**STUDY PROTOCOL**

Feasibility, acceptability and validation of wearable devices for climate change and health research in the low-resource contexts of Burkina Faso and Kenya: Study protocol

Sandra Barteit1,*, Valentin Boudo2, Aristide Ouedraogo2, Pascal Zabré3, Lucienne Ouremi2, Ali Sié2, Stephen Munga3, David Obor3, Daniel Kwaro3, Sophie Huhn1, Aditi Bunker1, Rainer Sauerborn1, Hanns-Christian Gunga4, Martina A. Maggioni5,6‡, Till Bärnighausen1,6,7‡

1 Heidelberg Institute of Global Health, Heidelberg University Hospital, Heidelberg University, Heidelberg, Germany, 2 Centre de Recherche en Santé, Nouna, Burkina Faso, 3 Kenya Medical Research Institute, Kisumu, Kenya, 4 Institute of Physiology, Center for Space Medicine and extreme Environment Berlin, Charité – Universitätsmedizin Berlin, Corporate Member of Freie Universität Berlin, Humboldt-Universität zu Berlin, and Berlin Institute of Health, Berlin, Germany, 5 Department of Biomedical Sciences for health, Università degli Studi di Milano, Milan, Italy, 6 Department of Global Health and Population, Harvard T.MLP. Chan School of Public Health, Boston, Massachusetts, United States of America, 7 Africa Health Research Institute (AHRI), Durban, KwaZulu-Natal, South Africa

‡ These authors are joint senior authors on this work

* barteit@uni-heidelberg.de

**Abstract**

As the epidemiological transition progresses throughout sub-Saharan Africa, life lived with diseases is an increasingly important part of a population’s burden of disease. The burden of disease of climate-sensitive health outcomes is projected to increase considerably within the next decades. Objectively measured, reliable population health data is still limited and is primarily based on perceived illness from recall. Technological advances like non-invasive, consumer-grade wearable devices may play a vital role in alleviating this data gap and in obtaining insights on the disease burden in vulnerable populations, such as heat stress on human cardiovascular response. The overall goal of this study is to investigate whether consumer-grade wearable devices are an acceptable, feasible and valid means to generate data on the individual level in low-resource contexts. Three hundred individuals are recruited from the two study locations in the Nouna health and demographic surveillance system (HDSS), Burkina Faso, and the Siaya HDSS, Kenya. Participants complete a structured questionnaire that comprises question items on acceptability and feasibility under the supervision of trained data collectors. Validity will be evaluated by comparing consumer-grade wearable devices to research-grade devices. Furthermore, we will collect demographic data as well as the data generated by wearable devices. This study will provide insights into the usage of consumer-grade wearable devices to measure individual vital signs in low-resource contexts, such as Burkina Faso and Kenya. Vital signs comprising activity (steps), sleep (duration, quality) and heart rate (hr) are important measures to gain insights on individual behavior and activity patterns in low-resource contexts. These vital signs may be

**Citation:** Barteit S, Boudo V, Ouedraogo A, Zabré P, Ouremi L, Sié A, et al. (2021) Feasibility, acceptability and validation of wearable devices for climate change and health research in the low-resource contexts of Burkina Faso and Kenya: Study protocol. PLoS ONE 16(9): e0257170. https://doi.org/10.1371/journal.pone.0257170

**Editor:** Manuela Cabiati, Institute of Clinical Physiology (IFC), National Research Council of Pisa (Italy), ITALY

**Received:** June 2, 2021

**Accepted:** August 23, 2021

**Published:** September 30, 2021

**Peer Review History:** PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0257170

**Copyright:** © 2021 Barteit et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**Funding:** We wish to thank the German Research Foundation (DFG) for supporting this study as part...
of the FOR “Climate Change and Health in sub-Saharan Africa”. The German Research Foundation (DFG) is supporting this study, but has not been involved in study design, collection, management, analysis or interpretation of data, neither in the writing of this report or in any decision to submit this report for publication (see S2 for informed consent forms). The study has been approved by DFG (FOR 2936 / project: 427397328).

Competing interests: The authors have declared that no competing interests exist.

Abbreviations: API, Application Programming Interface; CRSN, Centre de Recherche en Santé de Nouna; HDSS, health and demographic surveillance system; hr, heart rate; INDEPTH, International Network for the Demographic Evaluation of Populations and Their Health; KEMRI, Kenya Medical Research Institute; LMIC, low- and middle-income country; MEMS, micro electrical mechanical system; PPG, photoplethysmog.
Notably, self-reported research has generated many insights, including the HDSS, verbal autopsy amongst others, which proved to be an effective way of filling data gaps [1, 18].

Technological advances, such as non-invasive, consumer-grade wearable devices and their application in population-based studies [19–21], present an opportunity to gain insights on the individual level. Wearable devices track vital signs in the study participants’ environment, the so called ecological momentary assessment [22], and allow insights into hr and general activity, oftentimes providing further insights like sleep activity, body temperature, global positioning system (GPS) and electrocardiography (ECG) data [22, 23]. In most cases, consumer-grade wearables provide a software landscape with application programming interfaces (APIs) that can be used right out of the box, without having to invest into software development. Furthermore, many consumer-grade wearables employ direct data transmission via mobile data networks to a central, local server, allowing data to be accessed instantly or in real time. The use of wearable devices for research is increasing, particularly as more accessible and affordable options become available [24], and rates of clinical approval of respective regulatory bodies rise [25, 26].

Studies have shown the potential of such consumer-grade wearable devices for population-health contexts [27]. For example, Culp and Tonelli et al. (2019) conducted a study on heat stress exposure using wearable devices. Their research focused on agricultural workers’ physiological responses during agricultural work and linked them to working intensity and climate conditions (measured by the WBGT) [28]. The authors discovered considerably higher body temperatures, increased hr, and respiration rate in the uncomfortable intensity category. Lam et al. (2021) explored the association between short-term physiological and psychological thermal adaptation and outdoor thermal comfort in people who exercised in different temperature zones in China and found that addressing thermal discomfort early on can help prevent more serious heat-related disorders [29]. First studies employing wearable sensor in the field started approximately two decades ago in the military area [30–34]. However, most studies were conducted in high-income settings, like the US and Europe [19, 25, 35]. Consumer-grade wearable devices may provide a novel method to generate objective, highly-resolved individual data monitoring physiological parameters, such as hr, physical activity and sleep duration. This data may facilitate further research to consider aspects of climate change-induced extreme weather events on health outcomes in populations in low-resource contexts [36–38].

**Study goals and objectives**

The overall objective of this study is to elucidate whether consumer-grade wearable devices are an acceptable and feasible means to generate data in low-resource contexts. Furthermore, we evaluate the validity of consumer-grade wearable devices in comparison to gold standard wearable devices. We will conduct studies in two HDSS sites in low-resource contexts: (i) in the Nouna HDSS managed by the Centre de Recherche en Santé (CRSN) and (ii) the Siaya HDSS managed by the Kenya Medical Research Institute (KEMRI). The study is conducted in the two African countries of Burkina Faso and Kenya, as both countries are located in SSA and have one of the highest burdens of climate-sensitive diseases, but differ in their climatic, socio-economic and disease profile [2, 39–41].

The specific research questions are:

1. are consumer-grade wearables a feasible and acceptable means to generate vital sign measurements in a rural population in low-resource contexts of Burkina Faso and Kenya?
2. is it feasible (a) to generate insights on individual behavior with a recall activity journal and (b) to identify pre-defined activities based on this data?
3. when compared to gold-standard sensors, can consumer-grade wearables produce valid measurements in rural Burkina Faso and Kenya?

We will investigate the feasibility and acceptability with a Likert-scaled questionnaire that covers also demographic items: 13 items addressing feasibility with a strong focus on hardware reliability (i.e., are the devices functioning well in the sub-Saharan climatic conditions), and 29 items addressing acceptance (see S1 File for the questionnaire). If the wearable devices fail or we have data outages, we shall keep track of them in order to gain a quantitative overview of the types of failures and sources of data disruptions.

The validity of wearable devices is compared to gold sensor devices, further described in the section Validation study. The wearable devices are described in the section Study technology.

As part of this study, we have installed ten fully automated weather stations with the same configuration in the Nouna HDSS (5x) and in the Siaya HDSS (5x) that spatially cover the whole HDSS area. As a follow-up study to this feasibility, acceptability and validation study, it is planned to generate wearable measurements in a one-year study to account for seasonality and investigate whether weather (mainly based on WBGT) has an effect on individual behavior and health (climate-sensitive diseases, as available within the Nouna and Siaya HDSS). The local weather stations that have been setup as part of this research unit cover the continuous measurements of precipitation, wind speed, wind direction, radiation, temperature, and humidity, as well as WBGT. Seasonality has no bearing on the feasibility, acceptability, or validation of the wearable measurement in this study, hence it is not taken into consideration.

This study protocol is reported according to the World Health Organization recommended format for a ‘research protocol’ [42].

Materials and methods

Study design

Feasibility and acceptability study. The study will take place in two countries, respectively in the Nouna HDSS (n = 150) and in the Siaya HDSS (n = 150) with a total of n = 300 study participants using consumer-grade wearable devices (see section Study participants and sample size for sample size calculation, inclusion and exclusion criteria). Study participants will be interviewed three times during the study cycle (see S1 for questionnaire, see Fig 1 for details to study cycle), once each week.

A trained nurse or field worker will conduct face-to-face interviews with study participants using tablet-based questionnaires, which comprises four parts:

1. personal information of study participants (6 items): study ID, village name, gender, date of birth, weight, height
2. distribution and management by the field workers of wearable devices (13 items per wearable device): device returned or handed out (date), details of device (ID, wearable type), disinfection of wearable device, system registration of study participant, reporting of device damages, reported acceptance of study participant
3. acceptance (29 Likert-scaled items): perceived ease of use, self-efficacy, perceived enjoyment, anxiety, experience (variables based on Technology Acceptance Model [43])
4. activity journal (structured activity list, reflecting 21 most common local activities): study participants report retrospectively to the field worker or study nurse their activities the day prior to the questionnaire, respectively to the time frames: after getting up in the morning, during the morning, midday, afternoon, evening, night
The wearable outcomes of the study comprise: hr, sleep duration, activity (steps per day) and body shell temperature. Further quantitative components include: (i) the wearable device data, (ii) comparison data between the wearable devices and gold standard wearable devices (see section Study Technology for details).

Data collection will take place over a nine-week period which comprises three study cycles, where each cycle lasts three weeks comprising n = 50 study participants per study site (see section Study participants and sample size for sample size calculation). We obtained only a limited number of wearable devices (n = 50 Withings Pulse HR; n = 25 Tucky thermometer), as we were uncertain of the study outcome and did not want to exhaust financial resources. We will request study participants to give their consent before study participation and will exclude them otherwise. The details of the study cycles will be as following (see Fig 1 for details):

1. At first, the study nurse (study arm 1) or field worker (study arm 2 and 3) hands out the disinfected wearable devices to the study participants, based on their allocation to the respective study arm, study participants will receive (a) only the Withings Pulse HR, or (b) the Withings Pulse HR and Tucky thermometer. To decrease the likelihood to transmit infectious diseases like the Coronavirus disease (Covid-19), each study nurse and community field worker is equipped with a hygiene package comprising face masks, disinfectant spray, clean wipes and hand disinfectant. The wearable devices are first rinsed with water, then sprayed with disinfectant, and wiped clean. A protocol that details this process will be handed out to each study nurse and field worker. The wearable devices will be registered to the respective study participant.
2. Study participants will be trained on critical aspects about wearing and using the wearable device, such as battery charging, as well as receive a comprehensive introduction of the study’s procedures.

3. Every 7 days, we will collect data from study participants. Based on their study arm allocation, participants will be visited by the study nurse (study arm 1), by the field worker (study arm 2), or will be visited by the field worker at home (study arm 3). In study arm 1 and study arm 2, we will administer an acceptance questionnaire, collect HR, activity and sleep quality via the Withings Pulse HR and body shell temperature with the Tucky wearable device, whereby wearable data is synchronized with a tablet, and recharge the wearable device. Furthermore, the study nurse or the field worker (respective to their study arm) will fill out a structured activity journal in which the study participant will be asked about their activities (structured list) from the previous day (from the time they got up from bed to going back to sleep at night). In study arm 3, we will train participants to synchronize both the Withings Pulse HR and Tucky wearable devices themselves with a smartphone, and recharge the battery of the wearable devices using a foldable, portable solar panel with a USB-port which are provided to study participants as part of the study.

4. On day 21, the study participant will return the wearable device to the study nurse or field worker, who will then disinfect and deregister the wearable device. The study nurse or field worker will then assign the wearable device to the next research cycle’s study participant.

The questionnaire will be hosted on our local research server using SurveySolutions software, a data collection and management tool (https://mysurvey.solutions/en/).

Validation study. We will compare the consumer-grade to the gold-standard wearables during the last study cycle (week 6 to week 9). The validation study is divided into two runs of two weeks each. Per location, we will select a sub-sample of study participants of n = 20 (n = 10 females, n = 10 males), spanning over all study arms. During each run, study participants will wear both consumer-grade and validated gold standard wearables (see section Study Technology for details), which are detailed in full below:

1. For two weeks:
   - 24/7: (i) wearable Withings Pulse HR (consumer-grade), (ii) high-resolution wrist accelerometer (GENEActiv Original watch, ActiveInsights, UK, resolution up to 100Hz, which is a raw data actigraphy data logger that records a digitally integrated measure of gross motor activity as well as sleep schedule variability, sleep quantity, and sleep quality statistics and daytime), (iii) actigraphy-based data logger
   - during nights only (as device may not remain on the body during daytime activities): wearable thermometer Tucky (consumer-grade)

2. For 24 hours (starting after day 12 of GENEActiv wearing)
   - a wearable one-lead electrocardiography (ECG) device (Bittium Faros, Finland, sample rate 250 Hz)
   - a validated heat-flux sensor (Tcore, Dräger, Germany), connected to a miniaturized data logger (HFUM, KORA Industrie Elektronik, Germany) [44–48], both integrated in a custom-made headband, to be worn comfortably.

Specifically, data collected with Bittium faros ECG will serve as a reference for the HR measurements done with the Withings HR data. We will compare the raw data collected with the wrist accelerometer GENEActiv with the Withings Pulse HR data (hear rate, activity data), and
furthermore we will compare data collected with the Tcore sensor (core body temperature) with the Tucky thermometer data (shell body temperature).

Study participants and sample size

Feasibility and acceptability study. We will sample a total of n = 300 study participants for the feasibility and acceptability study (Nouna HDSS n = 150; Siaya HDSS n = 150). The sampling will be randomly drawn from the respective HDSS population, whereby the study population is stratified according to age (three groups: 6-16yrs, 17-45yrs, >45yrs) and gender (n = 150 females, n = 150 males).

Study participants are eligible for the study if individuals: (i) are residents within the Nouna and Siaya HDSS, (ii) are 6 years of age or above (as wristband size of the Withings Pulse HR is not deemed adequate for children younger than 6 years), (iii) are willing to use a Bluetooth or mobile data-enabled mobile device for research. After identification, the local study teams in the Nouna and Siaya HDSS will approach study participants face-to-face. In case an identified study participant will not want to participate in the study, we will draw a sample of n = 170 per HDSS, to have alternate study participants at hand.

Sample size calculation (survey/questionnaire) to comprise n = 150 study participants/HDSS was calculated based on a population size of n = 100,000 (total HDSS population excluding children under the age of 6 years), a confidence level of 95% and a margin of error of 8%.

For generating insights with the wearables devices data, we deemed n = 150 as sufficient, as reported in the literature [49].

For data collection, we will recruit a total of five interviewers, including two health workers and three field workers. All the interviewers will have strong expertise in electronic data collection and will be overseen by a statistician and a computer scientist with extensive experience in managing the HDSS.

Validation study. For the validation study, considering as a first main outcome HR, a sample size of n = 20 participants is deemed sufficient, as reported in the literature [50–52]. Here, we selected a total of n = 20 men and n = 20 women, considering both the HDSS in Nouna and Siaya (n = 10 females, n = 10 males per HDSS).

People will be eligible for the validation study if: 18–45 years of age, living and working in the area surrounding a health care facility (in walking distance), absence of any medical condition that would interfere with the data collection, such as for example cardiovascular or metabolic diseases (hypertension, diabetes mellitus, overweight or obesity), renal diseases as well as absence of acute malaria infection or other infectious diseases (such as HIV, tuberculosis, streptococcus, human papillomavirus, viral hepatitis and parasitic diseases).

Field workers and local study managers in Burkina Faso and Kenya will inform study participants about research details and proceedings. Only if study participants agree to participate in the study, they sign an informed consent form. There will be no personal relations between the field workers and study managers. However, some may be familiar with some study participants from prior studies. The respective HDSS will recruit field staff and interviewers. The study participants are reimbursed for their time commitment in the study and the type and scope are subject to local HDSS guidelines.

Study technology

Consumer-grade wearable devices. For this study, we will use the data collection platforms provided through the wearable devices’ manufacturers. A number of variables will be collected from each study participant throughout the study period, comprising the following:
Gold-standard wearable devices. According to the three main outcomes: hr, physical activity and core body temperature (CBT), we identified gold-standard wearable devices who will provide a reference measurement which we will compare with the consumer-grade wearable devices. For precisely measuring hr, we will continuously collect 24 hour one-lead ECG (sample rate 250 Hz), accounting for ectopic beats and arrhythmic events. We will continuously monitor activity with a validated wrist-worn tri-axial accelerometer (resolution up to 100Hz) device (GENEActiv Original, ActiveInsights, UK). The accelerometers are small, rugged, waterproof, actigraphy-based data loggers that record a digitally integrated measure of gross motor activity, as well as sleep schedule variability, sleep quantity, and sleep quality statistics and daytime [54–58]. In addition, the systems are equipped with luminous flux recording, to distinguish between time spent outdoors and indoors, and near body temperature sensor, to define precisely wearing time.

CBT will be continuously recorded for 24 hours by placing a non-invasive technology on the forehead. The double heat-flux sensor technology has been successfully tested during hypothermia, bedrest, and exercise on Earth and in space [44–48]. Based on this technology, for this study, we implement the Tcore™ sensor (Dräger, Lübeck Germany), a recently developed a new disposable, soft sensor which perfectly adapts to the forehead shape, in order to improve comfort and wearability. Briefly, the Tcore™ employs a non-invasive technology where a unique dual-sensor heat flux system accurately and continuously calculates CBT following a short ramp-up time. This single-use sensor is connected via cable to a miniaturized data logger (KORA Industrie Elektronik, Hambühren, Germany), that can be comfortably
worn with custom-made headband, which integrates both sensor and data logger (see Table 2 for overview of gold standard wearable devices).

### Setting

The Nouna HDSS, Burkina Faso [59], and the Siaya HDSS, Kenya [40], provide access to comprehensive, retrospective health and population data comprising of nearly 20 years of data and more than 260,000 people under surveillance. The surveillance area of the Nouna HDSS is characterized by a tropical climate with one rainy season usually lasting from May to September (mean annual rainfall of 800mm) and overall high temperatures throughout the year. Malnutrition and malaria are both common in the Nouna HDSS. In the surveillance area of the Siaya HDSS, the climate is tropical with two annual rain seasons, with the heaviest long rains usually occurring from March through May and short rains falling between October and December (mean annual rainfall of 1200mm).

We will conduct the study in two HDSS, as the two study sites are quite different in their climatic, socioeconomic and disease profile. Due to this unbalanced distribution of diseases, as well as different available levels of adaptation and mitigation measures, population impacts of climate change on health are likely to vary considerably between and within these countries.

### Analysis methods

**Feasibility of using wearable devices for populations in low-resource contexts.** We will use a deductive thematic analysis approach to analyze the feasibility questionnaire, grouping data into pre-defined categories and expanding categories if additional themes arise from the data, mainly from the free text fields of the questionnaire. To investigate disruptions in the wearable data generation, we will link the questionnaire data with the collected records of wearable device disfunctions and data interruptions.

**Feasibility to generate insights on individual behavior.** As a first explorative approach, we will extract activity patterns as collected with the wearable devices and correlate them to self-reported activity, that we will collect with the retrospective recall diary (for each study participant we will have three full days of reported activates). This is a first exploration to
investigate the feasibility of classifying common local activities like harvesting, fetching water and so on, using time-domain plots of wearable device data, as reported in other research [60].

Furthermore, we will investigate correlations of weather events on hr, activity, sleep, and body shell temperature. We will run a multiple linear regression with hr, activity, sleep, and body shell temperature as dependent variables and WBGT, precipitation, air temperature, relative humidity, solar radiation, and wind speed as independent variables. The weather data will be taken from the ten local weather stations that spatially cover both HDSS areas in the Nouna HDSS and Siaya HDSS.

Acceptance. The analysis of the acceptance questionnaire (based on 5-point Likert-scale, questions will be asked for level of agreement from strongly agree to strongly disagree) is conducted with a parametric analysis of variance (ANOVA) to compare means of the three study arms (see Fig 2 for details). The questionnaire items are grouped according to the employed Technology Acceptance Model constructs [43].

Baseline data will be reported for all three arms and summarized as mean (standard deviation, SD) or median (first quartile, third quartile) for continuous variables and as count and number (percentage) for categorical variables. Furthermore, we will calculate hourly, daily, and weekly means (SD) of hr, activity and sleep measures, as well as body shell temperature. Demographic data is descriptively analyzed in R with graphs for visualization (version 4.0.3; The R Foundation for Statistical Computing, Vienna, Austria). Collected data on the Withings’ Health Mate platform (variables: hr, steps, sleep of the Withings Pulse HR; weight, height), and on the Tucky E-Takescare platform (shell body temperature) will be exported, and then cleaned and analyzed with the statistical software R. The data (hr, activity, sleep, if available: body shell temperature) between the Nouna and the Siaya HDSS will be compared via ANOVA.
Validation. As for the validation study, we will assess the agreement between different methods—the difference between outcome values from consumer-grade devices and the respective values measured with gold-standard devices—following the Bland-Altman-plot [61] and the Lin Concordance correlation coefficient [62].

Ethics and consent
The study protocol was approved by the Kenya Medical Research Institute (approval date: 11th March, 2020; KEMRI/SERU/CGHR/327/3962), the Comité d'éthique pour la recherche en sante in Burkina Faso (approval date: 13th March, 2020; 2020-3-041), the ethical committee of the University Hospital Heidelberg (approval date: 6th May 2019; S-294/2019), Germany and the ethical commission of Charité, Berlin, Germany (approval date: 11th March 2019; EA1/060/19).

Expected outcomes of the study and discussion
Our study will evaluate the feasibility, acceptability and validity of consumer-grade wearables in the low-resource context of Burkina Faso and Kenya. We will generate critical insights on whether consumer-grade wearables that measure hr, activity (steps/day), sleep duration and body shell temperature can be used to generate valid and reliable data on an individual level in low-resource context. Wearable devices can be deemed unreliable, in particular when human activity impedes measurement [63]. A study has found that substantial differences exist between various devices and various activities, at times showing significantly high average error as compared to measured resting periods [64]. Wearables accuracy at rest and during physical activity differ, and we will generate insights by comparing consumer and research-grade wearables in this context. To understand the acceptability, feasibility and validity of wearable devices is vital and their ability to produce reliable data. In particular, objectively measured health outcomes continue to be limited due to a lack of appropriate measurement devices, manpower, and financial resources resulting in a scarcity of longitudinal data. We will also investigate whether wearables are reliable devices in these almost extreme environments of SSA, as well as whether they can provide insights into individual behavior and patterns in terms of activity, hr, body shell temperature and sleep, as these are the primary variables recorded by the wearable devices that we will employ in this study.

Furthermore, we will share our shortcomings and benefits for using wearable devices for research in low-resource contexts. We will detail participants' acceptance of wearable devices, and highlight the strategies for extracting data and managing wearable devices to ensure sustained use of devices. Currently, there is a paucity of research on the usability of wearable devices in low-resource contexts.

Conclusion
Our study will contribute to the general scientific body of knowledge for using consumer-grade wearable devices to measure individual vital signs in a low-resource research context. Particularly, our anticipated objective is to employ these consumer-grade wearable devices for climate change and health research, understanding, for example, the impacts of weather events such as heat and work productivity. Low-resource countries such as Burkina Faso and Kenya are predicted to be most vulnerable to climate change, as the burden of disease of climate-sensitive health outcomes is projected to increase considerably within the next decades [7]. Therefore, consumer-grade wearables may constitute a novel way to explore critical relationships between weather events and health outcomes. Furthermore, our research may be able to bridge the gap in the current lack of evidence since oftentimes research infrastructures
supporting health research in SSA, especially in health and demographic surveillance systems (HDSSs), are not equipped to investigate many of the most pressing climate change and health research needs [65].

**Supporting information**

S1 File. Feasibility and acceptability questionnaires, and retrospective activity diary. (PDF)

S2 File. Informed consent forms. (PDF)

**Author Contributions**

**Conceptualization:** Sandra Barteit, Valentin Boudo, David Obor, Rainer Sauerborn, Martina A. Maggioni, Till Bärnighausen.

**Formal analysis:** Sophie Huhn, Martina A. Maggioni.

**Funding acquisition:** Sandra Barteit, Ali Sié, Stephen Munga, Aditi Bunker, Rainer Sauerborn, Till Bärnighausen.

**Investigation:** Sandra Barteit, Valentin Boudo, David Obor, Martina A. Maggioni.

**Methodology:** Sandra Barteit, Aditi Bunker, Rainer Sauerborn, Hanns-Christian Gunga, Martina A. Maggioni, Till Bärnighausen.

**Project administration:** Sandra Barteit, Valentin Boudo, Aristide Ouedraogo, Pascal Zabré, Ali Sié, Stephen Munga, David Obor, Daniel Kwaro.

**Resources:** Sandra Barteit, David Obor, Daniel Kwaro, Till Bärnighausen.

**Supervision:** Sandra Barteit, Lucienne Ouremi, Ali Sié, Stephen Munga, David Obor, Rainer Sauerborn, Till Bärnighausen.

**Validation:** Sandra Barteit, Martina A. Maggioni.

**Writing – original draft:** Sandra Barteit, Martina A. Maggioni.

**Writing – review & editing:** Sandra Barteit, Valentin Boudo, Aristide Ouedraogo, Pascal Zabré, Lucienne Ouremi, Stephen Munga, David Obor, Daniel Kwaro, Sophie Huhn, Aditi Bunker, Rainer Sauerborn, Hanns-Christian Gunga, Martina A. Maggioni, Till Bärnighausen.

**References**

1. Sankoh O, Byass P. The INDEPTH Network: filling vital gaps in global epidemiology. Int J Epidemiol. 2012; 41: 579–588. https://doi.org/10.1093/ije/dys081 PMID: 22798690

2. Sié A, Louis ValérieR, Gbangou A, Müller O, Niamba L, Stieglbauer G, et al. The Health and Demographic Surveillance System (HDSS) in Nouna, Burkina Faso, 1993–2007. Glob Health Action. 2010; 3: 5284. https://doi.org/10.3402/gha.v3i0.5284 PMID: 20847837

3. Byass P, de Savigny D, Lopez AD. Essential evidence for guiding health system priorities and policies: anticipating epidemiological transition in Africa. Glob Health Action. 2014; 7: 23359. https://doi.org/10.3402/gha.v7.23359 PMID: 24848653

4. Lemma S, Janson A, Persson L-Å, Wickremasinghe D, Källestål C. Improving quality and use of routine health information system data in low- and middle-income countries: A scoping review. PLOS ONE. 2020; 15: e0239683. https://doi.org/10.1371/journal.pone.0239683 PMID: 35031406

5. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. Nature. 2005; 438: 310–317. https://doi.org/10.1038/nature04186 PMID: 16292302
6. Wang LK Shireen Bandyopadhyay Sushenjit. The Health Impact Of Extreme Weather Events In Sub-Saharan Africa. The World Bank; 2009. https://doi.org/10.1596/1813-9450-4979

7. Serdeczny O, Adams S, Baarsch F, Cournou D, Robinson A, Hare W, et al. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Reg Environ Change. 2017; 17: 1585–1600. https://doi.org/10.1007/s10113-015-0910-2

8. Green H, Bailey J, Schwarz L, Vanos J, Ebi K, Benmarhnia T. Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiological evidence and considerations for future research. Environ Res. 2019; 171: 80–91. https://doi.org/10.1016/j.envres.2019.01.010 PMID: 30660921

9. Stordalen GA, Rocklöv J, Nilsson M, Byass P. Only an integrated approach across academia, enterprises, governments, and global agencies can tackle the public health impact of climate change. Glob Health Action. 2013; 6: 20513. https://doi.org/10.3402/gha.v6i0.20513 PMID: 23653920

10. Hyatt OM, Lemke B, Kjellstrom T. Regional maps of occupational heat exposure: past, present, and potential future. Glob Health Action. 2010; 3: 5715. https://doi.org/10.3402/gha.v3i0.5715 PMID: 21165172

11. Smith K, Woodward A, Campbell-Lendrum D, Chadee D, Honda Y, Liu Q, et al. Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiologic evidence and considerations for future research. Environ Res. 2019; 171: 80–91. https://doi.org/10.1016/j.envres.2019.01.010 PMID: 30660921

12. Stordalen GA, Rocklöv J, Nilsson M, Byass P. Only an integrated approach across academia, enterprise, governments, and global agencies can tackle the public health impact of climate change. Glob Health Action. 2013; 6: 20513. https://doi.org/10.3402/gha.v6i0.20513 PMID: 23653920

13. Hyatt OM, Lemke B, Kjellstrom T. Regional maps of occupational heat exposure: past, present, and potential future. Glob Health Action. 2010; 3: 5715. https://doi.org/10.3402/gha.v3i0.5715 PMID: 21165172

14. Serdeczny O, Adams S, Baarsch F, Cournou D, Robinson A, Hare W, et al. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Reg Environ Change. 2017; 17: 1585–1600. https://doi.org/10.1007/s10113-015-0910-2

15. Green H, Bailey J, Schwarz L, Vanos J, Ebi K, Benmarhnia T. Impact of heat on mortality and morbidity in low and middle income countries: A review of the epidemiologic evidence and considerations for future research. Environ Res. 2019; 171: 80–91. https://doi.org/10.1016/j.envres.2019.01.010 PMID: 30660921

16. Stordalen GA, Rocklöv J, Nilsson M, Byass P. Only an integrated approach across academia, enterprise, governments, and global agencies can tackle the public health impact of climate change. Glob Health Action. 2013; 6: 20513. https://doi.org/10.3402/gha.v6i0.20513 PMID: 23653920

17. Hyatt OM, Lemke B, Kjellstrom T. Regional maps of occupational heat exposure: past, present, and potential future. Glob Health Action. 2010; 3: 5715. https://doi.org/10.3402/gha.v3i0.5715 PMID: 21165172

18. Foittrell E, Byass P. Verbal Autopsy: Methods in Transition. Epidemiol Rev. 2010; 32: 38–55. https://doi.org/10.1093/epirev/mxq003 PMID: 20203105

19. Radin JM, Vineinger NE, Topol EJ, Steinthubl SR. Harnessing wearable device data to improve state-level real-time surveillance of influenza-like illness in the USA: a population-based study. Lancet Digit Health. 2020; 2: e85–e93. https://doi.org/10.1016/S2589-7500(19)30222-5 PMID: 33334568

20. Evans GF, Shirk A, Muturi P, Soliman EZ. Feasibility of Using Mobile ECG Recording Technology to Detect Atrial Fibrillation in Low-Resource Settings. Glob Heart. 2017; 12: 285–289. https://doi.org/10.1016/j.ghheart.2016.12.003 PMID: 28302547

21. Fagherazzi G, El Fatouhi D, Bellicha A, El Gareh A, Affret A, Dow C, et al. An international study on the determinants of poor sleep amongst 15,000 users of connected devices. J Med Internet Res. 2017; 19: e363. https://doi.org/10.2196/jmir.7930 PMID: 29061551

22. Zapata-Lamana R, Lalanza JF, Losilla J-M, Parrado E, Capdevila L. mHealth technology for ecological momentary assessment in physical activity research: a systematic review. PeerJ. 2020; 8: e8648. https://doi.org/10.7717/peerj.8648 PMID: 32257648

23. Wright SP, Hall Brown TS, Collier SR, Sandberg K. How consumer physical activity monitors could transform human physiology research. Am J Physiol-Regul Integr Comp Physiol. 2017; 312: R358–R367. https://doi.org/10.1152/ajpregu.00549.2016 PMID: 28052867

24. Lopez X, Afrin K, Nepal B. Examining the design, manufacturing and analytics of smart wearables. Med DEVICES Sens. 2020; 3: e10887. https://doi.org/10.1002/mds3.10087
25. Dunn J, Runge R, Snyder M. Wearables and the medical revolution. Pers Med. 2018; 15: 429–448. https://doi.org/10.2217/pme-2018-0044 PMID: 30259801

26. Landi H. More wearables shift from fitness to clinical use with new Samsung and AT&T smartwatches. FierceHealthcare. 2019; N.PAG-N.PAG.

27. Mohammadzadeh N, Gholamzadeh M, Saeedi S, Rezayi S. The application of wearable smart sensors for monitoring the vital signs of patients in epidemics: a systematic literature review. J Ambient Intell Humaniz Comput. 2020; 1–15. https://doi.org/10.1007/s12652-020-02656-x PMID: 33224305

28. Lam CKC, Hang J, Zhang D, Wang Q, Ren M, Huang C. Effects of short-term physiological and psychological adaptation on summer thermal comfort of outdoor exercising people in China. Build Environ. 2021; 198: 107877. https://doi.org/10.1016/j.buildenv.2021.107877

29. Shaw GA, Siegel AM, Zogbi G, Opar TP. Warfighter physiological and environmental monitoring: a study for the US Army Research Institute in Environmental Medicine and the Soldier Systems Center. MASSACHUSETTS INST OF TECH LEXINGTON LINCOLN LAB; 2004.

30. Muller AM, Maher CA, Vandelanotte C, Hingle M, Middelweer A, Lopez ML, et al. Physical Activity, Sedentary Behavior, and Diet-Related eHealth and mHealth Research: Bibliometric Analysis. J Med Internet Res. 2018; 20: 29669703

31. Hickey AM, Freedson PS. Utility of consumer physical activity trackers as an intervention tool in cardiovascular disease prevention and treatment. Prog Cardiovasc Dis. 2016; 58: 613–619. https://doi.org/10.1016/j.pcad.2016.02.006 PMID: 26943981

32. Evenson KR, Wen F, Furberg RD. Assessing validity of the Fitbit indicators for US public health surveillance. Am J Prev Med. 2017; 53: 931. https://doi.org/10.1016/j.amepre.2017.06.005 PMID: 28755981

33. Dorsey ER, Glidden AM, Holloway MR, Birbeck GL, Schwamm LH. Teleneurology and mobile technologies: the future of neurological care. Nat Rev Neurol. 2018; 14: 285. https://doi.org/10.1038/nrneurol.2018.31 PMID: 29623949

34. Diboulo E, Siea A, Rocklov J, Niamb L, Ye M, Bagagnan C, et al. Weather and mortality: a 10 year retrospective analysis of the Nouna Health and Demographic Surveillance System, Burkina Faso. Glob Health Action. 2012; 5: 19078. https://doi.org/10.3402/gha.v5i0.19078 PMID: 23195510

35. Odhiambo FO, Laserson KF, Sewe M, Hamel MJ, Feikin DR, Adazu K, et al. Profile: The KEMRI/CDC Health and Demographic Surveillance System—Western Kenya. Int J Epidemiol. 2012; 41: 977–987. https://doi.org/10.1093/ije/dys108 PMID: 22933646

36. Mendt S, Maggioni MA, Nordine M, Steinach M, Opitz O, Belavý D, et al. Circadian rhythms in bed rest: monitoring core body temperature via heat-flux approach is superior to skin surface temperature. Chronobiol Int. 2017; 34: 666–676. https://doi.org/10.1080/07420528.2016.1224241 PMID: 27726448

37. Opatz O, Trippel T, Lochner A, Werner A, Stahn A, Steinach M, et al. Temporal and spatial dispersion of human body temperature during deep hypothermia. Br J Anaesth. 2013; 111: 768–775. https://doi.org/10.1093/bja/aet217 PMID: 23801744
46. Opatz O, Stahn A, Werner A, Gunga H-C. Determining core body temperature via heat flux—a new promising approach. Resuscitation. 2010; 81: 1588–1589. https://doi.org/10.1016/j.resuscitation.2010.05.025 PMID: 20638763

47. Gunga H-C, Werner A, Stahn A, Steinach M, Schlabs T, Koralewski E, et al. The Double Sensor—A non-invasive device to continuously monitor core temperature in humans on earth and in space. Respir Physiol Neurobiol. 2009; 169: S63–S68. https://doi.org/10.1016/j.resp.2009.04.005 PMID: 19428314

48. Stahn AC, Werner A, Opatz O, Maggioni MA, Steinach M, von Ahlefeld VW, et al. Increased core body temperature in astronauts during long-duration space missions. Sci Rep. 2017; 7: 16180. https://doi.org/10.1038/s41598-017-15560-w PMID: 29170507

49. Coughlin SS, Stewart J. Use of Consumer Wearable Devices to Promote Physical Activity: A Review of Health Intervention Studies. J Environ Health Sci. 2016; 2. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5395205/ https://doi.org/10.15436/2378-6841.16.1123 PMID: 28428979

50. Godino JG, Wing D, de Zambotti M, Baker FC, Bagot K, Inkelis S, et al. Performance of a commercial multi-sensor wearable (Fitbit Charge HR) in measuring physical activity and sleep in healthy children. PloS One. 2020; 15: e0237719. https://doi.org/10.1371/journal.pone.0237719 PMID: 32886714

51. Nazari G, MacDermid JC, Sinden KE, Richardson J, Tang A. Inter-instrument reliability and agreement of Fitbit charge measurements of heart rate and activity at rest, during the modified Canadian aerobic fitness test, and in recovery. Physiother Can. 2019; 71: 197–206. https://doi.org/10.3138/ptc.2018-25 PMID: 31719715

52. Nelson BW, Allen NB. Accuracy of consumer wearable heart rate measurement during an ecologically valid 24-hour period: Intraindividual validation study. JMIR mHealth uHealth. 2019; 7: e10828. https://doi.org/10.2196/10828 PMID: 30855232

53. Tamura T, Huang M, Togawa T. Current Developments in Wearable Thermometers. Adv Biomed Eng. 2018; 7: 88–99.

54. Stone JE, McGlashan EM, Facer-Childs ER, Cain SW, Phillips AJ. Accuracy of the GENeActiv Device for Measuring Light Exposure in Sleep and Circadian Research. Clocks Sleep. 2020; 2: 143–152. https://doi.org/10.3390/clocksleept2002012 PMID: 33089197

55. Siddall AG, Powell SD, Needham-Beck SC, Edwards VC, Thompson JE, Keyfalew SS, et al. Validity of energy expenditure estimation methods during 10 days of military training. Scand J Med Sci. 2019; 29: 1313–1321. https://doi.org/10.1111/smss.13486 PMID: 31136027

56. Burton E, Hill KD, Lautenschlager NT, Thegersen-Ntoumani C, Lewin G, Boyle E, et al. Reliability and validity of two fitness tracker devices in the laboratory and home environment for older community-dwelling people. BMC Geriatr. 2018; 18: 1–12.

57. Montoye AH, Westgate BS, Fonley MR, Pfeiffer KA. Cross-validation and out-of-sample testing of physical activity intensity predictions with a wrist-worn accelerometer. J Appl Physiol. 2018; 124: 1284–1293. https://doi.org/10.1152/japplphysiol.00760.2017 PMID: 29369742

58. Powell C, Carson BP, Dowd KP, Donnelly AE. Simultaneous validation of five activity monitors for use in adult populations. Scand J Med Sci. 2017; 27: 1881–1892. https://doi.org/10.1111/smss.12813 PMID: 27905148

59. Sié A, Louis Valérie R, Gbangou A, Müller O, Niamba L, Stinglhuber G, et al. The Health and Demographic Surveillance System (HDSS) in Nouna, Burkina Faso, 1993–2007. Glob Health Action. 2010; 3: 5284. https://doi.org/10.3402/gha.v3i0.5284 PMID: 20847837

60. Liu Y, Nie L, Liu L, Rosenblum DS. From action to activity: Sensor-based activity recognition. Neurocomputing. 2016; 181: 108–115. https://doi.org/10.1016/j.neucom.2015.08.096

61. Bland JM, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. The lancet. 1986; 327: 307–310. PMID: 2868172

62. Lin Li-K. A Concordance Correlation Coefficient to Evaluate Reproducibility. Biometrics. 1989; 45: 255–268. https://doi.org/10.2307/2532051 PMID: 2720055

63. Tarar AA, Mohammad U, Srivastava SK. Wearable Skin Sensors and Their Challenges: A Review of Transdermal, Optical, and Mechanical Sensors. Biosens-BASEL. 2020; 10. https://doi.org/10.3390/bios10060056 PMID: 32481598

64. Bent B, Goldstein BA, Kibbe WA, Dunn JP. Investigating sources of inaccuracy in wearable optical heart rate sensors. NPJ Digit Med. 2020; 3. https://doi.org/10.1038/s41746-020-0226-6 PMID: 32047863

65. Sauerborn R. A gaping research gap regarding the climate change impact on health in poor countries. Eur J Epidemiol. 2017; 32: 855–856. https://doi.org/10.1007/s10654-017-0258-7 PMID: 28573342