Transforming Personal Healthcare through Technology - A Systematic Literature Review of Wearable Sensors for Medical Application

Anne-Katrin Witte
Technical University of Berlin
a.witte@tu-berlin.de

Rüdiger Zarnekow
Technical University of Berlin
ruediger.zarnekow@tu-berlin.de

Abstract

Wearable Sensor Health Technology (WSHT) captures, analyzes and aggregates physiological data to improve personal well-being. Recently the technology market is flooded with wearable sensors that measure health-related data and have a high user adoption. Nevertheless, these devices are almost exclusively used for fitness purposes and the healthcare sector still faces the challenge of constantly increasing costs. To respond to the necessary but rare use of WSHT in professional healthcare, we aim to identify the most promising areas for future medical implementation. Therefore, we performed a systematic literature search and reviewed 97 papers with regard to disease treatment, application area, vital parameter measurement and target patient. As a result, we could identify five potential areas for further research: (RA1) concentration on widespread diseases, (RA2) expansion of WSHT's functionality, (RA3) diversity of vital parameter measurements, (RA4) proactive analysis of sensor data for preventive purposes and (RA5) promoting patient adoption through enhanced usability.

1. Introduction

Fitness wearables that track the personal health status have become very popular in the past years and the technology market is flooded by commercially available sensor wristbands and fitness trackers. This is caused by (a) the push of the technology industry as well as (b) a pull from the consumer side [1].

The sensor industry (a) wants to integrate the prominent technological progress into products that are obtainable for the consumer. Recent advances in hardware (e.g. miniaturized sensors, wireless transmission, mobile internet and smartphone technology) and software (e.g. improvement of algorithms, machine learning and artificial intelligence) drive the application of fitness wearables. Through numerous scaled-down and wirelessly connected sensors a vast amount of vital parameters can be captured (online or offline) and analyzed.

The consumer (b) wants to apply this technology to enhance personal well-being. Emerging movements e.g. quantified self and patient empowerment are driving the use of wearable sensors. Thereby the patient-physician-connection moves away from a traditional and paternalistically shaped relationship towards an autonomous patient that is able to engage in self-tracking of physiological data to make informed decisions [2], [3]. Especially in the western culture this movement is driven by an emerging focus on consumerism and individualism [4].

While there is frequent application and high adoption of WSHT in the fitness and lifestyle market, it is generally considered that one untapped potential lies in the area of professional healthcare [5]. But the healthcare market itself faces the challenge of increasing costs. In developed countries this is especially due to the demographic transition which means that the proportion of elderly people is constantly increasing. For this reason, a higher percentage of the population is dealing with more and serious health problems. This rising demand of the elderly population can be met by new advancements in health technology [6] e.g. through continuous monitoring of home-bound patients or fall detection [7], [8]. Next to this expense factor, there are also high amounts (up to 213 billion in the U.S. [9]) in the medical domain spent every year that are avoidable e.g. to cure people from diseases that could have been prevented or compensate medical errors due to incomplete patient data. This illustrates that despite recent advancements, the technology is not as integrated in the treatment process as it could be. Therefore, wearable sensors can have a great impact on the provision of healthcare and enhance its abilities [10]. As a result of the aforementioned challenges, there is an enormous potential to improve the current patient treatment; nonetheless the implementation of

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wearable sensor health technology in a medical context has only been gradual so far [11].

To respond to the infrequent application of wearable sensors in a professional medical context, we reviewed relevant scholarly contributions that present practical use. While in the literature there are many papers dealing with the subject of WSHT, so far many of these works explore new sensor possibilities and measurement techniques (e.g. [12], [13]) or develop future scenarios and desirable architectures (e.g. [14], [15]). In both cases no proof of feasibility can be found. Nonetheless, scholarly literature has already developed frameworks/taxonomies and aims to give an overview of the topic of WSHT [16]-[21]. Despite their different foci, many of these reviews call for testing the accuracy or effectiveness in connection with real users.

Therefore, this work reviews the status quo of practical WSHT which means the feasibility of the system needs to be proven by a pilot study or implementation with a subject group. To the best of our knowledge a systematic literature review has not been performed in this particular context so far. The outcome of this review is expected to show state of the art application areas of WSHT. This indicates if the technology meets the challenges of the healthcare system and presents promising areas for continuative research. Additionally, potential research gaps within underrepresented application scenarios can be shown. This is the case if there is sparse literature to prove the practicability of the treatment for a common disease. For this purpose, two primary research questions have been formulated:

1. Which prevalent application areas for practical WSHT can be identified?
2. Which underrepresented application areas for practical WSHT do exist?

To answer the first research question, the definition of health technology published by the World Health Organization is taken as a basis: “A health technology is the application of organized knowledge and skills (application area) in the form of devices (vital parameter measurement), medicines, vaccines, procedures and systems developed to solve a health problem (disease treatment) and improve quality of lives (target patient)” [22].

2. Literature Review

In the area of personal, sensor-based healthcare technology there are a lot of different terms emerging. While the concept of Wireless Body Sensor Networks (WBSN) or Wireless Body Area Networks (WBAN) consists of many different biological sensors that are positioned on or implanted in the body, it focuses on the inter-sensor communication. There is a central coordinator node with more processing power with which all other sensor nodes can communicate [23]. The related term of fitness tracker is commonly defined as wrist-worn wearable fitness technology that uses integrated sensors to collect health data of the user [24]. But especially the word fitness tracker is often mentioned in connection with the fitness and lifestyle market to improve overall well-being. Sensors do not necessarily need to be attached to the wrist but can also be spread across the user’s body e.g. in smart clothing that can collect various physiological parameters in an unobtrusive way. Despite the high potential of sensors integrated in clothes there are still open issues and design challenges that need to be addressed before this technology can be used for many different applications [25]. Another frequently discussed concept is Smart Home or Ambient Assisted Living. It focuses on the enhancement of the life and health of its residents enabled by Internet of Things technologies [26]. To do so there are body and environment sensors, often supported by video or infrared monitoring. But next to emerging privacy issues of the residents there are concerns about mobility and flexibility of this concept [25].

Keeping in mind all these related terms, this work focuses on Wearable Sensor Health Technology (WSHT). The word “*Wearable*” implies a flexible and mobile sensor that can be worn constantly on the patient’s body and used at home independently without the assistance of a physician. The term “*Sensor*” represents some kind of sensor technology that measures and collects vital parameters of the user. The most commonly used sensors are inertial measurement units (linear and angular motion), electrocardiography sensors (electrical impulses through heart muscle), photoplethysmography/optical heart rate sensors (blood volume changes), electroencephalography sensors (electrical activity of the brain), galvanic skin response sensors (skin conductivity) and temperature sensors (ambient/body temperature). The explicit position of the sensor on the user’s body can be manifold and vary from sensor wristbands, to headbands and sensor equipped clothing. “*Health Technology*” defines the application of sensor technology in a health and medical related context.

In order to collect relevant literature on the status quo application of WSHT, a structured approach was performed according to the common practice of Webster and Watson [27]. The search was carried out on four electronic literature databases to provide a representative sample of literature. This includes databases that comprise (leading) journals as well as conference proceedings to enable a keyword-based search across all contributions [27]. Because Information Systems Management is an interdisciplinary field this review does not only comprise databases from Information Systems Management (Science Direct, SpringerLink) but also interdisciplinary literature from the field of Computer Science (IEEE) and Medicine (PubMed) [27]. All databases were searched for papers that include the terms “*Wearable*” AND “*Sensor*” AND “*Health*” AND “*Technology*”. This combination of search terms ensures that the results are within the predefined scope that was chosen after a pre-test in all considered literature collections.

The consequent papers were limited to the time between 2013 und 2018. We consider the most recent WSHT developments being included in this timeframe. The search process itself was conducted during April and May 2018. The detailed search process for the final choice of literature sources is depicted in figure 1.

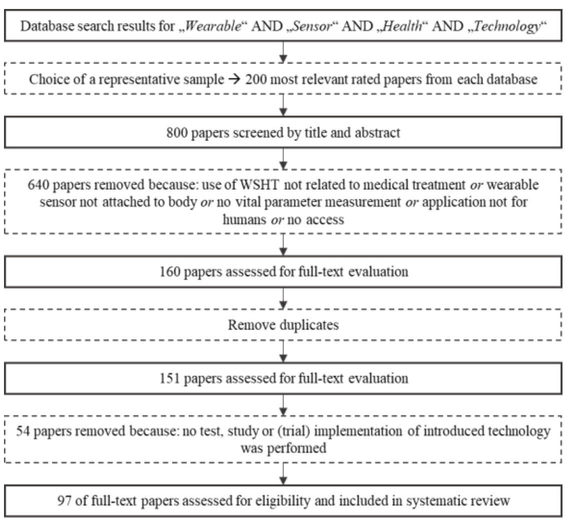

Figure 1. Literature search process

In accordance to Webster and Watson [27] the coverage of the literature review should be as complete as possible. To do so a pre-scanning on Science Direct was completed. The limit of the review was set to 200 papers per database. After this threshold no new concepts could be identified in the pre-test which is a sign of nearing completion.

For all search results there was a scan of the title as well as the abstract of the 200 most relevant (“relevance” is determined by the respective database filter function) rated papers to determine whether the papers were in the scope of the literature review [28]. After that the duplicates were removed, starting with the results from the first data base search. Because there is not only an investigation of a certain topic but rather on papers that focus on a proof of practicability, forward and backward search would not improve the value of the purpose [29].

Further inclusion and exclusion criteria were defined to make sure only papers in the concrete context of WSHT that prove the practicability of the application scenario are considered:

Inclusion criteria:

i. (At least one) Wearable sensor is attached to the human body at any position
ii. Wearable sensor is either commercially distributed or independently designed by researcher
iii. Wearable sensor measures vital parameters
iv. Wearable sensor does not restrict patient’s general mobility
v. Wearable sensor is applied in a medical context
vi. Wearable sensor is used to diagnose, prevent, treat, cure or medicate any kind of physical or psychological disease or disorder
vii. Wearable sensor replaces, supports or prevents a treatment or examination that was originally carried out by a physician
viii. Wearable sensor is used independently from a physician in a noninvasive way or an ambulatory setting/at home
ix. Wearable sensor communicates collected data to physician or information system in a synchronous or asynchronous way
x. Wearable sensor is prototyped and/or (pilot) tested with subject group to verify practicability

Exclusion criteria:

i. Wearable sensor is a camera or Kinect sensor or RFID chip that only measures activity indirectly
ii. Wearable sensor is used in a (professional) sports context to enhance the athlete’s performance only
iii. Wearable sensor is applied for one-time medical research study (e.g. to identify previously unknown disease symptoms) but does not improve the treatment process itself
iv. Wearable sensor is presented exclusively in the context of a promising scenario in the future
v. Wearable sensor is not proven to be practical e.g. only proposal or suggestion for future system design

Table 1. Literature selection process

Database	Science Direct	Springer Link	IEEE	Pub Med
# identified	5422	2821	906	573
# full text evaluation	38	59	30	33
# removing duplicates	38	58	30	25
# assessed for eligibility	16	31	26	24

The detailed number of papers within the selection process is presented in table 1. While reading all papers a concept matrix was developed to enable different units of analysis [27], [28]. Table 2 depicts the outline of the concept matrix that was completed during the database search process.

Table 2. Concept matrix outline

Database	Science Direct	Springer Link	IEEE	Pub Med
Disease treatment				
Application area				
Vital parameter measurement				
Target patient				

The main concept *disease treatment* defines the illness which is supposed to be treated using WSHT. It can also describe a health problem of the patient which is supposed to be solved. This includes physical as well as psychological illnesses. *Application area* describes the general medical purpose for which WSHT is used. This can involve any activity that is normally carried out by a physician. The main concept *vital parameter measurement* describes which biological signals of the patient are tracked using WSHT. This can range from capturing movement to track heart rate to analyze body fluids. *Target patient* describes the group of people for whom WSHT has been designed and is supposed to add value.

3. Results

The completed concept matrix is presented in table 3. For reasons of clarity only concepts that were mentioned at least one time in two different databases are included. The three most frequently discussed concepts within each main concept are highlighted in gray. To point out key findings and show their relationships, the concept matrix was translated into four network diagrams that depict the share of each concept accordingly within the main concept and show the inter-concept relationships (3.1.-3.4.). The diameter of the circle represents the number of entries in the concept matrix, which means the larger the circle the more frequently a concept was mentioned. The black line represents two concepts being mentioned together in the same paper. The thicker the line width the more often the concepts were mentioned together. Overall, concepts that were mentioned together in at least three papers are connected by a black line. In order to represent not only the connection within the concepts of one main concept, but also across all main concepts, 3.5. points out the prevalent application scenarios.

Table 3. Concept matrix

Main concept	Concept	Science Direct	Springer Link	IEEE	PubMed
Disease treatment	general health	3	6	17	4
	cardiac disease	2	6	3	3
	gait/balance disorder	2	3	3	6
	mental disorder	3	7	2	1
	frailty/fall	2	3	4	3
	Parkinson's disease	2	3	1	3
	stress	1	3	1	1
	movement disorder	1	3	-	2
	posture/spine disease	1	2	-	2
	diabetes/hypoglycemia	-	1	-	2
	obesity	1	-	-	2
	wound/skin infection	1	1	1	-
Application area	monitoring	8	17	20	16
	diagnosis	8	12	14	11
	emergency alert	2	3	10	5
	rehabilitation	2	5	1	6
	training	1	7	-	5
	management	2	3	2	4
	prevention	5	4	-	1
	therapy	1	2	-	2
	medication	1	-	1	1
Vital parameter measurement	physical activity/movement	10	18	14	19
	heart rate	4	10	17	2
	body temperature	1	6	11	3
	respiration	1	2	6	3
	GSR	1	4	3	1
	blood pressure	1	3	3	1
	SpO2	1	-	3	-
	nutrition/hydration	-	1	1	2
	BGL	1	-	1	1
	EEG	2	1	-	-
	energy expenditure	-	2	1	-
Target patient	healthy	9	13	11	16
	affected	11	14	3	12
	elderly	2	6	13	4
	physically impaired	-	2	3	1

3.1. Disease treatment

This is the unit of analysis where the largest number of concepts, 12 in total, have been identified. The most frequently mentioned concept of general health (30 papers) describes a medical context which can enhance the patients well-being in different ways, but is not specialized in a certain disease yet.

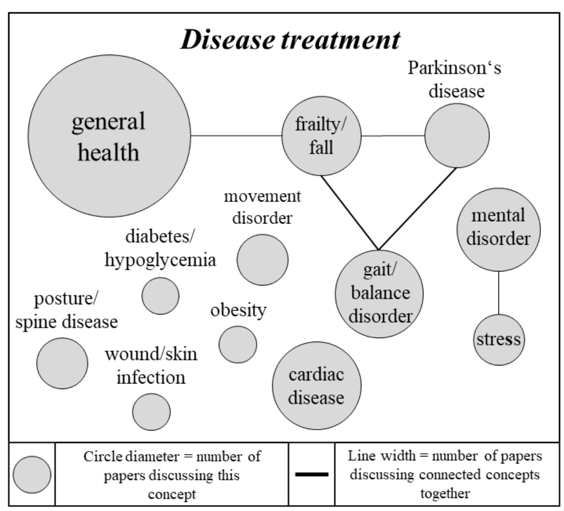

Figure 2. Concept matrix results for disease treatment

Another large share is represented by cardiac disease (14 papers), mental disorder (13 papers), gait/balance disorder (14 papers) and frailty/fall (12 papers). Mental disorders thereby include substance abuse, eating disorder, schizophrenia, dementia, depression and Alzheimer's disease. Gait and fall might sound very similar but differentiate in the simple analysis of a patient's walk and identifying the fall of a patient independently. The remaining large groups are Parkinson's disease (9 papers), stress (6 papers) and movement disorder (6 papers) as well as posture/spine disorder (5 papers). While movement disorder comprises osteoarthritis, frozen shoulder syndrome and spasticity, the concept of posture/spine disorder focuses on spinal illness also including back pain. Wound/skin infection, diabetes/hypoglycemia and obesity are discussed rather rarely (all 3 papers). Mental disorder and stress as well as general health and frailty/fall are mentioned together. Frailty/fall and gait/balance disorder are also often mentioned in connection with Parkinson's disease.

Table 4 depicts the diseases that were excluded from the network diagram due to their rare appearance (less than three times). While they make up nearly half of the main concept (42,9%), they appeared in under 10% of all discussed concepts. This represents that there were many papers specialized in a specific illness that was just brought up once or twice.

Table 4. Relative share within disease treatment

Concept names	Share within main concept	Share within single concepts
>= *3 papers*: (see figure 2)	12/21 = **57,1%**	118/129 = **91,5%**
< *3 papers*: (see *)	9/21 = **42,9%**	11/129 = **8,5 %**

*venous disorder, brain disease, tuberculosis, fetal health, erectile dysfunction, kidney disease, edema treatment, chronic pain and glaucoma

3.2. Application area

The main concept *application area* comprises 9 concepts. The largest circle is monitoring (61 papers) which describes a patient's vital parameters being observed (continuously). Diagnosis (45 papers) describes the assessment of the patient's status and is the second largest concept followed by emergency alert (20 papers) that sends an alarm when vital parameters exceed or undercut a predefined threshold. Rehabilitation (14 papers) and training (13 papers) are closely related but training implies an explicit and repeated execution of exercises for recovery.

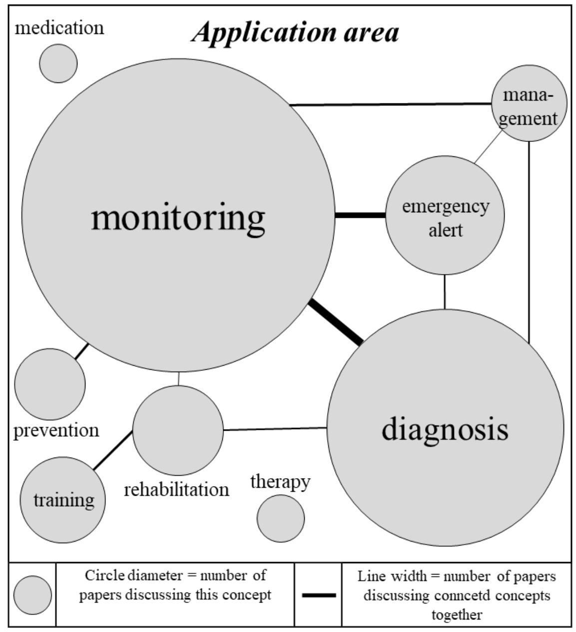

Figure 3. Concept matrix results for application area

Management (11 papers) defines the support provided for a patient. Prevention (10 papers), therapy (5 papers) and medication (3 papers) are addressed rather rarely. Monitoring, management, emergency alert and/or diagnosis are often mentioned together. The same applies to rehabilitation and training as well as rehabilitation and diagnosis or monitoring. Prevention is only connected to monitoring. Therapy and medication are isolated from the other concepts. Within this main concept, no concept was excluded due to rare discussion. As shown in table 5 the concepts of *application area* were discussed most frequently (182) within all main concepts.

Table 5. Relative share within application area

Concept names	Share within main concept	Share within single concepts
>= *3 papers*: (see figure 3)	9/9 = **100%**	182/182 = **100%**
< *3 papers*: none	0/9 = **0%**	0/182 = **0 %**

3.3. Vital parameter measurement

The main concept of *vital parameter measurement* makes up the second largest unit of analysis with 11 concepts. By far the most mentioned concept is physical activity/movement (62 papers) which is generally measured using accelerometers/gyroscopes.

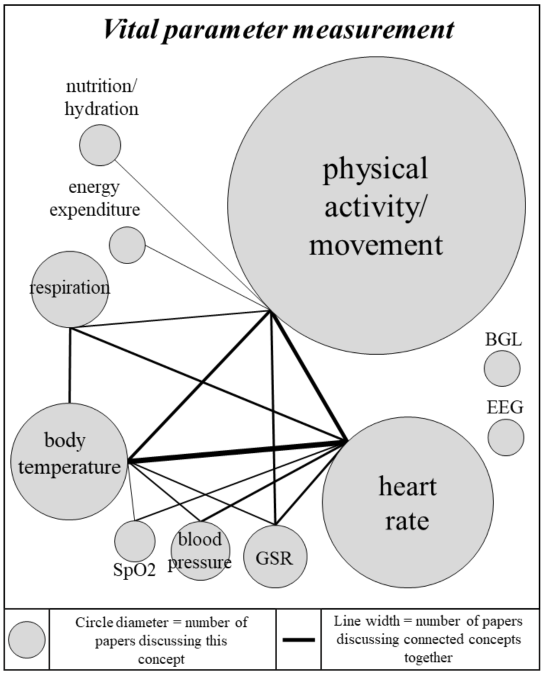

Figure 4. Concept matrix results for vital parameter measurement

The second largest circle is heart rate (34 papers). It illustrates the measurement of the pulse, heart rate variability or related values. Additionally, often captured vital parameters are the body temperature (22 papers), respiration (14 papers) and GSR (galvanic skin response, 9 papers). While a thermal sensor records the body temperature, the breath rate is obtained e.g. by nasal airflow sensor, [30], accelerometers [31], [32] or pressure sensors [33]. Bio impedance sensors analyze sweat by quantifying how well the body is impeding the flow of an electric current. Nutrition/hydration (4 papers) and SpO2 (blood oxygen level, 4 papers) as well as EEG (electroencephalography), BGL (blood glucose level) and energy expenditure (all 3 papers) are discussed rather rarely. As figure 4 illustrates heart rate and physical activity measurement are connected with many other sensors e.g. respiration, body temperature

Table 6. Relative share within vital parameter measurement

Concept names	Share within main concept	Share within single concepts
>= *3 papers*: (see figure 4)	11/18 = **61%**	161/171 = **94,2%**
< *3 papers*: (see **)	7/ 18 = **39%**	10/171 = **5,8%**

**uric acid concentration, interface pressure on the skin, tumescence/circumference, EMG (electromyography), sleep duration, gastric fluids and pH level

and GSR. While physical activity is mainly associated with exercise related parameters (e.g. nutrition/ hydration and energy expenditure), heart rate is connected to blood related data (like SpO2 and blood pressure). BGL and EEG are measured separately.

Table 6 shows that the concepts that were excluded for rare appearance (less than three times), make up 39% of the main concept *vital parameter measurement*. Still they only represent around 6% of all concepts within this main concept.

3.4. Target patient

Target patient is the smallest main concept including only 4 concepts. When there was no further specification of a targeted patient group, the concept healthy (49 papers) has been assigned. This describes patients in general who are not affected by any illness yet. These patients represent the largest circle followed by affected patients (40 papers) that are addressed second most commonly and describe persons that are already suffering from a certain disease.

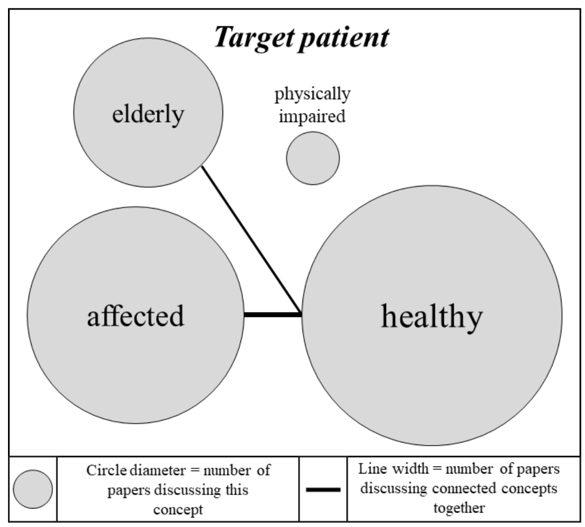

Figure 5. Concept matrix results for target patient

Elderly patients (25 papers) as well as physically impaired patients (6 papers) e.g. after an injury or accident are the remaining concepts. Looking at the circles all together, it strikes the eye that patients who are affected in any way make up the majority of the target patients. Figure 5 depicts healthy target patients being connected to affected as well as elderly target patients. Physically impaired target patients are not associated with other concepts.

Table 7 depicts one patient group being excluded because it was discussed only once.

Table 7. Relative share within target patient

Concept names	Share within main concept	Share within single concepts
>= 3 paper: (see figure 5)	4/5 = **80%**	120/121 = **99,2%**
< 3 paper: pregnant	1/5 = **20%**	1/121 = **0,8%**

3.5. Prevalent addressed application scenarios

Figure 6 shows the application scenarios that were addressed most often within the concept matrix. For their derivation, the following procedure was applied: (1) identification of the concept that was mentioned most often in *disease treatment*, *application area*, *vital parameter measurement* and *target patient* and definition of these concepts as a starting point (see table 8, bold concepts); (2) successive determination of the other three concepts that were mentioned most frequently in combination with the starting concept; (3) derivation of prevalent application scenarios by comparing their frequency of occurrence (see figure 6).

Table 8. Most frequently discussed concepts

Disease treatment	*Application area*	*Vital parameter measurement*	*Target patient*	*Paper*
cardiac disease	monitoring	heart rate	healthy	7
gait/balance disorder	diagnosis	physicial activity	affected	4
gait/balance disorder	monitoring	physicial activity	affected	4
cardiac disease	**monitoring**	heart rate	healthy	7
Parkinson's disease	**monitoring**	physicial activity	affected	5
gait/balance disorder	**monitoring**	physicial activity	affected	4
Parkinson's disease	diagnosis	**physicial activity**	affected	5
mental illness	monitoring	**physicial activity**	affected	4
mental illness	diagnosis	**physicial activity**	affected	4
cardiac disease	monitoring	heart rate	**healthy**	7
posture/spine disease	monitoring	physicial activity	**healthy**	3
posture/spine disease	diagnosis	physicial activity	**healthy**	3

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cardiac disease	monitoring	heart rate	healthy
gait/balance disorder	diagnosis/monitoring	physical activity	affected
Parkinson's disease	diagnosis/monitoring	physical activity	affected
mental illness	diagnosis/monitoring	physical activity	affected
posture/spine disease	diagnosis/monitoring	physical activity	healthy

Figure 6. Prevalent application scenarios

They can be aggregated to five main scenarios. While *disease treatment* varies for every scenario, it is noticeable that all scenarios include monitoring functionality. Regarding the *vital parameter measurements* only physical activity and heart rate are tracked, for healthy as well as for affected *target patients*.

4. Discussion

While there are various *target patients*, *disease treatments*, *vital parameter measurements* and *application areas* mentioned, some focus areas could be identified. By doing so, also rarely discussed but already existing areas could be observed that show the need for further research. Nevertheless, both areas have the potential for future application scenarios.

4.1. Prevalent application scenarios could be identified

Next to several application scenarios targeting health problems in general, some core themes could be found. These are applications for monitoring and diagnosing gait/balance disorders (e.g. [34]) or Parkinson's disease (e.g. [35], [36]) of affected patients as well as posture/spine disorder for healthy patients (e.g. [37]). Additionally, the monitoring of cardiac disease (e.g. [38]) and mental illness (e.g. [39]) was discussed very often.

According to an international OECD statistic [40] circulatory, digestive and muscular conditions as well as cancer and mental health make up almost 60% of the current spending of the healthcare industry. Thereby circulatory diseases account for 10% and mental health for 14% of healthcare costs. Comparing supply and demand of WSHT it strikes the eye that heart diseases, mental disorders and muscular diseases make up a high number of spending but are also discussed in context of many application scenarios. While it is very difficult to enable cancer treatment in a (strictly) noninvasive setting, digestive conditions are rarely discussed as well. According to the classification of ICD-10, K00-K93 this among others includes disorder of oral cavity, stomach, liver, pancreas, gallbladder as well as enteritis and colitis. Many of these diseases are organ based and sensors need to be implanted in the body. But often these diseases can also be caused by nutrition related manners. While many sensors can track and calculate energy expenditure, there are also few developments tracking food intake (e.g. [41]). In this area we identify a high potential for further research regarding:

Research area 1 (RA1): Application scenarios for (the prevention of) widespread diseases e.g. nutrition related disorders.

4.2. Application focus on monitoring and diagnosis functionality

Many observed WSHT applications focus on the use of continuous monitoring functionality in combination with diagnosis functionality. This could be due to the fact that the implementation of this functionality is the easiest. Vital parameters are observed and tested if they stay within certain thresholds or fulfil predefined criteria. This is essentially what all commercial fitness trackers on the market already do. If it comes to the area of management, training or even prevention the system itself becomes more complicated. In this context it needs to interact with the patient and actively influence user behavior which requires more intelligence. We presume that the rare application of these scenarios is based on legal challenges due to problems of accountability and insurance. We propose future research in:

Research area 2 (RA2): Additional integration of "more intelligent" functionalities to enhance the overall performance of WSHT. For example, this could be a disease intervention functionality that integrates actuators in the system which are implanted on or even inside the body [17].

4.3. Sensor measurement concentrates on physical activity and heart rate

Almost every WSHT application combines various sensors to measure physiological data. While there is a technical feasibility for many more sensors, the main focus of practical application lies in the area of physical activity recognition with accelerometers/ gyroscopes or heart rate measurement with optical sensors. The frequent use of this sensor types is probably due to the fact that there are already manifold fields of application from related areas e.g. the fitness sector. Therefore, the measurement algorithms are highly developed regarding their accuracy. Whereas their functionality can be manifold by being placed on different positions all over the human body, adding different sensors would improve and extend the application areas of WSHT much further.

In the review many existing but rarely used, specialized sensors are presented as well. This can be due to the reason of missing experiences regarding their application. Especially in the measurement area of bodily fluids lies a huge potential. For example GSR sensors have the potential to detect drug intake [42], [43]. Analyzing salivary can provide additional information about various health parameters, e.g. diagnose hyperuricemia [44] and detecting gastric fluid can help monitor medication adherence [45]. For this reason, we propose to direct further research in:

Research area 3 (RA3): Application of a diversity of vital parameter measurements within sensor devices.

4.4. Affected and impaired patients represent the largest target group

59% of the target patients are being represented by elderly, affected or physically impaired persons. Developing application scenarios for the elderly thereby meets the elementary challenge of the demographic transition. But it also reflects the general principle of the healthcare system. Here the treatment begins when the patient is already diseased and expenses are caused. In contrast to that we propose to anticipate the emergence of costs in the first place. One of the highest potentials lies in the area of prevention by collecting huge amounts of vital parameter data that were not accessible to this extent so far. Especially in the context of monitoring and diagnosing fall, patients are heavily injured when they fell. So the mere identification of the fall itself does not solve the problem of immobile patients needing further treatment or continuous care. For this reason, we suggest to put the focus of further research on:

Research area 4 (RA4): Application of proactive analysis of collected sensor data to provide prevention functionality.

4.5. Additional challenge of user acceptance and usability

Almost all papers used individually designed sensors that still need to be revised and improved regarding their outer appearance and ease of use. This may be due to the fact that the sensor measurements of commercially available sensors are not suitable for medical application yet [46]. But in addition to the essential criteria of technological feasibility and accuracy of the sensors, there are other influencing factors such as user acceptance, usability (above all in older people) and meaningful as well as simple integration into everyday life. That, in turn, is a point on which commercially available sensors are focusing on. Furthermore, in a medical context also security and data management issues as well as uncertainties regarding regulatory approvals and reimbursement from health insurance influence the patient's adoption of WSHT. For this reason, we suggest further research in:

Research area 5 (RA5): Convergence of commercially provided usability and scientifically proven efficacy to promote quick patient adoption.

5. Conclusion & Future research

To summarize there are already plenty application scenarios for WSHT with proof of practicability. While there are various concepts of *disease treatments*, *vital parameter measurements*, *application areas* and *target patients* discussed, some core themes but also underrepresented applications scenarios could be identified.

In connection with this, the review is limited by the selection of databases and search terms. Given our sample size of 200 papers considered from each database, not all application scenarios of WSHT may be represented accordingly. The assignment of concepts to the papers may be biased by subjective interpretation of the researcher.

Overall, there is a focus on cardiac and mental diseases, monitoring as well as diagnosis functionality, the collection of physical activity and heart rate data and affected or impaired patients. Almost all prevalent application scenarios are aimed to meet the demand of the healthcare market. That includes the monitoring and diagnosis of gait/balance, Parkinson's and posture/spine disease as well as monitoring of cardiac and mental disorders. Next to this core scenarios, there are also many different underrepresented scenarios which comprise a huge potential for further research. This is especially the case in the context of nutrition based illnesses and bodily fluid measurement sensors. Overall there should be a focus on more intelligent and proactive application combinations as well as prevention functionalities.

Finally, we conclude that there are already many promising and practical application scenarios in the healthcare sector. Still, further research is needed in the areas of underrepresented application scenarios to enable the treatment of more diverse diseases. Overall, a combination of commercially available sensor usability and medically applied sensor accuracy for all scenarios discussed, holds the potential to transform personal healthcare through technology.

6. References

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