The KnowsWatch: concept and prototype for a wearable chemosensory sensing device

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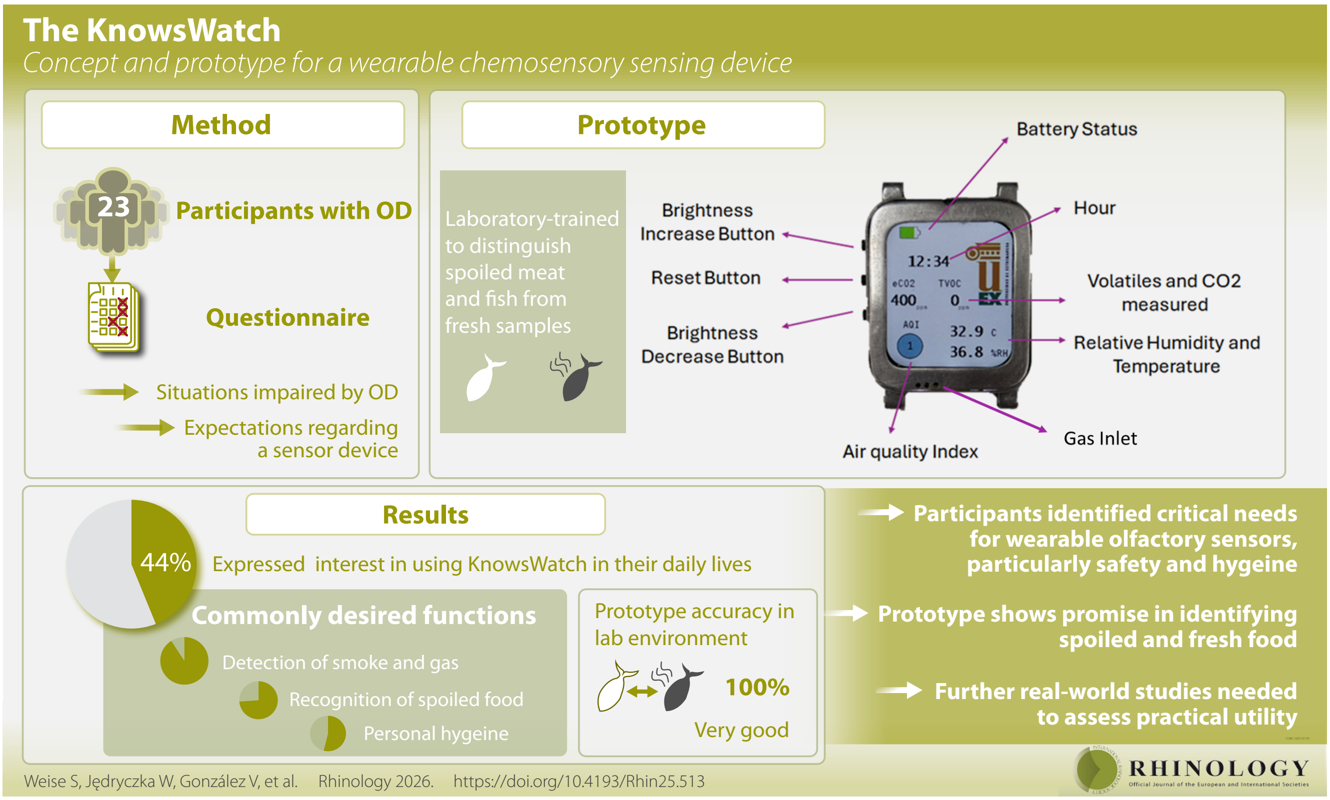

Abstract

Background: Olfactory dysfunction (OD) leads to significant consequences in daily life, including increased risk of exposure to toxic substances such as gas or spoiled food, concerns about personal hygiene, increased risk of depression about many other thinks.

Methodology: This study examined patient needs for an electronic olfactory sensor and tested one potential application of a prototype device. Twenty-three Participants with OD completed a questionnaire identifying situations impaired by OD and their expectations regarding a sensor device. The prototype KnowsWatch, a smartwatch integrating an electronic nose, was trained in a laboratory setting to distinguish spoiled meat and fish from fresh samples.

Results: Around half of the participants (44%) expressed interest in using KnowsWatch in their daily lives. Most prevalent mentions of desired functions were detection of smoke and gas (91%), recognition of spoiled food (74%), and personal hygiene (57%). KnowsWatch was trained to recognize spoiled and fresh meat and fish and achieved very good accuracy (100% each) in the laboratory environment.

Conclusions: Patients with OD identify critical needs for wearable olfactory sensors, particularly for safety and hygiene applications. The KnowsWatch prototype demonstrates promising laboratory performance to distinguish fresh and spoiled food. Further real-world studies are needed to assess the practical utility.

Key words: smell, olfaction, sensor, watch, wearable device

Introduction

Olfactory dysfunction (OD) affects 22 to 57% of the population, with around 5% suffering from complete anosmia [1–3]; resulting in no functional sense of smell in daily life. The global prevalence of OD has increased in the wake of the COVID-19 pandemic [4]. These disorders can lead to a considerable reduction in quality of life [5,6], affecting not only the enjoyment of food and beverages potentially influencing dietary habits [7], but also compromising personal safety [8] due to the inability to detect hazardous substances such as gas leaks or spoiled food [9]. Additionally, OD can lead to increased social insecurity, decreased well-being [10] and is associated with a higher risk of developing depression [11,12] among other things.

The available therapeutic options mainly consisting of olfactory training, pharmacotherapy, and surgery fail to improve olfactory function a substantial proportion of patients with OD, highlighting the need for additional therapeutic approaches [13].

Electronic noses, which are capable of detecting volatile olfactory compounds, are already widely used, for example in the quality control of foods [14,15]. Building on this technological advancement, using olfactory sensors current research is exploring the development of an olfactory implant designed to elicit olfactory sensations [16]. Surveys among patients with OD clearly indicate a strong unmet medical need for an olfactory implants [17,18], although the majority of patients expresses a preference for non-invasive approaches [17,18]. A promising alternative may be a wearable device capable of continuously detecting and interpreting olfactory stimuli. The present study investigates the interest of patients with OD in such a wearable device through a structured survey, assessing expectations and preferred features in olfactory assistance following a detailed explanation and demonstration of the device, a watch integrating an electronic nose (KnowsWatch). In addition, preliminary technical investigations are conducted to calibrate and validate the accurate detection of olfactory stimuli, serving as a proof of concept for future developments. Such novelty could potentially serve for hazard detection (smoke, gas) – but, as similar technology is already available in a form of non-wearable devices, KnowsWatch could bring new features – such as spoiled food detection or bodily odours evaluation.

There are two objectives of the study: firstly, to identify the needs and expectations regarding a wearable sensory device of participants, and secondly – to test the device in terms of its accuracy detecting odours.

Materials and methods

Participants

This prospective study was conducted in accordance with the Declaration of Helsinki at the Smell and Taste Clinic of the University Hospital in Dresden, Germany. Ethical approval was obtained from the local ethics committee prior to study initiation for an anonymized survey.

Participants were recruited from the outpatient consultations based on predefined inclusion criteria, which were olfactory dysfunction established by means of the Sniffin Sticks extended test [19], being 18 years of age or older, and providing consent for the anonymized questionnaire. Exclusion criteria were normal olfactory function, age under 18 years, pregnancy, breastfeeding, or refusal to complete the anonymized questionnaire. Only participants complaining of symptoms regarding OD and having a decreased olfactory function according to the normative data [20] were included in the study.

Questionnaire assessment

The questionnaire collected demographic information including age, and gender, as well as detailed information on OD (onset, course, severity, and aetiology). Participants were also asked to provide a subjective assessment of their current olfactory function.

After a demonstration of the device, participants were asked about their interest in such a device and which functions they would consider most important. These included the detection of smoke or gas, detection of spoiled foods, detection of body odours as a reminder for hygiene routines, detection of pleasant odours, and categorization functions (e.g., distinguishing between specific perfumes or beverages). Multiple responses were possible. Participants also had the opportunity to share their own ideas for potential features. Furthermore, the questionnaire assessed participants' acceptance of the device and any concerns they might have, such as comfort of wear, data privacy, and reliability. Finally, participants were asked about their willingness to pay for such a device.

Procedure

Following comprehensive study information and a demonstration of the watch nose participants completed a standardized questionnaire. Further, olfactory function was assessed using the standardized tests using the "Sniffin' Sticks" (Burghart Messtechnik GmbH, Holm, Germany), including odour threshold, discrimination, and identification tests [19].

To reduce potential confounding factors, participants were instructed to refrain from using fragrances, eating or drinking, smoking, or chewing gum for at least one hour before testing.

Tools – KnowsWatch Analysis

An electronic nose integrated into a smartwatch (Figure 3 and Figure S1) was used for the experiments. The device was designed by the Perception and Intelligent Systems research group from University of Extremadura [21].

The smartwatch integrates four different gas sensors to enable the detection of a broad spectrum of gases and volatile organic compounds (VOCs), along with a combined humidity and tem-

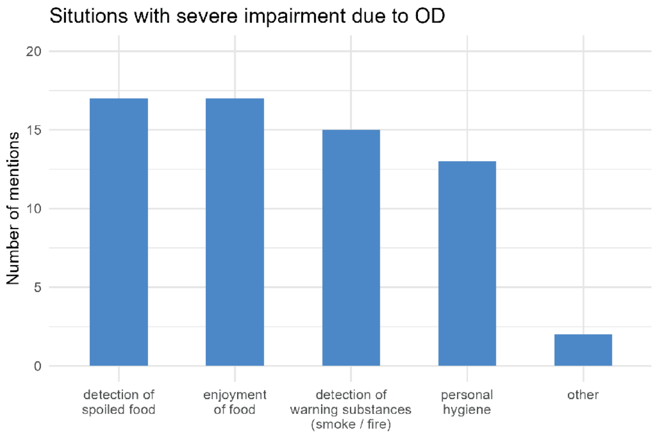

Figure 1. Situations with severe impairment due to olfactory disorders pointed out by participants.

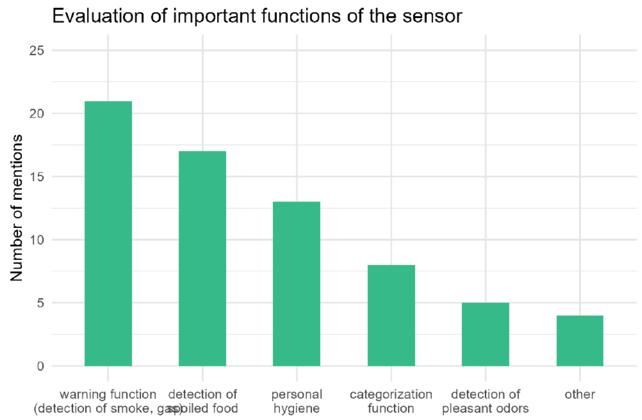

Figure 2. Evaluation of important functions of the KnowsWatch.

perature sensor, and an accelerometer. A detailed list of the sensors incorporated into the smartwatch is provided in Table S3. A detailed view of the device is presented in Figure S1. The system is enclosed in a polycarbonate housing that integrates and protects the electronic control board. User interaction with the smartwatch is achieved through three physical buttons, which enable functions such as screen brightness adjustment and device reset.

Sensor measurements are visualized on a liquid crystal display (LCD), which provides a clear and structured representation of the processed data, facilitating interpretation by non-specialized users. The displayed parameters include equivalent CO_2 concentration, volatile organic compound levels, air quality index, as well as ambient temperature and relative humidity.

As the warning function of gas or smoke is already available at some form in the market (i.e., smoke or gas detecting home sensors), this study focused on second most frequently mentioned need – recognition of spoiled food.

The KnowsWatch was trained and tested for distinction of spoiled and fresh meat and fish. The meat samples were ground pork in different conditions, and the fish samples were herring - all stored throughout the process in brown-glass containers, kept in chilly environment. The fresh samples were replaced daily, and the spoiled samples were aged up to 11 days out of the fridge.

Statistical analysis

Statistical analyses were performed using the SPSS program package (IBM SPSS vs. 27; IBM, Armonk, NY, USA). Non-parametric tests (Kruskal-Wallis test) were used to compare the three groups of interest in an OW regarding metric variables such as age, TDI, and duration of OD. The Chi-square test was used to compare the same three groups regarding nominal variables, such as gender. A Mann-Whitney U test was applied using the exact significance (two times the one-tailed significance) given the sample size of < 20. Fisher's exact test was used for the comparison between two groups of interest with ordinal data. A p-value of less than 0.05 was considered statistically significant.

Results

STAGE 1 – PATIENTS' NEEDS AND EXPECTATIONS

Study population

Out of the 25 individuals initially enrolled, two participants were excluded from the analysis because they tested normosmic as shown by the "Sniffin' Sticks" test, yielding a final sample size of 23 (aged 26 - 85 years, mean 59.6 ± 13.2 years, 8 [35 %] women). OD was caused either by an upper respiratory tract infection including COVID-19 (postinfectious OD, n = 13, 57%), by head trauma (post-traumatic OD, n = 3, 13%), by sinonasal diseases (sinonasal OD, n = 1, 4 %), congenital (n = 1, 4%) or without any known reason assumed as idiopathic (n = 5, 22%). Average OD duration was 2.2 ±2.3 years (0.16-8 years). Olfactory function assessed using Sniffin' Sticks revealed a mean of 17.6 ± 6.9, including 10 (43.5 %) anosmic and 13 (56.5 %) hyposmic patients.

Interest in the olfactory watch

The majority of patients with OD expressed interest in using the KnowsWatch in their daily lives (n = 10, 44 %), followed by 30 % (n = 7) who were uncertain and 26 % (n = 6) who declined its use.

Including the patients who stated they would decline the use of a KnowsWatch 91.3% (n = 21) rated warning functions of the KnowsWatch such as the detection of gas and smoke as important, followed by 73.9% (n = 17) for the detection of spoiled food, 56.5% (n = 13) for the detection of body odours as a reminder for personal hygiene, 34.8% (n = 8) for categorization functions (e.g., distinguishing between specific perfumes or beverages) and 21.7 % (n = 5) for the detection of pleasant odours (Figure 1).

Differences between groups of interest in KnowsWatch are

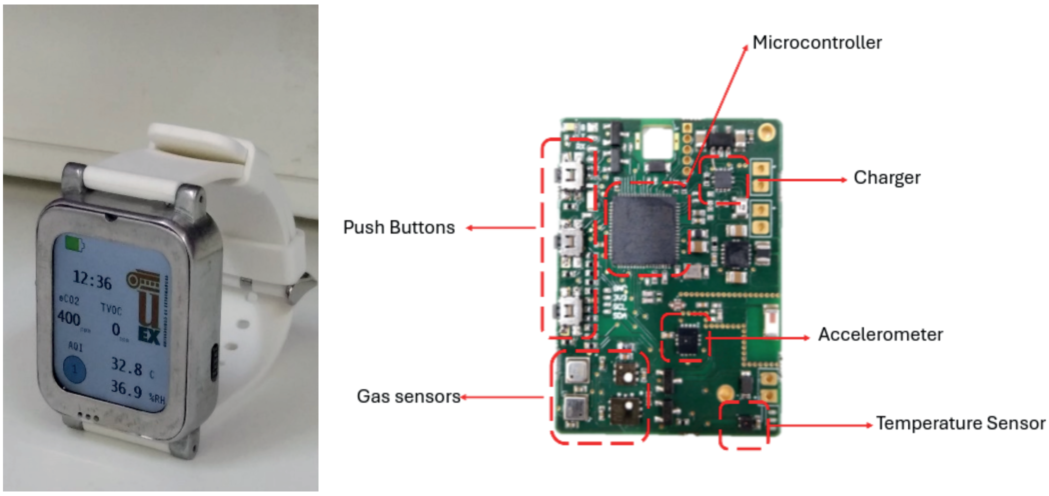

Figure 3. KnowsWatch (left) and electronic circuits (right).

displayed in Tables S1 and S2 in the Supplementary Materials, however, none of the aspects were found to be significantly different between the groups.

Characteristics of the KnowsWatch

According to participants' responses, the most important functions of the KnowsWatch were warning function in terms of detection of fire or gas (n = 21) and detection of spoiled food (n = 17), followed by personal hygiene (n = 13), categorization of odours (n =8), and detection of pleasant odours (n = 5), see Fig. 2. The majority of patients reported a preference for vibration (n = 15) as the alerting signal, followed by visual (n = 14) and acoustic signals (n = 5). The major concerns were related to comfort (e.g., wearability; n = 14, followed by reliability (n = 7), data protection (n = 4), and other issues (n = 5) such as using new technical devices. Patients also expressed a desire for the KnowsWatch to include additional features, such as displaying the time and date (n = 8), or smartwatch-like functions (n = 5).

STAGE 2 – KNOWSWATCH ANALYSIS

Sensor measurements are visualized on a liquid crystal display (LCD), which provides a clear and structured representation of the processed data, facilitating interpretation by non-specialized users. The displayed parameters include equivalent CO_2 concentration, volatile organic compound levels, air quality index, as well as ambient temperature and relative humidity.
As the warning function of gas or smoke is already available at some form in the market (i.e., smoke or gas detecting home sensors), this study focused on second most frequently mentioned need – recognition of spoiled food.
The KnowsWatch was trained and tested for distinction of spoiled and fresh meat and fish. The meat samples were ground pork in different conditions, and the fish samples were herring - all stored throughout the process in brown-glass containers, kept in chilly environment. The fresh samples were replaced daily, and the spoiled samples were aged up to 11 days out of the fridge.
During the process, the watch was trained on a balanced number of fresh and spoiled samples. One training trial is presenting one sample of the watch facing the smell, and sampling for 30 seconds. After this time, the result was evaluated (as correct or incorrect measure) by the experimenter. To assess the number of trainings sufficient for achieving a good accuracy, the training progress was evaluated at various stages - every 50 training trials. The training was final when consecutive trainings were no longer enhancing the accuracy of smell recognition in testing mode.
Analyses were performed in Rstudio, using the following packages: dplyr [22], ggplot2 [23] and patchwork [24].
The proportion of correct and incorrect results was compared at different stages - the visual representation of the ratio is presented in Figure 4 (meat) and Figure 5 (fish).
Tests after 50, 100, 150 and 200 trials consisted of 20 balanced trials - 10 of spoiled and 10 of fresh meat. After 200 trainings (100 trials with fresh and spoiled meat) the watch obtained 100% accuracy. Fifty more trainings were conducted to ensure this result was not random, and to ground the model. After 250 trainings, the meat was tested an additional 20 times, still providing 100% accuracy.
Following this we investigated, if the model trained exclusively on one kind of meat - pork – or whether it would also recognize spoiled and fresh samples of different origins, using different kinds of meat, i.e. salami and chicken. Both types were tested in 20 trials, balanced between spoiled and fresh conditions, resulting in 100% accuracy.
Regarding the fish, KnowsWatch was correct after 200 trainings, but after 250 made two mistakes (5%). Additional 50 trainings were applied, and the test consisting of forty trials was repeated. This time it was 100% accurate and the training of the model was finished. Ratio of correct and incorrect responses at all

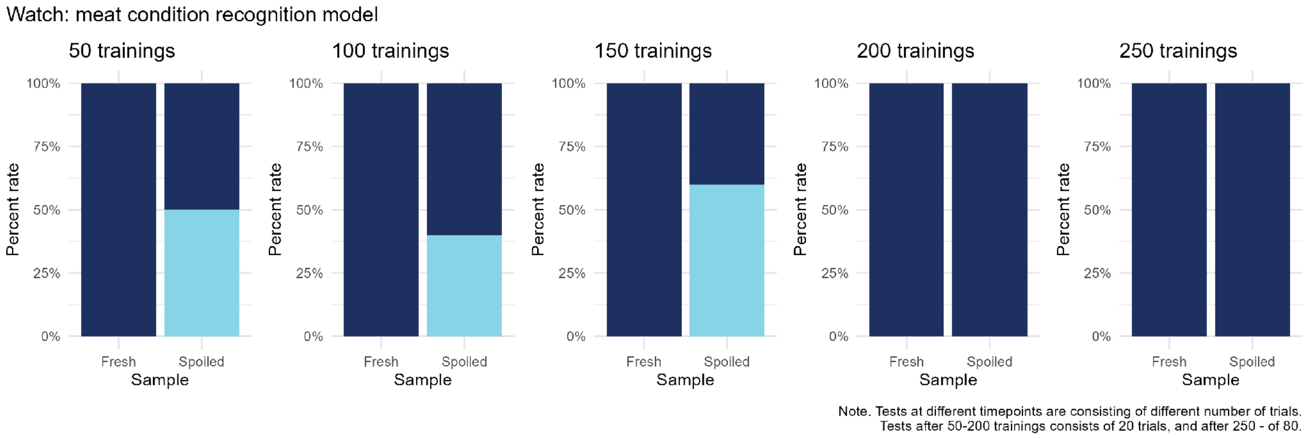

Figure 4. The ratio of correct (dark) and incorrect (light) results of the KnowsWatch recognitions throughout the training.

stages is presented in Figure 5.
Both models – meat and fish – proved adequate accuracy in recognition of spoiled and fresh samples and require no further training.

Discussion

To characterize the needs and preferences of patients with OD for a wearable olfactory sensory device (KnowsWatch), a survey was conducted at a smell and taste centre where the device was also demonstrated and explained, the following main results emerged: i) Around 44% of the patients with OD expressed their interest in the daily use of an KnowsWatch. ii) The most important functions for an KnowsWatch were evaluated as the warning function (detection of gas, smoke), detection of spoiled food, followed by personal hygiene, odour categorization, and detection of pleasant odours. iii) The prototype KnowsWatch was trained in the laboratory and achieved 100% accuracy in distinguishing fresh from spoiled fish resp. meat.
In our survey, slightly less than half of participants (44%) expressed interest in using the KnowsWatch device. This proportion is somewhat higher than the interest reported for an olfactory implant (34%) by Besser et al. [17] and for a non-invasive olfactory implant (24%) by Stanley et al. [18]. One possible explanation is that, in the present study, the device was demonstrated in detail, providing a concrete example rather than an abstract concept presented only in a questionnaire. This approach was chosen to more realistically assess the potential interest of patients with OD in support for their daily-life. Notably, some participants explicitly declined interest in wearing such a watch, stating that it might feel like giving up hope for future recovery of their sense of smell or that they were concerned about possible stigmatization associated with wearing a visible assistive device. Thus, when counselling patients with OD about possible treatment options, including the future use of KnowsWatch it would be essential to take individual preferences and life circumstances into account, as is the case for many medical consultation settings.
The aspects identified in the questionnaire as helpful for such a device reflect limitations in quality of life commonly reported in numerous studies on OD such as the elevated risk of exposure to toxic substances (e.g., gas) or spoiled food, as well as uncertainty regarding personal hygiene [5]. The collected data thus align well with the consequences described in the literature.
One limitation of this study is the rather small cohort of patients with OD. Further, the patient group represents a heterogeneous cohort characterized by diverse aetiologies of OD, varying degrees of olfactory function, and different durations of impairment. The aetiology distribution of OD in this study is comparable to those reported at other specialized smell and taste centres [25]. These characteristics like aetiology of OD, duration of OD, along with other individual factors such as sex, age, and familiarity with technology may influence specific patient needs and expectations for a wearable sensory device. A larger-scale study would therefore be valuable to confirm the generalizability of our findings.

The KnowsWatch prototype, when trained in a laboratory setting, achieved 100% accuracy in distinguishing fresh from spoiled fish and meat. The models for meat and fish recognition were trained in the same manner, although the meat model reached high accuracy more quickly. The fish model achieved 5% error rates after 250 training iterations. This represents an acceptable margin, as the model was already performing correctly beforehand; however, to ensure reliable training, an additional 50 trainings and 40 trials of testing were conducted – and when this was accurate, the training was as well completed. The model was trained in a laboratory environment with limited variety of samples and conditions. It proved the device to be able to achieve great accuracy. Our results align with previous work on electronic noses coupled with pattern recognition algorithms in

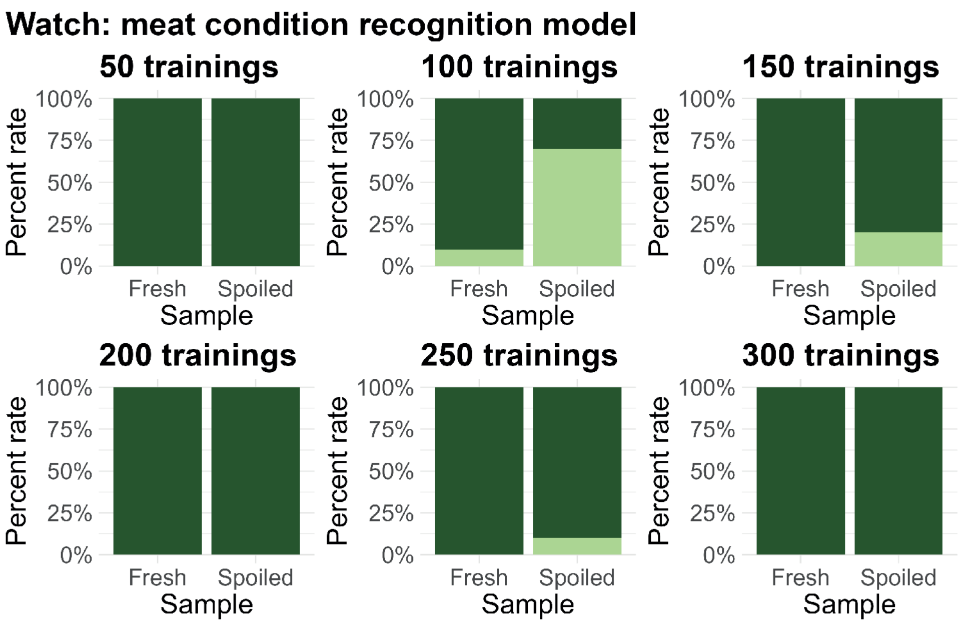

Figure 5. Correct (dark) and incorrect (light) responses for fresh and spoiled fish during the testing phases along the training process.

the food industry for quality evaluation in specific food classes, achieving accuracies exceeding 90% [15], however, as these preliminary results are based on a limited number of odours and samples, further validation in more diverse and real-world settings is necessary to assess robustness and generalizability. Future training outcomes may vary, necessitating establishment of standardized accuracy thresholds to confirm model readiness. The current prototype is suitable to be introduced to patients for real-world evaluation. Further, AI approaches integrating machine learning/deep learning could prove beneficial in enhancing detection accuracy and robustness [26]. Although it requires carrying an additional device, future versions might get more convenient. When proved meeting the expectations, the sensors could be potentially integrated into smaller devices or even existing electronics.

However, regulatory approval from entities like FDA or EMA is needed as this is an early prototype. A potential next development involves training the KnowsWatch for detection of hygiene-related odours, enabling patients to identify the absence of undesirable smells (e.g., sweat, faeces, urine) on their body or clothes.

The KnowsWatch device consists of non-selective gas sensors respond to gaseous compounds based on changes in electrical conductivity, providing a qualitative assessment of for example food quality. Precise quantitative analysis could be addressed in future work.

Conclusion

In two stages we examined whether patients with OD express the need for electronically assisted smelling device and tested the prototype accordingly. Slightly less than half of patients with OD (44%) expressed interest in using the KnowsWatch device. The most important functions for an KnowsWatch were evaluated as the warning function (detection of gas, smoke), detection of spoiled food, followed by personal hygiene, odour categorization, and detection of pleasant odours.

The KnowsWatch was trained and achieved great accuracy in distinguishing spoiled and fresh samples of meat and fish in laboratory conditions and can be now tested in real-life environment.

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Author contributions

SW: Conceptualization, data acquisition, analysis, writing, critical review; WJ: Conceptualization, data acquisition, data analysis, writing, critical review; VG: Conceptualization, critical review; AB: Conceptualization, critical review; JL: Conceptualization, critical review, administration, supervision; TH: Conceptualization, critical review, administration, supervision.

Conflict of interest

Since 2023 Thomas Hummel did research together with and received funding from Sony, Tokyo, Japan; Smell and Taste Lab, Geneva, Switzerland; Takasago, Paris, France; Baia Foods, Madrid, Spain. The other authors have no conflicts of interest.

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SUPPLEMENTARY MATERIAL

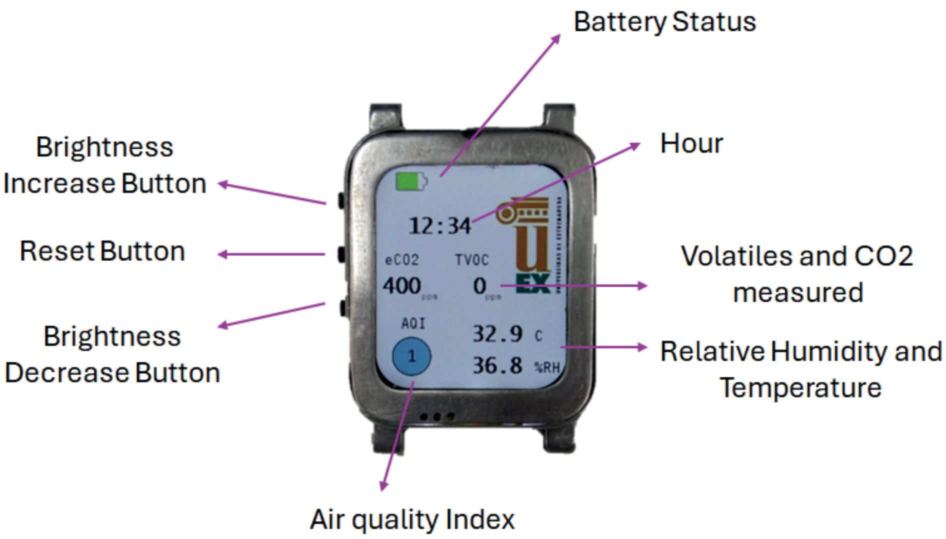

Figure S1. KnowsWatch interface.

Table S1. Comparison of interest in KnowsWatch (no interest, not sure about it, interest).

Comparison (No interest, not sure about it, interest_	Statistic	p
Age	1.17	0.56
Gender	0.83	0.66
Living arrangements	4.8	0.31
TDI	0.5	0.78
Subjective olfactory function	2.27	0.32
Duration of OD	1.04	0.60
Onset symptoms of OD	1.85	0.76
Cause of OD	5.23	0.73
Subjective impairment of olfactory function	1.85	0.76
Subjective taste function	0.18	0.92

For comparison of three groups test statistic is χ^2, and for comparison of the two groups test statistic is U Mann-Whitney.

Table S3. Sensors used in the Smartwatch.

Sensor	Manufacturer (Origin)	Type
ASM330	STMicroelectronics (Geneva, Switzerland)	Accelerometer
BME680	Bosch (Gerlingen, Germany)	Gas sensor
SGP40	Sensiron (Stäfa, Switzerland)	Gas sensor
ENS160	ScioSense (Eindhoven, The Netherlands)	Gas sensor
STC31	Sensirion (Stäfa, Switzerland)	Gas sensor
SHT40	Sensirion (Stäfa, Switzerland)	Temperature, Relative Humidity Sensor

Table S2. Comparison of interest in KnowsWatch and comparison of duration of OD.

Comparison of interest	Interest	No interest	Test statistic	p-value
Age (years), mean ± SD	56,6±16.9	59,2±11.6	t(14)=0.33	0.75
Gender, n(%)			Φ=0.20	0.61
male	7 (70.0%)	3 (50.0%)		
female	3 (30.0%)	3 (50.0%)		
Olfactory identification (I), mean ± SD	7.7±3.7	6.2±2.9	U=24.5	0.57
Olfactory discrimination (D), mean ± SD	6.9±3.5	8.3±3.9	U=22.0	0.41
Olfactory threshold (T), mean ± SD	1.5±1.0	2.2±2.1	U=24.5	0.57
Olfactory function (TDI), mean ± SD	16.1±6.4	16.7±7.8	U=29.0	0.93
Subjective olfactory function, mean ± SD	18.6±25.3	21.5±15.9	t(14)=0.25	0.81
Subjective gustatory function, mean ± SD	44.9±36.4	39.8±33.8	t(14)=0.28	0.79
Duration of OD (years), mean ± SD	2.3±1.7	2.3±2.8	U=21.5	0.51
Cause of OD			3.45	0.87
Comparison of OD	**OD shorter than 1 year (n=10)**	**OD longer than 2 years (n=9)**	**Test statistic**	**p-value**
Age (years), mean ± SD	58.6±11.2	63.4±12.1	t(17)=0.91	0.38
Gender, n(%)			Φ=0.51	0.06
male	4 (40.0%)	8 (88.9%))		
female	6 (60.0%)	1 (11.1%)		
Interest in KnowsWatch, n (%)			1.36	0.61
…no interest	3 (30.0%)	2 (22.2%)		
…interest	3 (30.0%)	5 (55.6%)		
…uncertain	4 (40.0%)	2 (22.2%)		
Olfactory identification (I), mean ± SD	8.8±2.6	6.4±3.5	U=26.5	0.14
Olfactory discrimination (D), mean ± SD	10.2±3.3	7.3±4.2	U=31.0	0.26
Olfactory threshold (T), mean ± SD	2.1±1.7	1.4±1.1	U=29.5	0.18
Olfactory function (TDI), mean ± SD	21.1±5.8	15.2±6.9	U=23.0	0.075
Subjective olfactory function, mean ± SD	20.6±15.1	23.8±20.2	t(17)=0.39	0.70
Subjective gustatory function, mean ± SD	37.9±26.5	46.7±35.8	t(17)=0.61	0.55
Cause of OD			2.54	0.88

Comparison of interest: Age was compared using an independent sample t-test. Gender was compared using fisher`s exact test. Olfactory identification, discrimination, and threshold were compared using Mann-Whitney-U-test. Subjective olfactory and gustatory function were compared using independent sample t-test. Duration of OD was compared using Mann-Whitney-U-test. The causes of OD were compared using Fisher-Freeman-Halton Exact test.

Comparison of OD: Age was compared using an independent sample t-test. Gender was compared using fisher`s exact test. Interest in the KnowsWatch was compared using Fisher-Freeman-Halton Exact test. Olfactory identification, discrimination, and threshold were compared using Mann-Whitney-U-test. Subjective olfactory and gustatory function were compared using independent sample t-test. The causes of OD were compared using Fisher-Freeman-Halton Exact test.