Ori-Vent: Design and Prototyping of Accessible and Portable Origami-Inspired Ventilators

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Abstract. The COVID-19 pandemic is responsible for hundreds of thousands of deaths worldwide and remains a challenge that humanity must still overcome. As hospitals continue to admit critical patients, they face medical equipment shortages that may hinder life-saving treatments. We seek to combat this equipment shortage by presenting a proof-of-concept portable automated ventilator that is simple, lightweight, and easy-to-fabricate based on an origami-inspired robotic approach. We discuss the design, fabrication, and initial testing of three such devices, two folded from a thin plastic film into a flexible bellows shape, and the other a 3D-printed version of the same design. We show that these initial designs satisfy most of the ventilator performance requirements for emergency portable automated use, with the 3D printed bellows being more flexible and capable of generating higher pressures. The next step is to expand our design and perform further testing to ensure our device is ready to save lives.

Keywords: Portable ventilator, origami-inspired robotics, pneumatics

1 Motivation, Problem Statement, Related Work

1.1 Motivation

There are more than 70 million confirmed cases of COVID-19 worldwide, and the death toll has surpassed 1.5 million [1]. As of Mid-December 2020, the US was reporting an additional hundred thousand cases per day, and hospitals remained in danger of being overwhelmed with patients who may require critical care and relatively long-term ventilation to stay alive. A spike in cases could lead to a dangerous shortage of ventilators, resulting in more deaths. It is clear that there is a growing need for inexpensive and easy-to-manufacture medical equipment to supplement hospitals' existing supplies and enable portable automated operation.

1.2 Problem Statement

The main requirements for our novel ventilator design are affordability, accessibility, and functionality. Our design must use inexpensive materials and simple manufacturing methods. It must not depend on any medical parts that may also suffer a shortage or take away from their primary uses, such as bag valve masks (BVMs). Additionally, the design must be small and portable, without depending on a hospital's infrastructure or large rigid machines. In order to design a functional ventilator, we aim to meet the following criterion [2]:

* Capable of functioning for at least 48 hours
* Have a connection method to allow an adjustable O_2 source to be connected
* Capable of providing a respiratory rate of 12-40 breaths per minute (BPM)
* Capable of providing 5-24 cm-$H_2 0$ of positive end expiratory pressure (PEEP)
* Capable of delivering tidal volumes range 160-1500 cc with every breath
* Capable of limiting the peak inspiratory pressure to 18-40 cm-$H_2 0$
* Powered using 120 V or lower (ideally with a 12 V car battery)

1.3 Related Work

Because of the COVID-19 pandemic, the field of alternative ventilator design has recently become an urgent matter that has caught the attention of many organizations and labs. Some organizations have rapidly published open-source ventilator projects with the hope of quickly saving lives. For example, the team from University of Florida [3] is working on a bellows-based ventilator. MIT's E-VENT [4] project uses a linkage mechanism to compress BVM as the pressure source. Another low-cost open-source ventilator [5] is using vacuum to generate a pressure differential. These designs depend on relatively large machinery, a vacuum source, or a BVM to function, while our goal is to utilize inexpensive materials and create a portable design that can be added to the current stockpile of manual and automated ventilation machines and that can be built from scratch with off-the-shelf commonly available materials.

Origami structures, two-dimensional patterns that are folded into complex structures, are popular actuator designs because they are lightweight, controllable, and inexpensive to manufacture. One existing approach focuses around the proprieties [6] [7] and applications [8] of origami springs and bellows.

2 Technical Approach

Our proposed ventilator design leverages our existing work with origami continuum manipulators, where we have developed cable-driven origami-inspired soft robotic bending and axially compressing modules with integrated electrical motors, sensing, control, and communication systems [9]. The ventilator is based on this module crease pattern and consists of a flexible, air-tight bellows, either made from folded plastic or NinjaFlex, a flexible 3-D printed material. A single L-Bend geared DC Motor (224:1 gear ratio) mounted inside the structure drives a cable attached to the other end. When the motor wraps the cable around a spool, the bellows contracts and the system performs its intended function to push air as a ventilator (Cables are pulled with a clockwise rotation of the motor and are released with a counterclockwise rotation). The prototypes of the proposed design are shown in Fig. 1.

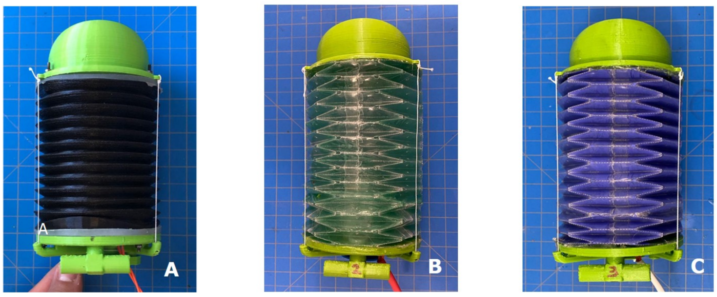


Fig. 1. Prototypes of a low-cost ventilator. (A) 3D Printed NinjaFlex Bellows. (B) Origami Bellows sealed with Stretchlon200 bagging film.(C) Origami Bellows sealed with Nitrile Latex.

2.1 Design and Prototyping

Origami bellows ventilator design Origami mechanisms have proved to be effective actuation modules because they are highly controllable and have a very simple design, making them easy to fabricate. The main body of our origami ventilators are based on the Yoshimura origami crease pattern, which results in a bellows that is easy to folds given the CAD model (shown in Fig. 2(B)). We use a CO_2 laser cutter to create perforation lines that create creases, but a simple plotting machine or manual folding are also possible. The material can be a thin film of PET (polyethylene terephthalate), or any other low-cost and accessible plastic or even cardboard.

We control the origami structure with a single DC motor, which sits on a 3D-printed mount and turns a spool, which pulls three cables firmly attached to the three corners of the other end of the bellows. We attach the motor mount to the origami module, then route the three cables outside the module.

Table 1. Major Parameters of the Prototypes

	3D Printed Bellows Ventilator	**OBV (Stretchlon200)**	**OBV (Nitrile)**
Volume (Ideally)	≈ 350 ml	≈ 350 ml	≈ 350 ml
Bellows Diameter	8 cm	8 cm	8 cm
Spool Diameter	2.5 cm	2.5 cm	2.5 cm
Full Length	17 cm	17 cm	17cm
Gear Motor	224:1	224:1	224:1
Voltage	6-8 v	6-8 v	6-8 v
Weight	158 g	126 g	124 g

To seal the holes within the origami structure, we tested two different materials and sealing processes. We selected sealing materials based on material's flexibility and safety data sheet. Nitrile exam glove material is perfectly suited to most medical environments, being exceptionally puncture-resistant. We glued multiple pieces of Nitrile exam glove onto the inner surface of the origami module using E6000 flexible, paintable glue. The other material we used was

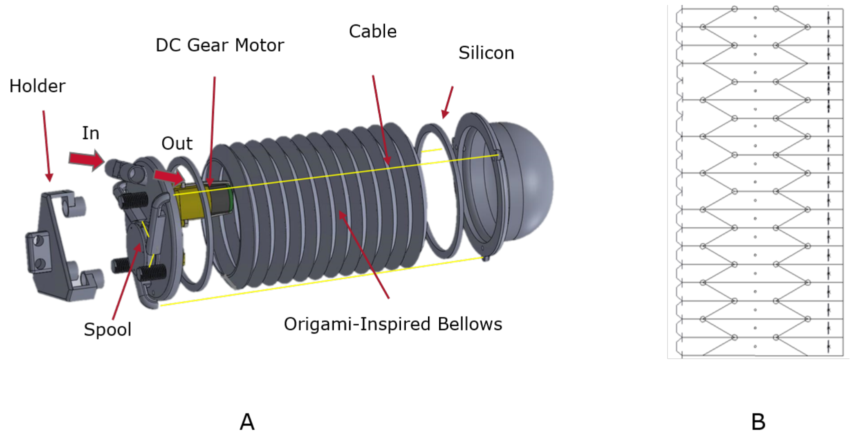


Fig. 2. CAD Design of Ventilators. (A) CAD model of ventilator. The rigid parts per printed out of PLA (B) Origami two-dimensional pattern cut using a laser cutter.

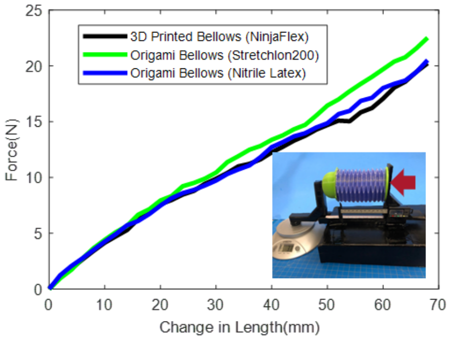
Stretchlon200 vacuum bagging film, which was chosen because it is suited for stretching over complex shapes and has a high elongation, which reduces bridging in corners.We glued the film to the inner surface of the partially-assembled origami module before folding completely.Both of these methods results in an air-tight and lightweight bellows, as shown in Fig. 1. As the motor pulls the three cables, the origami structure compresses and the ventilator delivers air.

3-D Printed bellows ventilator design As an alternative to origami, we also printed a bellows out of Ninjaflex, a flexible TPU filament by Ninjatek. This design requires less assembly than the origami design, as a user can print a complete bellows without folding the structure. The 3-D printed ventilator compresses the same way as the origami design, with the same overall cable mechanism where a DC motor spools cables routed outside the bellows to push air.

Ventilator and Parameters Setting The three ventilators presented above are initial proof-of-concept designs and are easily adjustable to change size and increase air volume output as required. For testing, we used the parameters shown in Table 1.

3 Experimental Results

Force-Displacement Tests To characterize the origami and 3D-printed bellows, we first performed a force-displacement test to relate the linear force applied to the actuator and the corresponding length change of the bellows. We placed each bellows on a scale, then manually compressed it while reading the scale's output. We compressed the bellows by 6.8 cm, and found that they each exhibited similar force-displacement curves as shown in Fig 3. The Stretchlon200 origami bellows was slightly stiffer (with 6.8 cm displacement occurring after



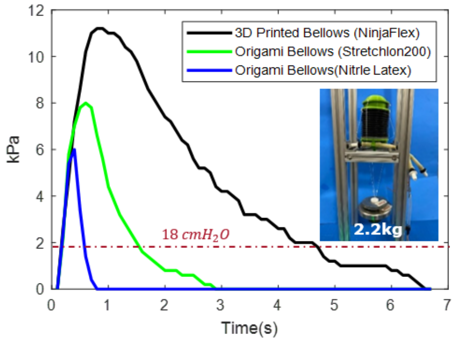


Fig. 3. Force-Displacement (left) and Sealing Test (right) Results: Force-displacement response of the proposed origami-inspired ventilator prototypes as they were compressed. Prototypes have a similar maximum force output when fully compressed.

23N of force instead of 20N for the other two bellows), likely a result it requiring additional glue in order to properly secure the film. However, this difference is small and allows each bellows to function properly with the same motor and gearbox.

Sealing Test Results To validate and characterize the proof-of-concept ventilator system, we performed initial tests to show that the bellows have a sufficient seal and can maintain a pressure when compressed and released. We sealed the inlet of each bellows, and applied a constant 22N force, measuring the pressure inside as air leaked out The experimental results (Fig. 4 right) show that proposed origami-inspired ventilator prototypes have a sufficiently good seal to generate the required 18 cmH_2O. Of the three bellows, the 3D printed one achieved the highest pressure and returned to atmospheric the slowest, likely the result of its being formed out of a single continuous piece of material, with leaks only possible at the interfaces on either end. The Nitrite-sealed bellows leaked the most, probably because it was sealed with a larger quantity of smaller sheets of the material.

System Functionality Results We performed experiments to test ventilator performance repeatedly contracting the bellows and measuring the pressure output. The Ventilator prototypes and the sensor are run by an Arduino Uno control board. We had the ventilators contract and relax themselves (instead of applying an external force) at 40 PBM (with two different I:E (inspiratory/expiratory) ratio [1:1], [2:1]) and 12 PBM (with I:E ratio [1:1], [1:4]) while sealing the exit and measured the resulting pressure waveform. The results of these experiments can be seen in Fig. 4, with the 3-D printed ventilator and Stretchlon200 and Nitrile ventilators generating peak pressures of 11 kPa, 6 kPa and 1.8-2 kPa (112, 61 and 18-20 cm-H_2O) respectively. This is in agreement with our previous results, with the 3D printed bellows maintaining the best seal and this achieving higher pressures. Additionally, we performed 40 BPM and 12 BPM pressure experiment under Non-Zero airflow rate. We attached balloon with little hole to

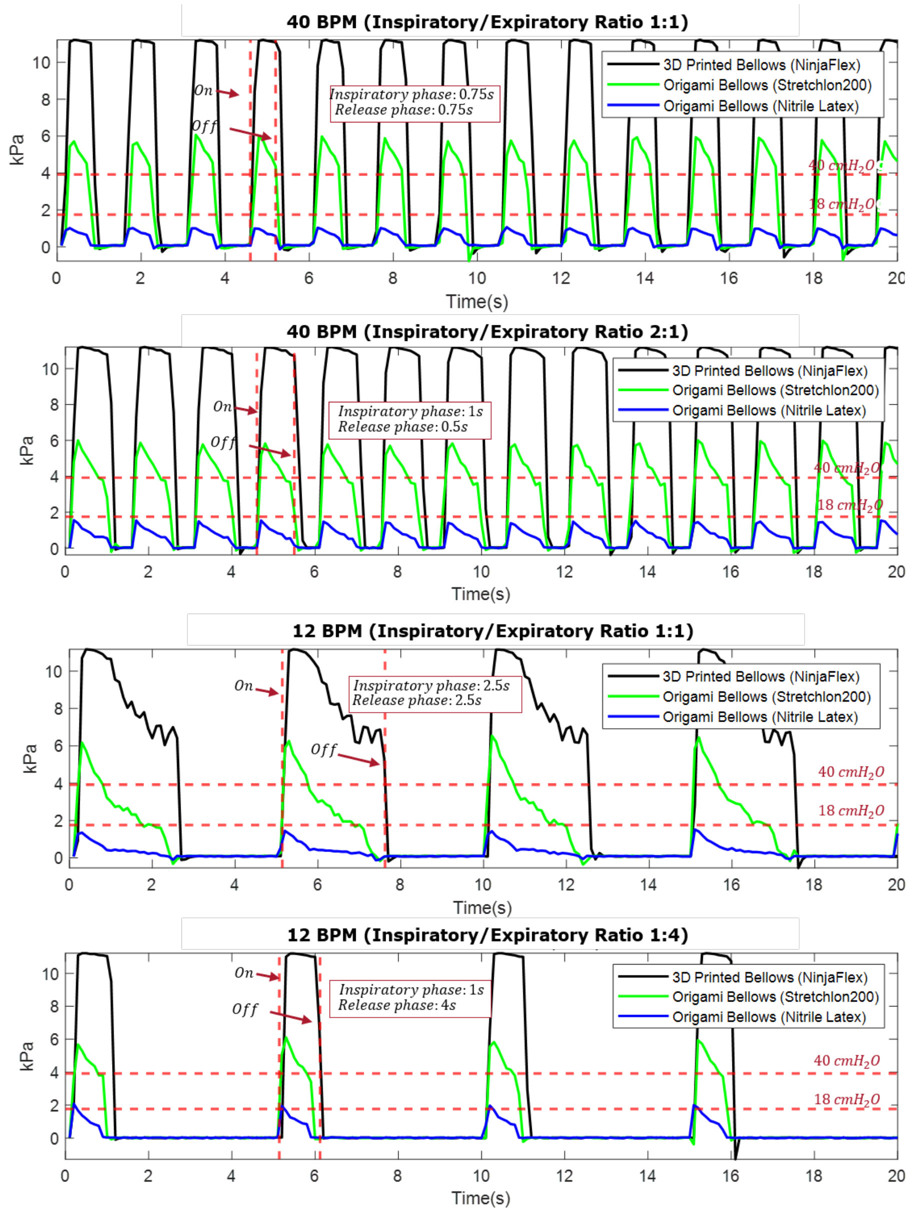


Fig. 4. Pressure generated within the proposed ventilators during cyclic operation with the outlet sealed. 40 Breaths Per Minute (BPM), Inspiratory/Expiratory ratio [1:1] and [2:1]. 12 Breaths Per Minute (BPM), Inspiratory/Expiratory ratio [1:1] and [1:4]. This highlights the range of rations our system can achieve.

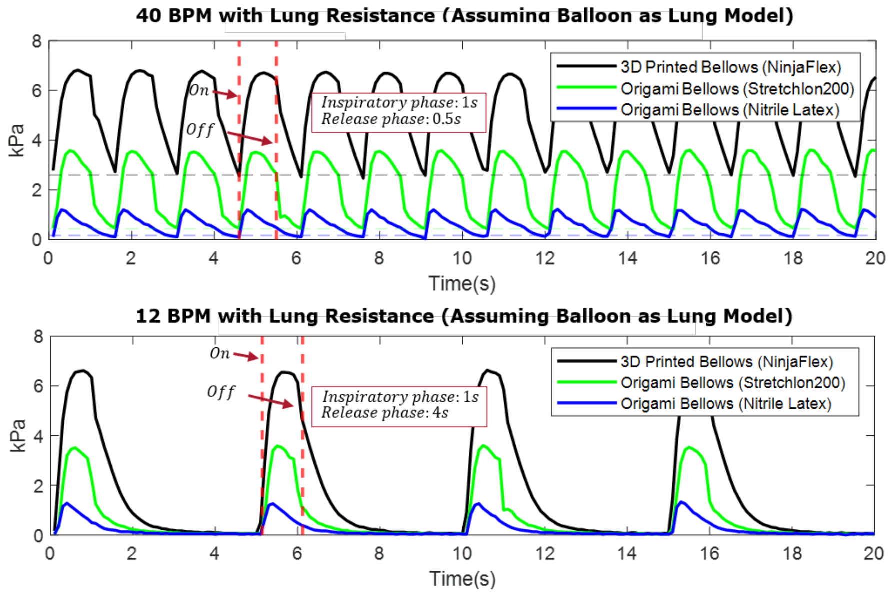


Fig. 5. Pressure readings from the ventilators with at 40 BPM and 12 BPM with a pierced balloon mimicking the resistance of a lung (balloon as lung model).

the outlet tube of the ventilator, which we used to represent a lung. We tested both 40 and 12 BPM for each bellows, the experimental results of which are shown in in Fig. 5. We can see that the 3D printed bellows still can output more than the maximum pressure required, while the Stretchlon200 bellows can output pressure in the middle of the required range.

Airflow Rate and Volume Test We also performed experiments to verify the flow rate the bellows could produce. We connected a balloon with a whole in it to the outlet of the ventilators to mimic them being connected to a patient's lungs, and mounted a custom differential pressure sensor to the tube to measure the flow rate. We run each of the origami ventilators at 40 PBM and 12 PBM for 60 seconds. The raw data is in 100 Hz sampling frequency and filtered by simple moving average. The results of these experiments can be seen in Fig. 6. The average tidal volumes from the 40 BPM experiments were 213 cc for the NinjaFlex, 120 cc for the Stretchlon200, and 62 cc for the Nitrile, while for the 12 BPM experimenbts they were 362 cc for the NinjaFlex, 257 cc for the Stretchlon200, and 78 cc for the Nitrile.

Robustness Test To assess the robustness of our bellows, we ran them continuously for 24 hours at a constant rate of 30 cycles per minute (frequency 0.5Hz). We recorded the peak pressure data of 10 cycles every 2 hours and averaged them, the results of which can be ween in Fig. 7. During the 43200 cycles of this experiment, all three ventilators continued to generate pressure without any

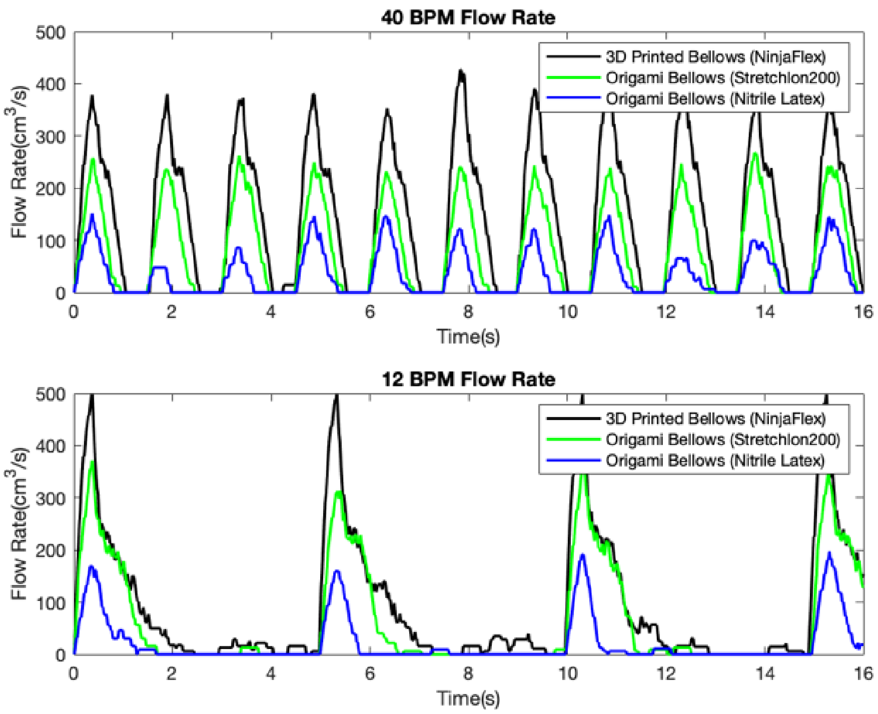


Fig. 6. The experimental results The Inspiratory Airflow Rate, where a custom flow rate sensor was to measure the unrestricted flow rate that the three ventilator prototypes could output.

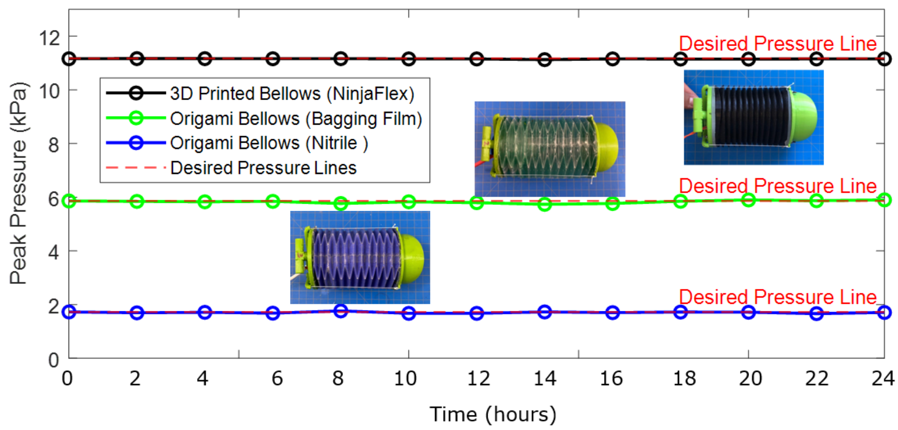


Fig. 7. Results from the robustness test, where we ran the ventilator prototypes at 0.5 Hz for 24 hours straight. The peak pressure was recorded for 10 consecutive cycles once every 2 hours, with the averages reported here. All three ventilators showed no change in behavior.

changes in performance. This, combined with the fact that these same bellows did not require repair in between the other experiments, makes us confident that they could perform more than 48 hours of continuous operation.

The performed experiments have provided the proof-of-concept validation to proceed towards the later stages of this project. Planned experiments include the ability to control the inhalation/exhalation frequency, maintaining desirable pressure and flow waveforms, as well as the overall robustness of the proposed devices including studies of variations in user requirements and fatigue.

4 Conclusion and Future Work

We have presented three different designs for a novel origami-inspired, lightweight, low-cost (less than $20), portable, and automated ventilator design as well as initial validation of their functionality as ventilator systems. Our experiments show that all three designs can generate the pressure required for use, and are robust enough to maintain this pressure over 24 hours of continuous use. Additionally, we have shown that the 3-D printed bellows prototype has a better seal. This may point to the 3-D printed bellows as the superior design, though more testing is required to confirm. On the other hand, the ability to 3-D print using flexible filaments may not be commonly available, while folding a thin plastic film into a bellows shape may be more accessible.

Our requirements, as stated in the Problem Statement, were affordability, accessibility, and functionality. The initial design uses inexpensive materials and is easy to manufacture, and initial testing has proven basic functionality. Additionally, the system is highly portable and does require external infrastructure or heavy, rigid components. We have met four of the seven ventilator requirements we discussed earlier: the ventilator allows for an adjustable O_2 source, can provide a respiratory rate and PEEP above the required ranges while runing on a 6V power supply.

Though the volumes of air displaced by the prototypes discussed in this paper are small, would be relatively easy to scale the system up. This could be done either by running several of these ventilators in parallel (which would also add increased robustness in the event of a catastrophic failure of one) or by a scaling up the bellows and increasing the size of the motor. This latter would represent a simple engineering task, as both the origami and 3d printed bellows designs can be easily changed to increase their height and diameter.

One requirement that we have not addressed was to limit the peak inspiratory pressure to 18-40 cm-$H_2 0$. This is just a matter of performing closed-loop control with pressure sensors and the motor controlling the contraction of the bellows. Nevertheless, it is an import component of our future work to make the system discussed fully suitable for use in the medical field.

Another aspect of future work is to improve the seal of all the bellows, but in particular the nitrile oragimi bellows. This could be done via a more secure seal around the ends of the bellows (especially for the 3D printed bellows), or by improving the seams between the material on the bellows.

We believe that our design, which emphasizes accessibility, portability, and ease of manufacturing, has the potential to seamlessly support a hospital's existing medical equipment, allowing doctors and nurses to work unhindered and save more lives.

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References

1. Who coronavirus disease (covid-19) dashboard (2020). URL http://covid19.who.int/.
2. DIY Hack-a-Vent Innovation Challenge : North Carolina Military Business Center. URL http://www.ncmbc.us/announcements/diy-hack-a-vent-innovation-challenge/
3. Open-Source Ventilator Project. URL https://simulation.health.ufl.edu/technology-development/open-source-ventilator-project/
4. MIT E-VENT — Emergency ventilator design toolbox. URL https://e-vent.mit.edu/
5. J. Lee. Jcl5m1/ventilator. URL https://github.com/jcl5m1/ventilator
6. J. Morgan, S.P. Magleby, L.L. Howell, **138**(5). DOI 10.1115/1.4032973. URL https://asmedigitalcollection.asme.org/mechanicaldesign/article/138/5/052301/473012/An-Approach-to-Designing-Origami-Adapted-Aerospace
7. J. Butler, J. Morgan, N. Pehrson, K. Tolman, T. Bateman, S.P. Magleby, L.L. Howell, (American Society of Mechanical Engineers Digital Collection). DOI 10.1115/DETC2016-59060. URL https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings/IDETC-CIE2016/50169/V05BT07A001/259263
8. J. Santoso, E.H. Skorina, M. Luo, R. Yan, C.D. Onal, in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (2017), pp. 2098–2104
9. M. Luo, R. Yan, Z. Wan, Y. Qin, J. Santoso, E.H. Skorina, C.D. Onal, IEEE Robotics and Automation Letters **3**(3), 1993 (2018)