Smart Prosthesis System: Continuous Automatic Prosthesis Fitting Adjustment and Real-time Stress Visualization

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***Abstract*—Prosthetic devices have significantly improved mobility and quality of life for amputees. Significant engineering advancements have been made in artificial limb biomechanics, joint control systems, and light-weight materials. Amputees report that the primary problem they face with their artificial limbs is a poor fitting socket. In this paper, we propose a smart prosthesis system, in which we measure the real-time force distributions within a prothetic socket and dynamically visualize the results in a mobile application. A major part of the overall proposed system, a wireless pressure sensing system and a force visualization method, are evaluated at current stage. Finally, corresponding works for fully completing this smart prosthesis system are discussed as well.**

***Index Terms*—smart prosthesis, fitting, visualization**

I. Introduction

Amputation constantly brings a lot of concerns for individuals, their families, and society. A survey indicated that 623,000 people live with a lower limb amputation in the United States [1]. Amputations, particularly of the lower limb, have already been a worldwide problem. The number of amputees are increasing in developed countries [2]. Factors leading to lower limb amputation, include vascular disease, infection, tumor, trauma, and diabetes. Wearing prosthesis for regular training is one of the most important processes of rehabilitation after limb amputation. Changes in body weight and size of residual limb, (ex. edema), can result in a poor fitting socket and discomfort. Even properly fit sockets stop fitting perfect after a few months. This results in chronic skin problems like pressure ulcers, dermatitis, infections [3], [4], [5] and pain [6], which seriously affects patient health and quality of life. Hence, making a prosthesis consistently fit well is a complicated and challenging process. First, there is a limited understanding of force distribution from external loading on residual soft tissues. The use of pressure and shear force sensors would allow for measurement of the force distribution across the limb/socket interface and thus optimize the prosthesis socket design, to minimize skin damage and discomfort [7]. Secondly, the force data can be used for adjusting the tightness of the liner around the residual limb, which is a crucial element for automatic and adjustable prosthesis fit. However, individual force sensor is not sufficient for constant collection of research data. The advantage of force sensor array over a single pressure sensor is that an array could measure the pressure distribution of an area with a higher spatial resolution. Since the shape and structure of residual limbs are varied from patient to patient, customizable sensor arrays are necessary to fit different prosthetic sockets. Furthermore, visualized force distribution can help medical providers and prosthetists collect clinically relevant information, and provide better fitting artificial limbs.

The objective of this particular application is to positively impact the prosthetics field by providing a smart prosthesis system. In the paper, the overall concept of the smart prosthesis system is proposed and discussed, specifically focusing on testing of the wireless sensing system and a force visualization method. The design method of the customizable pressure sensor array and corresponding signal processing system are discussed, with pressure distribution visualized on Hololens. Finally, corresponding work for fully completing this smart prosthesis system are proposed.

II. Related work

The most significant part for an ideal pressure-sensitive prosthetic system is continuous monitoring of interfacial stresses with high accuracy. Ideal transducers require being easily mountable, accurate data collection, being unaffected by prosthetic socket environment, and capable of accommodating to various prosthesis designs, without hindering the patient. Current popular transducers for in-prosthesis forces measurement can be classified as fiber-optic cables and waveguides [8], piezoelectric resistors [9], [10], gas-filled cavities [11], fluid-filled sensors [12], resistive strain gauges [13], diaphragm deflection gauge [14], [15], capacitance based individual sensor [16], [17] and sensor array based printed circuit sheets [18], [19]. Tim et al. placed four socket transducer arrays inside the prosthetic socket of all subjects using the same positioning protocol with the establishment of anterior/posterior axis with

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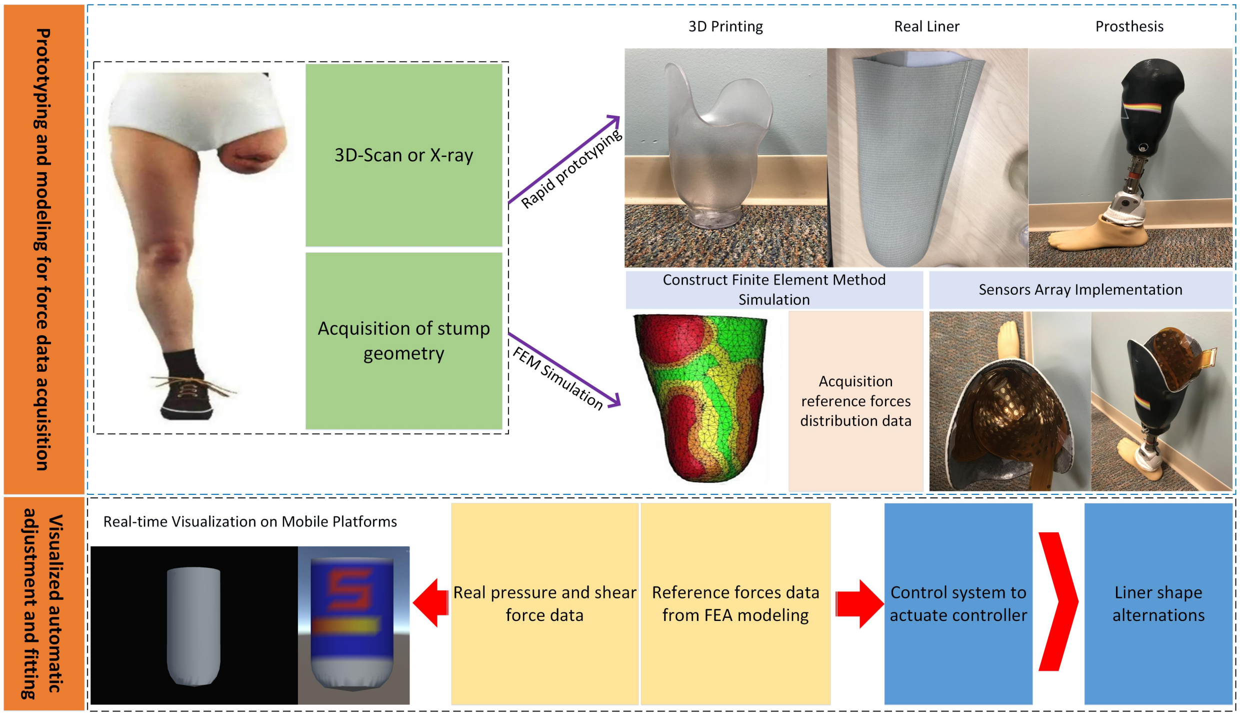

Fig. 1: The smart prosthesis system. The overall system can be divided into two stages according to its functions: (1) prototyping and modeling for force data acquisition, and (2) visualized automatic adjustment and fitting.

midpatellar bar as a reference point, and a medial/lateral axis perpendicular to the anterior/posterior axis [18]. Convery et al. used force sensing resistors to measure dynamic residual limb/socket interface pressures during the gait cycle of a trans-tibial amputee [20]. A total of 350 pressure sensors were attached to the inner wall of a hydrocast socket with sampling rate at 150Hz. In terms of the size and shape of a sensor, thinner and flexible sensors are suitable for inserting into the interlayers of the liner or attaching on the socket. Additionally, too large of a sensing element can only measure an average pressure over the area, while too small of a sensor may limited by edge effects [21].

III. System Design

The proposed smart prosthesis system as shown in Fig. 1 mainly consists of two stages: 1) prototyping and modeling for force data acquisition; 2) visualized automatic adjustment and fitting. In the first stage, patients residual limbs geometry will be acquired through 3D-scanning. Customized prosthesis sockets will be rapidly prototyped by using 3-D printing. The geometry information will be feed into the FEA (Finite element analysis) model for force distribution simulation. The FEA model is established based on the actual shapes of the socket, the residual limb surface and the internal bones of the subject. In simulation, all materials are assumed to be isotropic, homogeneous and linearly elastic. The poisson ratio is assumed to be 0.49 for soft tissues, 0.3 for bones, and 0.39 for liner, and the Young's modulus is 200 kPa for soft tissues, 10 GPa for bones and 380 kPa for prosthetic liner [22], [23]. Real-time pressure and shear force data from the stump/socket interface will be collected by the inner-socket sensors array. The continuously measured pressure maps and the simulation results will be important for guiding how to redistribute the force to adjust for areas of high pressure and shear in the second stage. In the second stage, the inner-socket force distribution will be visualized in real-time on various mobile platforms, such as Android, IOS and Hololens. This visualization can help patients and medical providers monitor the prosthetic system for abnormal force distribution changes. At present, the customizable sensor array and its supporting hardware circuit are designed and prototyped. Pressure map visualization on various mobile platforms has also been achieved.

The customizable pressure sensor array consists of a continuous and consistent pressure sensitive material, and the corresponding circuits to construct discrete pressure sensors [24], [25]. As shown in Fig. 2 on the left, a customizable pressure sensor array was pulled apart to show its three layered structure. Each discrete sensor within the array has a three layered design, with a piezo-resistive material covered by a pair of copper pads. All three layers are flexible. A commercially available piezo-resistive fabric material made by EeonTex^{TM} was used for designing the middle layer [26]. Similar to typical fabric materials, the piezo-resistive material is thin (with a thickness of 0.8mm), light weight (with a weight of 170 g/m^2), flexible, and easily trimmed. The resistance of this material correlates to the pressure applied to it. Therefore, through measuring resistance of the piezo-resistive layer, the force applied on it can be estimated. The mechanism of measuring the resistance of the piezo-resistive material is shown in the schematic diagram in the middle of Fig. 2. Since the resistance changes as a function of applied pressure, it is modeled as a variable resistor. The copper pad on the bottom layer connects the piezo-resistive material to the ground, and the copper pad on the top layer connects the piezo-resistive material to the source voltage via a fixed resistor. Then a voltage divider circuit is built and the voltage drop on the pressure sensor can be measured by the Analog to Digital Converter (ADC).

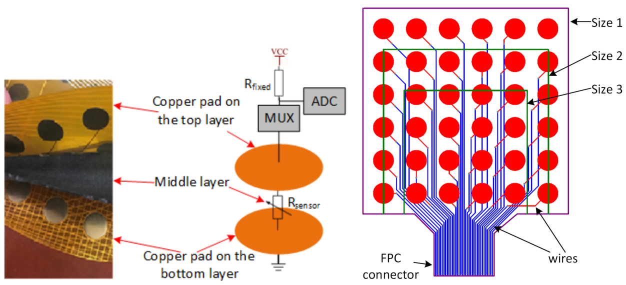

Fig. 2: The mechanism of piezo-resistive pressure sensor array. The figure on the left is a piezo-resistive pressure sensor array that is pulled apart to show its three layers structure. The top layer is shown on the right. Green lines indicate the outlines of two smaller sensor array.

Fig. 2 presents the top view of a customizable sensor array, where 36 discrete pressure sensors are uniformly distributed on this square array. Green lines indicate the outlines of two smaller sensor arrays. Trimming the sensor array along the corresponding green lines would allow for customization. In addition, circuit wires are designed to always be within the green lines, and ensure that all the sensors remaining on the array would be connected with the flexible printed circuit (FPC) connector after being trimmed to a smaller size.

Fig. 3 shows the details of the signal processing circuit. A FPC connector is used to connect the pressure sensor array with the signal processing circuit. Present circuit design supports a maximum of 96 sensors. Multiplexers are used to connect all the pressure sensors and form a voltage divider circuit. The measured data is transmitted through the wireless data transmission units (WiFi and Bluetooth) or stored on the attached memory card. Power management unit is used to supply suitable power to all of the components and a micro-controller unit (MCU) is used to control the work state of all the function modules.

In order to transform one visualization design to multiple platforms, the limb model is built in Autodesk Maya and then imported to and used in Unity3D. To visualize pressure sensor data, each sensor is mapped to a corresponding vertex of model mesh and the relation is saved. Markers are applied to ensure that sensor and vertex locations on the limb are the same as the model. The vertex index and matched sensor index are saved in matrix. The pressure data is shown by color map.

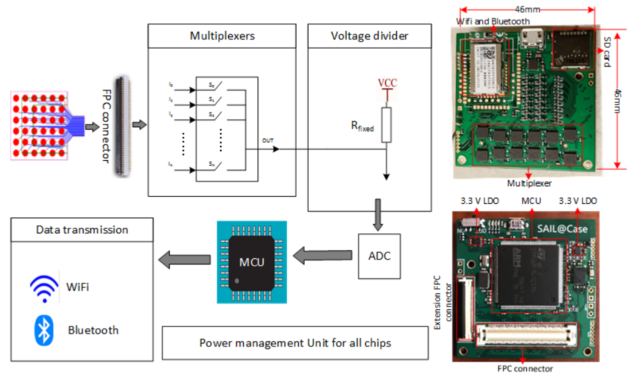

Fig. 3: Signal processing circuit design [24]. The left figure shows the architecture of the signal processing circuit. The figures on the right show both sides of the signal processing circuit prototype.

IV. Experiment and Evaluation

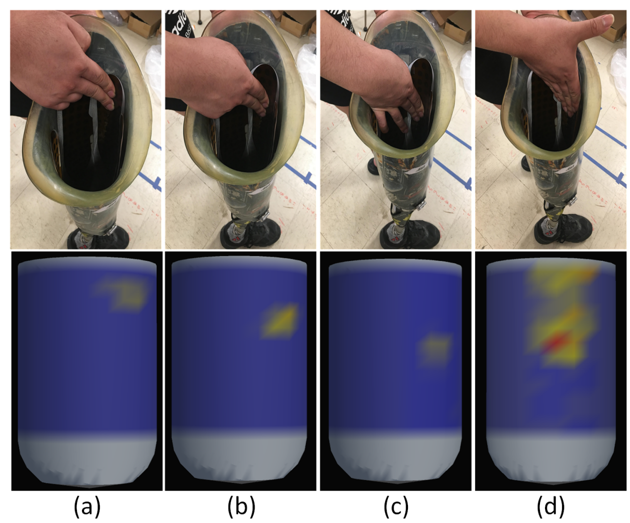

Fig. 4: Inner-prosthesis socket pressure sensor array evaluation with corresponding pressure mapping visualizations.

For testing and evaluation, we placed the sensor array in a plain low extremity (above knee amputation) prosthetic socket. Both the pressure data collection and the visualization on a mobile platforms are detected through the experiments of applying forces artificially by hand to the inner-socket sensor array as shown in Fig. 4.

When we apply the forces with two fingers on a side of the socket in a certain direction from top to bottom, the corresponding pressure mappings are visualized on the mobile app model dynamically ignore of Fig. 4 (a), (b), (c). In Fig. 4 (d), we test this pressure sensing-visualization system by applying force with a palm. Compared with finger pressure, the stressed area is increased with palm and force change is more predominant.

V. Future work

A complete prosthetic system requires comprehensive consideration of multiple factors, as discussed in this paper. Additionally, the material of the liner is an essential part of the system. Our goal for the liner is on electrically active polymers (EAP), which can change its conformation based on a low current. This change in shape would be used to redistribute the forces, based on the aforementioned model, to minimize areas of high stress and shear, and to therefore reduce the risk of pressure ulcers and skin breakdown. Furthermore, in the future a controller will be developed linking the sensor system to the actuator (EAP) system to create a closed-loop system.

VI. Conclusion

In this paper, we have proposed a smart prosthesis system, which could provide continuous automatic pressure sensing in a prosthetic socket. We have designed an in-socket pressure distribution visualization paradigm and evaluated its function. Future work for fully realizing this smart prosthesis system are discussed as well, which include liner material properties and evaluation, FEA modeling and design of a closed-loop control system.

VII. Acknowledgments

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