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Improved functional assessment in cancer patients using home-based digital technologies

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Accurate assessment of performance status (PS) in oncology care is crucial for improving clinical decisions, therapy selection and anticipated risks of treatment toxicity. While physical function is traditionally assessed in the clinic, in-clinic instruments do not capture the full spectrum of daily functioning. Digital health technologies (DHTs) can address this limitation by passively monitoring patients in their daily environment. Our study showed at-home physical activity and gait metrics from DHTs were associated with self-reported PS in participants with cancer, and these metrics had greater discriminatory power than in-clinic measures among this cohort. The DHT-derived metrics were also significantly correlated with patient-reported-outcomes, and used of the devices was broadly acceptable to study participants. Therefore, integrating DHTs into oncological practice could significantly refine how PS is measured and utilized, ultimately enhancing treatment decision-making and clinical outcomes. (ClinicalTrials.gov NCT03952767).

In oncology, accurately assessing performance status (PS) is crucial, as it is used as a proxy for anticipated tolerance of therapy in a clinical setting characterized by relatively toxic therapies with narrow therapeutic indices. Traditionally, tools such as the Karnofsky Performance Status (KPS) and the Eastern Cooperative Oncology Group (ECOG) performance status scale have been employed to evaluate patients' functional capabilities[1–3]. Each of these measures is typically assessed by clinicians during office visits and consists of a unidimensional, composite scale incorporating a person's ability to engage in activities of daily living, self-care, and work[2,4].

While these PS scales have prognostic value across various cancer types[5–9], these metrics often fail to capture the full spectrum of functional status, especially in older adults, and do not necessarily reflect day-to-day functioning in a home setting[4]. These limitations are critical as the demographics of people with cancer increasingly includes older and more comorbid individuals who may benefit from newer therapies with novel mechanisms of action[10,11]. Such therapies broaden treatment eligibility, necessitating more precise assessment methods to better tailor treatment plans and determine fitness for clinical trial participation.

Recognizing these limitations, researchers and clinicians have developed alternative methods to assess performance status and treatment risk. These methods primarily consist of two broad overlapping approaches. First, standardized, objective physical performance instruments such as the Short Physical Performance Battery (SPPB)[12], Timed Up and Go (TUG)[13], gait speed[14], and stair climb[15] have been evaluated. Such objective physical performance measures have been shown to have prognostic value in people with cancer[14,16–19]. Stair climb power has been recognized by regulatory authorities as a task-based physical assessment that may be suitable as a clinical trial endpoint for individuals with cancer and cancer-related cachexia[15]. Second, among older adults, geriatric assessment (GA) approaches have been adapted to oncology care settings. GA consists of a multidimensional evaluation of an older adult's physical capabilities, function, nutrition, comorbidities, cognition, and psychosocial status, potentially including one or more of the objective physical performance instruments above. Brief GAs have been evaluated in oncology care settings[20,21] and have been shown to identify deficits in older adults otherwise thought to have a good PS on routine evaluations[4,22]. Based on these results, organizations such as the American Society of Clinical Oncology (ASCO) recommend integrating abbreviated versions of GA into the routine care of older adults with cancer[23].

However, both approaches have their own limitations. Either of these assessment approaches requires some specialized training to administer. They are both more time consuming than historical PS assessment methods, which may limit their feasibility during clinic visits. Neither of these approaches allows for individuals to be assessed in their typical day-to-day environment, and neither readily lends itself to regular longitudinal

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reassessment. To date, there is no "gold standard" for assessment of functional status, which remains an important need.

The development of wearable digital health technologies (DHTs) offers an opportunity to enhance the assessment of performance status in this setting. DHTs can provide continuous, real-time data related to an individual's functional status in their home environment, thereby offering a potentially more accurate and dynamic picture of their health and treatment risk[24,25]. DHTs hold the potential not only for improving individual care but also for improving participant selection for clinical trials through more nuanced and timely fitness evaluations. Thus, integrating DHTs into oncological practice could significantly refine how PS is measured and utilized, ultimately enhancing treatment decision-making and clinical outcomes[26].

In this study, we sought to evaluate DHT-derived measures of physical activity and gait from wrist- and lumbar-worn accelerometers and to determine their association with traditional PS metrics. Such DHT-derived measures would offer the opportunity for functional assessment that could be used to guide routine clinical decision making, future clinical trial enrollment, and remote patient monitoring. To further validate the ability of these digital metrics, we compared the at-home physical activity and gait measures derived from participants with cancer to previously studied healthy individuals within younger and older age ranges. The associations between candidate device measures and participant-reported health status were also evaluated.

Results

Population

148 potential participants were assessed for eligibility. Of these, 62 participants consented, enrolled, and completed study activities. 8 of these participants opted for home-based observation only without in-clinic assessments. Thus, for the in-clinic assessments, the final dataset included 54 participants (14 in cohort 1 [KPS 100], 30 in cohort 2 [KPS 80–90], and 10 in cohort 3 [KPS ≤ 70]), whereas for the home-based assessments, the final dataset included 62 participants (17 in cohort 1, 34 in cohort 2, 11 in cohort 3). Among the full cohort, the majority of participants were female (74%, $N = 46$ out of 62) and had breast cancer diagnoses (50%, $N = 31$; Table 1). There were no significant differences across the KPS groups for gender ($X^2(2,62) = 1.24$, $p = .54$), age group ($X^2(2,62) = 6.17$, $p = .19$), and race ($X^2(8,62) = 5.52$, $p = .70$). Participant-reported KPS was assessed serially at in-clinic visits and weekly at home during the study, and the cohort designation for subsequent analyses was based on participant-reported KPS at the earliest available time point. The CONSORT diagram is depicted in Fig. 1.

At-home physical activity and gait measured by DHTs reflect self-reported performance among participants with cancer

During the two week at-home monitoring period, participants' daily activity and gait patterns were continuously measured by a wrist and lumbar device. The KPS scores were stratified into three groupings with self-reported PS as (1) KPS [100] - Normal no complaints; no evidence of disease; (2) KPS [80–90] Able to carry on normal activity, minor signs or symptoms of disease - Normal activity with effort; some signs or symptoms of disease; and (3) KPS [70 below] - Cares for self; unable to carry on normal activity or to do active work, and worse. We observed several measures that were associated with self-reported KPS, such as decreased activity and slower gait speed associated with inferior participant-reported KPS. Figure 2 depicts box plots of the at-home physical activity and gait metrics derived by DHTs stratified by KPS groupings, where each point reflects the average value of a participant's at-home data. The linear regression model showed significant differences in physical activity across KPS groups. For instance, moderate activity time differed by up to an average of 1 h per day (mean difference (95% Confidence Interval (CI)); KPS [100] – KPS [70 below] = 0.94 (0.27, 1.61) hours $p = .007$; KPS [80–90] – KPS [70 below] = 0.73 (0.14, 1.31) hours $p = .016$), and total activity time (non-sedentary) differed by up to 1.5 h (mean difference (95% CI); KPS [100] – KPS [70 below] = 1.54 (0.43, 2.65) hours $p = .009$; KPS [80–90] – KPS [70 below] = 1.24 (0.27, 2.21) hours $p = .016$). Average activity level also differed across the groups (mean difference (95% CI); KPS [100] – KPS [70 below] = 42 (16.1, 67.9) arbitrary units (au) $p = .002$; KPS [80–90] – KPS [70 below] = 37 (14, 59.3) hours $p = .002$).

Participants' average gait speed and steps per day also decreased with lower KPS. Gait speed differed by up to 0.09 m/second (m/s) (mean difference (95% CI); KPS [100] – KPS [70 below] = 0.09 (0.028, 0.157) m/s $p = .006$; KPS [80–90] – KPS [70 below] = 0.07 (0.011, 0.124) hours $p = .02$) and number of steps per day differed by up to 3800 steps per day (mean difference (95% CI); KPS [100] – KPS [80–90] = 1903 (172, 3634) $p = .03$; KPS [100] – KPS [70 below] = 3856 (1735, 5977) $p < .001$, KPS [80–90] – KPS [70 below] = 1953 (87, 3819) $p = .04$); See Supplementary Table 1 for comprehensive list of measures and comparisons).

Clinical outcome assessments do not differ across self-reported performance score in participants with cancer

Assessments of functional performance, including hand grip strength, Short Physical Performance Battery (SPPB) and the 4-meter walk assessment, were performed during in-clinic visits. No significant differences were observed in these measures across the self-reported KPS groups (hand grip strength, mean difference (95% CI); KPS [100] – KPS [70 below] = 1.65 (-4.5, 7.8) kg $p = .6$; KPS [80–90] – KPS [70 below] = 3.4 (-1.94, 8.76) kg $p = .2$; SPPB, KPS [100] – KPS [70 below] = 1 (-0.7, 2.7) $p = .2$; KPS [80–90] – KPS [70 below] = -0.08 (-1.574, 1.407) $p = .9$; 4-meter walk, KPS [100] – KPS [70 below] = -0.007 (-2.8, 2.8) sec $p = 1$; KPS [80–90] – KPS [70 below] = 0.32 (-2.092, 2.739) $p = .8$; See Supplementary Table 1). SPPB weakly or moderately correlated with multiple DHT-derived activity metrics, while hand grip strength correlated with only moderate activity time and mean activity level (See Supplementary Table 2).

Variable	Cohort 1 (KPS 100)	Cohort 2 (KPS 80–90)	Cohort 3 (KPS ≤ 70)	Total
N	17	34	11	62
Gender, N (%)				
Male	3 (17.6%)	9 (26.5%)	4 (36.4%)	16 (25.8%)
Female	14 (82.4%)	25 (73.5%)	7 (63.6%)	46 (74.2%)
Race, N (%)				
White	16 (94.1%)	23 (67.6%)	9 (81.8%)	48 (77.4%)
Black	1 (5.90%)	8 (23.5%)	2 (18.2%)	11 (17.7%)
Asian	0	1 (2.9%)	0	1 (1.6%)
Unknown	0	1 (2.9%)	0	1 (1.6%)
Multiracial	0	1 (2.9%)	0	1 (1.6%)
Age (Years), N (%)				
18–44	5 (29.4%)	6 (17.6%)	1 (9.1%)	12 (19.4%)
45–64	11 (64.7%)	16 (47.1%)	6 (54.5%)	33 (53.2%)
> = 65	1 (5.9%)	12 (35.3%)	4 (36.4%)	17 (27.4%)
Neoplasms N (%)				
Basal cell carcinoma	0	0	1 (9.1%)	1 (1.6%)
Breast cancer	10 (58.8%)	17 (50.0%)	4 (36.4%)	31 (50.0%)
Colorectal cancer	3 (17.6%)	5 (14.7%)	1 (9.1%)	9 (14.5%)
Gastrointestinal cancer	2 (11.8%)	1 (2.9%)	2 (18.2%)	5 (8.1%)
Head and neck cancer	0	1 (2.9%)	0	1 (1.6%)
Leukemia	0	1 (2.9%)	0	1 (1.6%)
Lung cancer	3 (17.6%)	3 (8.8%)	1 (9.1%)	7 (11.3%)
Lymphoma	0	1 (2.9%)	0	1 (1.6%)
Multiple myeloma	0	2 (5.9%)	1 (9.1%)	3 (4.8%)
Mucinous appendiceal adenocarcinoma	0	0	1 (9.1%)	1 (1.6%)
Neuroendocrine cancer	0	1 (2.9%)	0	1 (1.6%)
Pancreatic cancer	0	3 (8.8%)	0	3 (4.8%)
Prostate cancer	0	1 (2.9%)	1 (9.1%)	2 (3.2%)
Renal cancer	0	1 (2.9%)	0	1 (1.6%)

Table 1. Demographic characteristics by KPS. Baseline characteristics of the 62 participants who completed at least the home-based portion of the study, and cohort designation is based on KPS at time of "Visit 1".

Participants with cancer exhibited inferior physical activity and gait metrics compared to healthy participants

We compared DHT-derived at-home physical activity and gait metrics to those observed among previously-studied healthy participants. We had previously shown reductions in at-home activity and gait metrics in older participants compared to younger adults[27,28]. This prior cohort of healthy participants included subgroups of younger ($N = 33$, mean age ± Standard Deviation (SD) [range] = 29.2 ± 4.6 [23–39] years) and older adults ($N = 32$, 72.3 ± 5.8 [65–85] years). When compared to this prior cohort, participants with cancer in the current study had significantly lower activity levels (wrist $N = 56$, 56.7 ± 11.1 [28–76], lumbar $N = 58$, 56.4 ± 12.2 [20–76]) compared to both the younger and older healthy subgroups. Box plots of activity and gait metrics among the healthy individuals and participants with cancer are depicted in Fig. 3. Compared to older healthy participants, who were around 15 years older than the participants with cancer on average, the participants with cancer had 30 to 45 min less time spent in moderate and non-sedentary activity (moderate: mean difference (95% CI); cancer – older healthy = -0.6 (-1, -0.2) hours $p = .004$, non-sedentary: cancer – older healthy = -0.75 (-1.3, -0.13) hours $p = .019$), and walked significantly slower (gait speed; cancer – older healthy = -0.1 (-0.14, -0.06) m/s $p < 10^{-5}$, total number of steps per day – 2625 (-3981,-1268) $p < .001$). See Supplementary Table 3 for all comparisons and model estimates. There was no significant difference in average wear time across the groups.

Patient-reported outcomes correlated with DHT-derived physical activity and gait metrics in participants with cancer

Several correlations between at-home DHT-derived measures and patient-reported outcomes (PROs) were observed, where increased activity and gait speed were correlated with higher reported physical function score (PROMIS Physical Function 10a, Fig. 4) and lower fatigue (PROMIS Fatigue 7a, Fig. 5). Time spent in moderate (Spearman's rho = 0.57, $p < .0001$) and non-sedentary activity (Spearman's rho = 0.55, $p < .0001$) as well

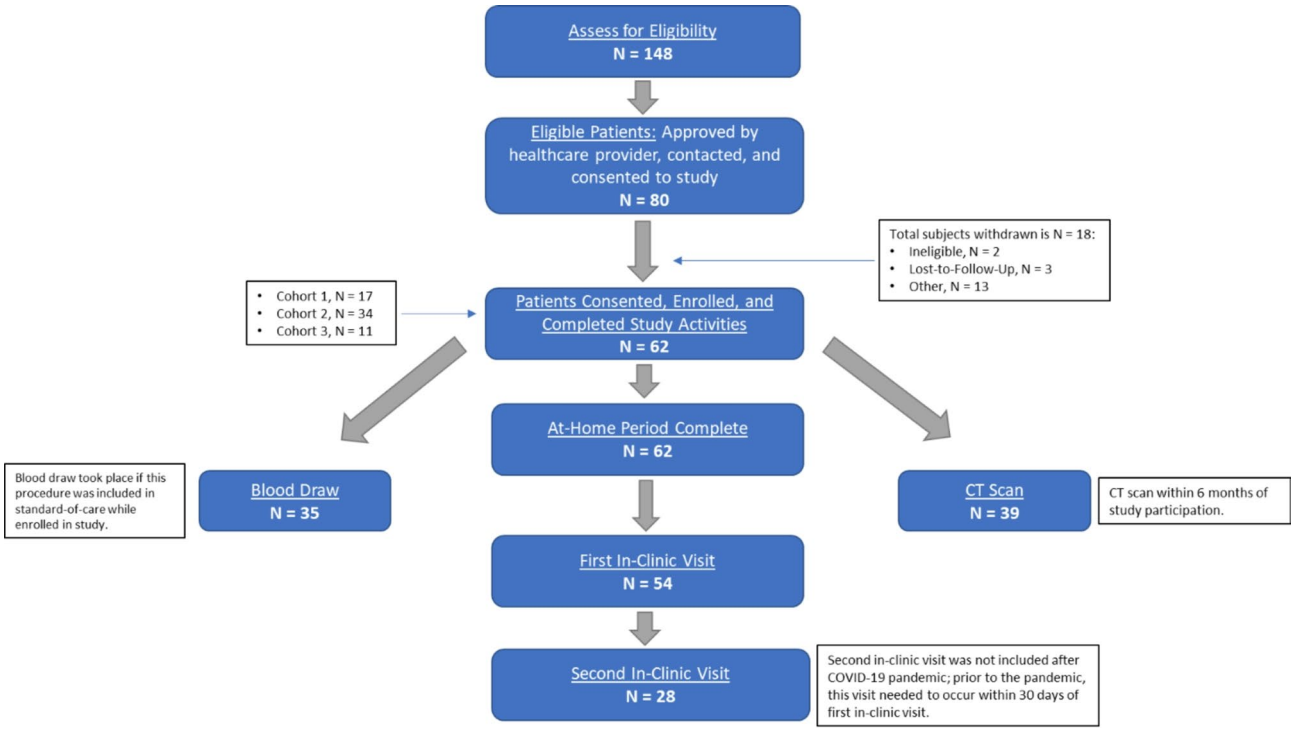

Fig. 1. CONSORT diagram for study participants.

as the mean activity level (Spearman's rho = 0.4, $p = .003$), were positively correlated with physical function and inversely correlated with fatigue (moderate and non-sedentary, Spearman's rho = -0.51, $p < .0001$; mean activity level, Spearman's rho = − 0.41, $p = .0018$). An hour of moderate and non-sedentary activity per day corresponded to around 5.5 and 3.3 points increase in PROMIS Physical Function 10a, and 4.6 and 2.8 points decrease in PROMIS Fatigue 7a scores, respectively (Supplementary Table 4). Gait speed (Spearman's rho = 0.41, $p = .0017$), 95th percentile of gait speed (Spearman's rho = 0.49, $p = .0001$), and total steps per day (Spearman's rho = 0.69, $p < .0001$) were also positively correlated with PROMIS Physical Function 10a score and negatively correlated with PROMIS Fatigue 7a score (Spearman's rho = -0.49 $p = .0001$; -0.52 $p < .0001$; Spearman's rho = -0.48 $p = .0002$). An increase of 0.1 m/s in average gait speed corresponded to 4.6 point score increase in PROMIS Physical Function and 4.8 point decrease in PROMIS Fatigue, and an increase of 1000 steps per day corresponded to a 2 point increase in PROMIS Physical Function and 1.2 point decrease in PROMIS Fatigue scores (Supplementary Table 4). Similarly, correlations were also observed between vigorous activity time and both physical function (0.5, $p = .01$) and fatigue (-0.34, $p = .01$), though vigorous activity time was highly clustered near zero within the cohort. No significant relationship was observed between total sedentary time and these PROs.

Participants with cancer found the DHTs comfortable, would wear them during treatment and would like their clinicians to have access to their data

In order to capture the willingness of the participants to wear the DHTs as well as comfort, participants were asked to provide feedback following the at-home period of wear (Fig. 6). All of the participants found the wrist device comfortable and 77% of the participants reported lumbar device comfortable to wear. When asked about wearing the DHTs for extended periods of time 93% and 71% reported willingness to wear the wrist and lumbar device for more than a week, respectively. The majority (87%) of the participants reported having an interest in wearing the DHTs during their treatment and monitoring their activity at home. Almost all the participants (95%) favored their clinicians having access to their physical activity and gait data during their treatment. The responses were similar across all KPS groups, suggesting that the participants had positive experiences with wearable DHTs independent of their reported performance status.

Discussion

We investigated the value of DHTs to provide continuous, objective and quantitative evidence on functional status among individuals undergoing cancer treatment. Our findings demonstrate that at-home physical activity and gait metrics as measured by DHTs, particularly time spent in moderate and non-sedentary activities, gait speed, and total number of steps per day, were associated with self-reported performance status. The threshold-free metrics such as mean activity level and mean activity level during most intense 6 min were also significantly associated with KPS, supporting the generalizability and reproducibility of these findings independent of algorithm and/or device manufacturer. Among this same cohort, in-clinic physical performance assessments, such as hand grip strength, SPPB, or 4-meter walk tasks failed to differentiate between the KPS groups. The at-home physical activity and gait metrics were also strongly associated with patient-reported physical function and

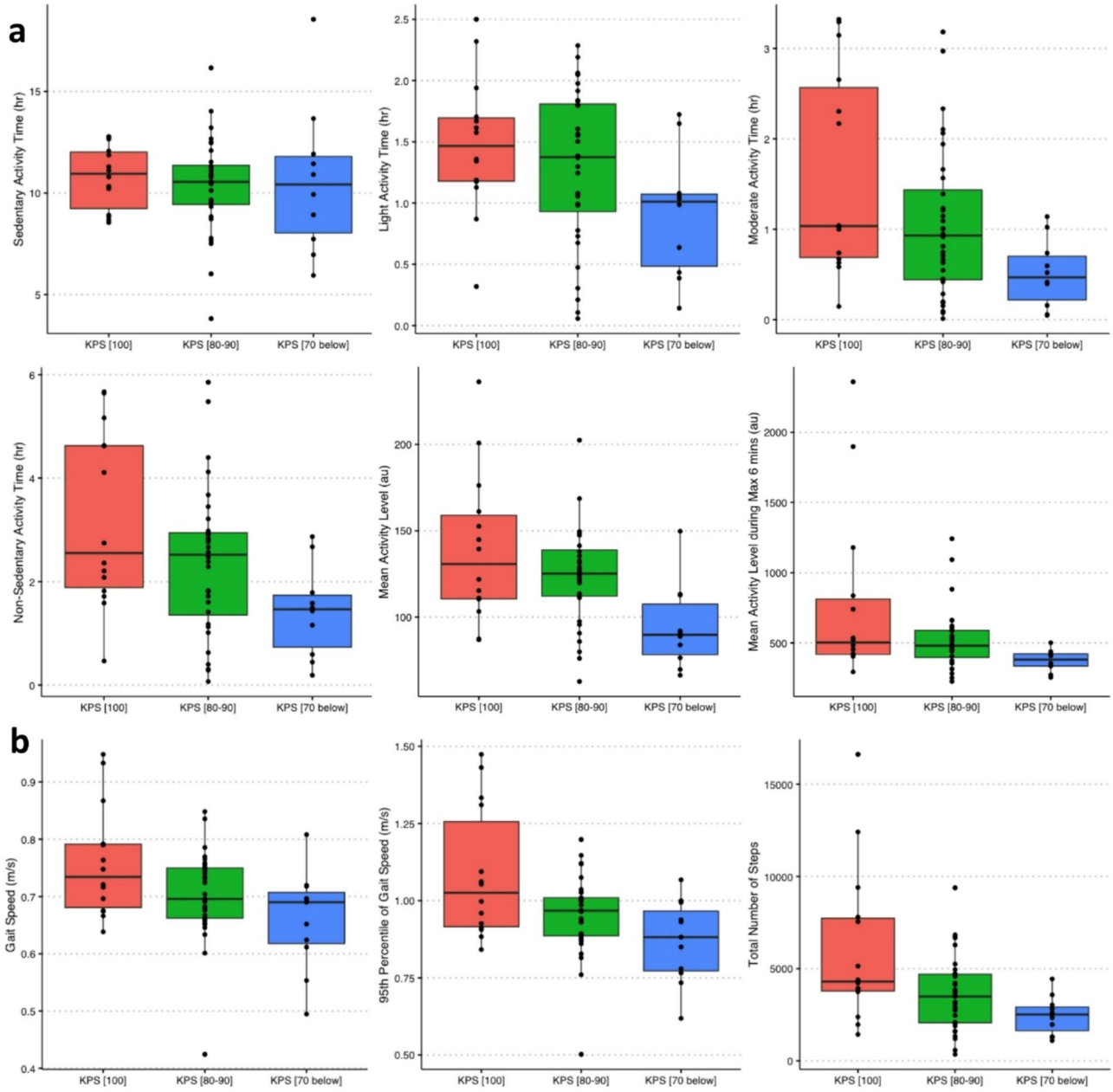

Fig. 2. At-home physical activity and gait metrics derived by DHTs stratified by self-reported KPS in participants with cancer. **a** Box-plot of overall activity metrics derived from the wrist accelerometer as measured by time spent in sedentary, light, moderate, non-sedentary activity, average activity and mean activity level within the most intense 6 min, based on the accelerometer signal magnitude. Moderate activity time, non-sedentary time, mean activity level and maximum 6 min activity level differed significantly across self-reported KPS (KPS [70 below] compared to KPS [100] and KPS [80–90]. **b** Box-plot of at-home gait metrics derived from the lumbar accelerometer: average and 95th percentile of gait speed and total number of steps per day, which showed significant differences across self-reported KPS. Each dot represents the average daily value of a participant over two weeks of monitoring. Au = Arbitrary units. m/s.

fatigue as measured by PROMIS Physical Function 10a and Fatigue 7a, and were significantly different between participants with cancer and healthy participants without cancer. Participants also showed interest in wearing these DHTs and would want their clinicians to have access to their data during treatment. Taken together, these findings suggest that DHT-derived measures of physical activity and gait speed offer a mechanism to enhance the assessment of functional status in people with cancer.

The most widely evaluated wearable-derived metric in cancer populations to date has been number of steps per day, which has unsatisfactory characteristics as a functional status metric due to wide variation within and across individuals as well as its vulnerability to incomplete data capture[29,30]. In this study, we evaluated a

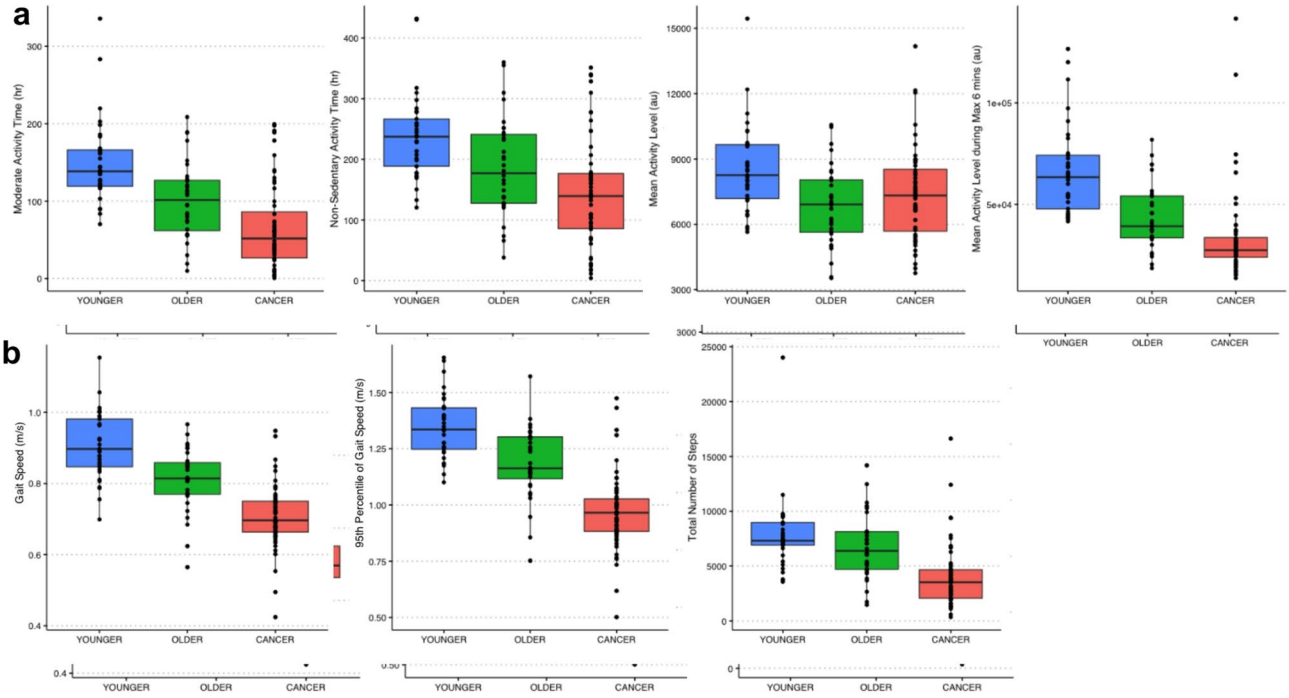

Fig. 3. At-home physical activity and gait metrics derived by DHTs among participants with cancer and previously evaluated healthy participants of younger and older age range. **a** Compared to healthy participants both in younger and older age groups, the participants with cancer showed significantly lower activity in time spent in moderate and non-sedentary activity and mean activity level within most intense 6 min of activity. **b** Average and 95th percentile gait speed and total number of steps per day were also significantly lower in participants with cancer compared to both the older and younger healthy participants. Au = arbitrary units.

set of physical activity and gait measures that showed significant relationship with self-reported performance status and PROs. These measures also distinguished participants with cancer from healthy adults, and they are therefore promising candidates for monitoring performance status during treatment.

Traditional performance score (PS) tools, including KPS and ECOG, are well-established and widely used in oncology to evaluate individuals' functional capabilities and inform treatment decisions. However, these metrics are limited by their reliance on periodic clinical evaluations and their inability to capture day-to-day variations in functional status, especially in older adults. The limitations in KPS and ECOG PS in detecting clinically significant functional deficits in older adults have been extensively described in prior literature[4,22,31,32]. Our study highlights the potential of DHTs to address these limitations by providing continuous monitoring in an individual's typical home environment. This approach could lead to more accurate and timely assessments, especially when traveling to clinic is burdensome or not feasible, capturing a fuller spectrum of functional abilities and daily variations, which are often missed in clinical settings. In this cohort, home-based measures were better at differentiating KPS groups than objective in-clinic performance assessments. Multiple at-home activity and gait metrics differed significantly between KPS groups, whereas total SPPB score in clinic, 4 m walk time (a SPPB component), and handgrip strength did not. This discrepancy suggests that home-base metrics may have an important role in elucidating individuals' typical physical performance. The performance metrics identified in this pilot study provide promising candidates for future research to determine how wearable device-derived measures can be effectively integrated into clinical workflows and leveraged to improve patient outcomes.

We additionally compared measures observed in the current cohort of participants living with cancer to prior results from a similar study of DHTs conducted among healthy participants[27,28]. In this prior study, healthy participants consisted of two groups of younger (mean age 29 years) and older (mean age 72) individuals. Healthy participants in the older cohort had inferior physical performance metrics, including lower activity time and slower gait speed, as expected with healthy aging. For example, gait speed was shown to decrease around 0.037 m/s per decade with aging and while being around 15 years younger on average, gait speed in participants with cancer (mean age 56 years) was 0.1 m/s lower than the average gait speed in the older healthy group[33]. Interestingly, in our cohort of people living with cancer, physical activity, gait speed, and step count were all lower than the values observed for either healthy volunteer group, despite the cancer cohort being between the two healthy groups in terms of age. This discrepancy likely relates to the impacts of cancer and its treatment on physical performance, and this finding provides additional face validity for the use of these DHT-derived metrics to assess physical performance and functioning.

Strengths of our study include its comprehensive data collection and the innovative application of technology to enhance PS assessment. Our findings support the feasibility of integrating wearable technology into routine oncology care. Particularly striking was the high compliance in device wear time (more than 22 h of wear

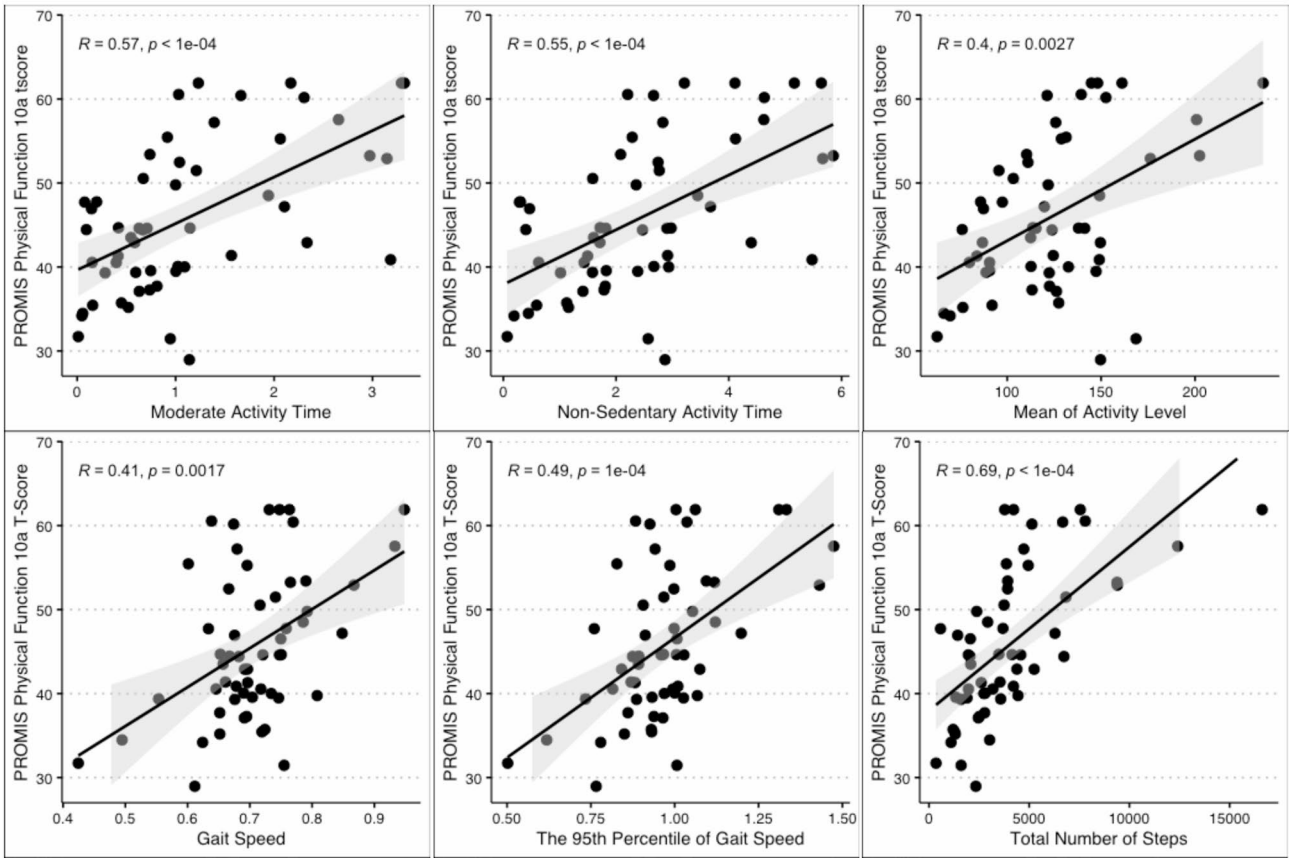

Fig. 4. Scatter plots between at-home physical activity and gait metrics and patient-reported outcomes - PROMIS Physical Function 10a. We observed increased levels of at-home activity associated with higher reported physical function scores. Higher PROMIS score indicates better self-reported function. Spearman's correlations are reported.

time per day and 12 compliant days for the wrist device, and around 14 compliant days for the lumbar device) we observed, suggesting that the use of these (or similar) devices would be acceptable to individuals in more routine care settings. This study also highlights positive feedback from participants with cancer about their preference to use DHTs in their daily life while undergoing treatment, and their willingness for clinicians to have access to their data. Our study and results demonstrate that it is feasible to implement DHTs in remote areas, extending their reach to various underserved populations, increasing diversity in clinical trials, and facilitating decentralized clinical trials with minimal or no need for clinical visits. In particular, DHTs offer a potential means for more objectively assessing the physical performance of older adults, a key demographic that has been historically underrepresented in oncology clinical trials[34]. This study can also serve as baseline activity data for future studies, where baseline data is missing.

There are limitations within the current study. The sample size was relatively small, and participants were recruited in central North Carolina, which may affect the generalizability of our results. The study included more female participants than male participants, which was accounted for during the statistical analysis. The study was conducted in-part during the height of the COVID-19 pandemic (30 out of 62 participants were enrolled during the pandemic), which limited additional in-person evaluations. However, we were able to continue to conduct the at-home portion of the study (primary objective) remotely with success. Potential daily routine changes during the pandemic were accounted for in statistical analysis. Changes in daily routines during the pandemic may also have impacted correlations between measured activity levels and PROs, even though PROs were collected weekly during at-home monitoring period. Furthermore, the accuracy of different DHTs in capturing certain physical activities may vary, and DHTs are not a direct report of a person's experience during cancer treatment. However, in this cohort, we observed significant correlations between device metrics and patient-reported outcomes, including fatigue and physical functioning. The comparisons between this cohort of participants with cancer and previously collected data from healthy participants could not be performed in an aged-matched manner, due to the design of the previous healthy participant study not including any participants aged between 40 and 65.

The integration of DHTs into clinical practice offers several potential advantages. These devices provide continuous, objective data on functional status, enabling more informed and personalized treatment adjustments and the potential for earlier recognition of treatment toxicity. The activity measures derived from DHTs have been shown to distinguish between different stages of cancer[35] and have been associated with chemotherapy

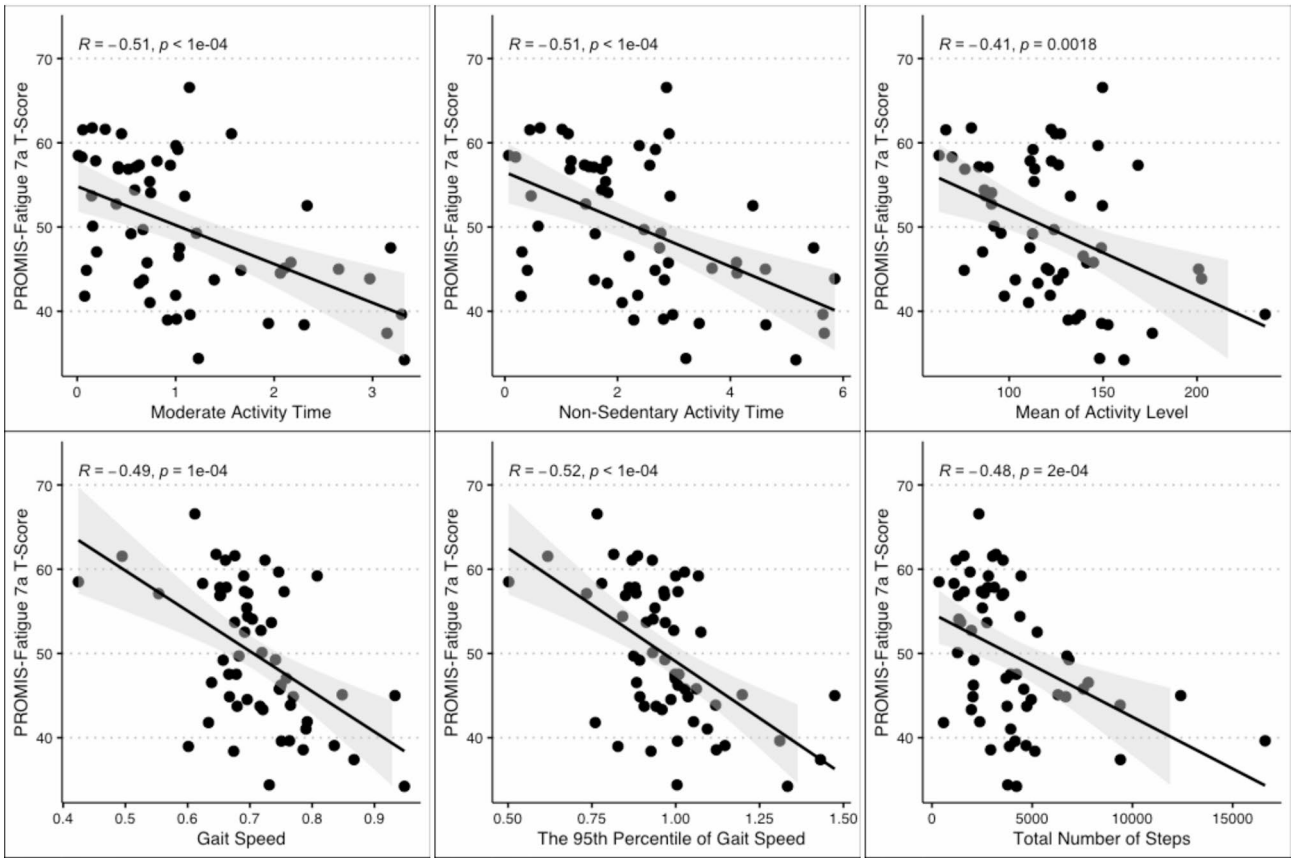

Fig. 5. Scatter plots between at-home physical activity and gait metrics and patient-reported outcomes – PROMIS Fatigue 7a. We observed that participants with lower reported fatigue have higher measured physical activity and gait. Higher PROMIS score indicates increased self-reported fatigue. Spearman's correlations are reported.

resilience[36]. Improvements in activity measures were shown to predict reduced hospitalizations, adverse events, and death in people with advanced cancer[37]. The use of wearable devices and home-based measures has the potential to overcome barriers to more detailed assessments of performance status in the limited window of oncology clinic visits. For instance, time constraints have been consistently cited as a barrier to wider implementation of GA in oncology practice[38,39]. Thus, continuous monitoring can also help in early detection of functional decline, potentially offering an opportunity for earlier intervention to improve treatment outcomes[40]. Physical performance data derived from DHTs, specifically average daily walking distance, has been linked to survival outcomes for individuals with cancer, supporting the prognostic value of such measures[41].

Future research should focus on validating these findings in larger and more diverse populations. Long-term studies are necessary to assess the sustained impact of DHT monitoring on clinical outcomes and to refine the technology for broader clinical application. How best to incorporate these data into clinical practice will require further study. Though our data suggest that home-based measures may provide useful information to understanding patient function, we acknowledge that there are several issues that would need to be addressed to facilitate implementation in a routine clinical setting, including access to devices, digital literacy, patient or clinician inconvenience, and clinical workflow disruptions. Nonetheless, implementation in a home-based setting avoids concerns related to in-clinic measures, including space and personnel limitations and clinical flow. We suggest that our findings may be an initial step towards highlighting potential candidate home-based measures that can be studied in more homogeneous settings along with a more explicit focus on barriers and facilitators to implementation, if the findings are validated. Additionally, advancements in wearable technology and data analytics could further enhance the accuracy and utility of these devices particularly in areas where access to oncologists may be limited. Collaborative efforts between technologists, clinicians, and researchers will be crucial in optimizing the integration of wearable devices into routine oncological care.

In conclusion, our study demonstrates the feasibility and utility of wearable devices in assessing functional status among adults undergoing cancer treatment. While traditional PS metrics like KPS have significant prognostic value, they are limited in capturing the full spectrum of daily functional status. Wearable devices offer a promising solution by providing continuous, real-time data that can enhance clinical decision-making and improve outcomes. Continued research and technological advancements will be essential to fully realize the potential of wearable technology in oncology, ultimately leading to better-tailored treatment plans and improved quality of care for people with cancer.

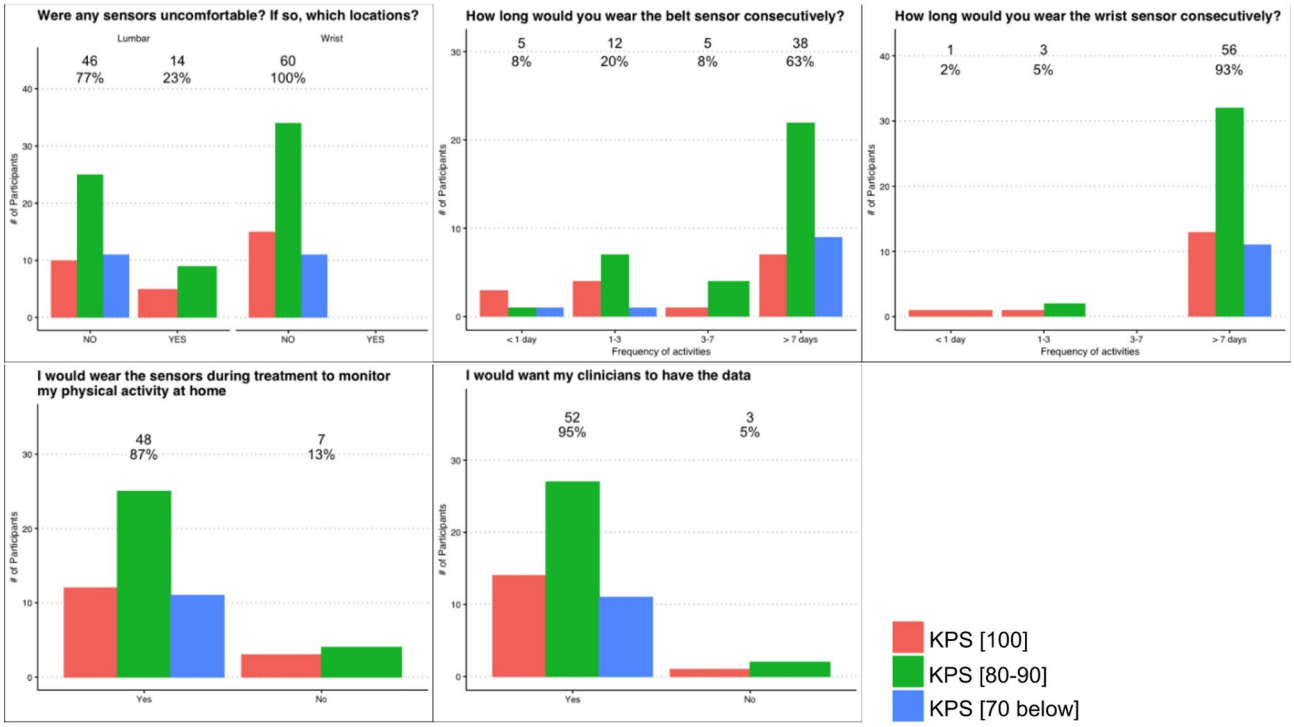

Fig. 6. Comfort and usability assessment of Digital Health Technologies among participants with cancer. Participants were asked to rate the comfort of wearing the DHTs at home and their usability at the end of the study. More than 75% and 100% of the participants reported comfort for lumbar and wrist sensors, respectively. While 63% of the participants reported that they would wear the lumbar sensor for more than a week, more than 90% reported they would wear wrist sensor for more than a week. 87% of the participants would wear the sensors at home during their treatment to monitor their physical activity, and 95% would like their clinicians to have access to their at-home activity data. Two participants did not complete the wearability questionnaires and seven participants did not complete the additional usability questionnaires.

Methods

Study population and sample size

Potentially eligible participants were screened by chart review, with suitability for participation confirmed by the attending physician. Participants were approached either during routine clinic visits or called at home. The self-reported KPS was administered during screening, and, depending on the result, enrollment was offered if places were available in one of the three KPS cohorts corresponding to the response of the potential participant. At study entry, participants provided self-reported KPS estimates and were subsequently enrolled into one of three cohorts: KPS 100, KPS 80–90, or KPS ≤ 70. There were no specific requirements for type of cancer, type of cancer treatment, or timing of cancer treatment relative to study procedures. Participants were required to be English speakers and determined to be literate. Exclusion criteria included patients: taking part in a clinical trial involving investigational drug treatments; with dementia and altered mental status; who are allergic to silicone or adhesives; and with cardiac pacemakers, electronic pumps, or any other implanted medical devices.

Data from a previously published study in healthy younger and older participants was used for cross-comparison using the same wearable devices placed at the same locations (i.e., non-dominant wrist and lumbar locations). The methods for this study have been previously described[27,28].

Sample sizing was performed based on data from physical activity monitoring in cancer patients[35,37] using the *number of steps per day* endpoint. A sample size of $n = 12$ participants per KPS group was estimated to be sufficient to detect differences similar to the average difference (50%) seen between consecutive ECOG categories in the two papers. Sample sizing was performed with the following parameters: one-tailed 2-sample t-test, alpha = 0.05, power = 0.8, sd on the $\log_{10}$ scale = 0.3, difference = 50%. The recruitment was performed using KPS at-screening and stopped when enough participants were stratified into each cohorts. The pre-defined statistical analysis used KPS scores at visit 1, as closest time point to at-home monitoring and visit 1. The primary results performed using the KPS scores during recruitment (see Supplementary Table 5) vs. visit 1 did not change the interpretation of the findings in this paper.

Study design

This was a single-institution observational study ran between 2019 and 2021 for individuals ages 18 or older receiving treatment for cancer, either solid tumors or hematologic malignancies (Sensors To Evaluate Physical Performance [STEPP]; ClinicalTrials.gov identifier NCT03952767). Prior to the COVID-19 pandemic, there

was one in-clinic visit, a two week at-home observation period where participants continuously wore two wearable devices on their non-dominant wrist and lumbar, and an optional second in-clinic visit. In order to accommodate for the COVID-19 pandemic, there was a mandatory two week at-home observation period where participants wore wearable devices and one optional in-clinic visit. The study took place in the UNC Lineberger Comprehensive Cancer Center for the in-clinic visit and virtually for the at-home observation period. All methods were carried out in accordance with relevant guidelines and regulations. The protocol was approved by the University of North Carolina Institutional Review Board. Informed consent was obtained from all participants.

In-clinic assessments

The in-clinic portion of the study lasted approximately 90 min. For the in-clinic assessments, participants wore Ambulatory Parkinson's Disease Monitoring (APDM) six sensor set placed on the lumbar region, both feet, both wrists, and sternum. Participants also wore a Cortrium C3 sensor in the midline of the chest. With these devices in place, participants performed a short physical performance battery (SPPB) comprised of a balance test, gait speed, five times chair stand test, and timed up and go (TUG).

Participants also performed tests of hand grip strength with an analog dynamometer (Takei 5401) and with a digital Vernier Hand Dynamometer and Qubit System S207. Lastly, participants were given the option to perform a stair climb test. All tests were administered as described in the literature under the supervision of trained study personnel.

At-home assessments

For the 14-day home-based observation period, which either began immediately following the in-clinic assessment or independently (for those participants not performing an in-clinic assessment after the COVID amendment), participants wore a GENEActiv accelerometer sensor (Activinsights Ltd., Kimbolton, UK) on the lumbar region and non-dominant wrist. During the at-home observation period, participants were instructed to wear the wrist device continuously and lumbar sensor during the day. No specific physical performance tests were prescribed for the participant during the at-home period.

Patient-reported outcomes

Participants completed self-reported KPS, PROMIS Fatigue 7a[42], and PROMIS Physical Function 10a[43] surveys via REDCap during the in-clinic assessment and again weekly during the home-based observation period where applicable.

Accelerometer data processing

Raw acceleration signals from lumbar-worn GENEActiv devices were used to derive gait features using the implementation in the open-source SciKit Digital Health (SKDH) (https://github.com/PfizerRD/scikit-digital-health (accessed on 28 September 2021)) Python library[44]. Full description of the methods used to process the data can be found in Czech et al., 2020 and Lin et al. 2023[27,28]. Raw acceleration signals from the wrist-worn GENEActiv devices were processed using the Microsoft Excel Macros accompanying the GENEActiv device to generate the PA features[45]. For full methods details on the algorithms used, please refer to the previously published paper by Lin et al. 2023[27].

Statistical analysis

Statistical analysis was performed in SAS version 9.4 and R with following main packages: "lme4" for linear mixed-effect regression. Linear models (or equivalent non-parametric methods such as Wilcoxon or Kruskal Wallis tests) were used to test if physical activity endpoints differed across KPS groupings. For the 2 week at-home monitoring period, the KPS groupings (categorical variable) was entered as the independent variable, COVID period (as categorical period, starting from 01 March 2020) and age (continuous variable) were entered as covariates. The height of the participant was added as a covariate within the models for the lumbar-worn sensor to account for the variability in gait parameters due to participant's height. The estimated least square means (lsmeans) or mean difference with 95% CI were reported. The uncorrected p-values are reported unless stated otherwise, then, correction for multiple comparisons was performed using false discovery rate (FDR). The correlations between patient-reported outcomes (PROMIS Fatigue 7a and PROMIS Physical Function 10a) and physical activity and gait metrics were performed using Pearson or Spearman's rank correlations. The PROMIS Fatigue and Physical Function were translated into T-scores, and summarized as the mode across the weekly measurements per participants. The comparisons of physical activity and gait metrics between participants with cancer and healthy participants were performed using linear models, with sex as a covariate for wrist, and sex and height as covariates for lumbar sensor, the summaries and comparisons are reported as above in terms of least square means and/or differences with 95% CI.

For the at-home monitoring, out of the 62 recordings for the wrist device, 3 were excluded during the initial quality checks due to issues in device configurations, 1 had short recording due to technical failure and was removed from analysis. One participant was excluded during the initial quality checks due to issues in device configurations out of the 61 recordings received for the lumbar device. The first and last days of recording (i.e., the clinical visit days) were not included in the at-home summaries to minimize bias and partial days. Two participants' data did not satisfy wear time criteria to be included in the statistical analysis for both wrist and lumbar devices (i.e., with at least 4 compliant days. S monitoring day was defined as compliant if total wear time is $\geq$ 10 h, and daily wear time from 8am–8pm $\geq$ 8 h for the wrist device, and a day was defined as compliant if robust gait endpoints can be computed for that day). Therefore, 56 and 58 participants' device data were included in the analysis for wrist and lumbar devices, respectively. For the gait metrics, only gait bouts that were

longer than 10 s and with more than four detected gait cycles were included in the analysis to ensure robust gait characterization. The median across the steps within each gait bout was computed, then averaged across the gait bouts within each day, finally each daily summary was averaged across the monitoring window. The average values of variables derived from wrist sensor were also computed across the monitoring period per participant.

The comfort and wearability questionnaires responses are summarized using counts and percentages. Two participants did not complete the at-home wearability and comfort questionnaires, and seven participants did not complete the additional usability questionnaires.

Data availability

Upon request and subject to review, Pfizer will provide the data that support the findings of this study. Subject to certain criteria, conditions, and exceptions, Pfizer may also provide access to the related individual de-identified participant data. See https://www.pfizer.com/science/clinical-trials/trial-data-and-results for more information. Please contact the corresponding author, W.A.W., for the data request.

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Study conception and design: F.I.K, X.C, M.S., A.T., W.A.W. Data collection and study execution: D.P., J.S., A.M., C.D. Analysis: F.I.K, D.P, L.A. Drafting of manuscript: F.I.K, C.E.J, X.C, M.S., J.S., W.A.W. Critical revision of the manuscript for important intellectual content: H.M., X.C., F.I.K, W.A.W.

Competing interests

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Additional information

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