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Human Kinetics
ORIGINAL RESEARCH

A Feasibility Study of the "Motus" System for Wearable-Based Movement Behaviors at Scale

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Background: For detailed, large-scale data on 24-hour movement behaviors, we designed a system "Motus" using state-of-the-art wearable and cloud technology, and tested its feasibility on randomly chosen Danish adults in a 2-stage evaluation. ***Methods:*** Stage 1: We invited 7735 adults, responding to a national occupational health surveillance-2021. Consented participants received a wearable (SENSmotion Plus) and downloaded the Motus app, which provided instructions for wearable attachment on the thigh and for self-reporting work and sleep hours. Following the 7-day measurement, participants completed a feasibility questionnaire. Administrators recorded time spent on Motus-related tasks (eg, postal package preparation). Identified feasibility issues led to revisions of protocol and Motus elements. Stage 2: We invited 6993 adults from a national public health surveillance-2023. Participants used the revised Motus version. We evaluated Motus on the key issues identified from stage 1. ***Results:*** Stage 1: Feasibility ranged from 77% for social acceptability to 98% for adherence to the measurement protocol. Participants reported spending 73 minutes per week (eg, attaching the sensors) on Motus, while administrators reported 15 minutes per participant. We identified 3 issues: 6% consent rate, 20% lost wearables (but not the data), and 10% wearable patches becoming loose. We addressed these issues by sending reminders, using stronger return envelopes, and replacing patch adhesive with higher quality alternatives, respectively. At stage 2, we observed a higher consent rate (23%) and lower patch complaints (<3%) but higher wearables loss (25%). ***Conclusion:*** Motus displays promising feasibility for collecting large-scale 24-hour movement behavior data. However, the low participation rate and high sensor loss require improvement before broader implementation, especially in surveillance.

Keywords: accelerometry, domain-specific physical activity, work, SurPASS (Surveillance of Physical Activity, Sedentary Behavior, and Sleep)

Key Points

- Accurate and large-scale 24-hour movement behaviors data is paramount in cohort studies and surveillance.
- A "Motus" system was designed using state-of-the-art wearable and cloud technology for such a purpose.
- Motus displays promising feasibility for collecting large-scale 24-hour movement behaviors data.
- Motus needs to address the issues of low participation rate and high wearable loss before broader implementation, especially in surveillance.

Recent research indicates that health outcomes are influenced not only by physical activity but also by the interaction between movement behaviors—physical activity, sedentary behaviors, and sleep—over a 24-hour period.[1–3] This realization highlights the need for obtaining large-scale, precise data on 24-hour movement behaviors in both surveillance and cohort studies.[3,4]

To collect such large-scale data, we require a system providing valid measurements while minimizing the burden on participants

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and the surveillance administration. Traditionally, data collection on movement behaviors relies on questionnaires, offering large-scale data with minimal burden on participants and administration. However, the accuracy of questionnaires is compromised by social desirability, recall issues, and poor validity.[5,6]

Wearable (accelerometry) systems offer a promising alternative for large-scale data collection on movement behaviors and have been used in surveillance efforts, such as the National Health and Nutrition Examination Survey,[7] and in cohorts such as the UK Biobank.[8] These systems typically include triaxial accelerometers, a data processing framework to convert raw data into physical behavior measurements, protocols for device calibration, participant and administrator instructions, and quality control. While these systems collect high-quality data, they are rather burdensome for both participants and administrators.[4] This is because they often require in-person meetings to attach the wearable, manual data downloading, and laborious data processing. Additionally, these systems risk data loss if the wearable is lost and rarely offer automatic integration of diary data for identifying the domain of movement behavior.

The new generation of wearable systems presents a promising alternative that may address these limitations of previous wearable-based systems. The new generation systems transmit data wirelessly via Bluetooth, smartphone, and internet to a secure cloud solution, where it can be stored, processed, and analyzed automatically.[4] Using this technology, we developed an advanced internet- and wearable-based system of 24-hour movement behavior measurement, called "Motus".[9] Motus consists of an app for participants that guides them through the self-attachment of the wearable and a secure cloud enabling automated data management and streamlined data processing, potentially being feasible for large-scale measurements of movement behaviors (Figure 1).

A unique feature of Motus is that it uses validated, open-source software algorithms to identify movement behaviors.[10,11] Moreover, Motus enables convenient self-reporting of daily domains in the app (such as work, nonwork, and sleep) and automatically integrates these data with movement behavior data to measure domain-specific movement behaviors. These features may make Motus suitable for large-scale measurements of movement behaviors in occupational and public health settings to capture both work and leisure time.

We have previously described the development of Motus and evaluated its usability.[9] Overall, we found Motus to have a high degree of usability; however, the feasibility of Motus has not previously been evaluated.

Thus, in this study, we aimed to evaluate the feasibility of Motus to measure 24-hour movement behaviors among adults in real-life surveillance settings for occupational and public health.

Methods

We conducted the feasibility evaluation in 2 stages. In Stage 1, we evaluated Motus in an occupational health surveillance setting, focusing on adherence, technical acceptability, social acceptability, practical acceptability, time usage, and financial cost of Motus. Table 1 outlines the definition and elements of each construct. After identifying feasibility issues, we revised Motus. In Stage 2, we evaluated the revised Motus in the public health surveillance to evaluate improvements on the issues identified in Stage 1.

Stage 1: Feasibility Evaluation in Occupational Health Surveillance

Study Population

The Danish working population is invited to participate in the established biannual occupational health surveillance, "Danish National Surveillance of Work Environment of Employees (NOA-L)."[12] In 2021, a total of 30,099 workers from various job groups responded to the NOA-L questionnaire. From this group, a random sample of 7735 workers were invited to participate in our study in 2022.

Results from previous NOA-L rounds indicated that employees that are young and engaged in nonoffice jobs (like blue-collar jobs) are difficult to recruit.[13] Thus, we oversampled these groups (Supplementary Material S1 [available online]) to improve their representation in the study sample.

NOA-L's administration team contacted the participants via a secure e-mail with a link to a registration web page. Individuals who opted out provided reasons for nonparticipation. Those who consented to participate reported any allergies to patch adhesive and provided their address and phone number. NOA-L's administration team provided descriptive data on all individuals who were sent invitations.

Motus

Figure 1 visualizes Motus consisting of a wearable sensor to be attached to the thigh, a smartphone application, a secure cloud for data storage, the analytical software "ActiMotus," and a web-based application for administrators. A detailed description of the iterative development of the Motus is available elsewhere.[9]

Procedure

Participants were invited to use Motus for 7 days. They received a package containing a SENSmotion Plus (SENS Innovation ApS) wearable, an attachment patch (SENS motion SENS patch), an alcohol swab (Mediq), extra adhesive strips (Medipore), a prepaid

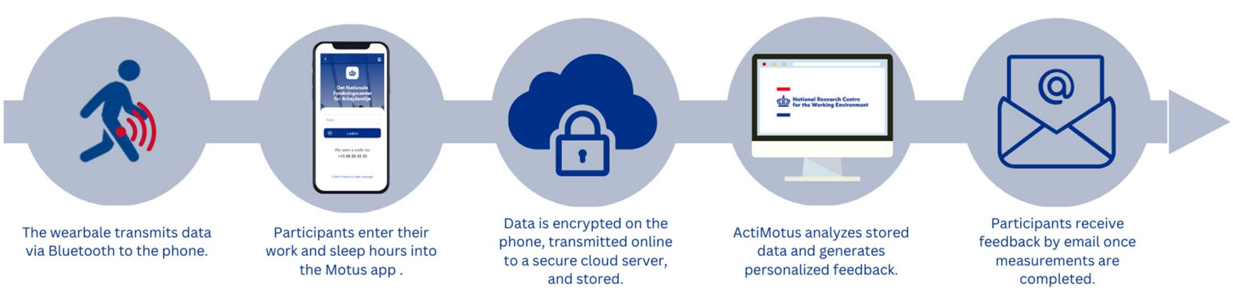

Figure 1 — The main components of Motus and their functionalities.

Table 1 Description of the Elements of Each Feasibility Construct, Data Collection Methods, and Type of Data Collected in the Evaluation of the Motus Measurement System in an Occupational Health Surveillance Setting

Elements of each construct	Method	Data
Adherence construct: Usage of the Motus and its protocol as intended		
Could download the app	Interactions with participants	Participant interactions regarding issues with downloading the app
Could activate and attach the wearable	Interactions with participants, web app, and wearable-based data	Participant interactions regarding patch issues, understanding in-app instructions, and wearable attachment issues; web app displaying wearable activation status; wearable data indicating if flipped during attachment
Could complete in-app diary	Web app	Manual checking of incomplete diary entries
Could initiate data upload via the app	Interactions with participants and web app	Checking upload status on web app and addressing upload issues
Had at least one valid day measured	Wearable-based data	A day with at least 20 h of valid (no errors or nonwear time) measurements
Technical acceptability: Capability of a system to function without encountering technical failures		
No errors with wearables	Web app and wearable-based data	Checking wearable measurement status; wearable nonwear time
Compatible smartphone	Interactions with participants	Interactions with participants regarding the compatibility of their phone with Motus
No technical errors during the test	Interactions with participants	Interaction with participants regarding any technical errors
Social acceptability: Perception if the system is desirable, suitable, and acceptable by individuals		
Recruitment rate	Participant flow (Figure 2)	Individuals who consented to participate
Satisfied	Post measurement questionnaire	Responded on a 5-point Likert scale (strongly agree to, agree, neutral, disagree, and strongly disagree) regarding satisfaction with the system. The first 3 response categories were categorized as "satisfied."
Willing to participate in future	Post measurement questionnaire	Responded with yes or no to participate again
Recommend a colleague	Post measurement questionnaire	Responded with yes or no to recommend a colleague to be measured using Motus
Overall confidence in participating	Post measurement questionnaire	Responded on a 5-point Likert scale regarding concerns or worries about making mistakes while using Motus. The first 3 response categories were categorized as "confident."
Practical acceptability: Practical convenience of system usage		
No skin irritation	Post measurement questionnaire	Responded yes or no to experiencing skin irritation during the measurement
Patch intactness	Post measurement questionnaire	Responded to open-ended questions about any issues with Motus. Responses related to the patch (eg, loose, broken, falling off) were categorized as patch issues.
Follow data collection steps	Post measurement questionnaire	Responded on a 5-point Likert scale regarding ease of use with Motus. The first 3 response categories were considered "easy to use."
No data upload issues	Post measurement questionnaire	Responded to open-ended questions about any issues with Motus. Responses related to eg, slow upload speed, were categorized as data upload issues.
Wearables delivered successfully	Interactions with participants and web app	Interactions with the participants if they did not receive the postal package Checking wearable measurement status on web app indicating "activated" or not
Wearables received back and the reasons for lost wearables	Tracking the packages received back and interactions with participants	Packages received and checked for the presence of the wearable Interactions with the participants regarding the return of the wearable
Time: Time used by administrators/researchers and participants through engaging with Motus		

(continued)

Table 1 *(continued)*

Elements of each construct	Method	Data
Time usage	Post measurement questionnaire and administrators time usage	Time usage was calculated based on reported time spent by the administrators and participants for administering and using Motus, respectively. Specifically, the administrator monitored the time used on packaging and setting up participants in the web app, sending notifications, monitoring data collection, analysis and feedback, and participant interaction during the measurement period. Participants reported time used on getting started on day 1 (starting up the Motus app and attaching the sensor), time used filling out the diary, and uploading the data every day.
Cost: The direct and indirect costs of including Motus in movement behavior surveillance (calculated in DKK and converted to EUR using the conversion rates from the European Central Bank in the year 2022)		
Indirect costs	Post measurement questionnaire, administrators time usage, and Denmark Statistics data	Indirect costs for (1) participants; time reported by each participant was multiplied with the salary estimates, sourced from Denmark Statistics,[34] corresponding to their educational level, and weighted based on the proportion of participants and (2) administrators; average time used was multiplied with salary estimate of a research assistant obtained from Denmark statistics.
Direct cost	Invoices, number of participants, and wearable loss/errors	Direct cost (wearables, patches, etc) was calculated from invoices. For the wearable, the cost was calculated by multiplying cost of wearable per usage (based on the previous experiences, a wearable can be used 5 times before refurbished or replaced).

Abbreviations: EUR, Euro; DKK, Danish krone.

envelope for wearable return, and an introductory letter providing the necessary information, for example, how to download the Motus app.

Participants downloaded the app from the App Store or Google Play that provided pictorial and written instructions for attaching the wearable and registering their daily work and sleep hours in the app. The measured accelerations along with self-reported diary entries data were encrypted and transmitted to the cloud via the phone's Bluetooth when the participant opened the app, as background data upload functionality was not available. After measurements, the participants were instructed to return the wearable using the prepaid envelope. Returning the wearable was not essential for obtaining the measured accelerometry data, but for reusing the wearable. At the end of the 7-day measurement period, participants received a brief report of their week's movement behaviors in the app and a detailed report in their email. Upon completion, participants received an e-questionnaire containing the questions on the Motus feasibility.

We sent SMS-based reminders, using a semiautomated system. Participants received reminders if they (1) did not initiate the measurements within 20 days after dispatching the postal package, (2) did not fill out the in-app diary for 2 consecutive days, (3) had >36 hours of un-uploaded data on the wearable, or (4) administrators did not receive the wearable within 2 weeks after measurement completion. An administrator monitored the status of these tasks daily via the web app and activated the reminders accordingly.

Data Collection and Analyses

Measurement of Movement Behaviors Using Motus. Participants attached the wearable to the anterior midsection of their right thigh. The wearable sampled at 25 Hz and initialized when participants logged into the Motus app using a 2-factor authentication login. Then, participants were instructed to stand upright for 20 seconds to perform a calibration of the wearable (to obtain the angle between the leg and accelerometer axis). Thereafter, participants entered their daily work and sleep hours in the app. Participants also reported their nonworking days and sick days.

The encrypted raw acceleration data in the cloud were downloaded as a *.bin* file format that is compatible with ActiMotus. It is a Python program that is based on the valid Acti4[10] and ActiPASS MATLAB program.[14] The ActiMotus classifies each second of measurement as an activity, based on features derived from the raw acceleration data (ie, angles and intensity). We considered a day of measurements to be of high quality if it contained at least 20 hours of measurements.[3]

The encrypted diary data were converted to a .csv file format in the cloud and was used to identify the 2 predefined domains (work and leisure). By synchronizing the diary data of the domains and the classified acceleration data, we separated the data of the computed movement behaviors—physical activity, sedentary behavior, and sleep—into the work and leisure domains, respectively, using ActiMotus (Figure 1).

Data Collection and Evaluation of Motus Feasibility. To evaluate adherence, technical acceptability, social acceptability, practical acceptability, time usage, and financial cost of Motus, we collected data by monitoring the interactions with participants, web app data, wearable data, and the time participants and administrators reported spending on performing tasks related to Motus. Table 1 describes the type of data we collected using these methods on various feasibility elements.

Data on feasibility elements (Table 1) were converted into percentages by dividing the number of positive cases (eg, participants who adhered and encountered no acceptability issues) by the total number of cases. A higher percentage indicated greater feasibility and vice versa. The average of all elements under each construct was calculated to summarize the results.

Revision of Motus Based on the Stage 1 Feasibility Evaluation

We noted all issues related to the feasibility of Motus and those that occurred frequently (>5% of the participants) were presented to the main stakeholders and experts to obtain suggestions for improvements and revisions in Motus and protocol. We then developed a specific plan for implementing the proposed solutions in the Motus.

Stage 2: Feasibility Evaluation in Public Health Surveillance

Study Population and Procedure

Stage 2 assessed the feasibility of the revised Motus on the identified issues from stage 1 (Table 2) in the Danish Health and Morbidity Survey (DNHS), 2023. It is a public health surveillance platform established in 1987, developed as a collaboration between the 5 Danish administrative regions, the Danish Health Authority, and the National Institute of Public Health. DNHS aims to monitor the general health and disease status of the Danish population (16 years or older) every 4 years.[15]

The participants for the feasibility trial were recruited from responders to the online version of the DNHS in 2023.[16] Overall, 25,000 individuals aged 16 years or older were randomly selected from the Danish Civil Registration System[17] to participate in the DNHS-2023. Invitations (invitation letter attached in Supplementary Material S3 [available online]) were sent via secure digital mailbox for online responses or in the mail for paper-based responses, if invitees opted out of digital mail. Up to 5 reminders were sent to online invitees (consisting of a mix of physical questionnaires in the mail and digital reminders).[16]

The invitation to this feasibility study was presented as the final question of the online version of the DNHS and invited respondents to participate in a 7-day measurement of their physical activity, sedentary behavior, and sleep using the Motus system. Respondents wishing to participate registered themselves by entering their phone number and postal address and were then sent a package including a wearable and other material. Participants registered for the substudy between February and June 2023, and the research team shipped the wearables in a letter within 11 weeks on average (SD = 6 weeks) from registration. The procedure for sending out the postal package and using Motus for 7 days was similar to that of stage 1.

Data Collection and Evaluation

At stage 2, we evaluated the revised version of Motus on the key identified issues from stage 1. To do so, we collected data by monitoring participation rates, protocol adherence at various stages, processes such as participant interactions and wearable loss, as well as using the Motus web app to monitor technical issues or errors. Data collection protocol was similar to stage 1 and detailed in Table 1.

Results

Stage 1: Feasibility Evaluation in Occupational Health Surveillance

Participants Flow

The flow of the participants who were invited to participate in stage 1 evaluation of Motus is visualized in Figure 2.

We invited 7735 individuals to participate, of whom 482 (6.2%) consented to participate. When stratified by type of work, there was no large difference in the consent rate among blue-, pink-, and white-collar workers. A total of 338 (70%) of those who consented attached the wearable, of whom 334 (99%) wore the wearable for 7 days.

Of the 7253 individuals who did not consent to participate, 1601 individuals filled out a questionnaire providing their reason for declining to participate in the Motus feasibility study. The primary reasons for their refusal were “lack of time to participate” (32.4%), “no new knowledge/learning for them” (21.4%), and “did not wish to get their movement measured” (11.4%).

Difference Between Consenters and Nonconsenters and Participants and Dropouts

Compared with consenters (n = 482), nonconsenters (n = 7253) were more likely to be men, smokers, had higher body mass index, and engaged in nonwhite collar (especially blue-collar) jobs. Of those who were sent the package (n = 472), we found no clear difference in the demographics between those who attached the wearable (n = 338) and those who did not (n = 134) except for more smokers among those who did not attach the wearable.

Sample Description

The characteristics of the individuals in the NOA-L 2021 who volunteered to participate are described in Supplementary Material S2 (available online).

Feasibility Evaluation of Motus

The feasibility of Motus was evaluated under 5 main constructs: adherence, technical, social and practical acceptability, as well as time and financial cost implication associated with Motus usage. The results are presented in Table 3.

Adherence. On average, 98% of the participants adhered (used Motus as planned) to use Motus for 7 days. Of them, 96.6% did so without any help from the administrators. Of the 338 participants who attached the wearable, 26.7% flipped it inside out (with its internal side facing outward instead of inward as intended) and 1.5% flipped it upside down but ActiMotus automatically corrected this issue. We found that of those who wore the wearable and filled out the in-app diary for 7 days (n = 334), 9.9% filled out the diary incorrectly (eg, incomplete entry; refer to Crowley et al[9] to get a description of the content of the app-based diary). We rectified these errors manually.

Technical Acceptability. The average technical acceptability of the Motus was 95.8%. The main issues included 7.9% of participants experiencing wearable error (ie, wearable did not initialize or stopped in the middle of measurement) and 4.4% having in-app issues (eg, app bugs) (Table 3).

Data Quality. Of the 7 measured days, we expected to obtain at least 20 hours of daily measurements on at least 5 days. Thus, among the 365 participants who received the wearable and did not withdraw their participation after receiving it, we expected to obtain 1825 such days. However, we lost a total of 169 such days (9.2%) due to various issues indicated in Table 4. Of these lost days, 95.5% were attributed solely to wearable errors.

Social Acceptability. We measured social acceptability of Motus by evaluating the recruitment rate and whether participants found it satisfactory and acceptable to use. The average social acceptability of Motus was 76.8%. The main issue was the low recruitment rate of 6%. Otherwise, 91.2% participants reported that they were satisfied with the system, 97.6% were willing to participate again, and 93.6% were willing to recommend the system to their colleagues.

Table 2 The Issues With Motus Identified During the Stage 1 Feasibility Evaluation in the Occupational Health Surveillance on Adults, the Suggested Solutions by Stakeholders, the Implementation Plan, and the Results From the Stage 2 (n = 1050) Feasibility Evaluation of the Revised Version of the Motus in the Public Health Surveillance on Adults

Feasibility construct	Issue	Solution	Who suggested	Plan for implementation	Who implemented	Results from Stage 1 (Table 3)	Results from Stage 2
Adherence	Missing entries in the app diary	To get feedback at the end of the test (an incentive to participate), make it mandatory to indicate an end time for all entries in the diary	Researchers	Implement features in the app and release the update	Manufacturer	11.4% had missing entries in the app diary	100% of participants received the feedback and only 4 had a missing entry in the app diary
Technical acceptability	Wearables had technical errors	Manufacturers to implement a strict quality assurance program	Manufacturer	Appointing a dedicated person performing the quality assurance and quality management and optimizing the production of wearables	Manufacturer	8% of wearables had errors	No errors
	Could not finish the measurement in the app	Bug correction in the app	Manufacturer	Gather intelligence data on the causes of app bugs and iteratively revise, test, and correct the app	Manufacturer	4.4% had the issue in the app	No errors
Social acceptability	Low recruitment rate	Send reminders A better and more attractive offer in the invitation to use Motus and the invitation is sent with the main questionnaire for surveillance Provide monetary incentives	Researchers	One reminder via secure e-mail service and 3 reminders via postal service Questions about participating in the study were integrated into the main survey questionnaire The consented participants were informed about a lottery prize of 1000–3000 DKK for engaging in the study both in the invitation and in the information letter with wearables	Administrators from project team	6.2% consented	23% consented
Practical acceptability	Patch became loose over time	Improve the patch material and the instructions in the app for attaching the wearable correctly	Manufacturer	A new patch material (4076 SC Spunlace Extended Wear Nonwoven Tape) to be introduced. This new material has been clinically tested by the manufacturer (3M) for 2 wk of wear time without the wearable patch getting loose Revision of the visual and textual instructions provided in the app	Manufacturer and project team	9.6% had patch issues	<3% of participants complained about wearable patch issues
	Slow data upload via app	Improve the software for uploading data and decrease the sampling frequency of wearable	Manufacturer and project team	Data upload software update; decrease sampling frequency of wearable from 25 to 12.5 Hz; validation study to assess the accuracy of measuring movement behavior types at 12.5 Hz compared with 25 Hz	Manufacturer and project team	2.6% of participants complained about the slow data upload; reported average data upload time = 49 min/wk	No complaints about slow data upload
	Lost wearables	Better envelopes	Administrators	Use envelopes with bubble wrap and strong material	Project team	20% lost the wearables	25% lost the wearables

Abbreviation: DKK, Danish krone.

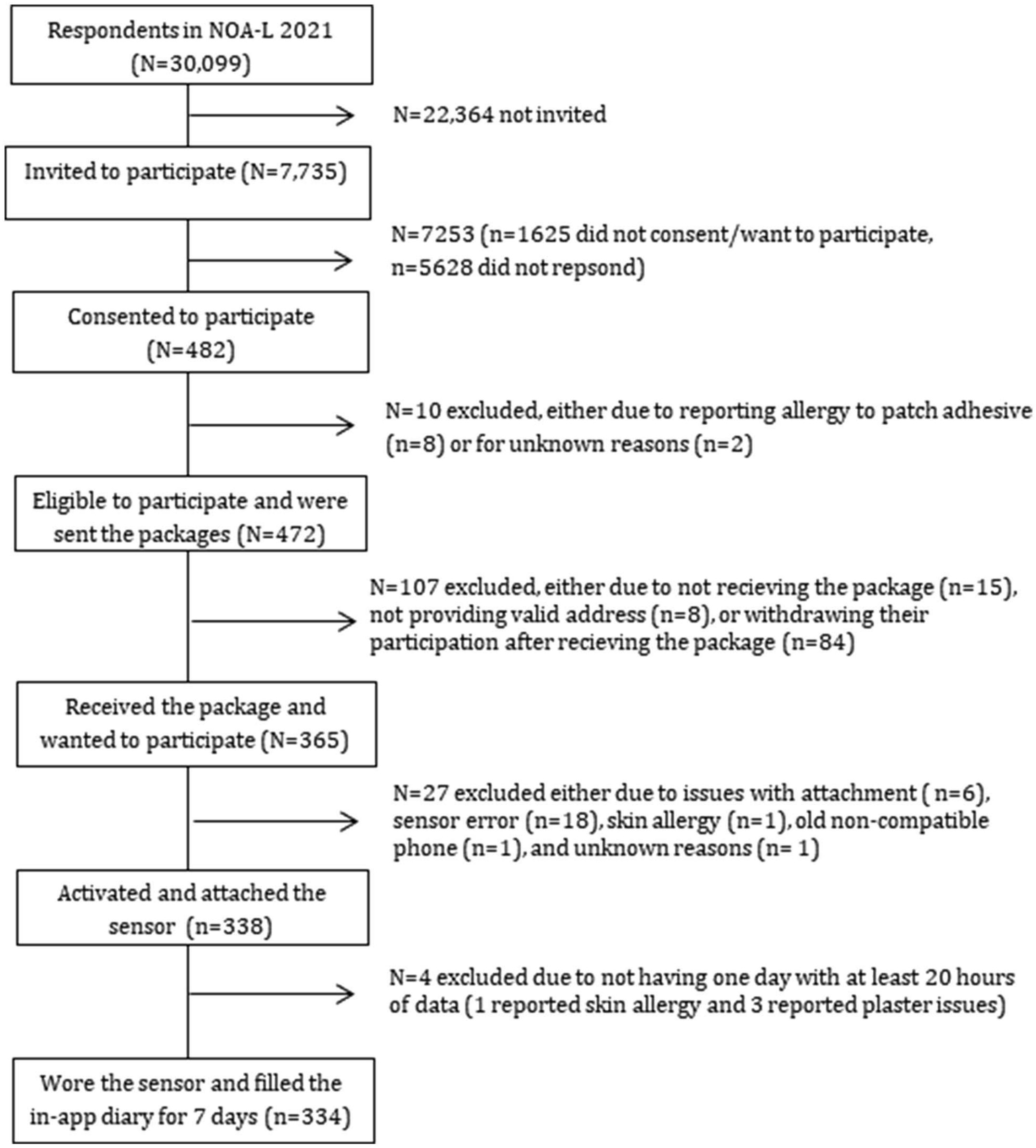

Figure 2 — Flow of participants in the feasibility evaluation of Motus among 30,099 respondents to the Danish National Surveillance of Work Environment of Employees (National Overvågning af Arbejdsmiljøet blandt Lønmodtagere [NOA-L]), 2021.

Practical Acceptability. We evaluated the indicators of the practical convenience of Motus usage in real life such as skin irritation during measurement, ease of use, and wearable loss during measurement. The average practical acceptability of the Motus was 94.8%. The main issue was the loss of 20% (n = 93) of the wearables. Specifically, 47 wearables were lost in the post (including those lost due to faulty envelopes [The envelope was received with a hole, likely caused by the paper becoming soft during transit, possibly due to humidity.]), 31 were lost due to participant errors (either misplacing the wearable or forgetting to return it), and 15 were lost due to unknown reasons.

Time and Financial Cost. Table 5 describes the time and financial cost of using Motus in the study. Participants reported spending an average of 73 minutes per week on Motus. This included 10 minutes spent on getting started on day 1 (eg, starting up with the Motus app and attaching the sensors), 14 minutes (2 min daily) on diary entry, and 49 minutes (7 min daily) on data upload. Administrators used a total of 15 minutes per participant (eg, for participant registration and reminders) during the measurement period. The total cost of using Motus in the study was 92.7 EUR/participant, including the cost of consumables such as purchase and usage of wearables, cloud services, and patches. Specifically, the participant time on Motus incurred a cost of 55 EUR/participant (Table 5).

Revision of Motus Based on the Stage 1 Feasibility Evaluation

At stage 1 feasibility evaluation of Motus in occupational health surveillance on adults, we identified the following issues: incomplete app diary entries, technical errors in the wearables, technical issues in the app, low recruitment rate, wearable patch becoming loose over time, slow data upload via the app, and loss of wearable that needed to be returned by the participants. Based on the

Table 3 Results of the Feasibility Evaluation of Motus Among Adults in the Danish National Surveillance of Work Environment of Employees Survey, 2021

Feasibility constructs and elements	Eligible	Actual	%
Adherence construct: Usage of the Motus and its protocol as intended			
Downloaded the app	365	364	99.7
Attached the wearable	364	338	92.9
Wore the wearable for 7 days	338	334	98.8
Made in-app diary entries for 7 days	338	334	98.8
Could upload the data via the app	334	334	100.0
Average adherence, %			98.0
Technical acceptability: Capability of a system to function without encountering technical failures			
No errors with wearables	365	336	92.1
Compatible smartphone	365	364	99.7
No app issues during test	364	348	95.6
Average technical acceptability, %			95.8
Social acceptability: Perception if the system is desirable, suitable, and acceptable by individuals			
Recruitment rate (consented)	7735	482	6.2
Satisfied	331	302	91.2
Willing to participate	332	324	97.6
Recommend a colleague	332	311	93.7
Confident participating	331	315	95.2
Average social acceptability, %			76.8
Practical acceptability: Practical convenience of system usage			
No skin irritation	342	331	96.8
Plaster intact	342	309	90.4
Easy to			
Follow instructions in app	331	314	94.9
Attach wearable	331	320	96.7
Make diary entry in the app	331	324	97.9
Detach wearable	331	324	97.9
Send wearable back	331	328	99.1
No data upload issues	343	334	97.4
Wearables received back	472	379	80.3
Wearables lost in postage		47	
Wearables lost by participants		31	
Wearable lost due to other reasons		15	
Average practical acceptability, %			94.8

discussions with stakeholders, we made a revision plan for addressing these issues which is described in Table 2.

Specifically, to minimize the loss of wearables, administrators suggested using high-quality envelopes since many wearables were lost in the post due to torn envelopes. To improve the recruitment rate, researchers suggested sending reminders and developing more attractive recruitment material. To reduce wearable error, the manufacturer suggested tightening their quality control process even further. For improving the data upload speed from the phone to the cloud, the manufacturer suggested updating their software to facilitate the upload process. Additionally, the manufacturer also suggested using a lower sampling frequency from 25 to 12.5 Hz since lowering the frequency decreases the volume of measured data, making data uploads relatively faster. Researchers supported the idea but recommended conducting a validation study of the ActiMotus to identify movement behavior types and postures accurately using 12.5 Hz compared with 25 Hz, and subsequently revising the ActiMotus accordingly.

All of these revisions were subsequently integrated into Motus before being evaluated in stage 2.

Stage 2: Feasibility Evaluation of Motus in Public Health Surveillance

A total of 10,196 responded to the questionnaire in the DNHS, 2023. Of them, 6993 individuals delivered a web-based DNHS-2023 response and were eligible for participation. They subsequently received more information about the Motus feasibility substudy and were invited to participate.

Of the 6993 individuals, 1617 (23.1%) consented to participate in evaluating the feasibility of Motus. Of them, 22 provided either wrong or incomplete postal details. Thus, wearables were sent via postal service to the remaining 1595 (98.6%) individuals and of them, 1050 (64.9%) received and attached the wearable (Figure 3). Of 1050 participants, 1036 completed the study with data for ≥3 days.

The findings from stage 2, evaluating the revised version of Motus in a public health surveillance of adults, are described in Table 2. We found that Motus improved on most identified issues from stage 1. The recruitment rate improved from 6% to 23% from stages 1 to 2, respectively. However, there was a difference between participants and nonparticipants with respect to their socioeconomic status and health status; compared with nonparticipants (n = 5945), participants in the stage 2 evaluation had higher educational attainment (24.2% vs 17.8%), were more frequently employed (60.6% vs 45.9%), more commonly met WHO physical activity recommendations (52.2% vs 44.7%), and slightly more often rated their health as excellent, very good, or good (82.1% vs 78.2%).

Participants complaining about the wearable patch decreased from 9.6% to <3%. Errors in the wearables, missing entries in the app diary, and app issues all decreased from 7.9%, 11.4%, and 4.4% to 0%, 0.3%, and 0%, respectively.

The wearable loss increased from 20% to 25%. Of the 1595 participants who were sent a wearable, 395 (25%) were not received back. Over 80% of these losses occurred among dropouts (either those who informed us of their intention to withdraw or those with whom we lost contact during the study).

Discussion

To address the challenges of compromised accuracy of questionnaire data and burdensome accelerometry methods employed in large-scale movement behavior measurements, we developed Motus using the latest wireless wearable technology.[9] The aim of this study was to test the feasibility of Motus in real-life surveillance settings in Denmark, employing a 2-stage evaluation. Specifically, in stage 1, we evaluated Motus in an occupational health surveillance setting, identified feasibility issues with Motus, made a revision plan to address these issues, and revised Motus accordingly. In stage 2, we evaluated the revised version of Motus in a public health surveillance setting to determine if the revised version of Motus improved on the issues identified in stage 1.

At stage 1, we observed high participant adherence and overall satisfaction with the Motus system. This indicated its ease of use and potential for large-scale data collection with a self-attachment

Table 4 Distribution of Participants (n = 365 Participants Who Received the Postal Package) by Number of Days With a Minimum of 20 Hours of Measurements per day and Reasons for Data Loss, Using Motus in the Danish National Surveillance of Work Environment of Employees, 2021

		Reasons for lost days					
N days ≥ 20 h data	N	Patch issue	Skin irritation	Attachment/instruction issues	Wearable error	Other technical issues	Unknown
0	29	0	1	7	19	1	1
1	1	0	0	0	1	0	0
2	4	2	1	0	1	0	0
3	2	1	0	0	1	0	0
4	4	0	0	0	4	0	0
≥5	325	0	0	1	3	0	0
Total	365	3	2	7	29	1	1

Abbreviation: n, number of participants. Note: Patch issue: Patch became loose and fell off; attachment/instruction issues: The attachment/instruction process was not executed correctly due to unclear instructions, resulting in a loose patch that fell off on the first day of the measurement.

Table 5 The Time and Financial Cost of Using Motus by the Administrators and Participants During the Feasibility Study in the Danish National Surveillance of Work Environment of Employees, 2021

Category	n	Total time used, h	Time used/ participant, h	EUR/ h	Total cost, EUR	Cost/participant, EUR
Participants						
Time used on starting up	323	53.8	0.2	45.2	2431.9	7.5
Time used to fill diary in app	324	75.6	0.2	45.2	3415.3	10.5
Time used by the app to upload data	324	264.6	0.8	45.2	11,953.4	36.9
Total		394.0	1.2		17,800.7	55.0
Administrators						
Packaging and setup	472	20.8	0.0	50.8	1058.3	2.2
Notifications and monitoring	472	34.0	0.1	50.8	1729.4	3.7
Analysis and feedback	472	47.5	0.1	50.8	2413.2	5.1
Participant interaction	472	10.6	0.0	50.8	540.4	1.1
Total		113.0	0.2		5741.3	12.2
Consumables						
Wearables purchased	287				19,288.7	
Wearables lost	101				6788.0	
Wearable usage costs[a]	186				4986.8	
Wearable cost available[a]					7513.9	
Back-end service	472				5054.0	
Patches	472				1586.1	
Alcohol swaps	472				87.1	
Extra plaster and stationery	472				232.7	
Paid posting envelope	472				751.8	
Paid return envelope	472				751.8	
Total					20,224.9	
Global total					43,766.9	92.7

Abbreviations: EUR, Euro; n, number of participants.

[a]In this study, we assumed that each wearable can be used at least 5 times before it reaches its operational life or is lost. Therefore, the 287 purchased wearables could be used 1435 times (287 × 5). We used the wearables 472 times and lost 101 wearables (101 × 5). Thus, the total usage or loss cost associated with the wearables is 11,774.8 EUR (4986.8 + 6788.0), resulting in an available cost of 7513 EUR for usage (19,288.7–11,774.8).

procedure of wearables and automatic data upload. Furthermore, administrators noted that it took little time (on average 15 min per participant) to gather high-quality data, including preparation of the postal package, participant support, data processing, analysis, and providing feedback on domain-specific physical activity. Most previous studies using wearable-based methods for surveillance do not detail time and burden measures, making the direct comparison challenging.[18] However, based on our experience with the

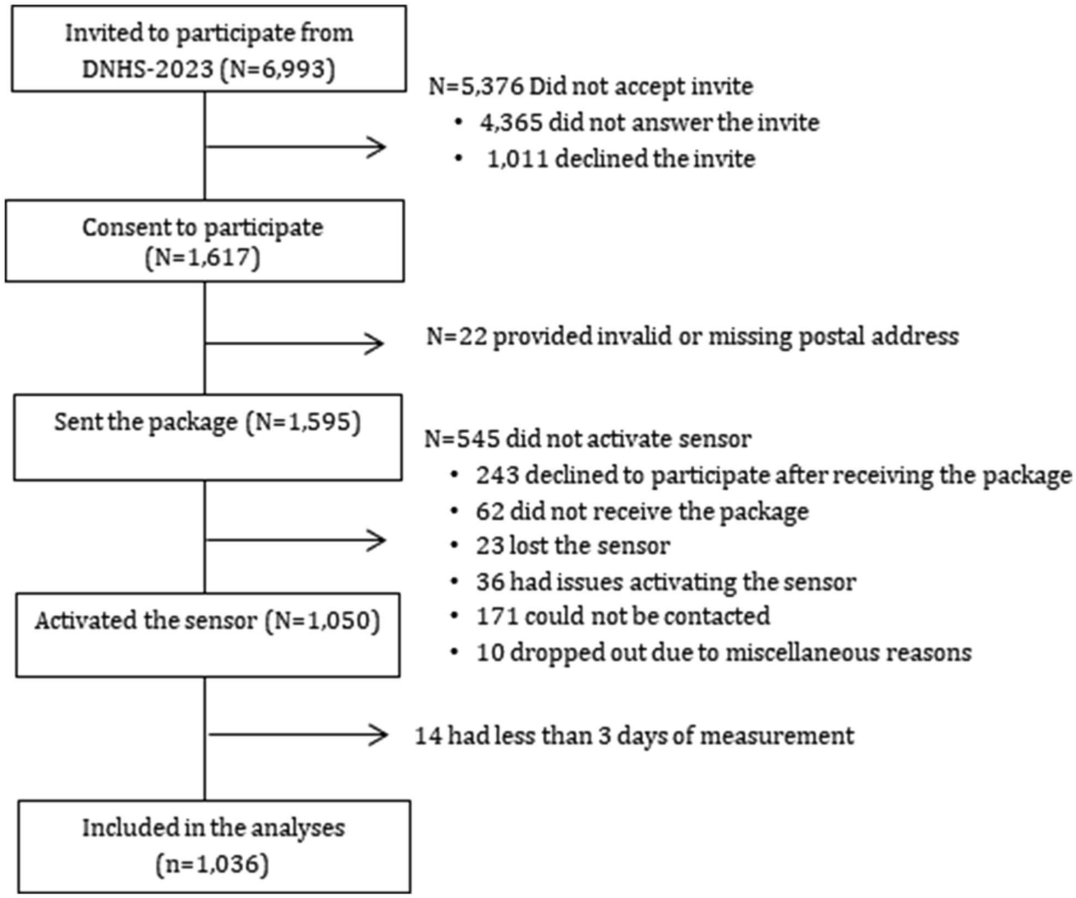

Figure 3 — Flow of participants in the feasibility evaluation of Motus among 6993 eligible individuals who responded to web-based DNHS-2023. DNHS-2023 indicates Danish Health and Morbidity Survey, 2023.

Acti4 method, which is widely used for collecting data on domain-specific physical activity, the burden on administrators using Motus appears to be relatively low.[19] These findings highlight the significant advantages of Motus over traditional wearable-based methods, reducing the need for administrative assistance. However, we did not directly compare the total time and financial cost associated with Acti4 or similar methods to Motus. This is an important area for future research to better understand the practical benefits of Motus compared with other methods.

Despite high satisfaction and adherence, and low administrative burden, there were significant challenges to the feasibility of using Motus for large-scale data collection, including a 20% loss of wearables. Although Motus regularly offloads data to the cloud, the loss of wearables imposes a significant financial burden. In stage 1, the wearable loss was primarily due to postage issues and poor-quality return envelopes, which often arrived damaged, likely due to humidity. The 20% loss rate is high compared with previous accelerometry-based methods,[20,21] which have reported losses up to approximately 13%.[22] The difference may be explained by the lack of in-person interaction in our study, which has been shown to improve recruitment and adherence,[22–24] and thus potentially wearable return. Future studies should assess cost-effective strategies to minimize wearable loss, considering the possible influence on recruitment, adherence, and the representativeness of the movement behaviors estimates. Another issue in our study was the high participant time usage, due to slow data upload. To facilitate the upload, participants had to keep the Motus app open contributing to the total time used by the participants. Solutions are needed to minimize loss of wearables in postage and speed up data upload before Motus can be recommended for large-scale use.

Another major issue was the low recruitment rate of 6%. There is no evidence of the consensus on an acceptable recruitment rate, but previous device-based surveillance studies have reported rates ranging from 18% to 98%.[18] Similarly, in device-based population studies, the average recruitment rate is around 71% (SD = 23.6%).[22] Our lower recruitment rate may be attributed to the intentional oversampling of participants in blue- or pink-collar occupations, which are typically more difficult to recruit. Additionally, the absence of reminders[25,26] and the lack of in-person interaction with participants may have contributed to the low recruitment rate. Previous studies have shown that individuals are more likely to accept the invite if there is face-to-face interaction compared with pure digital or remote interactions.[22,24] The prime reason reported by the nonconsenter was the lack of time to participate and the lack of clear value in using Motus. Future recruitment materials should clearly communicate the value of participating in such a study and the expected time required to use Motus. In general, Motus could be recommended for collecting large-scale data in cohort studies where a low recruitment rate is not a major issue.[27,28] However, before it can be recommended for surveillance of movement behaviors, we need to develop and evaluate various strategies to encounter a low recruitment rate.

In stage 1, we made a Motus revision plan to address the identified feasibility issues based on the stakeholders' feedback. The revised Motus improved on most issues. The recruitment rate improved from 6% in stage 1 to 23% in stage 2 likely due to sending reminders and using informative and attractive recruitment material. The recruitment rate of 23% aligns with that of previous studies utilizing comparable recruitment methods.[29] However, the nonparticipants were more likely to be men, from lower socioeconomic status, and had poorer health, likely leading to nonresponse bias in obtained estimates of movement behaviors using Motus. Thus, the revisions in the recruitment strategy at stage 2 remain insufficient for achieving representative data in the surveillance of movement behaviors. This issue of sample nonrepresentativeness in wearable-based surveillance is a well-known challenge in research, with few proposed solutions.[18] Researchers continue to call for further advancements before wearables can be effectively used for surveillance of movement behaviors.[18]

In stage 2, complaints about slow data upload via participant phone to the cloud reduced from 3% in stage 1 to 0% in stage 2. In stage 2, we did not collect data on the reported time used by the participants. Nevertheless, we anticipate that the time required for uploading the data from phone to the cloud would have reduced significantly with the revisions. Reducing the sampling frequency speeds up the data upload, reducing the participant burden of Motus. However, this may affect the accuracy of identifying movement behaviors.[30,31] Thus, an ongoing validation study is investigating the overall accuracy of Motus in identifying movement behaviors and whether the reduction in sampling frequency influences the results.

We addressed the issue of wearable loss by using high-quality envelopes, and thus at stage 2, we did not receive any damaged envelopes. However, the rate of wearable loss actually increased from 20% to 25% from stages 1 to 2. In stage 2, most wearable loss was observed among those who consented and thus received the wearable, but ended up dropping out and not returning the wearable (the dropouts; n = 322). In the future, a more rigorous screening procedure might be required before sending the wearables to minimize the risk of wearable loss among dropouts. Additionally, discussions with participants, researchers, surveillance authorities, and social partners are needed to develop and evaluate strategies for minimizing wearable loss, especially among dropouts.

Practical Implications of the Study

Motus uses wireless wearable and cloud technology that has the potential to enable large-scale measurements of movement behavior while minimizing some burden on participants (eg, physical meeting to attach the wearable) and administrators (eg, manual data processing). By making iterative improvements, Motus could be a promising alternative for cohort studies in occupational and public health in countries with high penetration of smartphones and iOS/Android platforms. However, in regions with low penetration of smartphones, we should explore ways to make Motus more feasible. For example, Motus could be further developed so a single phone could act as a central hub, connecting multiple wearables and allowing shared access for those without a smartphone. Additionally, developing the Motus app for alternative platforms could ensure accessibility in regions where iOS or Android usage is limited. If the issues of low and nonrepresentative recruitment and sensor loss could be addressed, Motus could improve movement behavior surveillance by providing accurate data at a large scale for evidence-based decision-making and tailored interventions.

Strengths and Limitations

Utilization of a 2-stage development and evaluation design enables iterative development and improvements based on participant feedback, enhancing Motus' robustness and relevance. Furthermore, the assessment of feasibility across multiple constructs provides a thorough understanding of Motus' feasibility. One limitation was the low participation rate in the study, although our sample had a balanced representation of various job groups, sex, and age. Another limitation was the absence of sending reminders to participate. We also did not verify the accuracy of self-reported app diary entries on domain times which should be performed in the future. However, previous studies have demonstrated that such self-reports are sufficiently valid for capturing domain-specific physical behaviors, such as sleep.[32,33]

Future Development of Motus

Motus already addresses many weaknesses of previous questionnaire- and wearable-based methods. However, several limitations of Motus need to be addressed. Motus currently uses self-reports to obtain information on the time spent on various domains of the day. In the future, Motus should strive to predict domain start and end times using more objective data. For instance, Motus currently does not identify sleep but time in bed. Thus, in the future, Motus should include a robust algorithm for identifying sleep time as well. As a cloud-based system, Motus may face concerns from new administrators regarding General Data Protection Regulations (GDPR) compliance, even if Motus adheres to the GDPR. Clear communication regarding the handling of data following GDPR is crucial for the scalability of Motus. Motus currently uses many manual or semimanual features such as sending notifications. In future studies, Motus should be developed to make these features as automated as possible to minimize the burden. To further reduce the burden on participants, Motus will aim to implement automatic data upload functionality that operates in the background, thus not requiring the participants to keep the app open for the data upload.

Conclusion

Motus demonstrates promising feasibility for large-scale 24-hour movement behavior measurements. However, developing and evaluating strategies to improve recruitment rate and sensor loss is necessary before recommending Motus for movement behavior surveillance.

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