



A Noninvasive Miniaturized-Wireless Laser-Doppler Fiber-Optic Sensor for Understanding Distal Fingertip Injuries in Astronauts

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Abstract

During extra-vehicular activities (EVAs) or spacewalks astronauts over use their fingertips under pressure inside the confined spaces of gloves/space suite. The repetitive hand motion is a probable cause for discomfort and injuries to the fingertips. We describe a new wireless fiber-optic probe that can be integrated inside the astronaut glove for noninvasive blood perfusion measurements in distal fingertips. In this preliminary study, we present blood perfusion measurements while performing hand-grip exercises simulating the use of space tools.

Introduction

The fingernails are made-up of a protein called keratin which acts as a protective shield. The nail acts as a counterforce to the fingertip and because of many nerve endings in the fingertip it provides sensory input when an object is touched. Health Care providers (e.g., Paramedics) often use the fingernail beds as a cursory indicator (blanch test) of distal tissue perfusion of individuals who may be dehydrated or in shock. Fingertip injuries and its care in preventing permanent disability of the hand are described in detail by Wang and Johnson (Ref. 1).

In astronauts, the main cause for finger and hand injuries is focal force accumulation (axial loading and pressure-induced transitions) within the Extravehicular Mobility Unit (EMU) gloves. Therefore, by understanding and redistributing these forces, injuries to the distal extremity can be reduced or eliminated. Astronauts also deal with cold hands during EVAs causing discomfort and potential injury since the temperature on the glove can be as low as -150°C in the shaded side (opposite to Sun). The EMU gloves have built-in heating elements to mitigate this risk. Astronauts are extensively trained in the Neutral Buoyancy Laboratory (NBL) which contains 6.2 million gallons of water to simulate conditions similar to the weightless environment of space. The fingertip discomfort and injuries experienced during EVA and

NBL training is due to reduced skin blood flow caused by contact pressure and reduced temperature. Since the tissue blood perfusion is a primary factor in the transport of heat, drugs, oxygen, waste products, and nutrients, its measurement can provide critical information to help mitigate the risks to finger injuries. The newly fabricated laser-Doppler flowmetry (LDF) probe (described) embedded in the EMU glove will help establish the correlation between the blood flow (perfusion), contact pressure, and temperature in the fingertips of astronauts during NBL training and simulated and actual EVAs.

Fingertip Injuries and Current Countermeasures

Extra-vehicular activities (EVAs) are defined as the tasks performed by astronauts away from the Earth, and outside of a spacecraft (e.g., spacewalks and moonwalks). Since 1965, about 175 successful EVAs have been performed in the past 43 years. Very early-on in the space program, astronauts recognized problems in working with their gloves. During the Apollo missions and lunar surface EVAs, the astronauts reported that fighting the internal pressure of their gloves at 4.3 psi made their hands tired (Ref. 2). The EMU glove is arguably the most complex and most critical part of the entire suit. Twenty-two recently interviewed Apollo-era astronauts made a consensus statement that of all the future improvements in the EMU suit, improving the glove is the most important (Ref. 3). Existing EVA gloves significantly reduce hand dexterity, range of motion, tactility, strength, and endurance. In addition, they are often uncomfortable to the point of pain and/or minor physical injury to the hand (Ref. 4).

Viegas et al. (2004) has shown that approximately half of the astronauts had problems related to the fitting of the gloves in their EVA space suits (Ref. 5). In most of the cases, the problems involved hand fatigue, subungual redness, fingernail pain, and subsequent onycholysis (nail delamination) occurring over succeeding weeks (Fig. 1). Fingernail delamination is by far the most common injury reported among astronauts training in the NBL and performing EVA tasks, and is caused by axial loading of the fingernails when the gloved hand is closed repeatedly to grasp an object (Ref. 6). This may be due to the semi-rigid finger caps of the newest series of glove that concentrate the load at the fingernail and nail matrix, compared to the older model that transmits the load more uniformly throughout the fingertip.

The most effective countermeasure for onycholysis as reported in the suit symptom study of Strauss (2004) is to ensure optimal glove fit (Ref. 6). To solve this problem, countermeasures are devoted to the design of the astronauts' gloves, which are in continuous technological evolution. This is done with the assistance of an EMU glove fit-check chamber, also called the glovebox, which is a vacuum chamber that simulates the 4.3 psi pressure difference from within the glove compared with the outside glove pressures. Other countermeasures include the crewmembers keeping their fingernails short and for them to apply dressings to their fingertips for protection and to keep the fingers free of moisture. These countermeasures alleviate symptoms but do not leave crewmembers free of injury (Ref. 6).



Figure 1.—Problems due to the fitting of the gloves from the EVA space suits involve hand fatigue, subungual redness, fingernail pain, and subsequent nail separation (onycholysis). Onycholysis is by far the most common injury reported among astronauts training in the NBL and performing EVA tasks (Ref. 6).

Quantitative Evaluation of Blood Perfusion to Understand Fingertip Injuries

In this preliminary study, we focus on measuring the blood perfusion in the fingertips in real-time inside an EMU glove. The tissue blood perfusion is a primary factor in the transport of heat, drugs, oxygen, waste products, and nutrients around the body. Therefore, its measurement provides critical information in a number of clinical and research applications. The hemodynamic state of a human fingertip is altered when it is pressed against a surface or bent. Normal force, shear force, and finger extension/flexion all result in visibly distinct patterns of blood perfusion beneath the fingernail. In a paper by Mascaro and Asada (2006) (Ref. 7), photographic techniques were used to indicate that there are at least seven different states of force and posture that yield distinct coloration patterns that are statistically significant and common to people in general. These patterns of blood perfusion can be used not only to monitor the state of the finger, but also to understand how the fingernail interacts with the bone and surrounding tissues when various forces or postures are applied (Ref. 7).

Development of a New, Noninvasive, Real-Time System for Microvascular Perfusion Measurements

The LDF is an established technique for the real-time measurement of microvascular red blood cell (RBC) or erythrocyte perfusion in tissue. Perfusion is also referred to as microvascular blood flow or RBC flux. It works by illuminating the tissue under observation with low power laser light from a sensor containing optical fibers. Laser light from one fiber is directed onto the tissue. Another optical fiber collects the backscattered light from the tissue and returns it to a photodetector. Most of the light is scattered by the tissue that is static, but a small percentage of the returned light is scattered by moving RBCs. The light returned to the detector undergoes signal processing whereby the emitted and returned signals are compared to extract the Doppler shift related to moving RBCs. This Doppler shifted signal yields parameters such as the RBC speed, volume, and flow. It is important to note that the LDF signal is often referred to as tissue perfusion rather than blood flow, as it cannot be directly calibrated in units, such as mL/min. However, both terms (blood flow and perfusion) are frequently used interchangeably. The light that is Doppler shifted is optically mixed with the light that has been scattered by the static structural components and detected by a photo detector.

The photodetected voltage is analyzed according to the scheme developed by Bonner and Nossal (1990) to obtain the LDF parameters (Ref. 8):

$$\text{Blood volume} = \frac{1}{A_{DC}^2} * \int P(f)df \equiv \left[\frac{W}{V^2} \right] \quad (1)$$

$$\text{Blood speed} = \frac{\int f * P(f)df}{\int P(f)df} \equiv [\text{Hz}] \quad (2)$$

$$\text{Blood flow} = \text{Blood volume} * \text{Blood speed} = \frac{1}{A_{DC}^2} * \int f * P(f)df \equiv \left[\text{Hz} * \frac{W}{V^2} \right] \quad (3)$$

where $P(f) df$ is the power spectrum and A_{DC} the voltage of the analyzed signal.

Relative changes in the signal can be related to effects such as local vasodilatation/constriction and so this method is useful for some pharmacological studies where more invasive methods are not suitable.

The blood volume (Eq. (1)) is expressed in W/V^2 where W is the power density and V is the voltage. The blood speed (Eq. (2)) has a unit of Hz and is proportional to the mean speed of the blood within the volume sampled by the laser light. Finally, the blood flow (Eq. (3)), which is the product of the volume and speed, is expressed in $\text{Hz} * W/V^2$.

In order to apply the LDF theory to actual measurements, it is first necessary to filter out the low-frequency artifacts due to the tissue movement (e.g., subjects' breathing, muscle twitch, and motion of the probe relative to the tissue). We therefore utilize the following algorithm to calculate the effective Doppler-shifted frequency at 30 Hz and 30 kHz cutoff frequencies (Eq. (4)):

$$\text{Blood flow} = \frac{1}{A_{DC}^2} * \int_{30 \text{ Hz}}^{30000 \text{ Hz}} f * P(f) df \equiv \left[\text{Hz} * \frac{W}{V^2} \right] \quad (4)$$

The LDF technique offers substantial advantages over other methods in the measurement of microvascular blood perfusion. It is highly sensitive and responsive to local blood perfusion and is versatile and easy to use for continuous monitoring.

Experimental Setup

Using the Doppler formulation (Eqs. (1) to (4)), we have recently developed a miniaturized prototype LDF sensor for remote (wireless) monitoring of fingertip hemodynamics under various conditions of contact forces, temperature, and use of EVA tools. The sensor can be placed at various anatomic finger locations (pad, tip, lateral, nail, etc.) using simple scotch tape and then integrated inside a comfort glove over which an astronaut EMU glove is fitted. The method is noninvasive and does not alter the normal physiological state of the microcirculation. Furthermore, the small dimensions of the sensor have enabled it to be employed in experimental environments not readily accessible using other commercially available LDF sensors, especially for use inside the astronauts' gloves/space suits. The flexibility and miniaturization of the optical probe over commercially available devices is accomplished by a custom-made assembly of multimode optical fibers and reflective miniaturized prisms allowing the light to be side-fired, resulting in a much smaller probe size, which enables the probe to be placed inside the astronauts' gloves. The blood perfusion measurements are limited to a penetration depth of approximately 2 mm (epidermis tissue).

The main components of the blood perfusion measurement system includes a newly designed fiber optic LDF probe (Fig. 2), a 780 nm laser source (Melles Griott 57ICS010/S), a newly assembled two-layered electronic circuit board powered by 4 AA batteries remotely connected to a lap-top computer with

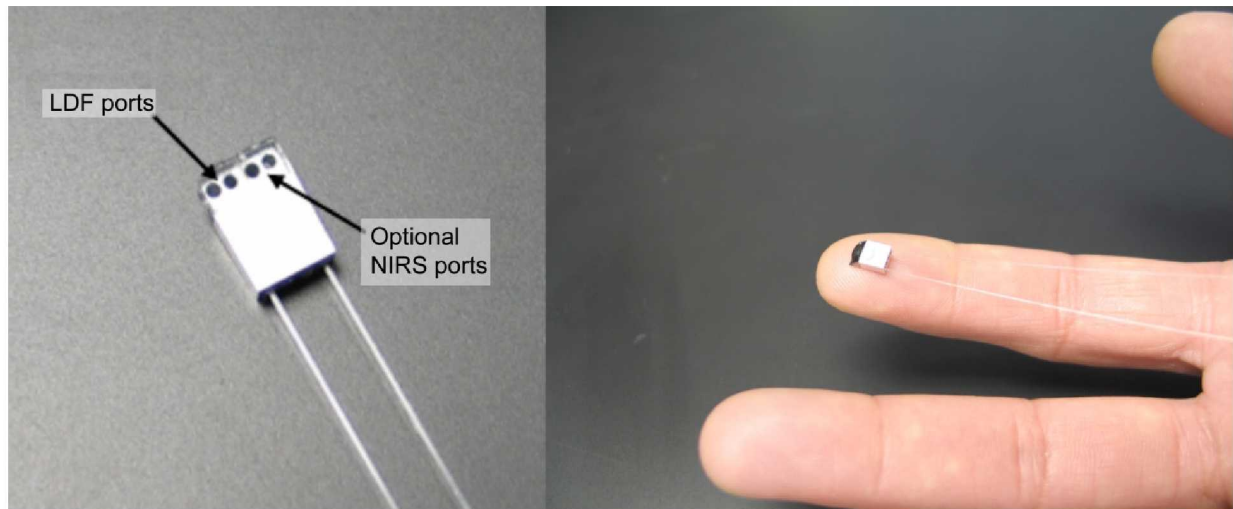


Figure 2.—New miniaturized LDF Sensor (2 by 4 by 6 mm) for fingertip blood perfusion measurements in the astronaut glove. If desired, the sensor can be converted into a NIRS device through the optional optical port to provide tissue oximetry measurements (percent oxygen, oxygenated hemoglobin concentration, and deoxygenated hemoglobin concentration). The NIRS feature is not discussed since the focus of the present study is only on blood perfusion LDF measurements.

bluetooth technology (Fig. 3). The circuit board consists of a photodiode (Hamamatsu model C5460-01), a digital signal processing microchip (Texas Instruments DSPIC model 33FJ256GP710) which performs power spectrum/FFT calculations, and a Bluetooth module (Parani ESD-200) for wireless data transmission. Currently, our device transmits the data in real time to a remote receiver 30 m away to a laptop computer (Fig. 4). The data is recorded and processed in real-time by software we developed in MATLAB (The Mathworks, Inc., Natick, MA) (Fig. 4).

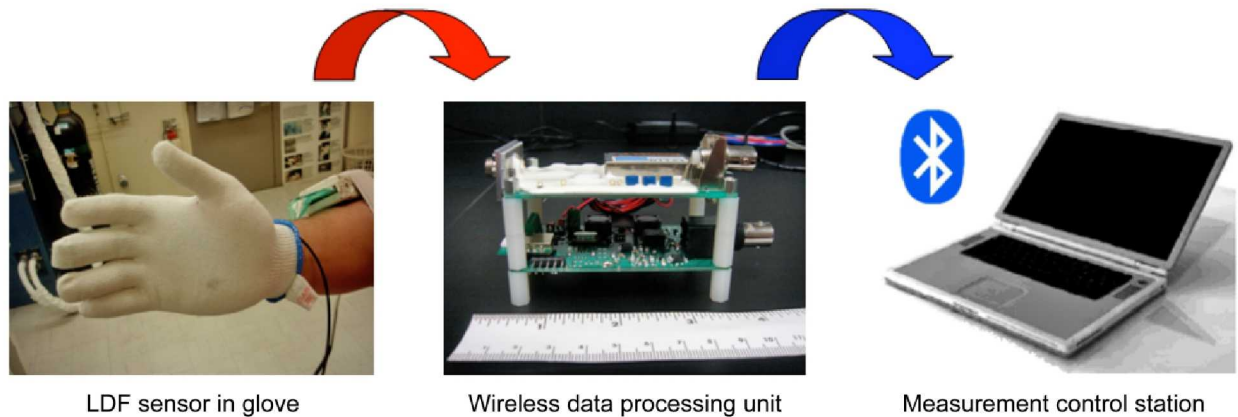


Figure 3.—The new LDF system sends data to a custom made, 4 by 4 by 2 in., wireless data processing unit (shown in middle picture without its cover). The processing unit can be Velcroed to the suit or body during testing. The data is then sent to a computer via Bluetooth technology, allowing the system the flexibility to make measurements remotely from the EMU glove.

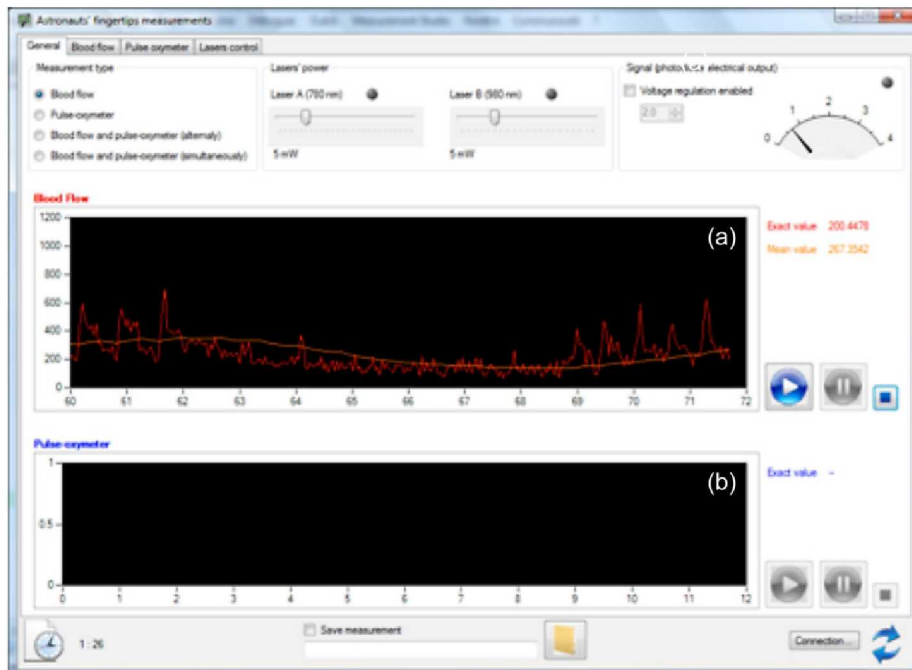


Figure 4.—A screenshot of the graphic user interface for the custom-designed software developed for the LDF sensor. The software provides real-time data. (a) Blood flow. (b) Pulse oximetry (optional).

Results

The most prominent trauma experienced inside the astronaut suit is that of fingernail delamination, which is attributed to axial loading of the fingers during repetitive gripping of EVA tools (Ref. 6). In this preliminary pilot study, we place the new LDF sensor inside an EMU astronaut glove to study the correlation between skin blood flow and contact pressure. The effects of blood flow occlusion were studied to see how different loading conditions influences skin blood flow in the finger as well as contact pressure on the hand. Seven subjects (six male and one female age: 24 to 56 years) were tested in ambient conditions and two subjects were tested at reduced pressure inside the glovebox (hypobaric chamber). The results show that occlusion is more severe in the case when the finger pad is loaded as compared to loading the fingertip. Pronounced hyper-perfusion is also observed when finger loading ceases. It was also observed that higher loads produce an increase in blood flow due to tremors in the hand.

Pressure Distribution on Hand and Blood Perfusion Measurements in Fingertips

The I-Scan pressure measurement system, (Tekscan, Inc. South Boston, MA) was used for collecting the contact pressure data (Fig. 5). The series 4305 vascular sensor consisting of an array of sensels was placed over the dorsum, around the middle finger, and under the palmar region of the hand. The 0.2 mm thick sensor is ideal for this analysis, as it is thin enough to be placed between the skin surface and the glove without interfering with the glove fit. This testing proved that the sensor could be easily placed along the dorsal and palmer surfaces of the finger, and that pressure measurements could be obtained.

The subjects pressed down on an electronic force plate (tabletop weigh-scale) in two different configurations. First, the subject pressed down on the force plate while holding his/her dominant hand in a horizontal position with the distal segment of the middle finger (Fig. 6(a)). Second, the subject pressed down onto the scale with the fingertip while the hand was held in a vertical position (Fig. 6(b)). Measurements were taken as the applied load was incrementally increased from 0 to 10 N in 1 N increments. Three measurements were taken for a 10 N loading and another three for 20 N of load. This procedure was followed for the fingerpad and tip configuration. Blood flow was measured on the side of the tip of the same finger.

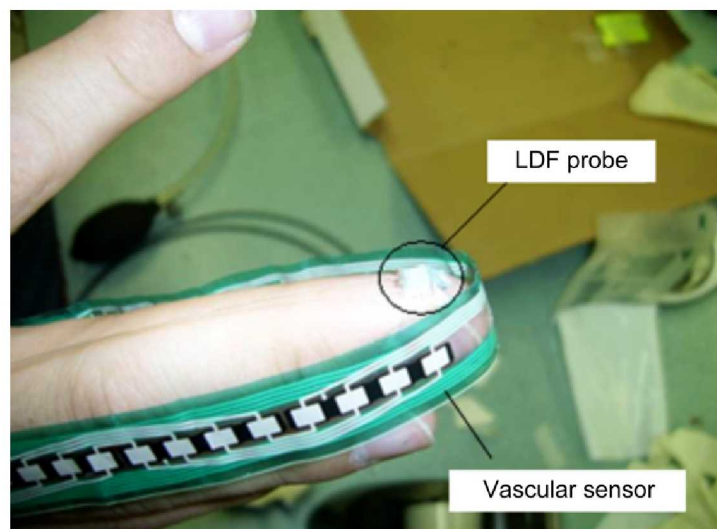


Figure 5.—The vascular sensor detects the pressure on the skin caused by pushing and grasping tasks, while the LDF sensor measures the blood perfusion at the tip of the finger.

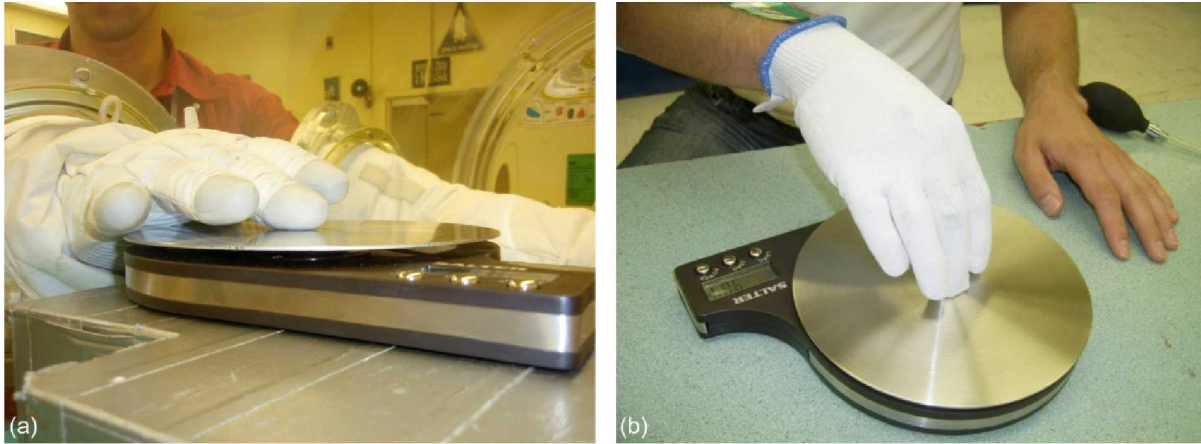


Figure 6.—(a) A subject applying pressure to the scale with the pad of the middle finger fitted with pressure and new LDF blood perfusion sensors while wearing an EMU glove inside the hypobaric glove-fit chamber. (b) The tip of the middle finger with the same instrumentation inside the comfort glove under ambient conditions.



Figure 7.—A subject demonstrating use of the sphygmomanometer assembly during testing. The pressure exerted by the bulb represents the force from gripping an EVA tool.

To represent gripping an EVA tool, a second test was performed. This test involved compressing the bulb of a sphygmomanometer to 100 mm hg (13.3 kPa) three times and to 200 mm hg (26.7 kPa) three times. Figure 7 shows the subject's hand fitted with the vascular sensor and LDF probe, wearing an EMU comfort glove while compressing the sphygmomanometer bulb to a pressure of 100 mm hg (13.3 kPa). This test was performed both inside and outside of the hypobaric chamber to identify differences in skin contact pressure and blood flow due to the EMU glove in a reduced pressure environment.

Figure 8 shows the blood perfusion results for the fingerpad and fingertip configurations. It is observed that blood flow drops more rapidly in the case of the fingerpad and stabilizes at a load of 6 N. The blood flow does increase again for the 20 N load conditions. This apparent rise in blood flow around 20 N could be attributed to tremors in the hand as the subjects expressed that they had difficulty in maintaining the 20 N loading for an extended period of time. This hyper-perfusion of blood may be the main contributor to nail delamination. The ultimate goal is to see if differences in these effects can be measured for injured and uninjured crewmembers.

Skin compression and normalized blood flow for different regions of the hand during the sphygmomanometer tests are presented in Figure 9. It indicates that the bottom of the middle finger experiences the highest compression levels, followed by the palmar region of the hand. Blood flow reduces by approximately 50 percent for the 100 mm hg (13.3 kPa) compression data with a slight increase during the 200 mm hg (26.7 kPa) compression trials, following the same trend as the fingerpad and fingertip experiments.

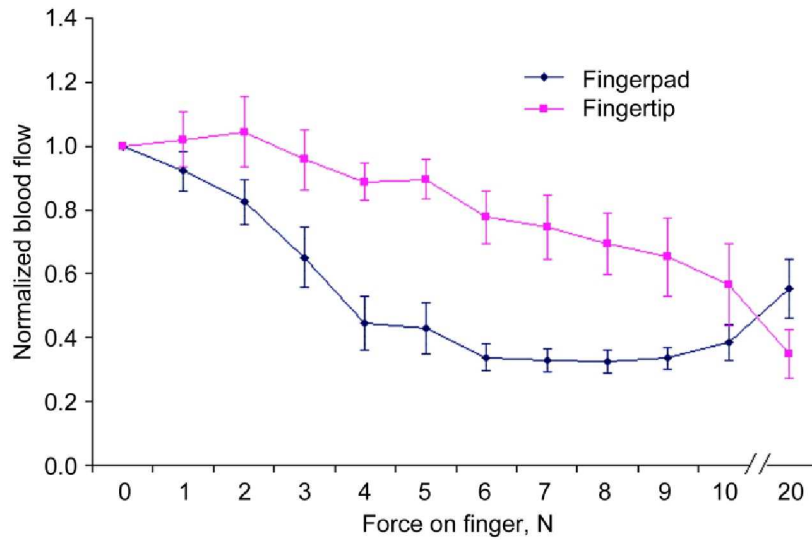


Figure 8.—As the force on the finger is increased, the measured blood flow decreases. This decrease is more rapid for the case of the fingerpad as compared to the fingertip.

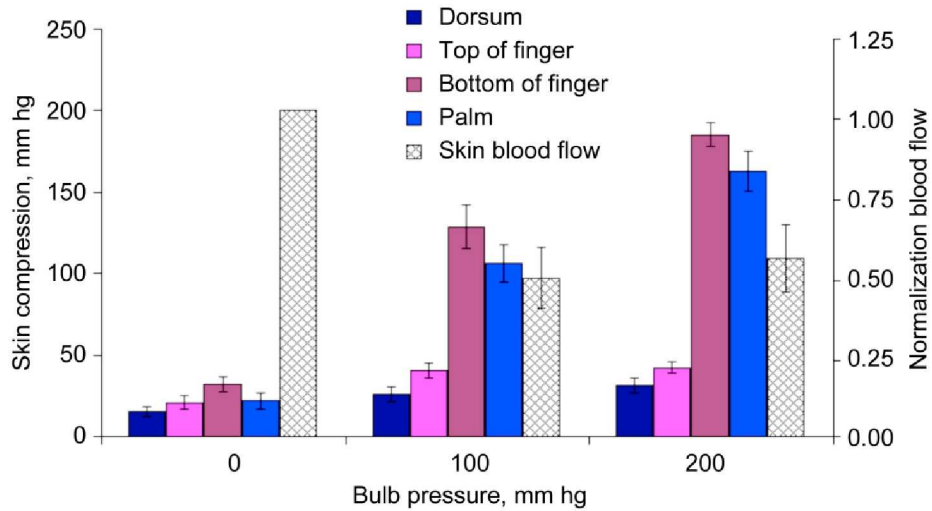


Figure 9.—Skin compression and blood flow for different regions of the hand. The bottom of the middle finger experiences the most skin compression during squeezing of a sphygmomanometer bulb. The blood flow to the tip of the finger is reduced by about 50 percent indicating that using EVA tools may reduce perfusion to the fingertips.

Conclusions

The preliminary results suggest that forces on the finger and hand lead to changes in the blood flow at the tip of the fingers, and this phenomenon can be measured using the non-invasive LDF sensor inside the astronauts' EMU glove. By measuring contact pressures and blood flow for crewmembers wearing the EMU glove inside the hypobaric chamber, possible differences between the injured and control group can be identified and analyzed further to better understand the causal mechanisms for fingernail delamination.

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