Supplementary material

Image and video data

Informed consent from all subjects and/or their legal guardian(s) has been obtained for both study participation and publication of identifying information/images/video in an online open-access publication.

Supplementary video

Video entitled '***Autonomous Swab Robot for Naso- and Oropharyngeal Coronavirus Screening (SR-NOCS).***' The video captures the initial test trials during the pandemic and the first lockdown in Europe (April 2020). It also depicts a full trial run for a patient at the automated COVID-19 test station, as conducted in both experiments.

COVID-19 PCR test

Routine confirmation of SARS-CoV-2 infection was based on the detection of unique sequences of virus RNA by real-time reverse-transcription polymerase chain reaction (rRT-PCR) and was conducted by the Institute for Virology and Bacteriology at the Klinikum rechts der Isar, Technical University of Munich. For testing for a COVID-19 infection, nucleic acids (DNA and RNA separated) were extracted on m2000sp Liquid Handler. The Taqman real-time PCR running on a Thermo Fisher 7500 Cyclers was checked with N1 primers of the 2019 Novel-Coronavirus (2019nCoV) rRT PCR Panel and Primer as provided by CDC (CDC, Atlanta, GA 30333). If positive a confirmation test was run against N3 primers of the same panel.

Safety & hygienic measures

The two identified main risks of this kind of study are the physical interaction with the robot and the risk of cross-infection. Therefore, several precautionary measures were implemented for this prototypic setup. A plexiglass wall was placed to restrict the robot’s motions mechanically. Direct physical interaction with the test subjects was only possible via a flexible swab through the fixture hole in a restricted motion range. The test subjects controlled the robot's start (with confirmation from the operator) and could always freely move away from the plexiglass wall. The interaction with the trained hospital employees only occurred if the robot was stopped. To prevent cross-infection, the employees changed gloves, and mouth-and-nose disposable fixtures and fully disinfected the station, robot, and chair surfaces using Perform © fabrics (Schülke & Mayr GmbH, Norderstedt, Germany) between tests. Additionally, the robot’s cover and finger gloves were changed every few tests or if a test subject coughed. The tests were performed in a well-ventilated open garage with the employees and test subjects maintaining a safe distance between themselves.

\subsection*{Data availability statement}

The study has been registered to the German Registry of Clinical Studies (DRKS) with the ID DRKS00021420 (www.drks.de). The study is also approved by the WHO Registry (http://apps.who.int/trialsearch/). The datasets generated and/or analyzed during the current study will be available via these repositories.

Additional information

- Supplementary information is available for this paper.
- Correspondence and requests for materials should be addressed to Sami Haddadin (haddadin@tum.de).

Extended data figure/table legend

Table S1a. Demographic data of the 31 test subjects in clinical study of Experiment 1.

Characteristic	Value
Average age (range) [years]	37.2 (22 - 62)
Sex ratio male:female (percentage)	12:19 (38.7:61.3)
Number of HCWs among test subjects (percentage)	24 (83.9)
Number of physicians among test subjects (percentage)	7 (22.6)

Table S1b. Demographic data of the 21 test subjects in clinical study of Experiment 2.

Characteristic	Value
Average age (range) [years]	33.6 (19 - 75)
Sex ratio male:female (percentage)	13:8 (61.9:38.1)

Table S2. Performance of the SR-NOCS screening procedure.

Variable	Value	Comment
Programmed test duration [s]	41.9	Duration of an ideal test excluding waiting times. It is composed of robot motions as well as swabs and corresponds to all periods (a) and (c) in Fig. 5.
Test conduction time (mean | SD | min | max) [s]	108 | 39 | 60 | 242	Recorded by the robot from the moment the robot motion started the test until it was ready for sample handover, including interruptions and restarts due to explanations, clarifications, errors or repetitions, for all 31 tests.
The number of tests with repeated steps	4	When a swabbing procedure (left/right nostril or mouth) had to be restarted once or several times due to either an incorrect start by the operator or an unexpected reaction by the test subject (e.g. moving away from the station). Corresponds to test subjects n°1 (3 swab repetitions), n°4 (2 swab repetitions), n°13 (2 swab repetitions), and n°16 (1 swab repetition).
Test conduction time for tests without repetitions (mean | SD | min | max) [s]	99 | 28 | 60 | 177	Includes waiting periods and repetitions, for all 27 tests without repeated swabs.
Test conduction time for tests with repetitions (mean | SD | min | max) [s]	171 | 55 | 109 | 242	Includes waiting periods and repetitions, for all 4 tests with repeated swabs.
Shortest time between tests [minutes]	4	The minimum time between two consecutive test starts (minute accuracy) for all 31 tests. It includes all interactions with the test subject (see Methods). A 4-minute difference in test starts took place once between test n°4 and test n°5 while there were 8 occurences of 5-minute differences between test starts.
Maximum relative contact forces* (mean | SD | min | max) [N]	5.1 | 1.3 | 2.6 | 7.2	Maximum magnitude of the relative force* along a whole test, for all 31 tests.

*See methods.

Table S3. Comparison between the manual test performed by HCWs and the SR-NOCS

Count		Robotic Test 1=negative, 2=positive		Total
		1	2	
Standard Test 1=negative; 2=positive	1	30	0	30
	2	0	1	1
Total		30	1	31

Symmetric Measures		Value	Asymptotic Standardized Error[a]	Approximate T[b]	Approximate Significance
Ordinal by Ordinal	Kendall's tau-b	1.000	.000	1.052	.293
	Spearman Correlation	1.000	.000[c]		
Interval by Interval	Pearson's R	1.000	.000[c]		
N of Valid Cases		31			

Correlations			Standard Test 1=negative; 2=positive	Robotic Test 1=negative, 2=positive
Spearman's rho	Standard Test 1=negative; 2=positive	Correlation Coefficient	1.000	1.000**
		Sig. (2-tailed)	.	.
		N	31	31
	Robotic Test 1=negative, 2=positive	Correlation Coefficient	1.000**	1.000
		Sig. (2-tailed)	.	.
		N	31	31

The statistical analysis applying a 2-sided Spearman correlation revealed a completely positive correlation.

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

**. Correlation is significant at the 0.01 level (2-tailed).

Trial Timeline:

The diagram below (current iteration, evaluated in this study) illustrates the flow of the automated tests being studied.

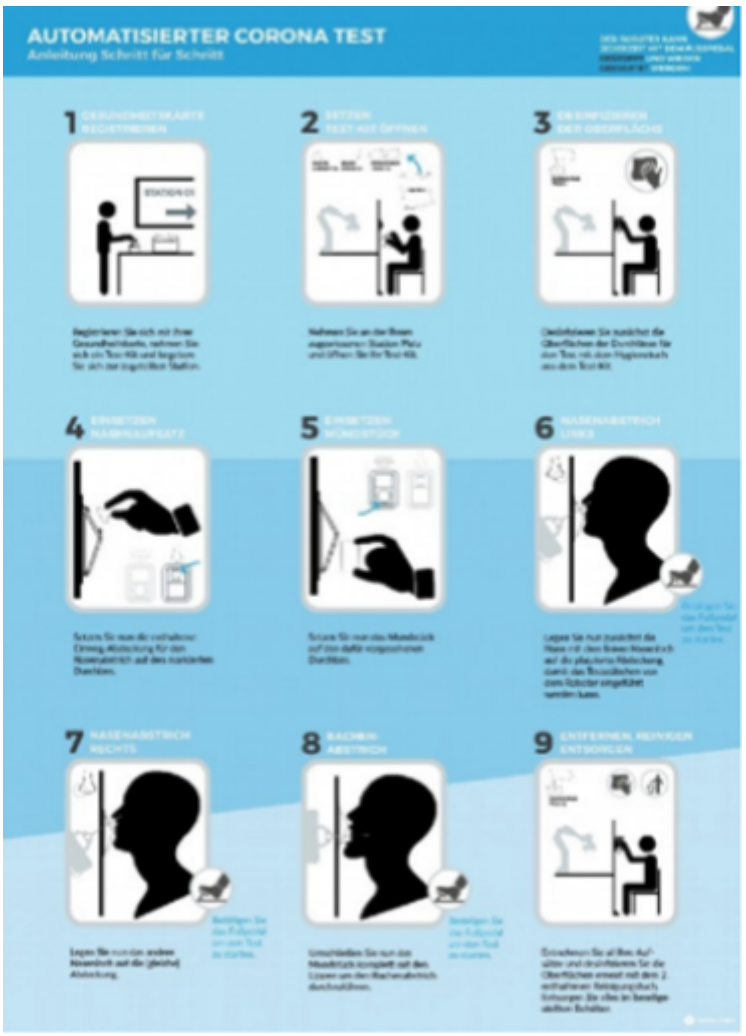

Figure 1. Steps within single trial timeline.

In the clinical study, the initial step (registration) is manually performed by the scientific staff due to the limited number of subjects (a detailed description of the subject information sheet is provided). Before a subject enters the test station, the station is prepared and cleaned by the scientific staff. This process includes removing the nose and mouth adapter, immersing it in disinfectant liquid following the manufacturer's instructions, and conducting a thorough surface disinfection of the Plexiglas disc, chair, robot, and gripper. The sterile nose and mouth adapter is then reinserted before releasing it for the next test.

The test station comprises two adjacent cubicles physically separated by a wall. Typically, two subjects are accommodated per test run, and their scheduling is coordinated to avoid overcrowding in the waiting area. Subjects are called into the study room one at a time, with subject 2 entering once subject 1 is seated. After the test run, subjects exit the study room sequentially to prevent direct contact between patients at a microscopic level.

Macrologistics and waiting room administration are not within the scope of this study. However, we will analyze the impact of parallelization and micrologistic measures on waiting times to optimize patient organization during clinical deployments.

The main steps are outlined and demonstrated in Figure 1. These steps correspond to those performed at the existing prototypical station. Here below we detail those nine steps depicted in Figure 1.

1. ***Registration and test kit handover:*** Easy-to-understand instructions about the study procedure, including manual registration and contactless handover of the test kit.

2. ***Open test kit:*** Before opening the test kit, the individual must wash and disinfect their hands. The process of opening the kit is demonstrated in advance, and each component is explained. The kit includes disposable gloves, a mouthpiece, a nosepiece, a mask, and disinfection materials.

3. ***Post-disinfection by test subjects:*** After the technical staff demonstrates the disinfection process, the test subject is responsible for disinfecting their station. They should use the disinfection materials provided in the test kit, along with the gloves and mask.

4. ***Inserting the nose disposable fixation:*** the test subject is trained to insert the disposable nose fixation while wearing gloves.

5. ***Inserting the mouth/throat disposable fixation:*** the test subject is trained to insert the disposable mouth/throat fixation while wearing gloves.

6. ***Nasal swab left:*** The test is initiated following instructions from qualified personnel. Each examination step and robot movement can only be initiated by pressing the foot pedal. Once the robot reaches the test starting position, the subject should place their nose on the nose cap and begin the test by pressing the foot pedal. The subject can interrupt the test at any time by pressing an emergency stop button to halt the robot. Additionally, the test subject has the option to make unlimited evasive movements to the rear at any time.

7. ***Nasal swab right:*** Similar procedure as point 6.

8. ***Throat swab:*** The test is initiated following instructions from qualified personnel. Each examination step and robot movement can only be initiated by pressing the foot pedal. Once the robot reaches the test starting position, the subject should place their throat on the mouth/throat fixation and begin the test by pressing the foot pedal. The subject can interrupt the test at any time by pressing an emergency stop button to halt the robot. Additionally, the test subject has the option to make unlimited evasive movements to the rear at any time.

9. ***Cleaning and fixations removal by test subjects:*** After a successful test procedure, the test subject should remove the disposable mouth and nose fixations, pre-disinfect their station, and dispose of all used materials. Subsequently, qualified personnel will clean and disinfect the test station. The station operator ensures the complete removal of the nose and mouth fixations, immerses them in disinfectant liquid following the manufacturer's instructions, and conducts a thorough surface disinfection of both sides of the Plexiglas disc, the chair, the robot, and the gripper. Swabs are collected and sent to the laboratory. Finally, the sterile nose and mouth adapter is replaced and prepared for the next test.