Here, we report an integrated operation of microfluidic pumps and valves only by finger actuation. As the working principle of the finger-actuated microfluidic pumps includes deflection of the poly(dimethylsiloxane) (PDMS) membrane, the pneumatic valves for controlling the flow direction can be easily integrated with the pumps. Using a single button, the flow path can be determined and flow generation can be achieved. We also verified the integrated operation of finger-actuated pumps and valves by demonstrating nucleic acid purification.

In microfluidics for diagnostic applications, specifically for point-of-care testing (POCT), it is important to miniaturize the overall system and simplify the operation principles. The use of external pumping systems can make the systems bulky, expensive, and not user-friendly. To address these issues, various types of simplified pumping systems have been developed using capillary forces, degassing pumps, syringes, pipettes, screws, and finger actuation. Although fluid flow can be generated easily in microfluidic devices, it is difficult to control the flow direction without valves. Deformation of a polymer membrane driven by pressure is a common working principle for controlling the flow direction in microfluidic devices. Application of this working principle has resulted in the development of Quake valves, doormat valves, curtain valves, and plunger valves. Simple pneumatic microfluidic valves have also been introduced using Braille pins and screws. Microfluidic valves with simpler operation principles, which are favorable for simplification of overall microfluidic systems, have also been reported, including capillary burst valves, aligning valves, and plug-type valves. Although a number of methods for simply actuating individual microfluidic pumps and valves have been developed, the integration of pumps and valves is still required to achieve a simplified operation of microfluidic devices, including flow direction control.

For easy integration, it would be advantageous for valves to operate on the same principle as pumps or passively. If additional operations are needed for the actuation of microfluidic valves, however, the advantages offered by the simple working principle of microfluidic pumps are lessened. In this manner, passive microfluidic valves are advantageous for integration into simply operated microfluidic devices, as no additional operations are required. It has been demonstrated that the simultaneous operation of pumps and valves can be achieved by deforming the poly(dimethylsiloxane) (PDMS) structure using a roller. Several studies have demonstrated simple control of flow directions in microfluidic devices, but on-demand flow control in complicated fluidic circuits was hard to realize. It would be advantageous to integrate on-demand controllable pumps with valves that work according to the same operation principle.

Here, we report finger-actuated microfluidic pumps and valves that work as a single unit. Pneumatically operated microfluidic pumps and valves can achieve on-demand flow control in complicated fluidic circuits. Recently, we developed a novel working principle for a finger-actuated microfluidic pump that can achieve a constant volume regardless of differences in end users. As the working principle includes pneumatic deflection of the PDMS membrane induced by pressure changes in the pneumatic channels, the additional pneumatic valves can be easily integrated to determine the flow direction. However, it is impossible to integrate pneumatic valves into other types of finger-actuated microfluidic devices because their working principle does not include pneumatic channels. By applying this working principle, various types of fluids that flow into different fluidic paths can be determined based on the predesigned logic circuit and actuated button. We tested the integrated operation of the finger-actuated microfluidic pumps and valves via sequential delivery of multiple reagents on a device with four branched microfluidic channels. As a proof of concept, we...
then designed a device for nucleic acid purification and used it to purify synthetic hepatitis B virus (HBV) DNA without any external equipment.

The finger-actuated microfluidic pump, which consists of two pneumatic valves and an actuation chamber, operates according to the pressure change in the pneumatic channels induced by pushing the button. The PDMS membrane between the fluidic and pneumatic channels is deflected depending on the pressure changes in the pneumatic channels. When the button is pushed, the increased pressure in the pneumatic channels closes pumping valve 1 (PV1) and compresses the actuation chamber. Then, the fluids in the actuation chamber flow by opening pumping valve 2 (PV2) (Fig. 1A). When the button is released, PV1 is opened and the actuation chamber is decompressed. Expansion of the actuation chamber results in a decrease in the pressure of the fluidic channels, which leads to closing of PV2. As the pneumatic and fluidic channels are separated by the PDMS membrane, the pneumatically actuated switching valves which are operated with the same button can be integrated to control the flow direction. The additional switching valves (SV1–SVn) are closed by the deflection of the PDMS membrane when the button is pushed, and are opened as the button is released. Therefore, the finger-actuated pumps and the switching valves can work as a single unit sharing the same actuation, and two types of backflow occurred according to whether the button was pushed or released (see Fig. S2, ESI†). The backflow when pushing the button was due to the operation of the pump before the switching valves were closed. The average pressure change of the pneumatic channel must be constant at equilibrium, but the instantaneous pressure change of the pneumatic channel when the button is pressed depends on the length of the pneumatic channel. The shorter the length of the pneumatic channel connecting the button and the switching valves, the greater the pressure change in the pneumatic channel connecting the button and switching valves, allowing the switching valves to operate before the pumping valves. However, when the switching valves were located farther from the button than the pump, a small section of the actuation chamber was squeezed first before the switching valves were closed, resulting in backflow into other channels. This type of backflow can be reduced by shortening the pneumatic channel connecting the button and the switching valves, or by slowly pushing the button. In addition, the backflow upon the release of the button was due to the actuation volume of the switching valves. When the button was released, the switching valves were opened, and backflow into the other channels occurred. This type of backflow can be improved by reducing the actuation volume of the switching valves.

By applying the working principles of the finger-actuated pumps and valves, a device for nucleic acid purification was designed as shown in Fig. 3A and B. Solid-phase nucleic acid purification was achieved using silica microbeads, and the

Fig. 1 Concept of the integrated microfluidic pumps and switching valves operated by finger actuation. (A) Schematic representing the simultaneous operation of pumps and switching valves with a single button. (B) Schematic showing the working principle of the pumps and switching valves acting as a single unit. (C) Fluids can be dispensed by the finger-actuated pumps into the predesigned flow paths.
nucleic acid with negative charge could be adsorbed onto the surface of the silica microbeads in the presence of chaotropic ions. The device consisted of three inlets, the silica bead column and two outlets. Two weir structures allowed the silica microbeads to be packed at the microfluidic channels. The finger-actuated pumps were off and the valves were initially open before the device was actuated. Once the buttons were actuated in programmed order after loading the reagents into each inlet, the switching valves were systematically closed and the corresponding pumps were actuated to achieve sequential delivery of multiple fluids via the predetermined flow paths for purifying the nucleic acid (Fig. 3C and D). When button 1 was actuated, the unpurified nucleic acid from inlet 1 flowed into the silica bead column and bound onto the surface of the silica microbeads. The remaining impurities in the silica bead column were removed with a washing buffer from inlet 2 using button 2. The waste during the nucleic acid binding and washing processes was collected at the waste chamber (outlet 2). After removing the waste from outlet 2, the silica bead column was dried to remove residual ethanol on the surface of the silica microbeads, which can inhibit the polymerase chain reaction (PCR). Blowing air into outlets 1 and 2 using an air gun for approximately 10 s each removed the residual ethanol. The nucleic acid bound onto the surface of the silica beads was then eluted with an elution buffer by pushing button 3. Finally, the purified nucleic acid was obtained at outlet 1. The finger-actuated pumps operated with buttons 1, 2, and 3 were designed to dispense 2, 2.5, and 4 μL, respectively. As the device was not pre-filled with fluid in the initial state, the actuation chamber cannot measure the volume of the liquid corresponding to the actuation chamber on the initial operation of the button. On the second push of the button, fluid corresponding to about 60% of the actuation chamber volume was dispensed into the outlet, and the whole actuation chamber was filled with the fluid when the button was released.

Fig. 2 Feasibility test for the operation of the finger-actuated pumps and valves. (A) Schematic of the device with four inlets and a single outlet, in which each button can cause the flow of reagents from each inlet. (B) Enlarged view of the red dashed box in panel A showing the positions of the pneumatic valves connected to each button. The images show (C) the valves when they are open or closed and (D) the fluid flow at the branches when each button is actuated (see Video S1, ESI†).

Fig. 3 Configuration and working principle of the device for the nucleic acid purification. (A) Schematic and (B) picture of the device consisting of three inlets and two outlets. (C) The images showing the actuation of the pumps and valves, as well as the flow direction according to the actuated button. (D) Schematic showing the nucleic acid purification procedure at the silica bead column. (E) Graph showing that the volume dispensed by the finger-actuated microfluidic pump was not dependent on the silica bead column. (F) Results of the nucleic acid purification. (Top) The fluorescence signals of the amplified nucleic acid were seen after purification. (Bottom) There were no fluorescence signals when the nucleic acid was not purified.
On the third push of the button, a volume of fluid corresponding to the volume of the actuation chamber was dispensed into the outlet and the same amount of fluid was charged from the inlet. Hence, button 1 was operated five times, button 2 was operated five times, and button 3 was operated four times to allow the flow of 6.5 μL of unpurified nucleic acid, 8 μL of washing buffer, and 10 μL of elution buffer from each inlet. Before performing nucleic acid purification using the device, whether finger-actuated pumps operated well or not was determined, given the high flow resistance of the silica bead column. After designing the single microfluidic channel connected to the silica bead column, the dispensed volume was compared between the conditions with and without the presence of the silica beads (Fig. 3E). There was no significant difference in the dispensed volume when the silica bead column was located downstream of the finger-actuated pump, but it was necessary to hold the button for a longer time to discharge the fluid from the actuation chamber of the finger-actuated pump due to the higher flow resistance of the silica bead column. In the absence of the silica bead column, a pushing time interval as short as 1 s would not affect the dispensed volume as shown in our previous study.24 However, in this study, the button holding time was set to a minimum of 3 s to discharge the whole volume of the reagent into the actuation chamber of the finger-actuated pump due to the hydrodynamic resistance of the silica bead column. The dependence of the button holding time on the hydrodynamic resistance means that the system is not robust. The hydrodynamic resistance of the downstream channel would differ depending on the application of the system, and it would be helpful for end users to provide a guideline regarding the minimum button holding time for a specific application. Integration of a timer showing the button holding time would also be helpful.24

To evaluate the feasibility of nucleic acid purification using the finger-actuated microfluidic device, we purified synthetic HBV DNA in lysis buffer. An internal control (IC) was used in conjunction with a PCR master mix to verify the operation of enzymes for the PCR. The signal of the IC should always be visible regardless of the presence or absence of HBV DNA; no IC signal indicates that the PCR is inhibited by the lysis buffer or impurities in the lysed sample. As shown in Fig. 3F, the PCR was performed successfully for different concentrations of purified HBV DNA (2 × 10^5 and 2 × 10^6 copies) while no signals were present in the negative control. Higher concentrations of HBV DNA showed lower threshold cycle numbers. Fluorescence signals of the IC were always present for the above three cases. However, for the unpurified HBV DNA, no fluorescence signals were seen, indicating that the PCR was not successful due to PCR inhibitors in the lysis buffer.

**Conclusions**

In summary, finger-actuated microfluidic pumps and valves were operated simultaneously by pushing a button. The valves were actuated first to determine the flow paths, and the pumps dispensed the fluid into the flow paths. No external equipment was required to pump the fluid or control the flow direction. It should also be noted that the same operation principle was used to actuate both pumps and valves for controlling the flow in the microfluidic device. Although the simplest method of finger actuation was used to operate the microfluidic device, a constant flow volume was achieved via the predesigned flow paths according to the actuation of the valves. Furthermore, as the finger-actuated pumps and valves are actively operated by pushing the button, they can be used repeatedly as needed by the end user. In addition, the number of pumps and outlets, and the design of the fluidic circuit, can be adjusted. The results demonstrated the sequential delivery of multiple fluids and control of the fluid outflow direction by applying the finger-actuated pumps and valves. As a potential application, we also demonstrated nucleic acid purification using synthetic HBV DNA. Application of the integrated operation of the finger-actuated microfluidic pumps and valves is not limited to nucleic acid purification, and we expect that such integration will find wide applications in POCT.

**Author contributions**

Conceptualization, J. P. and J.-K. P.; formal analysis, J. P.; funding acquisition, J.-K. P.; investigation, J. P.; methodology, J. P.; supervision, J.-K. P.; validation, J. P.; writing—original draft, J. P.; writing—review & editing, J.-K. P.

**Conflicts of interest**

There are no conflicts of interest to declare.

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**Notes and references**