Comparative analysis of methodologies for flat foot parameter determination

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Abstract— **Flat foot represents a foot deformation where the arches on the inside of the feet are flattened allowing the entire soles of the feet to touch the floor when person is standing. The flat feet pathology is normally detected by human experts based on the footprint images, but the lack of trained experts preludes the massive routine diagnostic of this pathology among the population. In present there are the main two groups of approaches to capture and estimate arch-foot parameters: Vision Based Measurement (VBM) approaches and Foot Plantar Pressure (FPP) measurement and processing. The main characteristics of both approaches will be analyzed and compared in this paper.**

Keywords- flat feet, vision based measurement, foot plantar pressure, sensors

I. Introduction

The foot represents a strong and complex anatomical structure, consisting of 26 bones, 33 joints, and more than a hundred muscles, tendons and ligaments responsible for controlling the movement of the foot. The foot is required to do many different activities such as walking, running and balancing the weight of the body, redistributing it in response to position changes. Among other foot elements, the medial longitudinal arch is the primary shock absorbing structure of the foot and it is characterized based on its height relative to the plane of the ground.

Flat feet (pes planus) is a postural deformity that occurs when the arches of the foot collapses and come into complete or near-complete contact with the ground. Due to the deformed foot structure, patients with flat feet often have problems regarding the even distribution of their body weight on the foot during movement, which may result in overloading of the bones or muscles, and difficulties and pain during standing for long period of time, long distance walking or running.

Different parameters used for evaluation of the foot type exist and have been verified in several studies. Most of them are calculated based on the shape of the footprint. The commonly used parameters for determination of the healthy foot and the foot with functional abnormalities are: the arch index (AI), the arch width (AW), and the arch height (AH). The Cavanagh's AI determine arch type as the ratio of the mid foot area to the entire footprint area excluding the toes (see Fig. 1a). The AI parameter can be determined as follows: first, the line of the foot axis between the center of the second toe and the posterior point of the heel (point K in Fig. 1a) is drawn. Then, a line tangential to the most anterior point of the main area of the footprint and perpendicular to the first line is drawn, and the intersection point is marked (point L in Fig. 1a). Two parallel lines perpendicular to line L-K are drawn to divide the area of the footprint excluding toes into equal thirds. The AI is calculated as the ratio of the middle third area relative to the total area of the toeless footprint. The AW and AH are defined as the horizontal and vertical distances from the midpoint of the line connecting the most medial border points of the metatarsal and heel region of the foot called medial border line (MBL). These parameters are considered as an important prediction and diagnosis tools in lower limb pathology, such as plantar fasciitis. These parameters can be determined as follows. First, the MBL is drawn. Then, a perpendicular line is drawn from the mid-point of the MBL in the arch area to the mid-foot. The length of this line represents the AW, while the length of a perpendicular line from the mid-point of the MBL to the plantar surface of the foot sole represents the AH.

The traditional approaches measure above mentioned parameters manually using an ink footprint on a grid paper. Even though the procedure is simple, the accuracy of the measurement is dependent on the expert skills and undesirable in a clinical

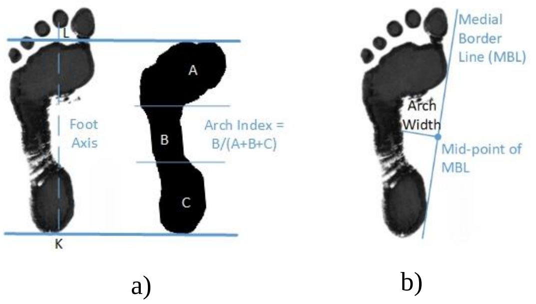

Figure 1. The foot-arch parameters: a) arch index (AI) measurement and b) medial border line (MBL) and arch width (AW) measurement from the footprint.

Figure 2. Ink based footprint printer [1], [2]

aspect since the subject must cover his/her foot in ink to create the footprint image. Except this, a reliability and repeatability are usually poor. In Ink based footprint subject stand statically with one foot on the Ink-type footprint printer that prints the footprint of the subject (Fig. 2). But, the measurement and prediction of the foot parameters (described in the previous section) simultaneously using ink-type footprint is impossible, since the footprint does not contain 3D information of the foot shape, just 2D information about contact region of the foot sole.

Therefore, many scientific researchers have attempted to measure and analyze the foot shape by using one of the following approaches: Vision Based Measurement (VBM) approaches and Foot Plantar Pressure (FPP) measurement and processing. Usually, the VBM methodologies achieve better estimation of foot arch parameters (AI, AW and AH), while FPP measurement methodologies achieve better estimation of distribution of the foot plantar pressure. The both mentioned methodologies can be used for a static (subject is standing) and a dynamic measurement (subject is walking) of feet parameters. By VBM approach it is easy to obtain 3D shape of sole of foot from geometrical and visual data captured by the camera or laser scanner. In contrary, by using FPP measurement only 2D distribution of plantar pressure can be measured from which arch parameters can be estimated.

II. VBM BASED FOOT SHAPE ANALYSIS

The main idea of VBM based foot shape analysis approaches is to capture the foot surface using a camera or a scanner device and to analyze the captured visual and geometric data using computer technologies. These systems can be classified based on the applied sensing method into passive and active 3D shape measurement techniques. The first are based on finding correspondence between pixels from multiple images acquired by single or several cameras. The second are based on the 3D shape measurement by projecting or emitting and receiving light patterns.

The passive approaches are usually based on application of one or several cameras (Fig. 3) for the flat feet recognition either from the 2D images or by the 3D foot model obtained from 2D images. An automatic system for detection of the footprints obtained from an optical pedobarograph, constructed of the glass surface, fluorescent lamp, mirror and one camera, and analysis of the footprint morphology and pressure distribution was presented in [3]. Acquired images are processed to obtain the grayscale images, and those images are then thresholded with an empirically obtained threshold.

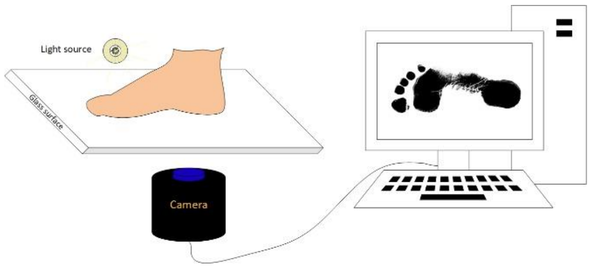

Figure 3. Pedobarographic system based on application of one camera

An opening followed by closing were applied to binary masks to smooth borders, delete isolated and small undesired particles, with a disk structuring element. Then, an algorithm of holes filling is applied. Morphological descriptors were obtained from the binary images and the Hernandez Corvo (HC) index was calculated to determine the type of foot. Pressure distributions were obtained by combining the binary masks with the intensity images, making a correspondence between light intensity in footprints and pressure. In order to perform a pressure analysis, the maximum and the mean pressure were found and the ratio between them that determines the uniformity of the distribution. Using HC index, a high correlation was found between this ratio and the type of foot is determined.

Another approach for images obtained with one camera, positioned underneath the glass/fiber sheet, was presented in [4]. The foot images were converted to binary images using the thresholding segmentation. Thus, total number of ‘0’s and ‘1’s represents the area, occupied by the footprint, and the remaining area of the glass plain, respectively. The ratio of these two quantities may be termed as the modified Brucken index (BI). BI of the human footprint is the ratio of the series of the lines connected between the medial and lateral border lines. In [5], the proposed system is using a commercial RGB-D camera for the scanning of the foot. The AI, AH, and AW parameters are extracted from the collected color and geometric data of foot through a following sub-modules: pre-processing, contact region detection, and foot-arch parameter computation. The preprocessing module performs noise removal from an input depth image, maps the input color image to the depth image and detects foot region using connected component labeling. To detect the contact region, the system first identifies the contact points and then determines the contact region from the dense and connected set of points using a Markov random fields (MRF) based method. The foot-arch parameter computation applies the principal component analysis and boundary tracing for the foot axis detection, the edge detection, the smoothing filter and AND operations for the AI computation, and the convex hull algorithm for AH and AW computation. The proposed method can be applied to the continuous and dynamic foot motion analysis.

In [6], authors investigated loaded and unloaded foot area ratio as special tests for the basis of clinical examination of flat and healthy foot. The footprints were obtained using digital footprint modified from document scanner. Type of foot is determined by calculation of the AI using the morphological operations in MATLAB. A foot measurement system comprising of a hand-held RGB-D camera, an A4-size reference pattern of AR code and a desktop computer is presented in [7]. The camera is rotated around the foot to capture the consecutive color and depth images. The AR reference pattern, located around the foot, is used to provide the camera pose estimation that is required for the 3D foot shape reconstruction. This system determines the foot length, width and ball girth using the 3D shape of foot, but it doesn't provide an information about the contact region of the foot that can be used to estimate AI, AW, and AW.

An automatic system for foot plant pathologies based on neural networks (NN) was presented in [8]. The footprint images are acquired with a digital color camera positioned in the interior structure of the podoscope instrument (constructed of a metallic structure with adjustable height, transparent glass in its upper part, and white light bulbs). The principal component analysis was used to reduce the number of inputs to the multilayer perceptron (MLP) trained with Bayesian regularization backpropagation.

The active methods typically acquire 3D foot shape or surface by using optical sensors such as the structured light method and time-of-flight (ToF) method. The structured light method captures the 3-dimensional topography of a surface using projection of specific patterns of light, and an imaging camera. It then uses information about how the projected pattern appear in the image, after being distorted by the foot surface, to recover 3D shape of the foot. The ToF method produce a depth images, where each pixel encodes the distance between camera and the subject by measuring the round-trip time of a light signal to the subject. In [9], an LCD projector-camera system is proposed to reconstruct the shape of the foot in motion. To reconstruct the 3D geometric shape of the sole, a pattern comprising of small rectangles with characteristic color distribution is projected onto the foot sole and the reflected patterns are captured by the camera. The 3D feet scanning system with a measuring head attached to the rotating arm, which rotates around the centre of the standing platform, was presented in [10]. The measuring head consists of a three laser line projection unit and two cameras symmetrically positioned on each side of laser projection unit. A 3D measurement of the foot is based on the laser-multiple-line triangulation principle. A dynamic ToF camera-based foot shape measurement system proposed in [11], was able to measure the entire surface of the foot at high speed and full dynamic reconstruction. This system was used in [12] to analyze foot roll-over under dynamic conditions. A foot sole image was computed by vertically projecting points from the 3D foot which were lower than a threshold height of 15 mm and a height of these projected points was determined corresponding to the initial vertical coordinates prior to projection. The foot sole images were segmented into seven regions of interest to process change in mean height and projected surface for each frame.

III. FOOT PLANTAR PRESSURE MEASUREMENT AND ESTIMATION OF FOOT ARCH PARAMETERS

Foot plantar pressure is the pressure with which the foot acts on a flat surface whether the patient is standing, walking, running or doing some other locomotor activities. Information derived from such pressure measures is important in: physio therapy, rehabilitation, sports or research and provide valuable information on gait disorders and the roll-off behavior of the feet. The currently available plantar pressure systems vary in sensor configuration to meet different application requirements and can be in form of pressure distribution platforms (floor based) and in-shoe systems. In [13] a review of foot plantar measurement system is performed.

Platform-based systems consist of flat platform with embedded array of plantar foot pressure sensors organized in the matrix shape (Fig. 4 and Fig. 5). In this way it is possible to make measurements during normal gait of patients.

By using the combination of software and hardware the platform-based measuring systems allow for fast stance, gait and roll-off analysis. They can be used for measurement of static and dynamic pressure distribution under the feet during standing or walking. They are available in different sizes.

In-shoe pressure distribution measuring systems are used for monitoring local loads between the foot and the shoe. The measuring system in this case is built into the sole of the shoe (Fig.6.). These systems are mobile and flexible to meet different testing needs: walking, running, climbing stairs, carrying loads, playing football etc. They can be connected to a PC using a fiber optic/USB cable or by using Bluetooth technology.

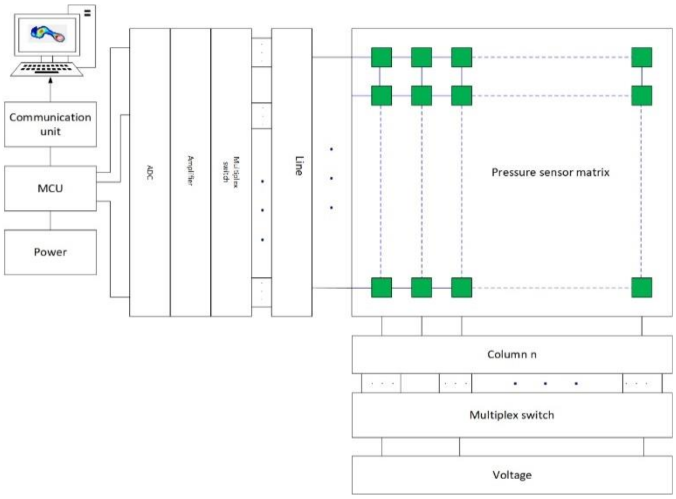

Figure 4. Plantar pressure distribution platform data acquisition system

Figure 5. Pressure distribution plates by Zebris Medical GmbH [14]

Figure 6. An in-shoe plantar pressure measurement [15]

In order to get foot arch parameters, data collected from both systems can be processed by using different approaches.

- In the first group of approaches plantar pressure is transformed to image and sophisticated imaging technologies are used to get foot arch parameters and foot disease classification [16],
- In the second group of approaches deep learning techniques to diagnose foot diseases have been used. Deep learning research is mainly used to solve classification problems that differentiate healthy and deformed feet of the subjects based on supervised learning. A multilayered neural network employing the backpropagation algorithm has been used as a classifier and classifier that combines the neural network capabilities and fuzzy logic qualitative approaches [17],
- The third group uses statistical methods (regression analysis) for getting regression models of foot arch parameters as function of foot plantar pressure [2].

A. Characteristics of foot plantar pressure sensors

Real time measurement and data acquisition of foot plantar pressure requires that, among others, sensor system should be used in shoe sole. As consequence it is desirable in these systems to use wireless communication such as Bluetooth. Except this foot plantar pressure sensors must be able, depending of weight of person under examination and type of application, to measure pressure with high accuracy in relatively broad range of pressure change. Accordingly, the main characteristics of these systems should be [13]:

- High mobility: The sensors must be small and light (a few millimeters in diameter and weighing 300 g or less).
- Short cables: It is desirable to use as short as possible cables and wireless communication.
- Sensors position: The sole of foot can be divided into 15 areas: heel (area 1–3), midfoot (area 4–5), metatarsal (area 6–10), and toe (area 11–15), as presented in Fig. 7. If sensors are placed in these areas most of the body weight will be measured by sensors.
- Sensors input range: Depending of body weight and type of application of sensors, input range of sensors must be carefully chosen. Usually foot plantar pressure sensor should be able to measure pressure between 1900 Pa and even 3MPa.
- Sensors size and number: Depending of position of foot anatomical area and in order to avoid underestimation of foot plantar pressure and achieving of higher spatial resolution, active surface sensor area should be less than 10 mm × 10 mm [18]. On the other side use of large number of small sensors increases resolution but complicates interface electronics and data processing [18].
- Sampling frequency: Foot plantar pressure sensors should be able to be applied to patients with a normal walking speed that can vary significantly. Taking this into account, the typical sampling frequency of a foot plantar pressure acquisition system should be between 50 Hz and 100Hz.

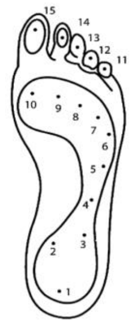

Figure 7. Foot anatomical areas

Different kind of sensors can be used for measurement of foot plantar pressure. Depending on the physical phenomenon on which their work is based, they may be: capacitive sensors, resistive sensors, piezoelectric sensors (and piezoresistive sensors), inductive sensors and fiber-optic sensors. These sensors change its capacitance, resistance, inductance or potential proportionally to the measured force/pressure which can be measured using appropriate designed electrical circuits.

1) Capacitive sensors

Capacitive sensors are usually made of two conductive metal plates between which there is a dielectric. One of the metal plates (membrane) is movable. When the pressure acts on this membrane, the distance between the plates changes, which causes a change in the electrical capacity of the capacitor (see Fig. 8). A change in capacitance is usually measured by using capacitive bridge by which impedance is converter to voltage. The main characteristics of these sensors are: linearity, stability, repeatability, possibility of measurement of static and dynamic pressure etc. Typical example of plantar pressure measurement system based on capacitive sensors is Pedar® in-shoe systems (Novel, Germany).

2) Resistive sensors

Force sensing resistor (FSR) is special type of resistor which shows a decrease in resistance with an increase in the pressure/force applied to the surface of the sensor. The FSR are generally made from polymer sheet or ink which is applied as screen printing (see Fig. 9). When force/pressure is acting on surface of sensing film then particles touches conducting material (electrodes) in which way resistance or the film changes. They can operate satisfactory in harsh environment. Their advantages are thin size, low cost, good shock resistance and simple interface circuits. The main disadvantage is low precision. Some commercial available Force Sensing Resistors are: Interlink 402 and FSR 402.

3) Piezoresistive (piezoelectric) sensors

Piezoresistors are resistors made from a piezoresistive material (semiconductors such as silicon, metals etc.) and are mostly used for measurement of pressure or force (see Fig. 10). When pressure or force is applied it cause a change in the electrical resistivity of a semiconductor or metal. In piezoelectric effect a change in electric charge/potential appears. They usually constructed by using piezoelectric ceramics, single crystal materials or thin film piezoelectric materials. The main disadvantage of piezoelectric sensors is that they cannot be used for static measurement.

B. An example of simple foot plantar pressure measurement system

A simple foot plantar pressure acquisition system presented in [2] is shown in Fig. 11. In this example 5 analog Interlink 402 FSR sensors has been used to measure foot plantar pressure. Analog signals from FSR sensor were collected by using the Arduino Micro Pro hardware platform. By using wireless connection (Bluetooth) user developed application (Python and Matlab) communicates with microprocessor on Micro Pro hardware platform.

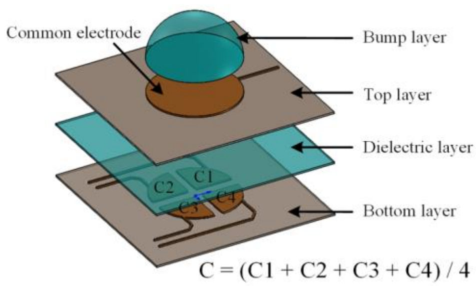

Figure 8. Capacitive sensor construction [18]

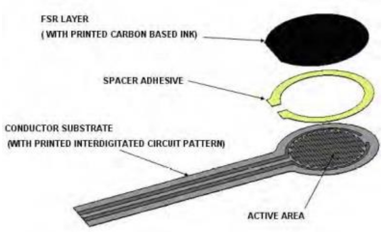

Figure 9. Force sensing resistor [19]

Figure 10. Piezoresistive pressure sensors [20]

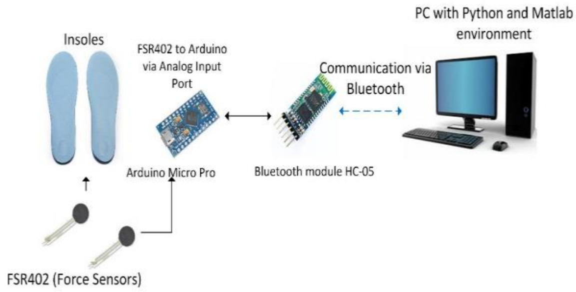

Figure 11. Example of hardware system for foot plantar sensor acquisition [2]

IV. Conclusion

Plantar pressure data and the data obtained by the scanner devices and cameras have been extensively studied as the potential measure of the patient foot deformations/abnormalities, for both static and dynamic assessments. This work presented a variety of techniques used for recognition of the flat feet deformation using Vision Based Measurement (VBM) approaches and Foot Plantar Pressure (FPP) measurement and processing.

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