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Research article

Continuously-deformable and stiffness-tunable soft manipulator achieving unmanned COVID-19 pandemic sampling

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ABSTRACT

In recent years, COVID-19 has spread across the whole world, and manpowered collection of pharyngeal samples undoubtedly increases the possibility of cross-infections. In this article, based on our previous fabricated soft manipulator (*Cell Reports Physical Science*, 2021, 2, 100600), we performed the COVID-19 sampling on real human volunteers by exploiting a pre-programmed unmanned system. The unmanned sampling system mainly includes a soft manipulator and a rigid motion platform, which are adjusted by pneumatic control box and the motor control modules, respectively. Drawn on the lead-through teaching method, the unmanned sampling of COVID-19 is realized by recording the applied pressure in soft manipulator and the feed motion of rigid platform. This research provides a potential approach for unmanned COVID-19 sampling, solving the risk of cross-infection during manual collection.

1. Introduction

In these two years, COVID-19 ravages the world, bringing large inconvenience and depriving many people's lives [1–3]. Nowadays, hundreds of thousands of people are still infected every day in the world. As is known, nucleic acid testing and medical face shield [4,5] is the most effective way to prevent the epidemic spread, and ensures that the infected people can receive timely treatment. However, in some remote areas, the infected people are usually transported to places with plenty of medical staff and facilities, which undoubtedly increase the difficulty of epidemic prevention and control. In addition, during the epidemic outbreak in India this year, the increasing positive rate of COVID-19 in India is reported above 20%, which is far above the other worldwide epidemic centers [6–8]. That shows the manpowered testing capacity cannot reach the needs of the actual pandemic situation. Compared with US or some European countries which did experience similarly rapid surge in the number of infections, the situation in developing countries may be far more worrying due to the limited capacity of their medical facilities, in particular the shortage of trained medical personnel. The difficulties in the access to medical service by the general public also added to the challenge. On the other hand, the manpowered sampling leads to large gatherings of people, which increases the cross-infection among people waiting to be tested and the medical

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personnel. Therefore, with automated robotics assistance [9–12], the need for medical manpower will be much reduced and the results of the tests will be available much faster, which is critical in containing the spread of the virus. Nowadays, rigid arms have been explored for COVID-19 sampling. Compared with the rigid arms, the emergence of soft robots [13–16] improves the operation safety greatly. A soft robot consists of lightweight and soft materials, such as gels [17,18], VHB elastomers [19,20], silicone elastomers [21], liquid dielectrics [22], and shape memory polymers [23,24]. Owing to the versatile properties of soft robots, medical manipulators and devices have also evolved toward the softening direction [25–27]. In recent years, the field of soft medical robots has emerged as a research area and various surgical instruments have been designed. Particularly, polymer-based approaches for the treatment and prevention of COVID-19 infection have been explored [28]. Furthermore, in the case of facing the challenge of widespread COVID-19 pandemic, a soft robot for effectively collecting the pharyngeal samples is in high demand. As illustrated in Fig. 1, a soft manipulator mounting throat swab can be potentially employed to replace the traditional rigid arms in the current COVID-19 sampling process.

2. Results

Based on our previously-designed soft polymeric manipulator [29], we further exploit it as an unmanned sampling device for COVID-19 pandemic, which is sketched in Fig. 2. For more details on the design and manufacturing process of soft manipulators, please refer to our recent publication [29]. The rigid motion platform, which includes three linear motors, is used to control the location of the soft manipulator, as shown in Fig. 2(a). The three linear motors ensures that the soft manipulator can move arbitrarily in three directions. Afterwards, the designed soft manipulator with three segmented units is assembled on the rigid motion platform, as displayed in Fig. 2(b). As reported in our previous research [29], each unit is a concentric tubular structure and comprises a pneumatic internal actuator (with three chambers) and fiber-based stiffness-tunable jacket. By applying driving pressure to the internal actuator, the soft manipulator produces bending deformation; at the same time, by applying interference pressure to the external jacket, the bending stiffness is improved. That is, the soft manipulator have the characteristic of 'alternating softness and stiffness'. Due to the advantages of light weight, small size, and convenient actuation and control, the soft manipulator can be utilized to sample COVID-19 pandemic by installing a miniature camera and a throat swab at the front tip of the soft manipulator. In addition, a medical bite mark is preset on the sampling area to help locate the human mouth (Fig. 2(b)). The rigid motion platform is regulated by the motor control modules (Fig. 2(c)), while the movement of the soft manipulator is tuned by a pneumatic control box (Fig. 2(d)). The integral sampling system is exhibited in Fig. 2(e). Furthermore, the soft manipulator can be expected to replace the rigid arms and install on the widespread-used COVID-19-sampling vehicle, which facilitates the possibility of mobile detection and avoids the direct contact between the patient and medical staff (Fig. 2(f)).

Afterwards, a pre-programmed unmanned system was developed to control the throat swab to enter the oral cavity and perform sample collection, as shown in Fig. 3. For the rigid robot, the position can be recorded by lead-through teaching method [30,31]. By collecting sequence of points, the walking track can be learnt in advance, and then the previous track can be reproduced afterwards. For the soft manipulator, we can also use this method to reproduce the pre-track. First, we realize the required walking path of the soft manipulator in advance through teleoperation, and record the basic sequence of the pneumatic pressure and feed motion of the rigid motion platform. Based on the saved sequences of pressure and feed motion, the trajectory reproduction can be realized.

During the control of soft manipulator, proportional valves are used to control the pressure in each chamber of the internal actuator. Therefore, the essence of the deformation control of soft manipulator can be attributed to the control of the pneumatic

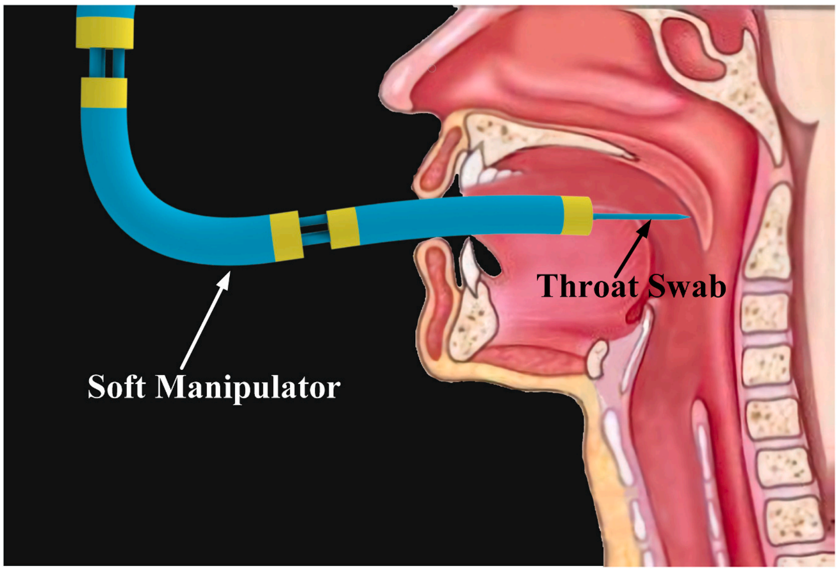

Fig. 1. Potential application of a soft manipulator mounting throat swab for COVID-19 sampling.

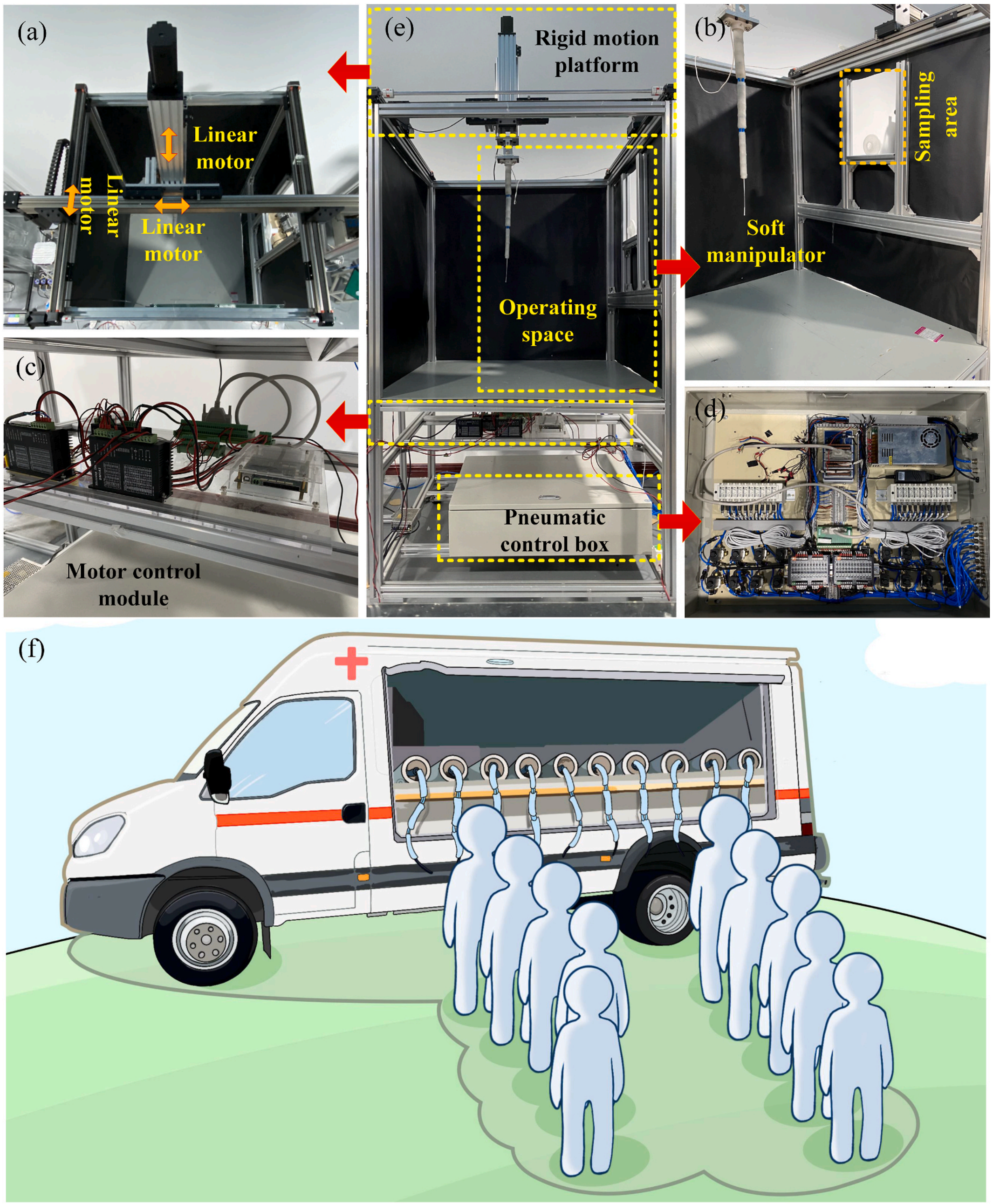

Fig. 2. Experimental sampling platform for COVID-19 pandemic using soft manipulator. (a) Rigid motion platform to control the movement of the soft manipulator. (b) Soft manipulator with three units, equipped with a miniature camera and a throat swab, is assembled on the rigid motion platform. (c) Motion control module for rigid motion platform. (d) Pneumatic control box for soft manipulator. (e) The integral sampling system for COVID-19. (f) Expectation of the soft manipulator to install on the COVID-19-sampling vehicle.

pressure and loading time in each chamber of soft manipulator. Hence, it is necessary to record the sequences of pneumatic pressure in the chambers of soft manipulator to realize trajectory reproduction. The recording program is implemented as follows (Fig. 3(a)). We use Labview for programming in the principal computer, and make Data Acquisition (DAQ) to generate the 0–10V analog quantity through NI DAQmax to control the outlet pressure of proportional valves. Therefore, voltage data sent by Labview program can be regarded as the pressure data. In order to simplify the collection procedure, the voltage data is recorded every 0.02s. After the collection of sequence of pneumatic pressure, the pressure in air chamber can be tuned by controlling the NI DAQmax to release the corresponding analog voltage. The specific programming procedure is presented in Fig. 3(b). Meanwhile, the front panel of the sampling system is given in Fig. 3(c). The corresponding control flow chart is shown in Fig. 3(d). The first sampling is realized through teleoperation of the bending deformation of soft manipulator and the motion of the rigid motion platform, during which the sequences

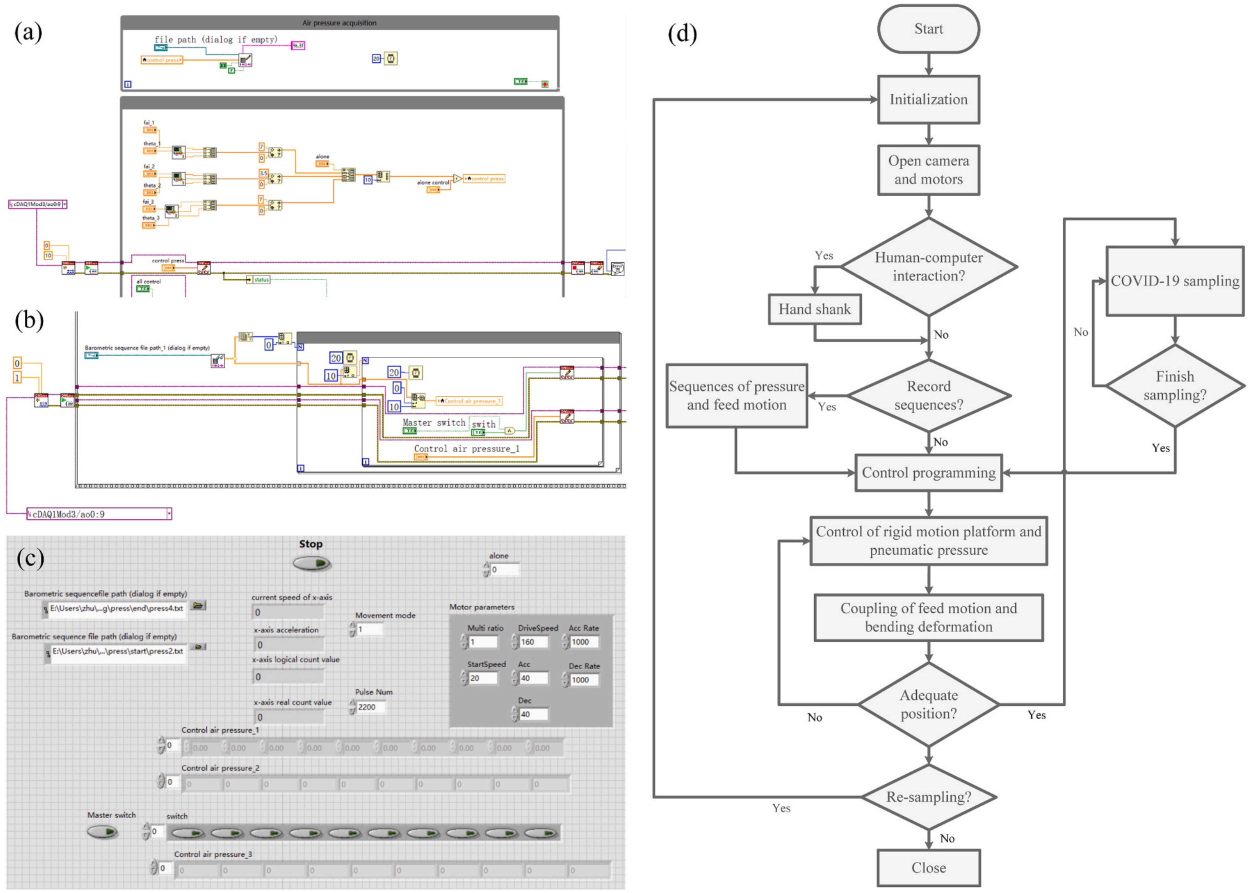

Fig. 3. Programming of unmanned sampling system based on soft manipulator. (a) Program chart of pneumatic pressure sequences acquisition. (b) Program chart of pneumatic pressure sequences loading. (c) Front panel of unmanned COVID-19 sampling. (d) Control flow chart of unmanned COVID-19 sampling.

of aerodynamic pressure and feed motion are recorded and preserved. Then, it can be switched to the unmanned control, that is, the movement of soft manipulator is completed by reading the saved sequence files of pneumatic pressure and feed motion.

The process of COVID-19 sampling on real human volunteer using the designed soft manipulator is shown in Fig. 4. The whole process can be completed within 40s. Firstly, the trial volunteer put his/her mouth on the medical bite, and the soft manipulator assembled with the camera and throat swab is kept in the soft state, as shown in Fig. 4(a). Afterwards, the tip of the soft manipulator is controlled to point towards the medical bite. In order to strengthen the output force of soft manipulator, the two units close to rigid motion platform is stiffened by applying a jamming pressure, as illustrated in Fig. 4(b). Then, the soft manipulator is controlled to make the swab approaching and sampling the throat of trial volunteer, as presented in Fig. 4(c). After finishing the sampling, the soft manipulator is adjusted to move backward to the starting position and prepare for the next sampling cycle, as shown in Fig. 4(d). During the re-sampling process, it is required that, people open plastic bag and take the throat swab, then insert the throat swab into the reserved space at the front of the soft manipulator. After collection, the people remove the throat swab from the soft manipulator and place it in a test tube. The non-fully automated sampling may be a limitation of this system. The detailed whole process can be found in the Supplementary Video S1.

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e13731.

Finally, the successful sampling rate of our system is considered. We have invited 10 volunteers, and each volunteer is sampled five times. According to the experimental data, 47 of the 50 collections are successful, and the other 3 failures are due to improper installation of the throat swab. Therefore, it is proved that our sampling system can guarantee a relative high success rate.

3. Conclusions

In a summary, based on our previous designed soft manipulator, we developed an unmanned COVID-19 sampling system, which is capable of operating in remote sites to conduct quick testing of patients. We have successfully tested the soft manipulator on the real human volunteers, and have expected a potential facility that can conduct quick testing using this soft robot to collect the samples and doing on site analysis of the samples in a vehicle equipped with the necessary facilities. Our work provides a potential unmanned

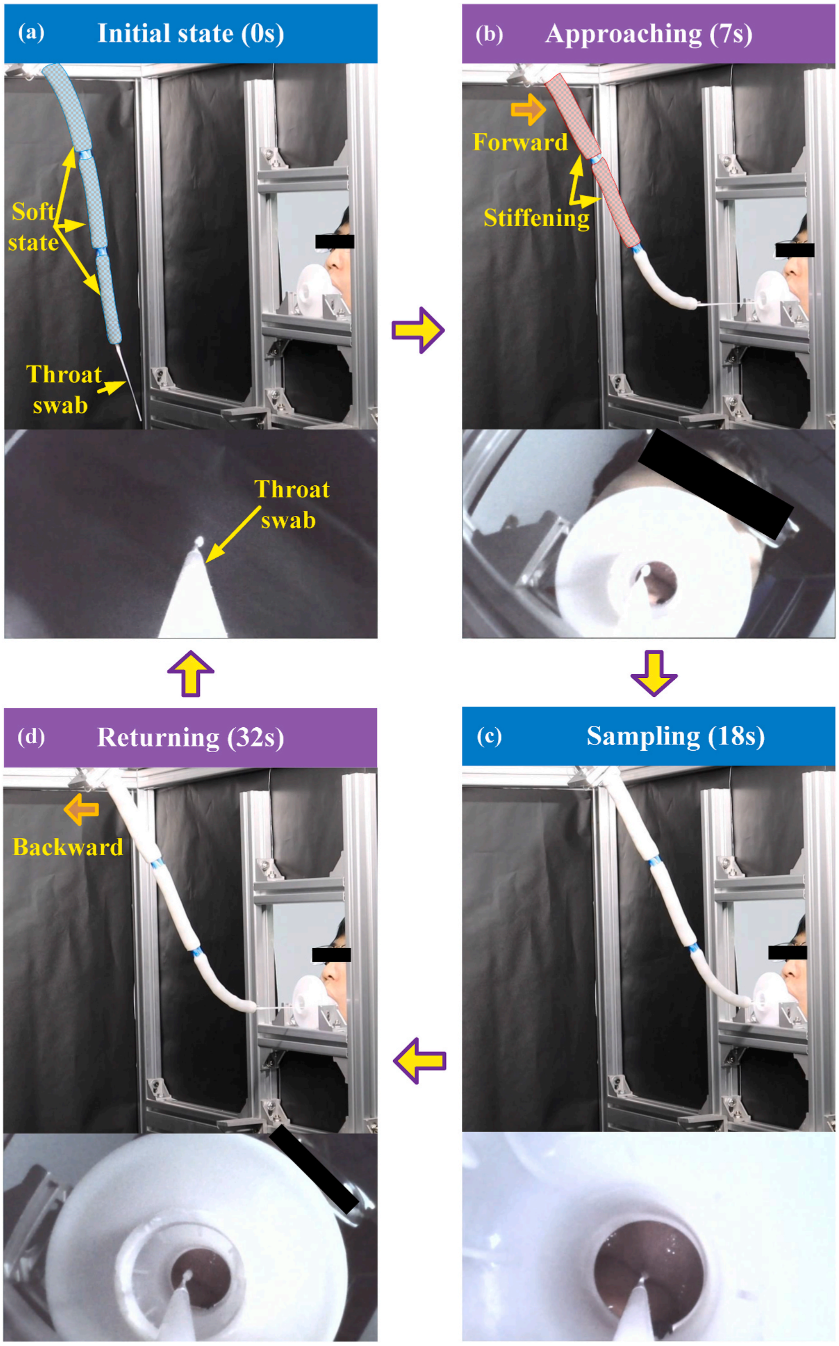

Fig. 4. Process of unmanned COVID-19 sampling on human volunteer using the designed soft manipulator.

sampling method for COVID-19 pandemic, and thereby overcomes the existing challenges of cross-infection between human beings.

Ethical statement

The human participants consented to take part in the study, and their participation was approved by the ethics committee of Xi'an Jiaotong University.

Declarations

Author contribution statement

Junshi Zhang: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
Lei Liu: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Mingliang Zhu: Performed the experiments.
Dichen Li: Analyzed and interpreted the data.
Jian Lu: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary Video S1.

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