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Multi-fingered haptic palpation using pneumatic feedback actuators

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ABSTRACT

This paper proposes a multi-fingered palpation method which employs pneumatic haptic feedback actuators allowing users to experience haptic sensations at multiple fingers while carrying out remote soft tissue palpation. Pneumatic actuators are used to vary the stress on the user's fingertips in accordance with the tissue stiffness, experienced during manual palpation. The proposed method reduces actuator elements compared to tactile actuators and provides more information than single-point force feedback. The results of our finite element analysis have proven that our pneumatic haptic feedback device can recreate the contact stress between fingertip and soft tissue during palpation. The accuracy (96.8% vs. 93.3%) and time-efficiency (4.6 s vs. 8.3 s) advantages of using three-fingered over single-fingered palpation have been confirmed in our user study results of stiffness levels discrimination. Relatively good tumor detection sensitivities have been demonstrated by the palpation user study which has showed a direct correlation between tumor size and detection sensitivity and has further proven the efficiency of the proposed actuator and multi-fingered palpation method for tumor detection in palpation simulation.

1. Introduction

Tactile actuators, which provide the user with tactile feedback as experienced during palpation, have been introduced for tumor identification in Minimally Invasive Surgery (MIS) as for instance described in [1]. Currently, tactile feedback display can be divided into two main simulation types: movable components and materials with variable stiffness. Providing distributed pressure (tactile information) to one finger during palpation has been conducted in [2–5]. Pneumatic activated tactile displays use air pressure to displace the skin, either by discharging air directly through nozzles against the skin or inflating conformable tactors. Kim et al. [5] have tested a pneumatic approach during which compressed air is discharged directly against the skin using an array of open nozzles. Culjat et al. [3] developed a pneumatic balloon tactile display, which can be easily attached to existing commercial robot-assisted surgery systems such as the da Vinci. Pneumatic activated tactile display has the potential to provide distributed pressure (tactile information) to one finger during palpation. However, its current application is limited due to its complexity, the lack of commercially available choices, and the high cost of the required tactile actuators (Fig. 1).

During open surgery, surgeons can identify the locations of tumors inside soft-tissue organs using their fingers. When palpating an organ, the distributed stress (tactile information) on the fingertip caused by the finger-soft tissue interaction can be interpreted as stiffness distribution across the organ—an important aid in detecting buried tumors in otherwise healthy tissue. Previous research has focused on haptic devices to feed back the tactile information during palpation to the surgeon during MIS [2–5]. However, the control complexity and high cost of tactile actuators limits its current application. Thus, single-point force feedback is more common currently, although the haptic information it provides is significantly reduced compared to the information conveyed by tactile actuators. Many commercially available haptic devices provide single-point force feedback ranging from the low-cost Falcon (Novint Technologies, Inc.) to the more advanced Sigma.7 (Force Dimension Inc.) [6–10]. However, multi-fingered palpation is more common and is considered more useful than single-fingered palpation when attempting to detect differences in stiffness in the examined tissue in real practice [11]. Compared to

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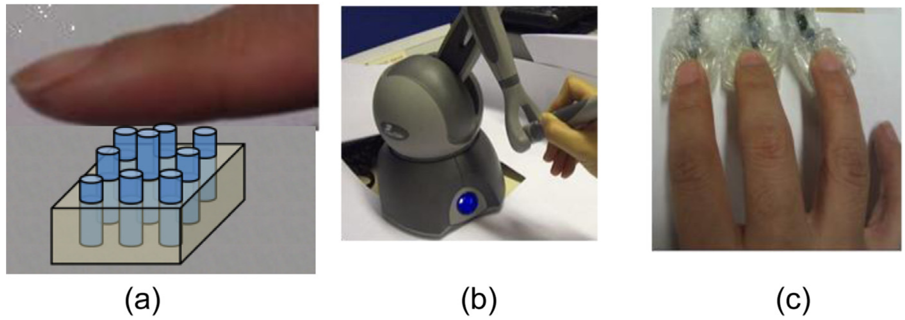

Fig. 1. Tactile feedback, shown in (a); single-point force feedback, shown in (b); multi-fingered haptic feedback, shown in (c).

tactile haptic methods, for example, as described in [2,3], the actuator elements in multi-fingered palpation haptic devices are much reduced. Among the reports about multi-fingered palpation simulation, Rutgers Master II force feedback glove [12] can feed back force up to 16 N to each finger using pneumatic actuators. However, the glove limits the range of motion of the fingers because cylinders are placed between the palm and fingers. The haptic Interface Robot (HIRO) device developed by Kawasaki et al. [13] has been used for breast palpation simulation [14]. It consists of a force actuated 6-DOF arm and three fingers with 3-DOF force output. And it has been updated to a five-fingered HIRO III device [15]. Nevertheless, the price is relatively high. Finger-worn haptic feedback devices can increase the flexibility of the multi-fingered feedback system. Initial studies of finger-worn force and torque feedback devices using dual motors have been reported in [16,17]. The combination of them and conventional kinesthetic feedback devices has also been investigated [16,17]. However, they have not been applied in palpation simulation.

This paper presents the creation and validation of a multi-fingered palpation method using pneumatic feedback actuators. Section 2 describes the methodology of the system design and the evaluation tests. Section 3 provides the results and discussions and Section 4 draws the conclusion.

2. Methodology

2.1. Design

During palpation, a stiff area and a healthy soft tissue area convey different levels of stress on the practitioner's fingertips at the same indentation depth. In this paper, a pneumatic actuator containing a deformable surface, a non-deformable substrate with a cylindrical hole, air tubing and a pressure-controllable air supply is proposed as a means to express soft tissue stiffness information. The user employs a finger to contact the surface of the actuator and the air pressure inside the actuator causes stress on the fingertip and gives an impression of the indentation when palpating a soft organ. Lower pressure represents softer regions while higher air pressure represents stiffer tissue regions.

Our pneumatic haptic feedback actuator (shown in Fig. 2) consists of a PDMS substrate (GE RTV615[1]) with a cylindrical cavity (4 mm in diameter), a soft silicone layer (RTV6166[2] A:B = 1:2, thickness: 3 mm), a silicone rubber film (SILEX Ltd., HT6240[3], 0.25 mm thick, tensile strength 11 N/mm^2, elongation at break 440%, tear strength 24 N/mm), and air tubing. The PDMS substrate has been made by using a printed mold made with a 3D rapid prototype machine (ProJetTM HD 3000 Plus) with a minimum layer resolution of 16 μm. Air was injected into the cavity of the PDMS substrate and caused the silicone rubber film to inflate. The upper soft silicone layer was used to limit the deformation of the silicone rubber film and to simulate the touch impression of soft tissue. The silicone

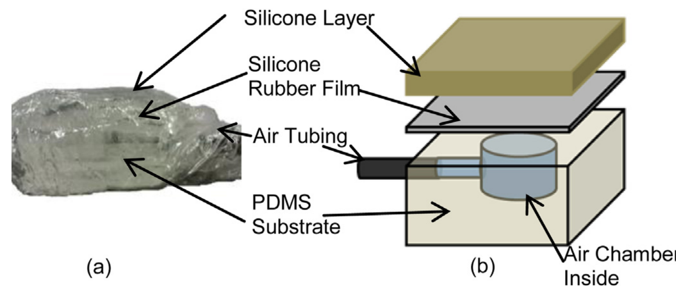

Fig. 2. A pneumatic haptic feedback actuator, shown in (a); schematic diagram of the components, shown in (b).

rubber film and the substrate were bonded with E41[4] translucent silicone rubber adhesive. The air tubing was connected to the PDMS substrate by using RTV108[5] clear silicone rubber adhesive sealant.

Fig. 3 shows the schematic diagram of the control of our multi-fingered palpation device. The calculation of the three channels of air pressure values is related to the tactile sensing input. In the following evaluation studies, predefined stiffness levels or premeasured tissue stiffness have been used instead of the tactile sensing input. Two NI DAQ cards (USB-6211) have been used as analog signal generators for the pressure regulators (ITV0010, SMC). Pneumatic supply was provided by a compressor (BAMBI 150/500 air compressor) with an output set to be 1500 kPa. The pressure regulators inflated each of the actuators with proportional pressures ranging from 0 to 100 kPa.

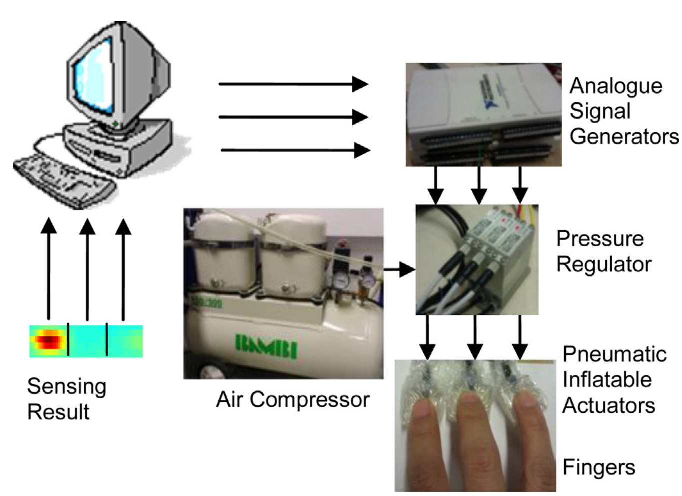

Fig. 3. Multi-fingered palpation device.