Wearable Physical Activity-Tracking Systems for Older Adults – A Systematic Review

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Physical activity (PA) positively impacts the quality of life of older adults, with technology as a promising factor in maintaining motivation. Within Computer Science and Engineering, research investigates how to track PA of older adults for various purposes. We present a systematic review of 204 papers and discuss wearable tracking systems according to their purpose, technological context, target audience as well as design and evaluation processes with particular attention to the meaningful involvement of older adults. Our results show that most systems focus on *supervising* older adults in the context of disease and frailty management. Only few systems focus on *supporting* older adults by promoting rehabilitation and respecting agency of older adults via self-monitoring PA, or encouraging PA to maintain healthy levels of activity. Moreover, systems are often narrowly limited to walking, although older adults may enjoy a broader range of activities. Likewise, the involvement of older adults in design processes is scarce, and their experience with a given technology is rarely considered relevant for evaluation. In sum, we contribute an overview of wearable technology for tracking older adults' PA, contextualize our findings within recommendations provided by Sports and Rehabilitation Science, and illustrate opportunities for future work.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; *Interaction design*; Accessibility.

Additional Key Words and Phrases: older adults, physical activity, wearables, activity tracking

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1 INTRODUCTION

Wearable technologies – devices containing sensors to observe movements, body parameters or the direct environment of a wearer – play an increasingly important role in the context of physical activity (PA). In terms of leisure, activity tracking systems such as the wrist-worn FitBit¹,

¹<https://www.fitbit.com>

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smartwatches, or smartphone-based solutions (e.g., Google Fit app²) track a range of activities (e.g., walking, running, or biking).

While many of these systems focus on young people in Western societies [131, 240], a growing amount of research investigates the potential of such wearables for older adults. Maintaining physical activity in late life has numerous health benefits, and can result in improved physical well-being, e.g., increased muscle strength, maintained flexibility, reduced risk of falling [194], and lowered health risks such as heart disease, diabetes, and osteoporosis [178]. The positive effects extend to improved cognitive functioning [52, 153] and a decreased risk of depression [247]. Physical activity is also a core component of many rehabilitation schedules addressing older adults, e.g., aerobic endurance exercises after a hip fracture [171] or balance training after stroke [20]. Wearables hold the promise of supporting older adults' efforts to remain or become more physically active again, e.g., by tracking overall activity [39] or motivating them to engage with rehabilitation routines [99, 158]. Trackers can increase older adults' self-awareness related to their physical condition and can provide a source of bodily data for health professionals, e.g., heart rate, muscle strength, or activity levels [206]. This promise is further solidified by a high acceptance of inexpensive, accessible wearables older adults perceive as useful [162, 181, 211]. These devices are also regarded as a means of contributing to ageing in place, e.g., to increase safety through monitoring, such as in the context of falls prevention or detection [115, 235]. Likewise, wearable technology is leveraged in medical settings, for example, to support disease monitoring through sensor systems [63].

Given the growing group of older adults in both industrialized countries and countries of low- and middle-income [289], developing a better understanding of the design and development of wearable systems for this audience is a timely issue. We provide a systematic review of wearable technology research on tracking PA among older people, with a focus on understanding the intended purpose of the wearable and how it satisfies older adults' needs and expectations on PA-tracking. We follow the classification of physical activity Bangsbo et al. [16] provide, where activities are structured or unstructured in the context of leisure or activities of daily living (ADL), and where exercise is a subset of structured PA benefiting the bodily condition, including muscle strength and fitness. While there have been several attempts at mapping the research on wearable systems for older adults, previous reviews do not always exclusively focus on physical activity. More specifically, Caldeira et al. [36] and Zheng et al. [297] limit their reviews to a subset of PA-related applications, respectively self-tracking systems for older adults and wearable breathing training devices. Other reviews consider only a subset of all possible forms of physical activity, e.g., human movement with emphasis on fall detection or energy expenditure [229], or activities related to health and wellness [179]. In this systematic review, we give a broader overview of PA-tracking systems without excluding any subgroups of activities or wearables. Most closely related, Steinert et al. [245] focus on the acceptability and usability that wearable systems provide for older adults, but do not address the experiential dimension, i.e., whether systems are engaging and provide a positive user experience (UX). However, critical work from psychology that examined behavioral outcomes of wearables as PA intervention for the general population suggests that a positive experience is one of the most important factors that predict, and currently hinder, uptake of wearable technology [75]. Given that many of the commercially available systems target younger populations, and older adults often have different needs and perspectives when engaging with technology [13, 29, 93, 107], this observation seems particularly relevant here.

We leverage the perspective of Human-Computer Interaction (HCI) to explore work in Computer Science and Engineering on wearable activity-tracking systems for older adults. Drawing from the

²<https://www.google.com/fit/>

IEEE (Institute of Electrical and Electronics Engineers) Xplore digital library³ and ACM (Association for Computing Machinery) digital library⁴, we include 204 papers in our review. We analyze these papers through the lens of user-centered design, an iterative strategy in which the intended users of the technology are systematically involved in design and evaluation processes to ensure the result meets the needs of the target users [101, 210]. In addition to this aspect, we examine wearables in terms of intended purpose, underlying technology, and target audience.

Our paper delivers a taxonomy of existing wearable systems tracking PA for older adults with a focus on design and evaluation processes. We reflect on the involvement and perspectives of older adults, and the mapping of technology-supported tracking onto activities older adults enjoy, all of which are crucial factors for long-term and large-scale technology uptake. Finally, we discuss our findings with a focus on future opportunities for researchers to develop physical activity-tracking wearables that are better at meeting the needs and preferences of older adults.

2 BACKGROUND

In this section, we provide an overview of perspectives on physical activity through the lens of Sports and Rehabilitation Science respectively, and illustrate the efforts within the HCI community to design and evaluate related technology.

2.1 Perspectives on Physical Activity Through the Lens of Movement Sciences

The percentage of people aged 60 and older is increasing at an accelerated pace worldwide and will account for 22 % of the world population by 2050 [289]. A key challenge for the future is to make it possible for older adults to maintain a high quality of life [185]. According to older adults, conditions for having a high quality of life include: being healthy and mobile, retaining independence and engaging in leisure activities of their choice [91]. Physical activity is instrumental in fulfilling these conditions of maintaining a healthy life and living as a community dweller, i.e., older adults that can live independently [1, 217]. As such, it has a sustained impact on both short- and long-term quality of life [74], and plays an important role in terms of leisure. We leverage the fields of Sports and Rehabilitation Science to examine their respective status quo on physical activity for older adults. Thereby, we contextualize our review and set the premise for further reflection on our findings.

2.1.1 Physical Activity for Older Adults: Views From Sport Science. In the field of Sport Science, researchers investigate the effects of physical activity on older adults. PA tends to decrease with age and can result in an increased risk of all-cause mortality while directly affecting health care costs [168, 209]. By maintaining a habit of staying physically active, older adults can improve their cardiovascular health [264], muscle strength [236], cognitive functioning [153], mood [6], and reduce the risk of falling [17].

Older adults can gain these positive effects through different forms of physical activity, e.g., recreational activities, occupational activities, household chores and games, but the recommended levels of physical activity depend on the intensity and duration of the activity [286]. The World Health Organisation recommends a minimum of 150 minutes of moderate aerobic activity per week or vigorous-intensity activity for 75 minutes per week [287]. According to the American Heart Association and American College of Sports Medicine, this is similar to the recommendations for adults in general, but it takes the aerobic fitness of older adults into account, and includes activities that increase or maintain flexibility and muscle strength [194]. Recommended aerobic activities include biking, dancing, golfing, swimming, vacuuming, and walking, while muscle-strengthening activities include carrying groceries, pilates, gardening, yoga, and washing windows [76, 194]. Even

³<https://ieeexplore.ieee.org/>

⁴<https://dl.acm.org/>

moderate levels of physical activity can be beneficial [71], and once-per-week resistance exercises can improve muscle strength and reduce the risk of falling [253]. Regular PA helps maintaining flexibility and prevents obesity and diabetes while retaining muscle mass [51, 133]. Hence, it is desirable to support older adults in maintaining a level of exercise that is individually tailored to their level of fitness.

2.1.2 Physical Activity for Older Adults: Views From Rehabilitation Science. The role of physical activity in Rehabilitation Science is to support rehabilitation processes and prevent negative outcomes of chronic conditions, e.g., it can help older adults with osteoarthritis [166], or allow them to increase confidence in their abilities after a hip fracture [201]. Rehabilitation often relies on following an exercise routine provided by a physical therapist [268]. For instance, as part of hip fracture rehabilitation, the person that underwent surgery engages in exercises including heel slides, straight leg raising, hip flexion, and ankle pumps [145]. For the exercises to be effective, the repetition and accuracy of execution are key.

Depending on the physical condition of an older adult and the particular circumstances of their situation, they can perform exercises at home, using an instruction booklet and video. Tracking systems can support their rehabilitation scheme by recording the progress, providing performance feedback and regularly informing the therapist [271].

Where Sports Science aims to prescribe physical activity recommendations as preventive measures, Rehabilitation Science promotes health after injuries or surgeries. However, Sports Science presents the levels of recommended activity in an abstract way, leaving a wide margin for interpretation and confusion. The repeated rehabilitation routines are clearer as they describe concrete exercises and routines. Regardless, they tend to be highly prescriptive and repetitive, and therefore can lower the immediate motivation of older adults to complete them [103]. Wearable technology tracking the physical activities can support older adults in maintaining their motivation to commit to the exercises, e.g., in light of long-term goals.

2.2 Human-Computer Interaction

Human-Computer Interaction has a long-standing history of designing technology for well-being [265]. The field has supplied numerous case studies along with design considerations and guidelines for the development of technology to support, foster, and guide PA. For example, previous work has addressed the value of technology to endorse activity among children (e.g., [92]) and the general population (e.g., [55]) through the development of a range of systems, including games [175] and mobile apps [224], with interventions addressing a variety of levels of physical activities such as walking, running, or aerobic exercise. Concerning the design of these technologies, for example, Consolvo et al. draw from the design and large-scale evaluation of Houston, a mobile application that tracks users' steps, and provide four design guidelines: *giving users proper credit for their activities*, *providing personal awareness of activity level*, *supporting social influence*, and *considering the practical constraints of users' lifestyles* [54].

Addressing older adults, the HCI community has designed technologies particularly fostering physical activity among individuals experiencing mobility impairment due to age or in the context of rehabilitation [95]. Here, a range of systems have been designed, including games for individuals living with Parkinson's [180], exergames for older adults living in long-term care facilities [97], and tools to support falls prevention [271] and rehabilitation [4]. In terms of guidelines, Flores et al. provide an overview of design considerations regarding older adults after a stroke [87]. Designs ideally include methods to effectively support stroke rehabilitation (e.g., meaningful tasks adapted to the motor skill level of an older adult and providing appropriate feedback) and entertain older adults (e.g., by containing elements of social interaction, providing learning opportunities, and posing an

appropriate challenge). Fan et al. describe four themes for successful interventions to empower older adults: *awareness of personal limitations*, *social motivation*, *establishing and adapting to routines*, and *finding enjoyable activities* [82]. Likewise, Gerling et al. provide design recommendations for full-body motion-based game interaction for older adults, and emphasize the need to consider the impact of age-related changes on their ability to engage with technology in physically challenging ways [94]. However, all of these considerations focus on older patients or frail⁵ persons. To the best of our knowledge, no prior work is available that addresses the preferences and needs of older adults in the context of wearables supporting physical activity as a leisure activity.

Finally, HCI has developed a number of wearable systems regarding physical activities in older adults. Shany et al. describe systems for gait analysis, posture identification, and balance testing to support independently living individuals [229]. Dhillon et al. compare different handheld and mobile sensing devices for telehealth, including smartphones and motion-based gaming controllers [64]. Mercer et al. conclude that existing systems show several usability issues in terms of accessibility, visualization, and familiarity of devices and set up process [181]. Likewise, Sun et al. discuss the challenge of finding a balance between technical requirements regarding the position of the system on the body for accurately collecting activity data and comfort, where unobtrusiveness of the wearable is important [250]. With older adults rarely directly involved in the design process of such applications [96], these issues remain common in existing applications. Complementary, we focus in our review on these wearable systems with the goal of further exploring trends and practices within this area of research.

3 RESEARCH QUESTIONS

The goal of this systematic review is to map the landscape of wearable technology for older adults to track physical activity. We first look at the demographics the systems target, e.g., older adults in general or a particular subgroup with specific needs. Furthermore, we are interested in the application areas of these, the employed hardware to sense activity, and the way results are shared with users.

Aside from the descriptive aspects of the systems, we look through the lens of user-centered design and take note of how they are designed and evaluated, in terms of usability, UX, and involvement of older adults, to fulfill their needs and preferences.

Summarized, in this systematic review, we answer the following research questions:

- RQ1: What kinds of studies on physical activity-tracking systems for older adults are available and how can they be categorized in terms of intended purpose, context in which the technology is used, and targeted audience?
- RQ2: How are these physical activity-tracking systems designed and evaluated in terms of usability and user experience, and how do they involve older adults?

4 METHOD

In conducting the systematic review, we adhered to the PRISMA guidelines [183]. We created a search query to collect all papers related to older adults and physical activity from both the ACM digital library and IEEE Xplore digital library. These databases primarily contain literature relevant to the fields of Human-Computer Interaction and Engineering and together provide an extensive overview of design achievements related to PA-trackers. As this work aims to provide an overview on technology and design practices, we did not include databases from other fields, such as Medicine (e.g., PubMed database). By including both ACM and IEEE, we were able to include

⁵Frailty does not refer to disability, but to an increased risk of loss of function [81]. It often is not how older adults would describe themselves; others label them as such.

Table 1. Words and phrases related to ageing and synonyms for older adults

ageing	age-related	aging	elderly	elders	geriatric
gerontechnology	gerontology	grandfather	grandmother	grandparent	later life
life course	older adults	older people	retired	retiree	seniors

Table 2. Words and phrases related to physical activity

exercise	fitness
physical activity	sport

a broader range of existing systems beyond approaches that solely focus on either algorithms or user interaction. This allowed us to produce a more encompassing overview of existing physical activity-related systems.

The search process and analysis is executed by the first author, who had training in engineering. Based on titles and abstracts, we screened the initial set of papers. We assessed their further relevance through full-text reading. All authors reviewed key decisions related to the collected data to ensure that interpretation was not the result of the engagement of a single researcher with the data.

4.1 Search Query

We searched for any paper that discusses both older adults and physical activity or any combination of synonyms. Next to commonly used words or phrases to describe older adults, the first part of the search query included different synonyms as identified by Vines et al. [281], both euphemisms and pessimisms (see table 1). In addition to references to this demographic, gerontechnology was included as a search term to cover potential papers that exclusively refer to the technology rather than the people it was created for.

The second part of the search query included words and phrases referring to physical activity in a broad sense (see table 2). *Activity* as a separate term in itself did not appear in the search query as it can refer to many different contexts, e.g., nuclear activity, organized events, etc. With the keywords of table 2, the search results still contained literature unrelated to physical activity, but the number of false positives was reduced.

We then searched for all papers containing at least one of the 18 words or phrases of table 1 and at least one of the four words or phrases of table 2. To further reduce any false positive results, we limited the initial set of papers by only looking for any combination within the title, abstract or keywords of the paper. The full search queries for the ACM and IEEE can be found in appendix A and B respectively.

4.2 Exclusion criteria

We applied the following exclusion criteria to the resulting set of papers:

- paper not written in English;
- technology not intended for older adults. Older adults did not need to be an exclusive target demographic, but the paper was excluded if there was no explicit mention of them;
- target application not involving PA, in any possible way;
- not at least part of the system is wearable by the user. We define wearables in a broader sense as an active component that has the ability to quantify and/or interpret one or multiple

aspects of the human carrying the component, either in a hand or pocket, or attached to the body.

- paper does not discuss an original system.

4.3 PRISMA Approach

The PRISMA approach was carried out by the first author in four distinct phases⁶ [183]. The papers brought up by the search queries of the ACM and IEEE libraries were combined, providing an initial set of 2162 papers. Figure 1 shows an overview of the process. We analyzed a final set of 204: 23 of these papers originate from the ACM library and 181 from the IEEE library.

Fig. 1. Overview of the PRISMA approach

4.4 Analysis

The first author analyzed the remaining 204 papers by evaluating 24 parameters, divided into four separate categories: system information, target audience, system evaluation and user involvement. ‘System information’ contains parameters that keeps track of the purpose and technology of the system, while ‘target audience’ contains data on the persons the system targets. We used these categories to answer the first research question (RQ1). For the second research question (RQ2), we collected information on ‘system evaluation’ and ‘user involvement’. All authors reviewed the first author’s key decisions related to the analysis of the papers in our corpus. Here, we provide an overview of all parameters within these four categories in appendix C.

Some parameters, e.g., ‘was at least one older adult involved in the evaluation?’, are expressed within a set of fixed possibilities, i.e., ‘yes’, ‘no’ or ‘unspecified’. Our procedure was similar for parameters that do not require a fixed input, e.g., purpose of the system. This often results in categories that are not mutually exclusive, e.g., when a system serves multiple purposes or targets several different demographics, it is included in more than one category. In such cases, the sum of all listed percentages exceed 100 %. Furthermore, we adhere to the word choice of the papers’ authors and either use the words they explicitly use or strongly imply in their paper.

All 204 papers included in the analysis were published between September 1995 and December 2018 (see figure 2). We observe an increased research output starting around 2005, with an even stronger increase the following years. As not all of this can be attributed to generally increased research output within computing, we deem that another influence to this interest lies in the 2002 recommendations of the WHO [285] on physical activity for older adults, along with technological improvement, reduced production costs and increased inclusion of kinematic sensors in consumer

⁶This was done in January 2019.

electronics, e.g., smartphones, which gives researchers the ability to use more affordable and readily available tracking solutions [151].

Fig. 2. Histogram of the number of published papers per year

5 RESULTS

In this section, we present our results along our research questions. At the end of each question, we provide a summary of the key findings. Throughout the results section, we refer to appendix D for tables containing an overview of all results, along with a list of the corresponding papers in our corpus.

5.1 RQ1: What systems exist in terms of intended purpose, context in which the technology is used, and target audience?

5.1.1 System Purpose. We identified two overlapping categories of purposes: systems that serve the purpose of *supervising* older adults (106 of 204 papers, 52.0 %) or those *supporting* them in staying physically active (76 of 204 papers, 37.2 %). Some systems combine both purposes (13 of 204 papers, 6.4 %, see appendix D, table 3). In our understanding, a supervising system comes with a top down approach of ensuring compliance, usually in a fairly rigid and restricted manner and oriented towards predefined goals using older adults as passive information input to external audiences (i.e., therapists or family members). In contrast (or as a complement), a supporting system allows for slightly more flexible interaction and provides less restrictive opportunities for older adults to actively engage with associated technologies or exercises largely on their own volition. The difference in approach is relevant as it indicates how older adults are conceptualised as passive or active and implicitly illustrates whose position is taken as relevant in the development of wearables for physical activities of older adults.

Papers discussing systems that can both support and supervise older adults are often described in a more general way, e.g., by discussing potential use cases for a newly developed activity tracking algorithm [117]. This also indicates how, in this space, some papers focus on a tracking solution to which they have to define potential applications later, where other systems try to address pre-existing problems.

For each of the two overlapping categories of purposes, the authors of the analyzed papers often use a broader range of words to express the system purpose. We list these purposes, as described

by the authors themselves, to reflect their word choice and prevent the loss of subtle nuances. As a note, most systems provide multiple purposes and are therefore included in multiple categories.

When looking at papers that describe supervising systems, we found that 20 of 204 papers (9.8%) *assess* physical activity in general. For instance, these systems can track daily walking [125], assist in quantitative gait assessment [257] or monitor their independence in performing everyday tasks such as walking, sitting or eating [221]. An equal number of papers (20 of 204 papers, 9.8%) present a system that *analyzes* gait or generalised physical activity, e.g., ankle-worn sensors that estimate toe and heel clearance [135] or an accelerometer on the back to examine activities of daily living [207]. Other papers discuss supervising systems for *fall detection* (19 of 204 papers, 9.3%), e.g., an emergency response system that sends a message to caregivers when an older adult fell [128]. *Diagnosing* can also be the purpose of a system (2 of 204 papers, 1.0%), for instance, if it tracks walking under different conditions to assist in diagnosing gait problems [226].

Within the category of supporting systems, we found that 21 of 204 papers (10.3%) discuss *prevention* systems, e.g., to avert falls through exercises provided and tracked by a smartphone [85] or to reduce the risk of disease outcomes [243]. Some tracking systems (13 of 204, 6.4%) aim to *promote* physical activity, e.g., by engaging in exergames [37] or walking [228]. Ten of 204 papers (4.9%) *encourage* physical activity and exercising, e.g., with a smartphone to track exercises [146] or by playing exergames to improve physical fitness [144]. Some of the authors use the term *supporting* to describe the purpose of the system (9 of 204 papers, 4.4%), e.g., a golf simulation game for physical activity among arthritis patients [231]. Six of 204 papers (2.9%) discuss a system that assists older adults, e.g., to stand up from a sitting position [196] or to *train* their muscles [294].

Figure 3 shows a summary of the purposes as specified by the authors of all analyzed papers and how we combined them into the overlapping supervising and supporting categories. For purposes like monitoring (96 of 204 papers, 47.1%) and rehabilitating (31 of 204 papers, 15.2%), intention can be supervision, support, or a combination thereof.

Fig. 3. The system purposes classified as supervising or supporting, based on the intended purpose of the authors and the vocabulary they used to express it, where systems in the overlapping part both describe supervising and supporting purposes

As an example of a supporting system for monitoring older adults, Sunwoo et al. [251] discuss a wearable that allows them to engage in exergames and monitor their own rehabilitation progress.

Ketabdar et al. monitor the intensity of activities and allow caregivers to supervise if older adults are walking or resting [137]. Likewise, Giotakos et al. support balance rehabilitation [99], while Bravo et al. track rehabilitation progress for supervision by a doctor [28]. Concerning the overlapping support and supervising category, Huang et al. study the accuracy of machine learning algorithms in a system that can fulfill the role of supportive fitness workout assistant, while it can also have a supervising role in monitoring activity of older adults and children [117]. Likewise, Wang et al. discuss a system that supports older adults to establish exercise habits, while it also provides features for caregivers to monitor their exercises [283].

5.1.2 Activities. The most frequently tracked activity is walking (87 of 204 papers, 42.6 %, see table 4). Some of the systems detect and count steps (e.g., [23, 43]), others can recognize high- or low-intensity walking (e.g., [137]). General exercising is also commonly tracked (48 of 204 papers, 23.5 %). This refers to exercises for rehabilitation (e.g., limb training for functional recovery [31]), to prevent falls (e.g., gentle bending through the knees while leaning against a wall or stretching legs while sitting on a chair [202]), exergames to support physical activity (e.g., picking up virtual fruit [72]), or gamified exercise programs to increase adherence to a presumably healthy lifestyle (e.g., receiving digital badges for perfectly completing a set of exercises [30]). Some systems track activities of daily living (39 of 204 papers, 19.1 %), which include physical activity done during common tasks or daily habits, e.g., routines at home, house work or leisure. Falling is a generally involuntary and potentially harmful activity, which is tracked by 23 of 204 papers (11.3 %) for supervision purposes. Less frequently tracked activities include biking (8 of 204 papers, 3.9 %) and swimming (1 of 204 papers, 0.5 %). Table 4 shows a full overview of all tracked activities. For example, swimming is an activity that older adults enjoy [80], but only one system tracks this activity, using a wrist-worn watch with an inertial measurement unit that keeps track of lap count, swimming speed, distance, etc. [61]. In general, some systems can track more than one activity, so they are included in more than one of the discussed activity types.

Some overlap can be observed in this list particularly with respect to walking; hence, it follows that about two thirds of the systems here track walking-related activities.

5.1.3 Tracking Hardware. The accelerometer is present in most tracking systems in our corpus (173 of 204 papers, 84.8 %), and is well-suited to track walking and similar activities. Other sensors used in the systems to quantify the amount of effort the user exerted are: gyroscope (67 of 204 papers, 32.8 %), heart rate sensor (28 of 204 papers, 13.7 %), and magnetometer (27 of 204 papers, 13.2 %). Table 5 shows a full overview of all used sensor types to track PA.

Considering the positioning of the tracking sensors, handheld devices, like smartphones, are the most commonly used hardware to track physical activity (see figure 4, table 6). They readily contain a number of sensors, e.g., accelerometer and gyrosensor, thus being available to users without having to purchase and carry an additional device. Some applications on smartphones track activities, like walking, by collecting and processing data while attached to people's bodies either by being carried in hand or in pockets (e.g., [88, 174]). Other tracking applications require more dedicated interaction, e.g., a smartphone application that promotes going out and walking to different locations to collect virtual rewards [255]. The legs, including the thigh, knee and shin, are also often used to carry sensors. Some systems rely on electrodes that are placed on the leg to measure muscle activity when engaging in muscle training [294], while others place the sensors on thighs to improve the accuracy of fall predictions [155] or gait cycle detection [120]. Other systems position sensors around the waist on a belt, e.g., for a gait assessment application [257], or attached to the chest, e.g., to measure the heart rate [66]. Some systems place sensors near the wrist or hand of the older adult, e.g., a ring-type pulse sensor on the finger [291] or a watch around the wrist to track activities of daily living [238]. To measure activities related to arm movement, e.g., in case of

monitoring symptoms of Parkinson’s disease [78] or assess functional activity [221], the sensors are attached to the upper or lower part of the arms. Head, back, and trunk more generally are less frequently used to attach sensors.

Note that systems can rely on more than one sensor to collect activity data. These sensors can be placed on different parts of the body and therefore are included in all relevant body part categories (see figure 4).

Fig. 4. Placement of tracking sensors on the body

In exactly half of all cases (102 of 204 papers, 50.0 %), wearables are the only hardware required for the tracking system. For the other half, additional hardware is required, e.g., a receiving device that collects sensor data wirelessly, a computer, or a television screen. Hence, while these systems use a wearable device in some way, certain functionality can only be used in certain places or limited areas.

5.1.4 Data Processing. Most systems (109 of 204 papers, 53.4 %, see table 7) rely on forwarding raw sensor data to either nearby listening devices (102 of 204 papers, 50.0 %), or to remote web servers (7 of 204 papers, 3.4 %) that collect and process the received data (e.g., [188, 273]). Other systems (30 of 204 papers, 14.7 %) log all data in a file that has to be transmitted manually to a different device for processing or send the file automatically after an event, for instance, when an exercise is completed (e.g., [45]). Eight of 204 papers (3.9 %) discuss systems that have the possibility to choose between forwarding and logging data or combine both methods at the same time (e.g., [136]). Some systems process the data in real time (69 of 204 papers, 33.8 %). This makes it possible to give immediate feedback to older adults about a performed activity, e.g., through vibrations as a performance indicator when engaging in exercises [90], or when using a smartphone to detect falls [85]. Smartphones can also process data in real time, which is required for applications that involve exergames or gamified experiences (e.g., [231]). A limited number of papers (4 of 204, 2.0 %) does not explain the data flow within the system, rendering it impossible to draw conclusions about how the data is handled.

The benefit of systems that process data directly on the body of the older adults is that they lend themselves well to a broader range of locations and use contexts, such as outdoors or places without an available Internet connection. Therefore, smartphones are often used as a processing device (e.g., [53, 113]). In some cases, older adults carry additional hardware, such as microcontrollers, to process collected data [208].

5.1.5 Data Output. Processed results about the physical activity are most often reported on a computer screen (122 of 204 papers, 59.8 %, see table 8) or a smartphone (52 of 204 papers, 25.5 %). A different way to share results is through actuators, e.g., to assist older adults with decreased muscle strength in standing up from a seated position [196]. Other systems use a VR headset (6 of 204 papers, 2.9 %) to augment the experience of older adults while engaging in physical activity (e.g., [99]). Five of 204 systems (2.5 %) use a smartwatch to display data on the physical activity (e.g., [24]). Other types of screens, e.g., televisions (3 of 204 papers, 1.5 %), are used for exergames (e.g., [243]), while tablets (2 of 204 papers, 1.0 %) are applied as picture frame-like interactive devices [5]. Two of 204 systems (1.0 %) rely on audio to provide personal assistance to older adults and visually impaired people [250]. The remaining seven of 204 papers (3.4 %) do not disclose how their system shares data. Some systems share data in more than one way, for instance, both through speakers and a screen, which results in these systems to be included in both categories. The way systems communicate their data with users has important implications for their use. For instance, outputting results on a television screen or a computer screen limits the portability of a system and, therefore, potential use contexts.

5.1.6 Target Audience. All papers explicitly refer to older adults as potential users, albeit with different concepts of what constitutes an older adult. The minimum age authors maintain to define older adults varies between papers, i.e., 55, 60 or 65 years old. These ages are used in 156 of 204 papers (23.5 %). The remaining papers (48 of 204, 76.5 %) do not mention a specific minimum age in their definition of older adults. While chronological age is not the only element relevant when trying to define late life, in most developed countries, 65 is widely accepted as the age to consider a person to be an older adult [285]. Similarly, we consider people over 80 to be in the category of oldest old. Compared to older adults, they show important differences in the way they wish to interact with technology in general, e.g., due to rapid development cycles [280].

Some systems explicitly target a specific group of people, such as *frail* older adults (41 of 204 papers, 20.1 %, see table 9), e.g., systems that aim to detect markers of frailty by combining accelerometer data and clinical information [88]. Other systems (28 of 204, 13.7 %) are aimed at people living with a chronic disease or illness, e.g., to monitor walking in pulmonary patients [132], or healthy older adults (9 of 204 papers, 4.4 %), e.g., to promote physical activity [260]. Interestingly, no system specifically targets active older adults, suggesting that PA as a form of leisure among older adults is currently insufficiently addressed by the research community.

Moving beyond older adults, 56 of 204 papers (27.5 %) discuss utility of systems for other groups of people, e.g., working parents and pregnant people to monitor standing up and sitting down transitions [22], persons who underwent surgery [45] or children in weight clinics [23]. All other papers (148 of 204 papers, 72.5 %) do not specify whether additional demographics would benefit from using the system.

5.1.7 Summary for RQ1. The intended purpose of most systems is to supervise the levels of physical activity of older adults, the progress they make during rehabilitation or to detect critical events, such as falls. More than half the systems rely on an accelerometer to track physical activity. The most tracked activity is walking, along with all related ones, such as running and jogging. Since accelerometers can track step detection and walk intensity, it is the most commonly used sensor in activity tracking systems. Tracking systems often rely on sensors included in devices such as smartphones, which can be carried in hand or in a pocket. Other systems attach sensors to the legs of the older adult (thigh, knee or shin) or at the waist. Generally, there is a big focus on older adults who are identified as *frail* or *ill*, with few systems addressing the needs of healthy older adults.

5.2 RQ2: How were older adults involved in the design and evaluation stages?

5.2.1 Design stage. The majority of papers (193 of 204, 94.6 %, see table 10) does not specify how systems were designed in terms of interaction between person and system. Only 11 of 204 papers (5.4 %) elaborate on the design process. All of these systems aim to *support* older adults in engaging in physical activity.

In ten of 204 papers (4.9 %), the authors describe a user-centered approach to design the system. Nine systems (4.4 %) support the execution of prescribed exercises, e.g., balance and muscle strength-improving exercises to prevent falls [70, 124], or exergames, e.g., a smartphone game that encourages walking, jogging and running and adapts to the abilities of the user [32]. The remaining system (0.5 %) uses an interactive photo frame that serves as a virtual coach to motivate older adults to walk [5].

Only one of the 204 papers (0.5 %) explicitly applied a participatory design approach, where participants were not only consulted as a source of relevant information, but actively shaped the design of the technology. This system involved kinesiologists, therapists and people with dementia in the design of a VR exercise application for people with mild cognitive impairment [72].

More specifically, when a user-centered or participatory design approach was applied, different kinds of populations were involved in the process, e.g., older adults, healthcare professionals, and patients. Table 11 presents an overview of the involved stakeholders.

5.2.2 Evaluation Stage. User involvement is more prevalent in system evaluation. The majority of papers (147 of 204, 72.1 %) included participants in assessing the usefulness of a given technology. While all systems are aimed at a specific or more general group of older adults, only 79 systems (38.7 %) involved at least one participant aged 65 or older (see table 12). In this context, 42 papers (20.6 %) did not include people older than 65, suggesting a disconnect between target audience and evaluation approach. The papers of the remaining 26 evaluated systems (12.7 %) do not explicitly report whether an older adult was included in the evaluation process.

Young adults are also involved in the evaluation of the systems (62 of 204 papers, 30.4 %). In some cases, they serve as proxies for older adults, for example, when evaluating a fall detection system (e.g., [159, 169, 295]). This implies a trade-off between the safety of the older adults and validity of the system as movement patterns and the subsequent risk of falling differ between age groups [47].

In terms of system evaluations, 147 of 204 papers (72.1 %) discuss system performance along parameters such as accuracy and efficiency of the applied algorithms or overall usability. However, only 16 papers (7.8 %) explicitly mention an evaluation concerning user experience. All of those discuss a system with a purpose of supporting older adults – which follows given that supervising technologies conceptualise older adults as passive input source. To evaluate user experience (UX), seven papers (3.4 %) exclusively used questionnaires. Five papers (2.4 %) conducted both interviews and questionnaires, while four papers (2.0 %) assessed UX through interviews (see table 13).

Most of these papers (14 of 204, 6.9 %) report overall positive results. For example, study participants found the interface of a system that provides limb exercises stimulating and liked the easy setup due to auto-calibration [31]. In other studies, participants enjoyed a system for encouraging physical activity through exergames, said it improved their social life and they would buy it if it were available [144]. In terms of neutral and negative outcomes, one paper (0.5 %) reports mixed findings concerning user experience, where some persons liked a balance exercise system and others did not [124]. Another paper (0.5 %), describing a golf game in the real world by using the phone as a virtual golf club [231], presents a more nuanced result concerning UX. There were no usability issues and the comparatively young study participants liked the level of realism of the application, but they did not find the game to be satisfactory due to slow loading of the map.

However, for the UX evaluation of this system, no older adults were included, as the system targets arthritis patients as a general audience rather than older adults exclusively.

Looking at our findings, it is difficult to determine a trend regarding older adults' experiences in the context of wearables and PA provision. Given the small number of systems that explored UX, this highlights a research opportunity for future work in this area: the field currently lacks a good understanding of the experiences older adults have with software systems associated with wearables to support their physical activity, and there is little focus on the suitability, comfort, and UX that the actual wearable offers to the population.

5.2.3 Summary for RQ2. Our results show that older adults have limited involvement in the system design of wearables tracking their physical activities; they were part of only seven of 204 design processes, two of which additionally included experts or other relevant users. However, older adults were better represented during the evaluation stage, where little more than one third of the analyzed systems included at least one person aged 65 or more in the evaluation process. Sometimes, young proxies for older adults evaluated the technologies, even when systems specifically targeted older adults. Evaluation tends to focus predominantly on system and usability testing; only 16 papers discuss how they also gauged user experiences. In these cases, reported experiences were generally positive, with only few papers reporting more nuanced results.

6 DISCUSSION

Based on an analysis of 204 papers, we present two main takeaways. **(1) Use of wearable technology to supervise rather than support physical activity among older adults:** Our findings suggest that the vast majority of approaches conceptualise physical activity from a supervisory perspective, leveraging wearables as a means of monitoring older adults in the context of health-related interventions. This can concern activity in the context of daily living (e.g., fall detection), or medicalized PA in the context of rehabilitation. In contrast, only a small number of systems focuses on the support or encouragement of physical activity. Among these, the most common activities are exercising (e.g., executing specific instructions for rehabilitation or muscle training, or playing exergames that include wearable devices) and walking. **(2) Lack of involvement of older adults in technology design and evaluation:** Only a small number of papers report the active participation of older adults in the design of wearables for physical activity tracking. A bigger set of papers involves older adults at the evaluation stage. However, the focus on the experience provided by such systems is limited. Here, we discuss and contextualize these findings and their implications, contrast them with approaches to physical activity in Sports and Rehabilitation Science, and highlight opportunities for the design of wearables to support physical activity with older adults.

6.1 Supervising Versus Supporting Physical Activity Among Older Adults

In our review, we illustrated that many systems take on a core stance of either *supervising* or *supporting* older adults in physical activity – rarely both. Supervising systems collect data on the state of the wearer, for instance, the current activity of the person, whether they fell or not, or if they engage in sufficient PA. Through these results, doctors, therapist, family members, and caregivers in general can infer the physical abilities of older adults and assess further needs. Supporting systems promote agency in older adults by sharing data with them, thereby giving them a tool to track their own activity and assist them to rehabilitate or maintain health. Our findings show a strong focus on systems that supervise older adults while being physically active, i.e., wearable monitoring systems that are worn during daily living or while walking. Many of these systems take a healthcare-centered perspective, and activity is tracked to either prevent or treat identified ailments. Given the prevalence of the active ageing paradigm both in Sports Science [79] and

the Human-Computer Interaction research community [108, 281], as a result of worldwide policy focus to maintain the health and functional capacity of older adults [285, 288], the prevalence of supervising systems warrants further reflection.

On the one hand, supervising systems hold the promise of allowing societies to manage a continuously growing older demographic, potentially facilitating ageing in place, and contributing to self-managed and therefore more affordable rehabilitation schemes. Such systems inherently require a monitoring component to facilitate the work of healthcare professionals or care providers. On the other hand, taking a supervisory approach entails the risk that older adults are predominantly seen as passive entities that are externally monitored which is evidenced by the existence of systems that do not share data with older adults, but make them exclusively available to healthcare professionals (e.g., [142, 158]), and additionally reflected in the lack of involvement of older adults as active stakeholders in the development of wearable systems. Viewing older adults as entities who need to be ‘fixed’ or ‘managed’ is a research practice previously criticized both by Sports Science (e.g., [203]) and critical work in Human-Computer Interaction (e.g., [281]). Despite these widely recognized findings, our review suggests that the practice of paternalising older adults in the design of systems that support active ageing and facilitate ageing in place still prevails. Likewise, systems that specifically aim to support and motivate older adults to remain or become physically active, often focus on performing externally established exercises or walking. While walking is one of the more preferred pastimes of older adults [252], it provides a limited choice of activity, as older adults enjoy engaging in a range of activities including (but not limited to) gardening activities, playing sports, swimming, dancing, golfing, or yoga [48, 80, 177, 205, 233, 252]. This mismatch between tracked and preferred activities implies that the research community needs to make a bigger effort to involve and listen to older adults to support the development of technology that more suitably address their needs and desires.

6.2 Involving Older Adults in System Design and Development

Many systems do not involve older adults at either the design or evaluation stage. This is a challenge in many respects: research into the effectiveness of wearables encouraging general audiences to engage in physical activities has demonstrated the importance of ‘functioning at HCI level’ (i.e., the usability and user experience that are provided) [75], and previous work on HCI and older adults has further highlighted the need to adapt systems for the oldest old [280]. Additionally, wearable systems introduce a new level of complexity in terms of system design: it is not only necessary to adapt the software component to the needs and preferences of older users; the design and placement of the wearable also play an important role in system adoption. Hence, systems need to be responsive to the desires of end-users, for example, in terms of ergonomic features, supported activities, and bodily placement. A lack of evaluation with the core target audience can have implications for system safety, e.g., in the context of fall detection or rehabilitation: as movement and, subsequently, fall patterns differ between the age groups [152, 160], the validity and reliability of systems is fundamentally challenged if evaluations are carried out with younger participants. Here, user-centered and participatory design are approaches that have a long-standing history in the human-computer interaction research community and have been demonstrated to successfully leverage core stakeholders’ perspectives. However, it is important to understand that despite their benefits, these design philosophies are no panacea: reconciling older adults’ preferences into a single solution can be challenging [63], and involving vulnerable end-users (e.g., older adults at risk of falls) in system evaluations needs to be carefully considered in the light of ethical conduct. Likewise, systems that support rehabilitation rather than general physical activity have a greater need for prescriptive activity, and may have to follow specific exercise routines, leaving less room for adjustment to individual preferences of older adults in terms of PA. Yet, this

does not justify exclusion of older adults during the design and evaluation phases altogether: only by attending to the perspectives and opinions of older adults as a systematic component of the research and development process, resulting systems have a chance in appropriately addressing their needs.

6.3 Opportunities for Future Research

Our findings reveal a number of gaps in current research addressing wearable technology, physical activity, and older adults. We outline two potential areas for future work from the perspective of Human-Computer Interaction, taking into account requirements and recommendations from Sports Science.

6.3.1 Older adults as actors with agency in development processes. Increased involvement of older adults during design and evaluation has the potential of resulting in wearable tracking systems that better meet the population's needs and preferences – as evidenced in previous research (e.g., [62, 134, 274, 292]). This is not limited to pragmatic aspects thereof, such as the goal to remain physically healthy, but also includes hedonic needs and preferences [109], e.g., memories and emotions that a system or an activity can evoke, or the way a system is presented in terms of looks and interaction flow. This can lead to an increased appeal and higher levels of enjoyment when using the system, with a positive user experience being an important precursor for prolonged system use, and, by extension, engagement in physical activity ([144, 178, 212]).

Likewise, involving older adults in the design and evaluation of wearable solutions to track PA recognizes them as independent actors with agency to make their own decisions, and make space for their preferences and needs (also see Cozza et al. [57] for a further exploration of this argument). Particularly in the context of PA, this could be a first step toward empowering older adults to shape the very technologies designed to support them in becoming more physically active, maintaining existing levels of PA, or exploring new forms of PA as a means of broadening leisure activities.

6.3.2 Aligning activities with those enjoyed by older adults and recommended by Sports Science. Adhering to physical activity recommendations as stated by Sports Science can be challenging for anyone. Specifically targeting older adults, the WHO recommendations include at least 150 minutes of moderate-intensity or at least 75 minutes of vigorous-intensity aerobic exercises per week [287], and are worded in an abstract way that can make it difficult for individuals to translate the advice into concrete, suitable activities. Likewise, our review shows that the majority of existing systems does not guide older adults in how to be physically active, but rather passively monitors their activity. Hence, we identified a potential to expand on the third category of systems – those that support physical activity with a perspective to reaching recommended levels of activity, while providing older adults with more freedom in the choice of activity and providing support and inspiration where needed. Drawing from the previously suggested user-centered approaches toward the development of such solutions could provide further insights into how to support PA in a way that aligns with the preferences and needs of older persons: the core challenge lies in the design of technology geared towards enabling older adults to contextualize PA recommendations for their individual lives, and make informed choices that are meaningful to them. In this context, perspectives from critical Sports Science (e.g., Phoenix on pleasure as a motivator to stay physically active [204]) can provide further insights into the role of PA as leisure and source of enjoyment in late life.

6.4 Limitations

We were specifically interested in the design and implementation of wearable systems for older adults. As a result, we narrowed down our literature query to databases relevant for those fields,

which drive technological advancements on wearables and provide new algorithms that allow more complicated activity tracking. We searched for work in the ACM and IEEE databases, but potentially missed out on work only available in other digital libraries, such as PubMed or Embase. In doing so, we have omitted work in other fields (e.g., medical disciplines and Rehabilitation Science). Furthermore, our review adopts a loose definition of the term ‘wearable’, and also includes systems leveraging smartphone sensors in analysis. Future work that aims to explore the potential of wearables for older adults in more depth may focus on only including systems directly attached to the users’ body in analysis: we would expect that user perspectives on systems will differ depending on how and where a system is worn. Likewise, our review provides basic insights into wearables for older adults, but does not explore the design of visualization components for this audience in depth. Additional research will be required to draw conclusions on these aspects, for example, building on previous projects in Human-Computer Interaction that more generally explore technology and PA for older adults (e.g., [68, 82]). Our work adopts the perspective of Human-Computer Interaction, but also analyses work carried out within this research community (as the ACM database also includes the most prestigious venues in HCI). Here, it is important to note that while propagating user-centered development approaches, the community itself does not always meet this standard, and further reflection is recommended to how and whether meaningful user involvement in development processes can be achieved realistically. Likewise, if users are involved in evaluations, there often are no standards as to what such evaluations should entail, making a systematic comparison of systems with respect to usability and effectiveness challenging. Here, we hope that the Computer Science and Engineering research communities will come together in the future to explore avenues toward ensuring rigor in system evaluations particularly when the deployment context is health.

Finally, our work may be of interest to other research communities beyond Computer Science and Engineering. In this context, we acknowledge several differences in methods and approaches to literature reviews between research communities and point out these limitations related to our method. Most importantly, we would like to point out that no librarian was used for this review. Additionally, the first author was responsible for searching and analysing all papers; while the review was not done in duplicate, key findings were discussed by all authors.

7 CONCLUSION

This paper provides an overview of wearable systems for tracking physical activity among older adults within the Computer Science and Engineering communities. For this systematic review, we analyzed 204 papers presenting such systems.

Our results show an overrepresentation of systems that *supervise* physical activity of older adults in the context of ageing in place and rehabilitation, leaving little room for systems that can *support* individuals desiring to stay active. As a result, the majority of systems only tracks walking instead of allowing for a broader range of activities commonly enjoyed by older adults; very few systems are relevant for healthy older adults, and there is little concern for enjoyment of PA as a form of leisure.

Likewise, the analysis of design and development processes revealed that older adults are rarely involved, which offers a possible explanation for the mismatch in supported activities. This highlights future research opportunities that build more useful, supportive and enjoyable systems through the involvement of older adults in development processes, which, in turn, holds the promise of improving system engagement, adherence to physical activity recommendations, and increased quality of life promised by many of the wearable solutions addressing older users.

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A ACM QUERY

Let X = (ageing "age-related" aging elderly elders geriatric gerontechnology gerontology grandfather grandmother grandparent "later life" "life course" "older adults" "older people" retired retiree seniors) and Y = (exercise fitness "physical activity" sport).

Query: (acmdlTitle: X OR recordAbstract: X OR keywords.author.keyword: X) AND (acmdlTitle: Y OR recordAbstract: Y OR keywords.author.keyword: Y)

B IEEE QUERY

(ageing OR "age-related" OR aging OR elderly OR elders OR geriatric OR gerontechnology OR gerontology OR grandfather OR grandmother OR grandparent OR "later life" OR "life course" OR "older adults" OR "older people" OR retired OR retiree OR seniors)

AND

(exercise OR fitness OR "physical activity" OR sport)

C CATEGORIES AND PARAMETERS FOR ANALYSIS

- System information
 - Tracked activities
 - Purpose
 - Supervising/supporting/both/unspecified
 - Body placement
 - Sensor type
 - Non-wearable hardware required? (yes, no, unspecified)
 - Data processing modality (forwarding, processing, logging)
 - Where are the results shown?
 - Does the user have access to the results? (yes, no, unspecified)
 - Who else has access to the results?
- Target audience
 - Target age
 - For healthy older adults? (yes, no, unspecified)
 - For frail older adults? (yes, no, unspecified)
 - For ill older adults? (yes, no, unspecified)
 - For active persons? (yes, no, unspecified)
 - For inactive persons? (yes, no, unspecified)
 - For whom other than older adults?
- System evaluation
 - Is UX evaluated? (yes, no, unspecified)
 - How is UX evaluated?
 - Does the author mention a conducted evaluation? (yes, no)
- User involvement
 - How was the system interaction designed? (related to HCI)
 - Who was involved in the design process?
 - Was at least one person (65+) involved in the evaluation? (yes, no, unspecified)
 - Was at least one person younger than 55 involved in the evaluation? (yes, no, unspecified)

D REFERENCE OVERVIEW BY CATEGORY

Table 3. System purpose of all papers classified as supervising, supporting, or both

Purpose	Systems	Papers
Supervising	52.0 %	[2, 7, 9, 18, 19, 21, 27, 28, 33–35, 40–45, 49, 50, 53, 56, 59–61, 65–67, 73, 77, 78, 83, 84, 86, 88, 89, 104, 110, 111, 113, 115, 116, 118, 120, 121, 126–129, 132, 135–141, 143, 147–149, 155, 158, 159, 161, 169, 172, 182, 186, 188–193, 195, 198, 200, 207, 216, 221, 222, 225, 226, 230, 232, 234, 235, 237, 239, 241, 242, 248, 249, 254, 257–259, 262, 266, 267, 269, 278, 282, 290, 293, 296]
Supporting	37.2 %	[3, 5, 8, 10, 11, 15, 24, 25, 30–32, 37, 38, 58, 70, 72, 85, 90, 98–100, 102, 105, 106, 112, 114, 119, 122–125, 130, 144, 146, 150, 156, 157, 163–165, 167, 170, 173, 187, 196, 197, 199, 202, 208, 213–215, 219, 227, 228, 231, 238, 243, 244, 251, 255, 256, 260, 261, 263, 270–273, 275–277, 279, 284, 291, 294]
Both	6.4 %	[14, 23, 26, 117, 142, 154, 220, 223, 246, 250, 283, 295, 298]
Unspecified	4.4 %	[12, 22, 39, 46, 69, 174, 176, 184, 218]

Table 4. Overview of activities and the relative amount of systems tracking these activities. ADL refers to ‘activities of daily living’

Activity	Systems	Papers
Walking	42.6 %	[5, 7–9, 12, 18, 24, 32, 34, 35, 44, 45, 49, 56, 59, 60, 65, 67, 69, 70, 77, 83, 89, 99, 102, 104, 113, 116, 117, 120, 125, 126, 129, 132, 135, 137, 139, 142, 143, 147–150, 161, 165, 169, 174, 176, 186, 188–190, 197–200, 215, 216, 218, 220–222, 225, 226, 228, 230–232, 237, 239, 241, 254–257, 260–262, 266, 267, 269, 270, 275, 283, 291, 293, 298]
Exercising	23.5 %	[3, 10, 11, 15, 21, 26, 30, 31, 37, 38, 46, 59, 70, 72, 73, 85, 90, 98, 100, 112, 119, 123, 124, 127, 130, 144, 146, 154, 156–158, 163, 170, 184, 187, 202, 208, 213, 214, 219, 227, 235, 243, 244, 271, 272, 294, 295]
ADL	19.1 %	[2, 12, 19, 21, 23, 27, 40–42, 50, 53, 66, 78, 105, 110, 111, 114, 118, 121, 128, 136, 140, 159, 164, 172, 182, 192, 195, 207, 238, 242, 249, 250, 258, 259, 263, 276, 278, 282]
Falling	11.3 %	[26, 41, 43, 44, 65, 66, 84, 115, 118, 128, 129, 138, 155, 159, 161, 193, 202, 234, 263, 278, 293, 295, 296]
Running	6.4 %	[7, 9, 24, 32, 69, 77, 83, 102, 117, 139, 165, 275, 283]
Biking	3.9 %	[7, 14, 69, 83, 86, 122, 139, 284]
Jogging	2.9 %	[7, 32, 104, 169, 173, 218]
Swimming	0.5 %	[61]

Table 5. Overview of the sensors used to track physical activities

Sensor	Systems	Papers
Accelerometer	84.8 %	[2, 5, 7–9, 11, 12, 14, 15, 18, 19, 21–28, 31, 33, 35, 37–39, 41–46, 49, 50, 53, 56, 58–61, 65–67, 69, 70, 73, 77, 78, 83–86, 88–90, 98–100, 102, 105, 106, 110–118, 120, 121, 123–128, 130, 132, 135–143, 146–149, 154–159, 161, 163, 165, 167, 169, 170, 172–174, 176, 182, 184, 186, 188–193, 195, 198, 199, 207, 213, 215, 216, 218–223, 225–228, 230–232, 234, 235, 237–239, 241–244, 249–251, 254, 257–259, 262, 263, 266, 267, 269–273, 275, 276, 278, 279, 283, 290, 291, 293, 295, 296, 298]
Gyrosensor	32.8 %	[7, 12, 18, 21, 26, 31, 35, 37, 49, 53, 56, 58, 59, 61, 65, 66, 83, 85, 90, 98–100, 111, 117, 118, 120, 126, 130, 135, 136, 141–143, 147–149, 156, 157, 163, 170, 174, 186, 189, 190, 195, 199, 216, 219, 222, 223, 225–227, 235, 239, 241–243, 250, 251, 254, 262, 267, 271–273, 279]
Heart rate	13.7 %	[9–11, 14, 19, 27, 33, 40, 41, 65, 67, 86, 119, 127, 154, 173, 228, 234, 242, 249, 258, 275, 283, 284, 290, 291, 295, 298]
Magnetometer	13.2 %	[21, 31, 35, 56, 59, 61, 83, 85, 90, 100, 117, 136, 141, 142, 156, 157, 170, 195, 219, 227, 235, 241, 243, 250, 271–273]
GPS	7.4 %	[7, 9, 32, 110, 150, 173, 231, 234, 250, 255, 256, 263, 266, 275, 291]
Pressure	6.4 %	[33, 99, 111, 118, 125, 170, 197, 199, 235, 241, 250, 260, 261]
Muscle	3.9 %	[40, 196, 202, 221, 228, 234, 284, 294]
Blood pressure	2.5 %	[11, 14, 86, 127, 291]
Oximeter	1.0 %	[10, 32]

Table 6. Sensor positions

Position	Systems	Papers
Handheld	26.0 %	[7, 11, 15, 22, 28, 32, 33, 37, 43, 53, 83, 88, 90, 105, 106, 110, 113, 121, 123, 127, 132, 136–138, 144, 146, 147, 150, 163–165, 167, 170, 174, 213, 215, 218, 220, 223, 227, 228, 230, 231, 239, 248, 251, 255, 256, 263, 266, 275–277, 291]
Leg	18.6 %	[12, 21, 31, 34, 46, 56, 59, 60, 85, 98, 104, 120, 126, 129, 130, 141, 142, 147, 154, 155, 186, 188, 191, 195–197, 199, 221, 222, 246, 260, 262, 269, 271, 272, 278, 284, 294]
Waist/belt	17.6 %	[10, 27, 38, 60, 89, 90, 102, 116, 117, 125, 126, 130, 142, 154, 156, 157, 161, 169, 172, 173, 184, 193, 198, 199, 221, 232, 237, 254, 257–259, 261, 269, 270, 283, 293]
Chest	15.2 %	[12, 27, 34, 41, 42, 45, 59, 60, 65, 66, 104, 119, 128, 129, 141, 142, 154, 155, 161, 189, 190, 221, 228, 234, 243, 246, 250, 262, 278, 290, 295]
Hand/wrist	12.7 %	[2, 3, 12, 19, 24, 25, 34, 39, 43, 50, 59, 61, 140, 164, 176, 182, 208, 219, 238, 242, 243, 258, 259, 283, 291, 298]
Foot/shoe	12.3 %	[5, 14, 18, 26, 33, 99, 104, 111, 118, 141, 143, 147–149, 184, 199, 216, 225, 226, 234, 241, 244, 261, 267, 273]
Arm	7.8 %	[21, 27, 31, 35, 58, 59, 78, 85, 100, 154, 164, 187, 191, 195, 221, 243]
Head	6.9 %	[32, 58, 59, 72, 99, 122, 154, 173, 195, 200, 214, 249, 250, 284]
Clothes/pocket	5.4 %	[8, 23, 33, 40, 41, 44, 67, 69, 77, 124, 139]
Ankle	4.9 %	[35, 70, 120, 129, 135, 184, 235, 258, 259, 296]
Back	2.5 %	[12, 112, 158, 192, 207]
Trunk	2.5 %	[21, 35, 73, 222, 290]

Table 7. Overview of how data is handled by the systems: forwarded to a separate device, processed on the body, or logged in a file for future processing

Data handling	Systems	Papers
Forwarded	53.4 %	[9, 10, 14, 15, 18, 21, 23, 26, 27, 30, 33, 34, 37, 38, 40, 41, 43, 46, 50, 56, 59, 60, 66, 67, 70, 72, 73, 77, 78, 84, 86, 99, 100, 104, 112, 115, 118–120, 122, 124, 126, 129, 130, 135–137, 139–144, 148, 149, 154, 155, 158, 159, 161, 163, 165, 167, 169, 184, 186–188, 191–193, 195–197, 199, 200, 202, 207, 213, 214, 216, 219, 225–227, 234, 237, 241, 243, 246, 249, 254, 257, 267, 269–273, 277, 278, 282–284, 290, 293–296]
Processed	33.8 %	[2, 3, 7, 8, 19, 22, 24, 25, 28, 31, 32, 44, 53, 58, 61, 83, 85, 88, 90, 102, 106, 110, 113, 116, 117, 121, 123, 125, 127, 128, 132, 138, 146, 147, 150, 156, 157, 164, 174, 176, 208, 215, 218, 220, 223, 228, 230, 231, 234, 235, 238, 239, 242, 244, 248, 250, 251, 251, 255, 256, 260, 261, 263, 266, 275, 276, 279, 291, 298]
Logged	14.7 %	[5, 12, 21, 23, 24, 30, 35, 39, 42, 45, 59, 65, 69, 88, 89, 105, 111, 136, 170, 172, 173, 182, 189, 190, 198, 222, 232, 258, 259, 262]
Unspecified	2.0 %	[49, 98, 114, 221]

Table 8. Output devices used by the systems to display results

Output device	Systems	Papers
Computer/web	59.8 %	[8–10, 14, 15, 18, 21, 27, 30, 34, 35, 37–43, 45, 46, 50, 56, 59, 60, 65–67, 69, 70, 73, 77, 78, 86, 89, 98, 100, 102, 104, 111, 112, 115, 116, 118–121, 124–126, 129, 130, 135, 137, 139–144, 148, 149, 154, 155, 159, 161, 163, 167, 169, 170, 172, 173, 182, 184, 186–193, 195, 198, 199, 202, 207, 216, 219, 222, 225–228, 232, 235, 237, 241, 242, 246, 249, 254, 257–260, 262, 267, 269–273, 277, 278, 282–284, 290, 293–296]
Phone	25.5 %	[7, 11, 22, 23, 28, 31–33, 53, 58, 83, 85, 88, 90, 105, 106, 110, 113, 117, 127, 128, 132, 136, 138, 146, 147, 150, 164, 165, 174, 218, 220, 223, 228, 230, 231, 234, 239, 242, 248, 250, 251, 255, 256, 263, 266, 275, 276, 279, 291, 295, 298]
Actuator	3.9 %	[3, 156, 157, 196, 197, 208, 260, 261]
Unspecified	3.4 %	[12, 19, 44, 49, 114, 215]
VR headset	2.9 %	[26, 72, 99, 122, 200, 214]
Watch	2.5 %	[2, 24, 61, 176, 238]
TV screen	1.5 %	[73, 213, 243]
Loudspeaker	1.0 %	[102, 250]
Tablet	1.0 %	[5, 244]

Table 9. The tracking systems’ target audience. All categories specifically apply to older adults, except for ‘Other’, which includes, for instance, children or pregnant women

Target audience	Systems	Papers
Other	27.5 %	[3, 18, 22, 23, 27, 31, 33, 34, 43, 45, 65, 67, 77, 78, 84, 90, 98, 100, 104, 114, 119, 123, 130, 132, 137, 138, 141, 146, 147, 156–158, 161, 163, 165, 174, 184, 195, 200, 208, 218, 219, 221–223, 234, 242, 244, 246, 248, 250, 256, 262, 269, 290, 293]
Frail	20.1 %	[23, 26, 28, 60, 72, 73, 88, 89, 99, 100, 113, 119, 121, 137, 141, 142, 147, 149, 155, 158, 176, 188, 196, 197, 202, 208, 219, 223, 227, 230, 237, 244, 250, 251, 260, 261, 271–273, 277, 279]
Ill	13.7 %	[23, 31, 34, 60, 78, 89, 90, 120, 121, 130, 132, 137, 141, 147, 157, 191, 195, 200, 219, 222, 223, 226, 231, 242, 251, 254, 259, 267]
Healthy	4.4 %	[27, 73, 141, 157, 226, 230, 242, 254, 260]

Table 10. Applied approach to design the tracking system, related to interaction between persons and systems

Design approach	Systems	Papers
Unspecified	94.6 %	[2, 3, 7–12, 14, 15, 18, 19, 21–28, 30, 31, 33–35, 37–46, 49, 50, 53, 56, 58–61, 65–67, 69, 73, 77, 78, 83–86, 88–90, 98–100, 102, 104–106, 110–123, 125–130, 132, 135–143, 146–149, 154–159, 161, 163–165, 167, 169, 170, 172–174, 176, 182, 184, 186–193, 195–200, 202, 207, 213–216, 218–222, 225–228, 230–232, 234, 235, 237–239, 241–244, 246, 248–251, 254–263, 266, 267, 269, 270, 272, 273, 275–278, 282–284, 290, 291, 293–296, 298]
User-centered design	4.9 %	[5, 32, 70, 124, 144, 150, 208, 223, 271, 279]
Participatory design	0.5 %	[72]

Table 11. Populations involved in the design process related to interaction between people and systems as percentages of the entire corpus

Population	Systems	Papers
Older adults	2.5 %	[5, 70, 124, 144, 271]
Experts	1.0 %	[150, 223]
Stroke patients & Related users	0.5 %	[208]
Younger adults	0.5 %	[32]
Older adults & Experts	0.5 %	[72]
Unspecified	0.5 %	[279]

Table 12. Populations involved in the evaluation process, papers that did not explicitly mention the age of those involved are omitted here

Population	Systems	Papers
At least one older adult	38.7 %	[5, 8, 12, 18, 25, 27, 30, 34, 35, 37–39, 41, 53, 56, 60, 70, 72, 73, 78, 88–90, 99, 100, 105, 106, 110, 120, 124–126, 132, 135, 141, 143, 144, 157, 167, 176, 182, 187, 189, 190, 193, 195, 198–200, 202, 208, 213, 216, 221, 222, 227, 228, 230, 232, 235, 237, 238, 241, 242, 244, 254, 255, 257–259, 261, 263, 267, 269–272, 276, 298]
At least one younger adult	30.4 %	[2, 8, 9, 14, 22, 24–27, 32, 35, 61, 77, 98, 100, 104–106, 114–116, 119, 122, 129, 130, 132, 135, 139, 148, 156, 159, 165, 169, 170, 172, 173, 176, 184, 186, 192, 195, 198, 221, 225, 226, 228, 231, 239, 244, 249, 251, 255, 256, 260–262, 267, 273, 276, 278, 294, 295]
No older adult	20.6 %	[2, 9, 14, 24, 26, 32, 49, 61, 77, 98, 104, 114–116, 119, 122, 129, 130, 148, 156, 159, 165, 169, 170, 172, 173, 184, 186, 192, 219, 225, 226, 231, 239, 249, 251, 256, 260, 262, 273, 278, 295]

Table 13. Different approaches for evaluating user experience

Applied approach	Systems	Papers
Questionnaires	3.4 %	[60, 119, 144, 167, 231, 244, 255]
Questionnaires and interviews	2.4 %	[5, 31, 122, 124, 271]
Interviews	2.0 %	[24, 30, 165, 272]