

Reduced Recovery Time after Free Flap Surgery by means of Textile Sensor Systems

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Summary:

Continuous postoperative perfusion monitoring enables individualized patient care after free microsurgical flap reconstruction of complex wound defects. Pressure and tissue perfusion are key parameters influencing recovery, motivating the development of a sensing system for their monitoring. The individual sensors were developed and demonstrated sufficient sensitivity and reliable performance, and are now being integrated into a single textile-based system, which will be further evaluated in clinical settings.

Keywords: Reconstructive microsurgery, free flaps, postoperative monitoring, pressure sensing, tissue perfusion

Background, Motivation and Objective

Free flap soft tissue reconstruction involves transferring a vascularized tissue from a donor site to a recipient site by means of microsurgical techniques. A common postoperative treatment following lower limb reconstruction with free flaps is the dangling procedure which is used to reduce the risk of complications such as partial or total flap necrosis due to early hydrostatic stress. During dangling, the reconstructed limb containing the transferred free flap is gradually subjected to systematic hydrostatic stress loading by placing the leg in a temporarily vertical position according to a defined protocol. This results in an increase in pressure within the flap due to the absence of lymphatic vessel connections, and may also lead to reduced perfusion at the tip of the flap relative to the supplying pedicle vessel [1]. Both these parameters are essential for successful recovery. Excessive or prolonged pressure impairs microcirculation and delays healing [2], while inadequate perfusion may lead to hypoxia and tissue necrosis [3]. Therefore, continuous monitoring of both parameters is essential to gain a better understanding about the healing conditions. Further, the technique should identify flaps that are early adapted to hydrostatic stress in order to circumvent the routinely used

dangling protocol that is usually performed over 5 days during the acute hospital stay. A detailed knowledge about the individual stress response would support clinical decision-making and enable a more personalized and shorter dangling protocol. Providing this information through a system integrated into a bandage would facilitate practical implementation. The aim of this study is therefore to develop a textile-based sensing system capable of continuously monitoring pressure and oxygen saturation.

Description of the New Method or System

The sensing system consists of oxygen saturation sensors integrated into a pressure sensing textile. The pressure sensing system was developed by FRTI a Business Unit of Inter Spitzen AG (St. Gallen, Switzerland) using the embroidered pressure sensing technology. The sensors based on piezoresistive fibers were arranged in a woven textile structure comprising 32 sensing elements (4 x 8 grid) with a sensing area of 10 x 22 cm².

Applied pressure induces changes in electrical resistance in each sensing element separately, enabling measurement of both pressure magnitude and spatial distribution across the flap reconstructed wound and the surrounding healthy

tissue. Conductive fibers integrated into the textile allow signal transmission to external electronics. The system was characterized within a pressure range of 0.5–5 kPa with step sizes of 0.1 kPa, 0.25 kPa, and 0.5 kPa. This range was selected to correspond to previously reported interstitial muscle flap pressures [4].

To simulate 3D conditions, the pressure sensors were tested using an artificial leg model consisting of a manikin limb covered with an inflatable sleeve. By inflating the sleeve, the stiffness of the structure increases, simulating oedema and inflammatory conditions. The applied air pressure was adjusted to represent normal and oedemic tissue states, as assessed by palpation performed by clinical personnel.

Electronics for the saturation sensor arrays were developed at the Transport at Nanoscale Interfaces Laboratory at Empa (Dübendorf, Switzerland). The system consists of eight sensors connected to a single control unit, allowing simultaneous measurements. Each sensor array integrates a pulse oximetry and heart rate biosensor module (MAX30102, Analog Devices, Inc., Wilmington, MA) connected to a PCA9615DP that converts the standard I²C interface to differential I²C signaling. This configuration provides signal integrity and proper line termination at both ends, one at the sensor node and one at the eight channel hub, ensuring reliable data communication over cable lengths of up to approximately 3 m. The battery powered system is managed by a central control unit equipped with an SD card slot for local data storage, a Bluetooth interface for wireless configuration, and a USB port for data transfer.

The presence of red and infrared LEDs enables measurement of absorption differences between oxygenated and deoxygenated hemoglobin. LED intensities were optimized individually for different anatomical locations (finger, forearm, thigh, calf, and neck). To ensure suitability for postoperative monitoring, the influence of bandaging on signal quality was also evaluated. Finally, sensor performance was validated against a commercial pulse oximeter (WristOx2 Model 3150, Nonin, Tilburg, Netherlands).

The two systems are currently being integrated into a single textile-based system. It is further laminated with polyurethane layer to ensure durability and allow cleaning between participants. Pressure and oxygen saturation measurements will be repeated to confirm that the integrated system maintains performance and that interaction between sensors remains minimal. This includes evaluation of measurement repeatability as well as comparison of sensor behavior before and after integration.

Results

The pressure sensing system demonstrated stable and repeatable responses under both increasing and decreasing pressure conditions. Pressure changes above 1 kPa could be reliably detected, with a sensitivity of approximately 0.1 kPa. Tests on the leg model confirmed the ability of the pressure sensing system to detect simulated inflammation by changes in local stiffness.

For the oxygen saturation sensors, signal quality was influenced by LED intensity, sensor location, and applied pressure. Optimal LED settings were determined for each anatomical site. When compared with the reference device, the developed sensors demonstrated good agreement with a root mean square error of 1.4% SpO₂, supporting their potential use for perfusion monitoring applications. Additionally, the application of a bandage improved the signal-to-noise ratio (SNR), increasing it from 19.2 dB (no bandage) to 25.6 dB (bandage). The bandaged configuration also exhibited more stable periodic pulsations, supporting the system's potential applicability in clinical settings.

Future studies will involve healthy participants, where the system will be tested under varying bandage conditions. Subsequently, clinical studies in patients undergoing free flap surgery are planned to compare standard monitoring methods during the dangling procedure with the developed system. This approach aims to enable data-driven personalization of the dangling protocol and ultimately improve postoperative outcomes.

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