Toward Patient-Centric Digital Monitoring of Obstructive Sleep Apnea: a mixed-methods study

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Abstract

Background: Obstructive Sleep Apnea (OSA) is a sleep disorder characterized by repeated breathing disruptions during sleep. Remote patient monitoring (RPM) of OSA is important yet contemporary methods are limited. Sensor-based digital health technologies (sDHTs) promise step advances in OSA RPM. However, for sDHT based RPM solutions to be adopted, they must be meaningful, actionable and usable for patients. While the centrality of considering patient views in sDHT development is widely acknowledged, patient perspectives and priorities are rarely assessed and thus included in new sDHTs.

Objective: To contribute towards addressing this gap, we explored by means of a mixed-methods study based on the Digital Medicine Society's (DiMe) Digital Measures That Matter framework meaningful aspects of health and digital measures that could enhance OSA care quality and patient experience.

Methods: We included individuals who had been formally diagnosed with OSA and reported persistent sleep problems (n=223), and asked them to (i) rank survey items to elicit key priorities, and (ii) provide additional data in open-ended questions to obtain initial qualitative insights. To gain deeper qualitative insights, we also conducted semi-structured interviews with formally diagnosed OSA patients, patient advocates, and healthcare professionals (n=11). The interviews covered the themes follow-up care, attitudes toward sDHTs and RPM, and preferences for future OSA-related sDHTs and metrics. To analyze our quantitative data, we used bootstrap-aggregated Borda counts to identify overall (broad) support per item, and Plackett-Luce modelling to assess agreement (intense prioritization) per item rank. Qualitative data elicited in the survey and interviews were analysed thematically.

Results: We found that, firstly, for patients, improving subjective sleep quality, increasing physical activity, and increasing daytime energy levels are key meaningful aspects of health. Secondly, sleep characteristics (particularly sleep fragmentation), daytime energy (focus on fatigue and excessive daytime sleepiness), and nighttime oxygen saturation, as priority targets for digital measure development. Thirdly, smartwatches, sleep mats, and smart rings are strongly preferred as modalities for sDHTs that can be integrated into future RPM solutions. Fourthly, when enhancing current digital monitoring practices the focus should be on: (1) expanding metrics beyond AHI, (2) improving measurement accuracy, and (3) ensuring that digital measures are meaningful, understandable and actionable for end-users. Finally, patients lack the ability to determine from RPM output whether they need to seek follow-up care and, if so, what type of care is appropriate.

Conclusions: Our findings underscore the need to expand and refine RPM solutions beyond traditional metrics, ensuring that

digital measures are accurate, transparent, and actionable to support comprehensive, patient-centered OSA management.

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Title: Toward Patient-Centric Digital Monitoring of Obstructive Sleep Apnea: a mixed-methods study

Key words: Obstructive Sleep Apnea; Digital Biomarkers; Remote Patient Monitoring; Patient-Centric Care; Wearable sensors; Digital outcome measures; Patient-reported outcomes

Abstract
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Objective
To contribute towards addressing this gap, we explored by means of a mixed-methods study based on the Digital Medicine Society's (DiMe) *Digital Measures That Matter* framework meaningful aspects of health and digital measures that could enhance OSA care quality and patient experience.
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We included individuals who had been formally diagnosed with OSA and reported persistent sleep problems (n=223), and asked them to (i) rank survey items to elicit key priorities, and (ii) provide additional data in open-ended questions to obtain initial qualitative insights. To gain deeper qualitative insights, we also conducted semi-structured interviews with formally diagnosed OSA patients, patient advocates, and healthcare professionals (n=11). The interviews covered the themes *follow-up care*, *attitudes toward sDHTs and RPM*, and *preferences for future OSA-related sDHTs and metrics*. To analyze our quantitative data, we used bootstrap-aggregated Borda counts to identify overall (broad) support per item, and Plackett-Luce modelling to assess agreement (intense prioritization) per item rank. Qualitative data elicited in the survey and interviews were analysed thematically.
Results
We found that, firstly, for patients, improving subjective sleep quality, increasing physical activity, and increasing daytime energy levels are key meaningful aspects of health. Secondly, sleep characteristics (particularly sleep fragmentation), daytime energy (focus on fatigue and excessive daytime sleepiness), and nighttime oxygen saturation, as priority targets for digital measure development. Thirdly, smartwatches, sleep mats, and smart rings are strongly preferred as modalities for sDHTs that can be integrated into future RPM solutions. Fourthly, when enhancing current digital monitoring practices the focus should be on: (1) expanding metrics beyond AHI, (2) improving measurement accuracy, and (3) ensuring that digital measures are meaningful, understandable and actionable for end-users. Finally, patients lack the ability to determine from RPM output whether they need to seek follow-up care and, if so, what type of care is appropriate.
Conclusions
Our findings underscore the need to expand and refine RPM solutions beyond traditional metrics, ensuring that digital measures are accurate, transparent, and actionable to support comprehensive, patient-centered OSA management.

Introduction

Obstructive Sleep Apnea (OSA) is a sleep-related breathing disorder characterized by repeated episodes of partial or complete blockage of the upper airway during sleep, leading to oxygen desaturations and reduced sleep quality[1]. Common symptoms include loud snoring, waking up gasping for air or choking, and excessive daytime sleepiness. OSA is a chronic condition and it has been estimated that approximately 14% of the global population are affected[2]. Due to aging populations and increasing rates of obesity, the prevalence of OSA is expected to rise in the upcoming years. The chronic nature of OSA, combined with its links to other health conditions and multimorbidity, not only imposes a high burden on patients but also significantly strains health system resources[3,4].

The Apnea-Hypopnea Index (AHI) is the standard for classifying OSA severity by counting the number of apneas (complete pauses in breathing) and hypopneas (partial reductions in breathing) per hour of sleep. While AHI is widely used, it has limitations, such as not accounting for the duration and depth of breathing interruptions, or their impact on oxygen levels and sleep stages[5]. Consequently, AHI scores show poor correlation with disease burden and treatment outcomes[6,7]. Moreover, AHI lacks meaning from the patient perspective, not only because it fails to capture symptoms or daily functional impairments, but also because many patients struggle to interpret clinical measures and understand what pertinent changes in their scores actually imply for their health[8].

Patient-reported outcome measures (PROMs) offer valuable insights into the subjective experiences of individuals with OSA, especially regarding disease-related quality of life[9]. However, PROMs are limited by respondent burden and various biases, such as non-response, fatigue, and recall bias[10,11]. Sensor-based digital health technologies (sDHTs), including wearables, have the potential to (partially) replace, or complement, existing PROMs – by passively and continuously capturing symptoms and functional states – and thereby offer more objective, real-time insights into patients' health[12,13].

The most common treatment options for OSA (in the Netherlands) include Continuous Positive Airway Pressure (CPAP) and Mandibular Advancement Devices (MADs)[14]. CPAP is routinely supported by remote patient monitoring (RPM) solutions. RPM refers to systems that allow healthcare professionals to assess, monitor, and care for patients virtually, often in extraclinical settings[15]. While CPAP RPM platforms provide data on usage, mask leaks, and AHI scores[16], they fail to capture patient-centered outcomes, and often do not prevent non-adherence[17]. In contrast, most MADs lack embedded sensors, so adherence and treatment effectiveness are typically assessed subjectively during follow-up visits[18].

Sensor-based Digital Health Technologies (sDHTs) can complement OSA RPM solutions by the continuous collection of objective, longitudinal data based on digital biomarkers. sDHTs are devices – often wearables – that utilize sensors (e.g. accelerometers, photoplethysmography) to capture health measures continuously[19,20]. In the context of OSA, sDHTs may be integrated directly into treatment devices (like CPAP devices or smart MADs) or used independently (e.g., wearable rings, watches, sleep mats). They hold potential to revolutionize OSA care by enabling prediction of treatment responses, optimizing titration, enhancing adherence. This supports the transition towards person-centered OSA care, that empowers patients to manage their own condition[21]. Additionally, patient-centric digital endpoints are becoming increasingly important for clinical research[22]. However, for these types of solutions to be adopted, they must be meaningful, actionable and usable for patients[20,22–25]. Although the importance of considering patient priorities in sDHT development is widely acknowledged, the former are rarely assessed and integrated in new sDHTs[26].

Efforts led by the Digital Medicine Society (DiMe) are paving the way for the development of sDHTs that are truly patient-centric[20,23]. According to DiMe's *Digital Measures that Matter* framework, this process begins with the identification of *Meaningful Aspects of Health*– aspects of a condition that an individual wishes to improve, arrest, or prevent – which then guide the selection of measurable concepts that reflect patients' lived experiences and priorities[20]. Noteworthy is that OSA patient perspectives are rarely reported in scientific literature and we are not aware of literature published on OSA patient priorities for sDHTs.

To contribute towards addressing this knowledge gap, our objective was to explore, from the perspectives of OSA patients and physicians based in the Netherlands and in a mixed methods study (survey and interviews), how contemporary OSA care can be improved based on key themes related to digital medicine facilitated OSA management inter alia using the Digital Measures that Matter framework. The survey focused on the themes *meaningful aspects of health*, *current utilisation and attitudes towards sDHTs or RPM*, and *preferences for future OSA-specific sDHTs and RPM solutions*. To gain deeper qualitative insights, we also conducted semi-structured interviews with formally diagnosed OSA patients, patient advocates, and healthcare professionals (n=11). The interviews covered the themes *follow-up care*, *attitudes toward sDHTs and RPM*, and *preferences for future OSA-related sDHTs and metrics,* see Table 1.

Table 1 | Overview of themes covered in mixed methods components

Theme	*Survey*	*Interview*
Meaningful aspects of health	Yes	No
OSA follow-up care in NL	Not explicitly queried – but some responses to the open-ended questions provided further information	Yes
Attitudes towards RPM and currently used sDHTs	Focus on sDHTs	Focus on RPM
OSA-related health metrics priorities	Yes	Yes
Future of sDHT-based OSA RPM	Yes	Yes

sDHTs; sensor-based digital health technologies, RPM; remote patient monitoring

Methods

Study design

This observational, exploratory study used a mixed-methods (concurrent) design to gather insights from individuals with OSA reporting persistent sleep problems and healthcare professionals involved in OSA care. Quantitative data were collected through a survey completed by n=223 respondents (which is a sample size considered sufficient in published studies with similar study aims, designs and settings)[27–29]between January and March 2024 (Table 2), while qualitative insights were obtained from semi-structured interviews conducted in May–June 2024 with six patients, two patient advocates, and three healthcare professionals (Table 3).

Survey

The survey targeted a broad population of individuals with self-reported sleep problems; inclusion criteria were being 18 years or older and experiencing sleep problems at least three times per week for a minimum of three consecutive months. For this manuscript, we included only those participants who reported receiving a formal OSA diagnosis from a healthcare professional. We excluded 84 respondents who lacked an OSA diagnosis and 30 diagnosed respondents with OSA who completed only the background information section (Q1-8). Survey participants were recruited via social media posts, flyers distributed in primary and secondary sleep care settings (including physiotherapy practices and sleep clinics), and a newsletter announcement by the Dutch Apnea Association (ApneuVereniging). The survey (originally developed in Dutch and translated into English for this manuscript) consisted of 18 questions (multiple choice, ranking, and open-ended) distributed through the online platform Survalyzer (Suppl. File 1). It was launched only after participants gave informed consent and met the inclusion criteria. Questions were grouped into four domains: demographic and background information (Q1–Q4) and medical history and sleep disorder profile (Q5–Q8), both based on validated instruments and relevant literature; meaningful aspects of health (Q9–Q12), developed using the Digital Measures That Matter framework[20]; and preferences and experiences with sDHTs (Q13–Q18), adapted from a previously used instrument in another disease area. While pre-testing is a standard step to ensure clarity and reliability, it was not feasible in this instance due to time constraints. Face validity of the complete survey was assessed by an internal panel of experts experienced in survey design.

Survey data analysis

The data analysis for this study primarily involved descriptive statistics, including the calculation of frequencies and percentages to summarize the data and identify patterns and trends within the dataset. Ranking items were analyzed using both Borda counts and the Plackett-Luce model. The Borda count is a point-based voting method in which each item receives a score based on its rank position, with scores aggregated across participants to produce a consensus ranking[30]. These scores are aggregated across participants to produce a consensus ranking. To enhance robustness and estimate uncertainty, we computed bootstrap-aggregated Borda scores using 10,000 resamples drawn with replacement. Within each question, we calculated mean scores and 95% confidence intervals. This method assumes complete rankings from all participants, which was not the case in this study. To address this, the Plackett-Luce model was used as a complementary approach[31]. The Plackett-Luce model estimates the relative *worth* or preference strength of each item based on observed rankings, including partial ones. Each item is assigned a positive worth parameter, and the probability of an item being ranked above others increases with its worth. The worth parameter is interpreted comparatively: an item with a higher worth than others is more likely to be systematically preferred. Observations were treated as independent despite potential within-subject correlation, as sparse data precluded models accounting for this, and results should be interpreted accordingly. All computations were performed in R (version 4.4.0) using the *PlackettLuce 0.4.3* and *emmeans 1.11.1* packages.

Open-ended survey responses were analyzed using thematic analysis as outlined by Braun and Clarke (2006)[32]. Coding was performed by one researcher and independently reviewed by a second researcher to ensure consistency. Themes were developed based on the frequency, emphasis, and contextual richness of participant responses. In some cases, subdividing themes into sub-themes was necessary to provide a deeper understanding of the data.

Interviews

We used purposive sampling to select adequate participants for the interviews. The inclusion criteria were: Dutch patients who have been formally diagnosed with OSA and have experience with (digital) RPM for OSA (current or discontinued utilisation; the latter, to elicit challenges for general use and adherence); healthcare professionals with a specialization in OSA and who have experience with (digital) RPM for OSA, to elicit their perspective on clinical workflows and patient interactions; and OSA patient advocates, to elicit perspectives on the pain points and needs of the broader OSA patient community in the Netherlands. Our sample was conveniently composed of individuals from (i) the pool of OSA patients who had participated in the survey (which we also report here) and had provided their email addresses for further research purposes, and (ii) TNO's network. The recruitment email included detailed information on the study, including the background of the research, its objectives and the informed consent form. If individuals agreed to participate, they were able to choose between an in-person or online interview via Microsoft Teams.

The interviews, which on average took about 60 minutes, were conducted and recorded via MS Teams by RY, who used an interview guide that had been expert checked (by NH and JKT) and piloted *a priori* (Suppl. File 2). The interview guide was based on a conceptual framework closely aligned with the Technology Acceptance Model which had been adapted to systematically elicit the perceived usefulness and ease of use of, perceived needs for, and willingness to engage with, OSA RPM and pertinent communication and reporting mechanisms in inter alia OSA follow-up care. The conceptual framework was also used to create the initial deductive code book.

Qualitative Data Analysis

The interviews were manually transcribed (verbatim) by RY. To support analysis, the transcripts were imported to the Computer-Assisted Qualitative Data Analysis Software (CAQDAS) Atlas.Ti (v8.02). The transcripts were analysed by RY based on the six steps of thematic analysis using deductive and inductive (complementary) coding approaches as outlined by Braun and Clarke (2006)[32]. To improve the credibility of the analysis, 10% of the transcripts (in this case, n=2 interviews) were independently coded by DS, see acknowledgments. Inter-coder reliability was ~90%. To increase dependability, codes were carefully tabulated and aggregated into themes based closely on the initial conceptual framework, analysed and discussed with NH and JKT, and finally reported by RY. RY also performed member checks (providing a summary of the preliminary analysis of an interview together with a couple of key quotes to the pertinent interviewer, and asking for comment) with multiple interviewees to improve confirmability. The code book and coding was reviewed by another researcher. Finally, the process of selective coding focused on selecting the most important and representative codes to develop overarching themes that addressed the research(sub)questions of this study[33]. Atlas.Ti version v8.02 was used for the coding process (Atlas.ti, 2023).

Data management and ethics

Ethical approval was obtained from TNO's ethical review board (study no 2023-103 and 2024-026). Informed consent was secured from all participants, and data were anonymized and securely stored. Validity measures included member checks, peer debriefing, and strategies to reduce social desirability and interview bias e.g. building rapport. The study adhered to qualitative research quality criteria.

Data availability

The datasets generated and analyzed during the current study are publicly available in the Harvard Dataverse repository under the title "Replication Data for: Toward Patient-Centric Digital Health Solutions for Obstructive Sleep Apnea Monitoring: Perspectives from Dutch Patients and Healthcare Professionals – a mixed-method study" [34].

The repository includes an anonymized survey dataset (n=223) containing quantitative responses on meaningful aspects of health, attitudes towards remote patient monitoring, and digital health technology preferences. All data are shared in accordance with ethical approvals from TNO's Ethical Review Board (study no. 2023-103). To protect participant confidentiality, direct identifiers have been removed and free-text fields have been redacted to avoid inadvertent disclosure of personal information.

Code availability

The analysis code used to generate the quantitative results reported in this study are publicly available in the same Harvard Dataverse repository [34].

Reporting guideline

This study adhered to the Mixed Methods Reporting in Rehabilitation and Health Sciences (MMR-RHS) guideline, and the completed checklist is provided as Suppl. File 3.

Results

Demographic information

223 Dutch patients formally diagnosed with OSA and persistent sleeping problems completed the survey. 48.4% were female and the mean age was 65±9 years (Table 2). The majority of the sample (133/223, 59.6%) was highly educated, and 67.3% (150/223) of the participants worked for less than 1 day per week or not at all. 34.1% (76/223) was formally diagnosed with at least one other sleep-related illnesses besides OSA. Also, other co-morbid conditions were reported by 71% (158/223) with obesity and cardiovascular disease being most prevalent. All interview participants were Dutch and purposefully selected; they had to be at least 18 years of age and have pre-existing experience with OSA RPM solutions (Table 3). We interviewed six Dutch individuals with a formal OSA diagnosis, two patient advocates affiliated with the national OSA patient association (Apneuvereniging), and three healthcare professionals experienced with managing OSA. This purposive sample was designed to capture a range of perspectives from key stakeholder groups (patients, advocates, and clinicians) (Table 3).

Table 2 | Population characteristics of surveyed cohort (n=223)

Age, year, median (range)		67 (28 – 86)
Sex, % (n)	Male	48 (108)
	Female	52 (115)
Education, % (n)	Secondary education	6.7 (15)
	Secondary vocational education	33.6 (75)
	Higher professional education and academic education	59.6 (133)
Care provider visited within last year, % (n)	General practitioner	38 (84)
	Medical specialist (outside sleep clinic)	50 (111)
	Company doctor	6 (13)
	Psychologist	6 (13)
	Sleep therapist	4 (9)
	Sleep clinic	27 (59)
	Other	3 (6)
	None	30 (67)
Sleep-related diagnoses, % (n)	Obstructive sleep apnea	100 (223)
	Insomnia	10 (22)

	Hypersomnia	12 (27)
	Sleep rhythm disorder	1 (2)
	Parasomnia	4 (10)
	Sleep-related movement disorder	15 (34)
	Other	3 (6)
Other diagnoses, % (n)	Obesity	33 (73)
	Cardiovascular disease	37 (82)
	Diabetes Type 2	15 (34)
	Depression	9 (20)
	Other	18 (42)
	None	29 (64)

Table 3 | Population characteristics of interviewed cohort (n=11)

ID	*Sex*	*Stakeholder group*
B1	Female	OSA patient
B2	Male	OSA patient
B3	Female	OSA patient
B4	Male	OSA patient
B5	Male	OSA patient
B6	Male	OSA patient
B7	Male	Somnologist
B8	Male	General practitioner and patient
B9	Female	Pulmonologist/somnologist
B10	Female	Patient advocate
B11	Male	Patient advocate

OSA; obstructive sleep apnea.

Meaningful aspects of health

Overall, we found that meaningful aspects of health for individuals with OSA and persistent sleep problems encompass both physical limitations and psychological burdens. Subjective sleep quality, daytime energy levels, and physical activity consistently emerged as key priorities—highlighted as important, considerable burdens when impaired, and as goals for improvement or resumption. In addition, psychological concerns such as worrying about health impacts and difficulties concentrating reflect the broader mental burden of OSA. We present results from ranking exercises of pre-specified health aspects and, separately, thematic analyses of responses to open-ended questions.

Burdens of living with OSA (ranking)

Worrying about OSA health impacts, *sleep interruptions*, and *problems concentrating* were ranked highest (Figure 1, panels a and b). Based on Borda counts, these items showed broad support across the cohort, while Plackett-Luce modelling revealed that certain concerns – such as *falling asleep while driving* or *problems concentrating* – were intensely prioritized by subsets of respondents. *Being too tired for hobbies or sport* was also considered an important burden (fourth place for both methods).

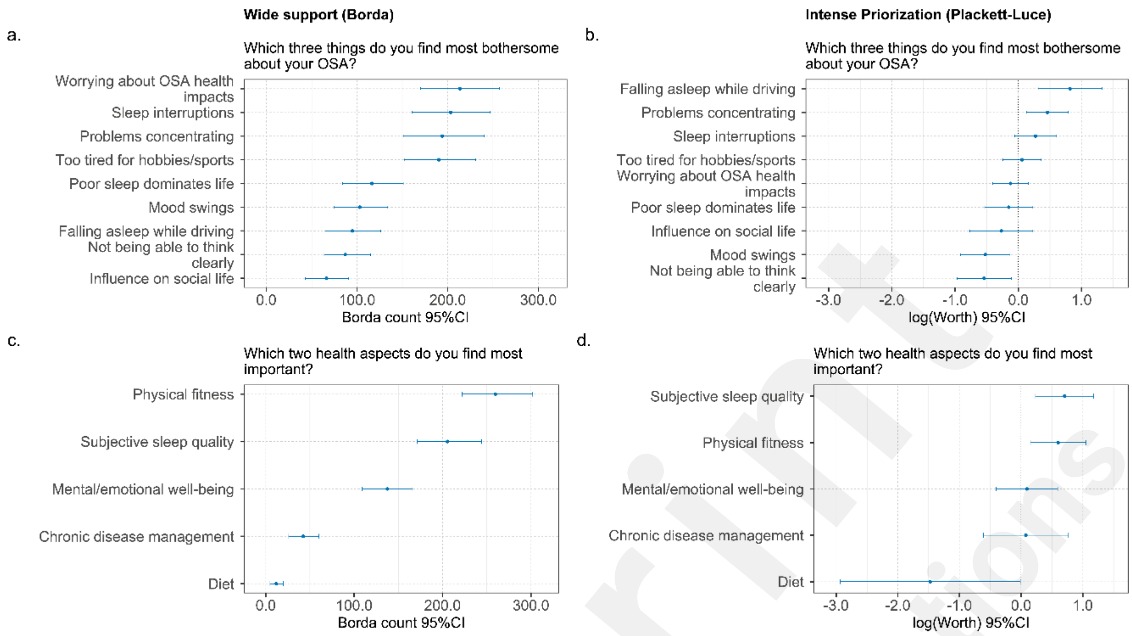

Figure 1 | Meaningful aspects of health identified through survey questions.
Panels a and b were derived from 3-item ranking question from 9 prespecified items (n=221). Panels b and c were derived from 2-item ranking question from 5 prespecified items (n=219). Panels a and c show items that received broad support (Borda), and panels b and d show items that were intensely prioritized (Plackett-Luce)

General health priorities (ranking)

While *physical fitness* attracted the strongest support overall, it came in second regarding rank concentration (Figure 1, panels c and d). This means that while *physical fitness* was considered most important overall, the agreement on specific ranks selected was less consistent than for, e.g., *mental/emotional well-being* or *chronic disease management*. *Subjective sleep quality*[a] was ranked second overall , and first, based on rank agreement (Figure 1, panel d), so the reversed relationship when compared with *physical fitness*. *Mental/ emotional well-being*, *chronic disease management* and *diet* came in third, fourth and fifth, for both analytical methods, respectively.

Restoring previous quality of life (open-ended)

A broad desire for *higher daytime energy levels* was expressed by 36% (72/202) of respondents (Table 4). For example, one participant reported that they missed "*getting through a whole day without constraints from extreme tiredness*". Another explained: "*I still do all things normally, only it […] [takes much longer] because you are so terribly tired*". Various types of *physical activities* were described by 25% (50/202) of respondents as aspects that they missed from their quality of life before disease onset, such as hiking, cycling or exercise more generally. Interestingly, *None* was the third most common theme (18%, 36/202), reflecting respondents who reported nothing from their previous quality of life they wished to restore. Social activities (17%, 34/202), activities requiring concentration, such as reading a book (16%, 32/202), and restorative sleep (15%, 30/202) were also mentioned.

Table 4 | Restoring aspect of previous quality of life derived from open-ended questions (n=202)

[a]Subjective sleep quality refers to the experienced quality of sleep as perceived by the individual, including aspects such as sleep fragmentation, feelings of restorative sleep, and more generally what respondents described as "good" sleep without providing a fixed definition.

Items	*n mentioned*	*% of respondents mentioned activity*
Having more energy	72	36.0
Physical activity	50	24.8
None	36	18.0
Social life & leisure	34	17.0
Concentration	32	16.0
Subjective sleep quality	30	15.0
Feeling more productive	22	11.0
Daily activities	16	8.0
Physical health	16	8.0
Being intervention free	3	1.5

Health goals relating to OSA symptoms (open-ended)

As shown in Table 5, *Subjective sleep quality* was the top health goal for our sample (46%, 93/200). For example, one participant explained that their goal was: "*no more lying awake after going to the toilet at night*". The themes *weight loss* and *daytime energy levels* both came in second (25%, 51/200). Participants explained their desire to feel less tired and more energetic throughout the day. The third most frequently mentioned aspect was *physical activity* (16%, 33/200)). Additionally, 14% (29/200) of participants wish to improve *health aspects related to physical health* including, for example, addressing night sweats, palpitations or restless leg syndrome.

Table 5 | Health goal related to OSA symptoms derived from open-ended questions (n=200)

Items	**n mentioned**	**% of respondents mentioned activity**
Subjective sleep quality	93	46.0
Daytime energy levels	51	25.2
Weight loss	51	25.2
Physical activity	33	16.3
Physical symptoms	29	14.4
Improved treatment	22	10.9
Concentration	16	7.9
Mental Health	13	6.4
Social life & leisure	8	4.0
Other	5	2.4
None	3	1.5

OSA follow-up care in the Netherlands

Based on the survey data, half of the participants reported contact with medical specialists, and 38% with general practitioners respectively. 30% (67/223) indicated that they had no physical follow-up healthcare visits. 27% (59/223) indicated that they had visited sleep centers during the past year (Table 1). Notably, several respondents who selected the option "other" explained that they had not attended physical follow-up visits but were, instead, relying on remote monitoring by their CPAP devices or self-monitoring of their condition. For example, one participant explained: "*No. I haven't seen a specialist since I got the […] [CPAP device]. According to the pulmonologist, everything was under control, and there was no need to return.*"

According to some interviewees, follow-up care is straight-forward but limited, as exemplified here by B8 (OSA patient who is also a GP): "*[…] [I was] diagnosed [with] sleep*

apnea [and] provided […] with the CPAP mask. A year later, I had a follow-up appointment […] to ensure my mask fit well and that everything was in order. After that, I received no follow-up care anymore." B3 (OSA patient) highlighted that they were not even sure what type of care they should be receiving: "*I received no follow-up care. I don't even know what follow-up care you should get.*" B11 (patient advocate) explained that this was likely due to resource constraints: "*Clinics don't have the capacity to provide follow-up care for all these patients. There are long waiting lists, and those waiting for OSA-diagnosis are prioritized, meaning that those who should receive follow-up care need to wait.*"
By the same token, the two interviewed somnologists highlighted that, on the one hand, patients have a role in taking charge, if issues occur, and, on the other, follow-up care can indeed vary greatly based on patients' needs and the severity of their OSA. B7 (somnologist) explained: *"Doctors expect that patients will initiate contact if there's a problem. […] Effective communication and reporting in follow-up care […] also requires patients to allocate time."* B9 (pulmonologist/somnologist) provided a top-level view of her patient-centred approach to follow-up care:

> *"I do an initial evaluation after 6-8 weeks post-diagnosis, then plan further check-ups based on the patient's condition and needs. If a patient is doing well, I schedule a follow-up after a year. […] If there are any issues, I see them sooner, using RPM data from their CPAP device to guide decisions." B9*

Nevertheless, as B5 (OSA patient) explained, other hurdles might exist in achieving good continuity of care: "*I called my supplier who said that they had sent a report of my monitored data to the hospital, but the hospital claimed they that hadn't received any report from my supplier.*"
sDHTs utilized, and attitudes towards RPM
Based on the survey data, 86 (182/212)% of participants agreed that sDHTs could contribute towards improving management of their OSA. Table 6 shows that, in our sample, the most frequently used device for (self-)monitoring was CPAP (87.1%, 155/178), followed by weight scales (47.8%, 85/178), blood pressure monitors (46.6%, 83/178), and smart watches (35.4%, 63/178 for heart rate measurements and 19.7%, 35/178 for sleep tracking). Sleeping mats were used least frequently (n=1). Figure 2, panels a and b, show that, when asked to rank different form factors according to their preference, a smart watch was ranked first, both in terms of overall frequency and subgroup concentration. The least preferred technology is clothing with integrated sensors. Notably, only one participant reported using a sleep mat, yet when participants were asked to rank their preferred technologies, sleeping mats were ranked among the top three. While the majority of participants (67%, 119/178) agreed that both they themselves, as well as their care providers, should have access to data collected with sDHTs, 28% (49/178) thought their care providers should have access only under certain conditions – merely 4% (7/178) indicated that they should be the only party with access to their data.
Also the majority of our interviewees held positive views towards the utility of RPM technologies for supporting OSA management. B6 (OSA patient), for example, was particularly enthusiastic: *"RPM tools […][are] a great addition because of the shortage of healtcare professionals now, so I think it's fantastic that we're focusing on that."* By the same token, some OSA patients had concerns regarding the dependebailty of the RPM ecosystem and actionability of information contained therein. For example, B3 (OSA patient) stated: *"I appreciate RPM, but it's only effective if I receive feedback from the RPM technology supplier or hospital. Ideally, it should alert you promply if issues like stopped breathing arise, which can ensure constant surveillance and timely intervention."* Moreover, there exists an unmet need regarding the interpretation of data: B4 (OSA patient) explained: "*I do see my sleep apnea values, for example an AHI score of 11.3, [but] is that good? What does this score*

mean for my health and how can I improve it? I'm missing this information [.][and] I think many do."
This was somewhat echoed, albeit in more general terms, by the Somnologist (B7), who was of the view that current RPM solutions have not yet reached the degree of maturity required for effective OSA remote management:

> *"Follow-up care cannot be provided as effectively through digital health technologies like RPM compared to clinical care. As a doctor, you need to see, touch and smell a patient to provide optimal care. You miss the human aspect of care when everything is digitized and managed through technologies that provide RPM." B7*

Nevertheless, our data indicate that some patients are actively engaged with their RPM data. B2 (OSA patient) explains:

> *"I read my reported data from the screen of my device. Then I have the DreamMapper app [patient-facing app showing CPAP data]. I take out the SD card of my [CPAP] device and plug it into my computer on which I have installed the Oscar program. This program gives me a comprehensive report on my monitored sleep apnea. Oscar is usually a very good program, but the hospitals don't want to use it because it' s not validated." B2*

This example quite vividly illustrates that, while solutions exist that can be meaningful for OSA patients, who want to dive deeper into their data and better understand their disease, these might be located outside of traditional clinical care pathways (and therefore lack clinical oversight / supervision).
Table 6 | Currently utilized technologies to monitor health derived from multiple choice question (n=178)

Items	n mentioned	% of respondents mentioned activity
CPAP	155	87.1
Weighting scale	85	47.8
Blood pressure monitor	83	46.6
Smartwatch (Heartrate)	63	35.4
Pulse oximeter	46	25.8
Smartwatch (Sleep)	35	19.7
Health app	21	11.8
Glucose monitor	16	9.0
Other	5	2.8
Sleep mat	1	0.6

Images of devices in Suppl File 1. CPAP; continuous positive airway pressure.

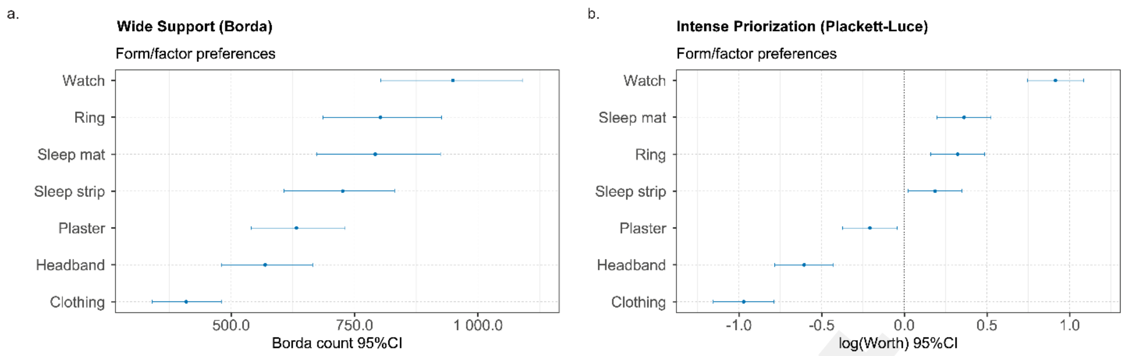

Figure 2 | Form/factor preferences.
Panels a and b were derived from full ranking of 7 prespecified items (n=109). Panel a shows items that received broad support (Borda), and panel b shows items that were intensely prioritized (Plackett-Luce).

Improving digital measures for the future of OSA RPM

Participants were asked to rank which three digital measures would help them gain more insight into their OSA. *Sleep characteristics* ranked highest overall. However, broad support in the Borda count analysis and rank agreement in the Plackett-Luce model for both *sleep characteristics* and *daytime energy levels* (second rank), indicates that these are the top targets for future digital measures (Figure 3, panels a and b). Physical activity was the only other item that came in at the identical rank (8) for both methods of analysis. When asked how current OSA measurement practices could be improved, the most frequently given answer related to suggestions for *additional measurements* (mentioned by 37% of respondents; Figure 3, panel c). Specifically, the majority of survey participants were interested in OSA vitals beyond AHI, such as heartrate-derived and saturation-based measures. Obtaining insights into sleep characteristics, such as sleep stages, was also mentioned by several survey participants. Other suggestions included improved *accuracy and reliability* of measurements, and more *comprehendible presentation* of monitoring data. For example, one survey participant highlighted the need for more clarity in analysis reports, such as presentation in layman's terms, whereas another patient expressed the desire for more monitoring and guidance from OSA professionals and home care providers. Also the more general value of digital measures for OSA monitoring was underscored. For example, one survey participant indicated that they would like to add monitoring options to their MAD-based treatment: "*Many people have MADs but have no proof – except through complaints (snoring) or feeling fit – [indicating] whether it helps. […] It would be great if […] [a wearable or smart watch], or other technology could do that [track and report]. .*"

The interview data provided additional detail on a range of potential improvements for future OSA management. The majority of OSA patients prefered non-invasive sDHTs and emphasized the need for a stronger product design focus on less disruptive and more convenient devices for daily use, and better integration with daily attire. B6 (OSA patient) explained: "*I already use a [smart watch] […] for my heart monitoring, but it would be nice if future RPM technologies are non-invasive, like an App or a small device beside the bed. Large or intrunsive devices are uncomfortable for light sleepers like me.*" B4 (OSA patient) also mentioned the (inter alia visual) product design of wearable RPM technology: *'A smartwatch-like device that tracks my heart rate and oxygen saturation would be ideal, as long as it's non-invasive and looks good.'* Regarding specific measures, B4 (OSA patient) said: *'I would like to measure my oxygen saturation during the night. This could be an improvement regarding RPM metrics for OSA.'*

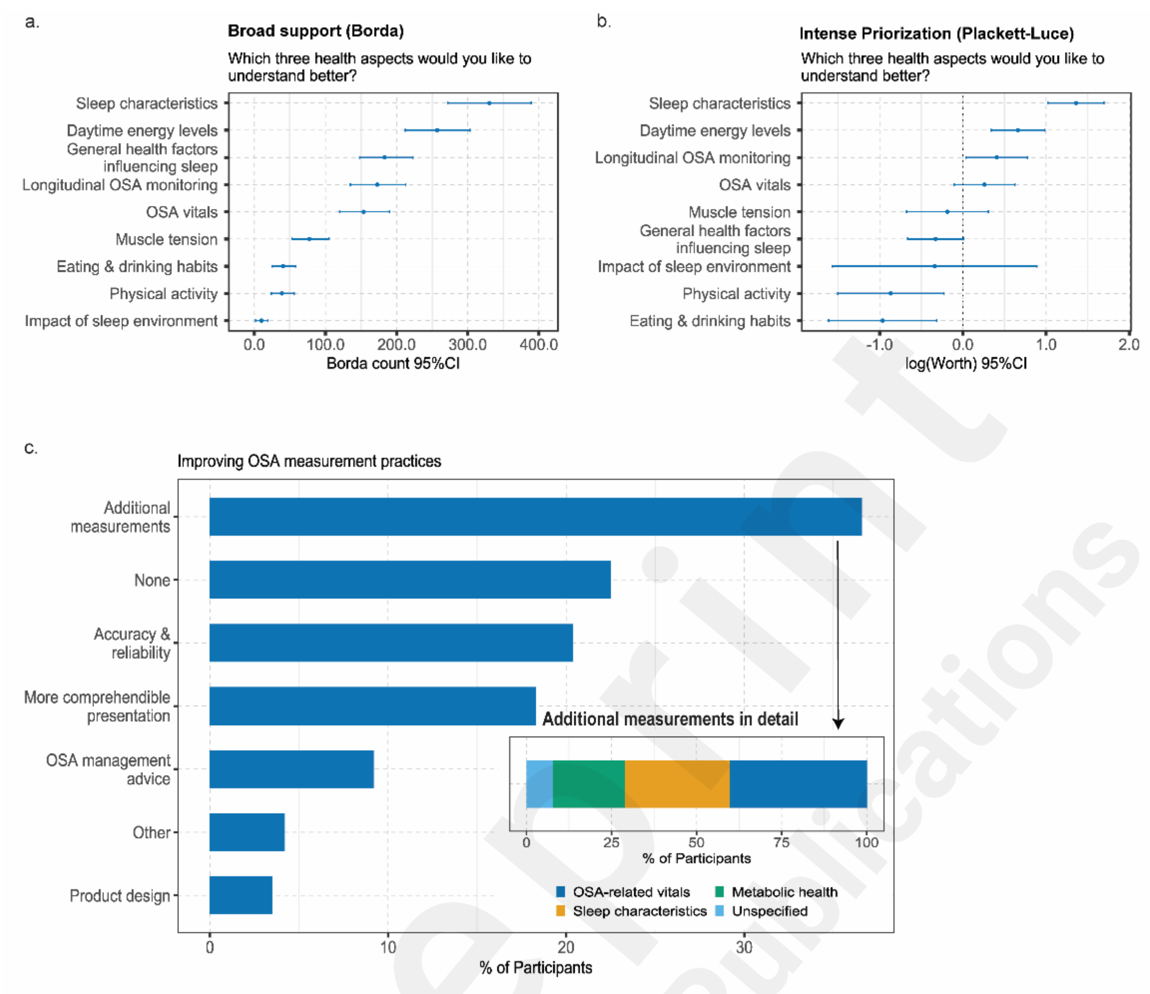

Figure 3 | Health aspects participants would like to understand better and suggestions for improving OSA measurement practices

Panels a and b were derived from 3-item ranking of 9 prespecified items (n=213). Panel a shows items that received broad support (Borda), and panel b shows items that were intensely prioritized (Plackett-Luce). OSA vitals: heartrate-derived measures, breathing, saturation. Panel c shows thematically analyzed responses to an open-ended question. OSA management advice: lifestyle advice & contact with care provider (n=142). OSA; obstructive sleep apnea.

Discussion

This mixed methods study guided by the DiMe's *Digital Measures That Matter* framework aimed to, first, identify meaningful aspects of health and care needs of individuals with Obstructive Sleep Apnea (OSA) and, second, inform the improvement of existing, and the development of new, pertinent digital measures and remote patient monitoring (RPM) solutions. Based on our two Dutch cohorts (patients, their representatives and specialized healthcare professionals) our principle findings are:

(i) Improving subjective sleep quality, increasing physical activity, and increasing daytime energy levels are key meaningful aspects of health identified by patients.

(ii) Prioritising sleep characteristics (particularly sleep fragmentation), daytime energy (focus on fatigue and excessive daytime sleepiness), and nighttime oxygen saturation, as targets for digital measure development.

(iii) Smartwatches, sleep mats, and smart rings are strongly preferred as modalities for sDHTs that can be integrated into future RPM solutions.

(iv) Enhancing current digital monitoring practices and focussing on: (1) expanding metrics beyond AHI (see point ii), (2) improving measurement accuracy, and (3) ensuring that digital measures are meaningful, understandable and actionable for end-users.

(v) Patients lack the ability to determine from RPM output whether they need to seek follow-up care and, if so, what type of care is appropriate.

Comparison with prior work

Our principle findings highlight that improving *subjective sleep quality*, increasing *physical activity*, and *enhancing daytime energy levels* are key meaningful aspects of health for OSA patients. Each can (potentially) be assessed using sDHT-derived metrics, though these technologies vary widely in maturity and clinical readiness.

Sleep was a consistently prioritized health aspect, essential to daily functioning and overall well-being. Participants expressed skepticism about the accuracy and clinical utility of sleep data from personal devices, echoing World Sleep Society recommendations that, while sDHTs hold potential for monitoring sleep patterns, their proprietary algorithms often lack validation in sleep disorders[35]. Recent studies in OSA populations show promising results for tracking metrics like total sleep time and sleep efficiency, with some devices showing moderate-to-strong agreement with polysomnography; however, broader validation is still needed to ensure accuracy and clinical relevance[36–40].

Physical activity emerged as another key health aspect, with participants identifying it as a health priority and an area they wished to improve. Physical activity is both a meaningful health goal and a key factor in OSA management, as increasing activity can help reduce OSA severity while effective treatment may in turn support higher activity levels. Structured exercise interventions can reduce AHI, improve oxygenation, and alleviate daytime sleepiness[41–43]. However, evidence for physical activity levels as an outcome of CPAP therapy is mixed, with studies reporting – despite improved symptoms – modest or no changes in physical activity levels[44–46]. sDHTs could help monitor physical activity as a potential biomarker of functional gains and support behaviour change in OSA care.

Daytime energy levels emerged as a top-rated health aspect, with participants identifying it as a key priority, an important health goal, and the most valued quality-of-life factor to restore. This reflects both excessive daytime sleepiness and fatigue, which present heterogeneously across patients and persist in some even after optimal therapy[47–49]. While these symptoms are typically assessed using PROMs, such as the Epworth Sleepiness Scale and Fatigue Severity Scale, their use is limited by respondent burden, recall bias, and low temporal resolution[49]. sDHTs offer a promising, non-invasive alternative for continuous monitoring of these symptoms. Metrics, such as heart rate variability and physical activity, are actively being explored, yet validated digital measures for routine monitoring are lacking – making this a clear priority for innovation[49,50].

Implications for practice and policy

Developing new digital measures and RPM solutions is complex and resource-intensive, often requiring significant time before their impact reaches clinical practice. On the short term, the rapid rise of consumer wearables creates an opportunity to validate and optimize digital measures – such as sleep and physical activity – for specific populations like OSA. This should be prioritized as a practical step toward innovation. Beyond creating new measures, improving existing RPM tools is equally urgent. Enhancing reporting platforms with clear explanations, contextualized feedback, and actionable suggestions could better support patients in managing their condition. Interfaces that let users toggle between simplified and detailed views would help accommodate diverse preferences and levels of health literacy.

On a broader scale, policymakers and payers should consider setting standards to ensure RPM systems deliver accurate, patient-centered, harmonised, and actionable data presentations. A key requirement is that digital measures embedded in RPM solutions are validated for accuracy, reliability, usability and clinical relevance in target populations, such as OSA patients[22,23]. Establishing such validation criteria will help ensure that these tools provide meaningful insights and support clinical decision-making. These standards could also guide reimbursement decisions and accelerate adoption of RPM solutions that empower patients, improve treatment outcomes, and reduce healthcare burden.

Limitations and strengths

Our study has several limitations. Firstly, the sample was skewed toward more highly educated individuals and included a higher proportion of women, likely reflecting the greater prevalence of comorbid insomnia in female OSA patients[51–53]. Secondly, the number of participating healthcare professionals was limited (three in total: one somnologist, one somnologist/pulmonologist, and one general practitioner), which means their perspectives may not fully capture the diversity of clinical views and could reflect individual experiences. However, several of their insights were echoed by patients, supporting their relevance to the themes identified. Futhermore, the surveyed cohort focused on individuals with OSA who report persistent sleep problems despite treatment. While this subgroup may not fully represent the broader OSA population, it highlights a group with substantial unmet needs and provides valuable insights into priorities for digital health innovations and RPM solutions. Another strength is that our patient-centered approach aligns with value-based healthcare principles and was guided by the *Digital Measures That Matter* framework to identify outcomes that matter most to individuals with OSA. The combination of quantitative survey data and qualitative interviews, including input from patient representatives, ensured the perspectives captured reflect a broad OSA population.

Conclusion

Rather than relying solely on clinical endpoints such as AHI, our findings suggest that outcomes such as physical activity, restorative sleep, and daily functioning are central to patients' lived experiences – and are therefore critical targets for sDHTs and RPM metric innovation. Developing and validating new digital measures that capture these experiences will require time, interdisciplinary collaboration, and ongoing involvement of patients to ensure relevance and usability. In the meantime, existing RPM systems can be strengthened by improving transparency, accessibility, and contextual interpretation of currently collected data, making these platforms more meaningful and actionable for patients. The broad patient priorities identified in this study can serve as an excellent starting point for defining patient-centric digital measures allowing for comprehensive disease management.

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Conflicts of interest

None declared.

Data availability

The datasets generated and analyzed during the current study are publicly available in the Harvard Dataverse repository under the title “Replication Data for: Toward Patient-Centric Digital Health Solutions for Obstructive Sleep Apnea Monitoring: Perspectives from Dutch Patients and Healthcare Professionals – a mixed-method study” [34].

Authors' Contributions

Ideation: NH, WvdB; theoretical concept / framework: RY; state of research / systematic review: JKT, NH; data collection: NH, RY; formal analysis: JKT, NH, RY, KS, TvnB; data management / statistical modelling: KS, TvdB; graphs/visualizations: KS, TvdB, NH; replication data: KS, NH; writing: JKT, KS, NH; review & editing: SO, WvdB, TvdB; Supervision: NH, JKT, WvdB. All authors agreed with the submission version of the manuscript.

Abbreviations

AHI; apnea-hypopnea index
CPAP; continuous positive airway pressure
DiMe; digital medicine society
MAD; mandibular advancement device
OSA; obstructive sleep apnea
PROMs; patient-reported outcome measures
RPM; remote patient monitoring
sDHTs; sensor-based digital health technologies

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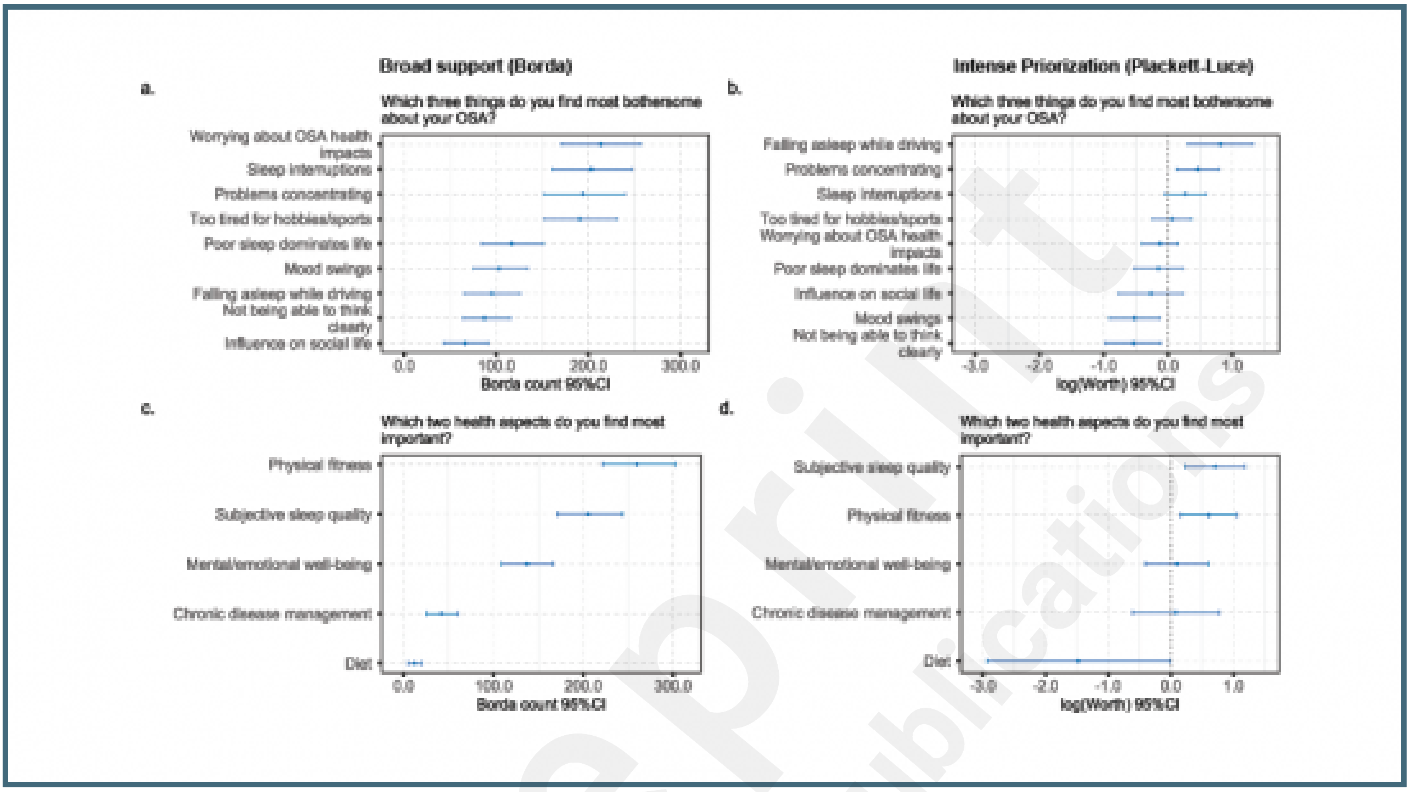
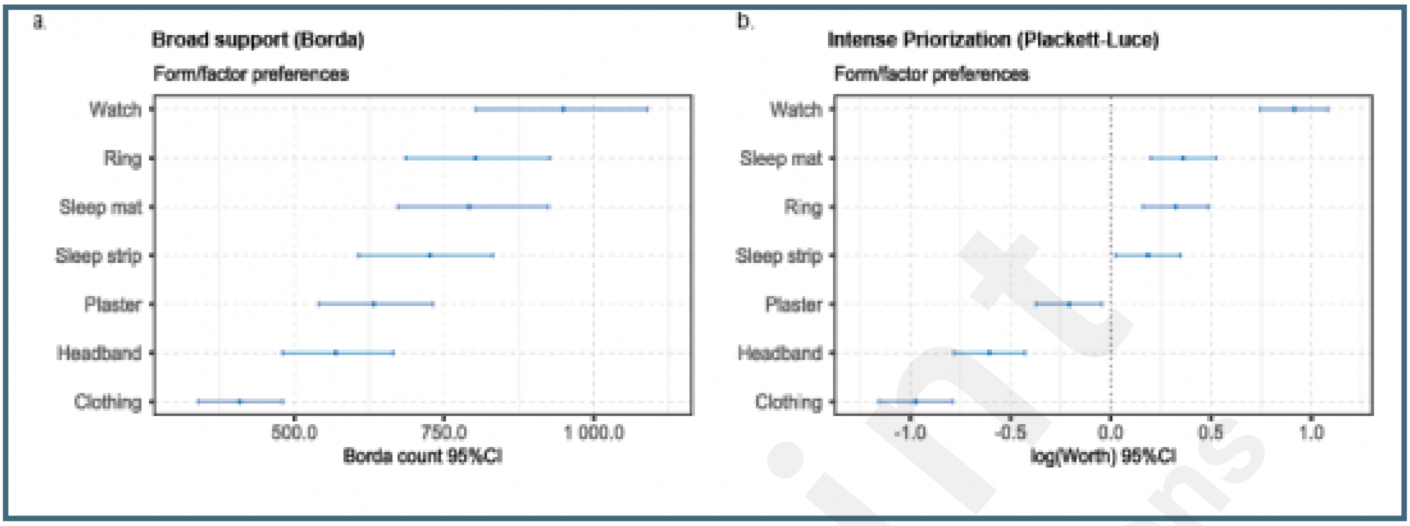
Supplementary Files

Figures

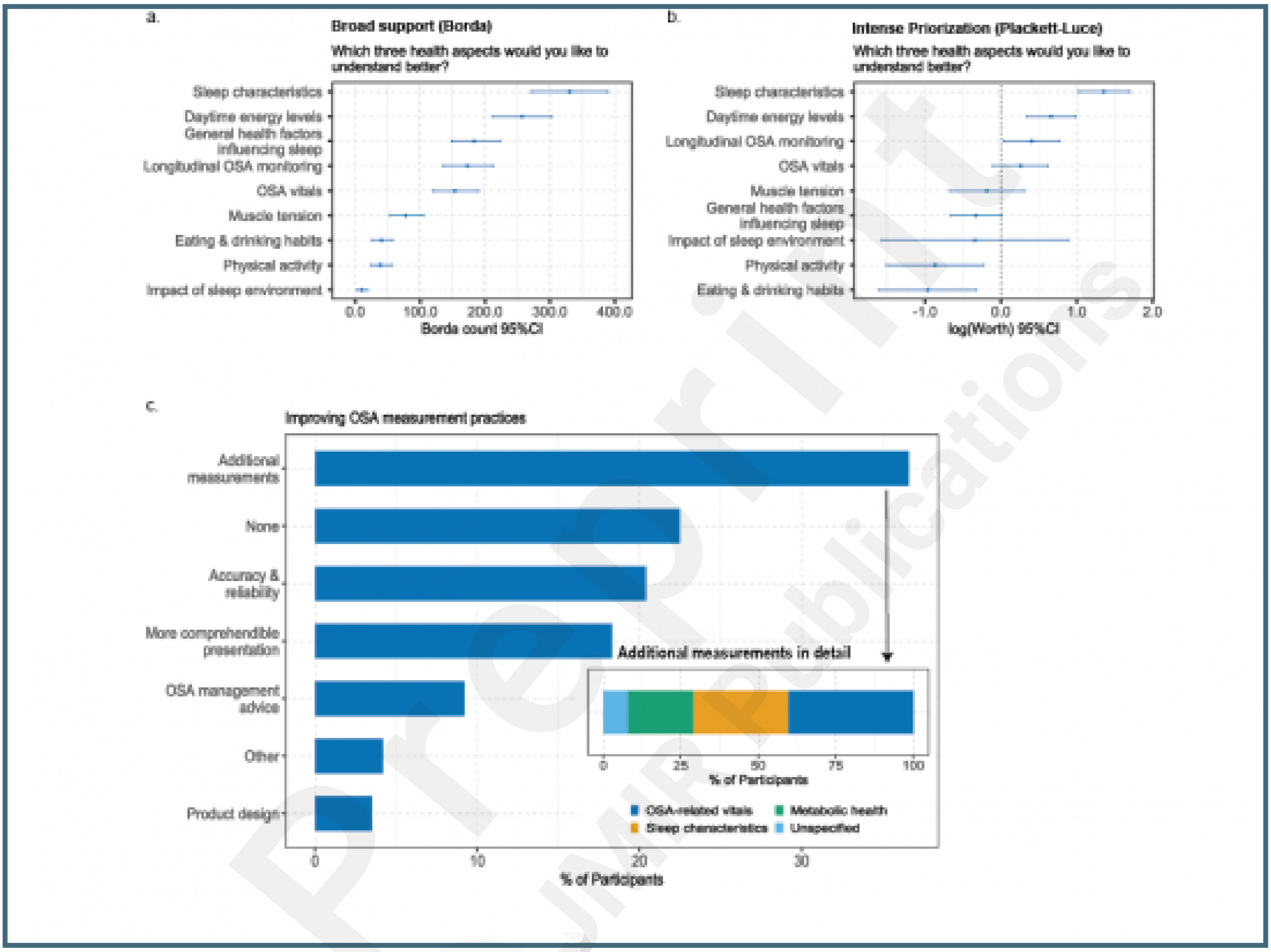
Meaningful aspects of health identified through survey questions. Panels a and b were derived from 3-item ranking question from 9 prespecified items (n=221). Panels b and c were derived from 2-item ranking question from 5 prespecified items (n=219). Panels a and c show items that received broad support (Borda), and panels b and d show items that were intensely prioritized (Plackett-Luce).



Form/factor preferences. Panels a and b were derived from full ranking of 7 prespecified items (n=109). Panel a shows items that received broad support (Borda), and panel b shows items that were intensely prioritized (Plackett-Luce).



Health aspects participants would like to understand better and suggestions for improving OSA measurement practices Panels a and b were derived from 3-item ranking of 9 prespecified items (n=213). Panel a shows items that received broad support (Borda), and panel b shows items that were intensely prioritized (Plackett-Luce). OSA vitals: heartrate-derived measures, breathing, saturation. Panel c shows thematically analyzed responses to an open-ended question. OSA management advice: lifestyle advice & contact with care provider (n=142). OSA; obstructive sleep apnea.



Multimedia Appendixes

Supplementary file 1. Survey (original in Dutch, for this manuscript translated to English). Supplementary file 2. Interview guide (original in Dutch, for this manuscript translated to English).
URL: http://asset.jmir.pub/assets/e65d3af2422a6a67589bdfd7d942d23b.docx

Checklist reporting guidelines Mixed Methods Reporting in Rehabilitation and Health Sciences.
URL: http://asset.jmir.pub/assets/1c6c42b318b3d8046960a973c5891034.pdf