruction of a 3D avatar. In this case, it was also necessary to examine the available technologies and choose the right one that will be applicable for this project. The technology with the best results for solving the reconstruction of 3D objects was Meshroom, which is free, open-source and brings satisfactory results.

In the final phase of the project, from the management point of view, data administration via a server CMS application is possible. From the end user point of view, this is the possibility of scanning their body via the mobile application and then viewing their data via the designed UI. The CMS application acts as a stand-alone server-side service that allows a mobile application to connect through the API to retrieve and write data. The Laravel framework on the back-end and VueJS on the front-end side were used as the primary technologies for creating a server application. The mobile application was developed using the Ionic framework, so it can be used on both platforms—iOS and Android.

The scientific and application benefits of the developed solution include the following points:

- Low-cost
  The first important feature of our solution is its cost-effectiveness compared to the solutions found during the investigation phase of the project. We use freely available tools for the photogrammetry or analysis of the human body. Thus, the solution is not dependent on expensive proprietary software.
- Portability
  As research has shown, similar solutions rely on expensive photographic cameras or even collections of such cameras. Our solution is based on the use of the camera of an ordinary smartphone of sufficient quality. Thus, our solution can be offered to the general masses, since owning a smartphone with a good quality camera is common nowadays.
- Construction of a realistic 3D human body model
  Our application is an all-in-one solution that is able to create a comprehensive 3D

model of a person, rather than just detecting the dimensions of specific parts of a person (waist, chest, thigh width, etc.).

The article also creates the basis for future solutions to measuring people for all the sectors mentioned in the Introduction section (medicine, sports, tailoring, fashion).

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Abbreviations

The following abbreviations are used in this manuscript:

LIDAR	Light Detection And Ranging
CMS	Content Management System
BMI	Body Mass Index
CCD	Charge-Coupled Devices
UI	User Interface
API	Application Programming Interface

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