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Validating a digital recovery tool for autologous breast reconstruction

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Summary *Background:* Recent research aims to leverage technology to further understand surgical recovery by using continuous data. Traditional metrics of readmission, flap failure, and patient-reported outcome measures are limited by poor accuracy and subjectivity. We aimed to validate smartphone-derived physical activity data to objectively measure and analyze trends in recovery following deep inferior epigastric perforator (DIEP) flap breast reconstruction.
Methods: A single-center, retrospective study was conducted. Eligible participants who underwent DIEP reconstruction downloaded a bespoke smartphone application, which retrieved data from 1 month preoperatively to 12 months postoperatively. Physical activity was compared and validated against wearable activity monitor data from a previous study. Temporal trends were visualized using mean daily activity values over predefined intervals. Univariable linear regression assessed associations between clinical variables and short-term recovery.
Results: Forty-one patients were included in the study. Wearable activity monitor and smartphone datasets ($n=10$) showed a positive correlation (0.6379, $p=0.0105$) demonstrating concurrent validity. Analysis of recovery in DIEP patients ($n=34$) demonstrated a median return to baseline activity at 27 days (IQR 12 days). Physical activity decreased after DIEP, with mean daily activity dropping to 18% of baseline in the first 2 weeks ($SD=11\%$, $p < 0.0001$) before improving to 107% at 8–12 weeks ($SD=78\%$, $p=0.9999$). Immediate postoperative reconstruction ($p=0.046$) and lack of postoperative complications ($p=0.0063$), were short-term predictors of physical activity.
Conclusion: This study validates smartphone physical activity as an objective recovery metric in DIEP reconstruction. Future applications include developing recovery prediction

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models for shared decision-making, implementing perioperative interventions, and postoperative monitoring.

Approximately 30% of patients with breast cancer undergoing mastectomy in the United Kingdom elect for autologous reconstruction.[1] The deep inferior epigastric perforator (DIEP) flap is considered the gold standard, offering higher patient satisfaction, cosmesis, and reduced donor-site morbidity compared to alternative methods.[1,2] Postoperative outcomes are usually evaluated with validated patient-reported outcome measures (PROMS) such as the BREAST-Q and BODY-Q questionnaires, or binary surgical outcomes such as flap failure.[3,4] However, PROMS are prone to recall bias, inter-patient variability, and insufficient sensitivity, whereas traditional surgical outcomes do not capture functional recovery.[5]

Wearable activity monitors (WAMs) have emerged as an alternative outcome measure allowing for objective assessment of perioperative physical activity (PA) as a surrogate marker of recovery.[6] WAMs have been validated as an objective measure of recovery in breast reconstruction and abdominal wall surgery, without the limitations associated with traditional outcome measures.[7-10] However, their scalability is limited by cost, patient adherence, data quality, and device-specific technical limitations such as battery life.[11,12] Additionally, there is limited evidence evaluating inter-device variability, and commercially available monitors often lack accuracy, particularly during slower walking speed, which is common during postoperative recovery.[13,14]

Smartphone-based monitoring presents a pragmatic and cost-effective solution. Knight et al. published a systematic review in 2021 highlighting the feasibility of mobile devices for measuring patient outcomes after surgery.[15] If validated, this method enables multimodal, objective, and continuous data collection with minimal burden to patients, and without additional equipment.[16] Smartphone sensors (e.g., accelerometer and global positioning systems) track user movements without any added input from the patient. This approach eliminates recall and sampling biases and helps mitigate the Hawthorne effect—the tendency of individuals to alter their behavior when they are aware of being observed.[17] The aim of this proof-of-principle study was to assess the validity of smartphone-derived PA data for measuring recovery after breast reconstruction and identify trends in recovery associated with patient and operative variables.

Methods

This single-center, retrospective observational cohort study was conducted at the Imperial College Healthcare NHS Trust, London, between February and May 2024. Ethical approval was granted by the National Research Ethics Committee (Ref: 15/LO/1038), and the study was registered on ClinicalTrials.gov (NCT03635723). All participants provided written and verbal informed consent. Recruitment involved the use of a custom-built mobile application ('StepHome Trial') which extracts hourly "walking and running distance (km)" via the Apple Health app from 28 days preoperatively up to 12 months postoperatively. This parameter is estimated based on phone movement data (accelerometry) and GPS data (if location services are enabled).

Inclusion criteria were: (1) adults (age ≥18 years from the time of data collection) who spoke English; (2) underwent breast reconstructive surgery more than 6 months before data collection; (3) and possession of an Apple iPhone (Apple Inc, Cupertino, California). Exclusion criteria included patients with significant movement disabilities, and those who do not use an iPhone. Patient demographics, disease status, and operative management data were collected, and the preoperative Charlson Comorbidity Index (CCI) was calculated for all patients.[18]

The "StepHome Trial" app was developed at the Imperial College London through iterative user testing, incorporating design elements to ensure streamlined data collection and compliance with UK General Data Protection Regulation (GDPR) and the Data Protection Act 2018. Data transfers employed Hypertext Transfer Protocol Secure (HTPS) encryption.

Data analysis

To ensure data quality, any highly aberrant daily activity levels (e.g., no data collected over 24 h) were excluded from the analysis, as these values likely reflect not carrying the phone for a prolonged period. This process was performed preoperatively and from 2 weeks postoperatively, as it is plausible that the activity was 0 in the acute postoperative period. This type of data processing has been well described in the literature.[19]

Smartphone and wearable device comparison

Although there is good evidence of the correlation between smartphone and wrist worn accelerometry data for measuring physical activity, data collected from a subgroup of patients who participated in a previous trial using a wrist-worn activity monitor were compared with smartphone PA data to provide reassurance of validity in the perioperative context.[9,10,20] Concordance between the mean daily WAM data and mean daily smartphone-recorded PA were assessed using the Spearman's rank-order correlation.[7]

Recovery analysis

Preoperative baseline PA was defined as the mean activity level in the 28 days preceding surgery. Postoperative PA was calculated as the daily postoperative activity expressed as a percentage of baseline activity. Return to recovery was defined as PA reaching 90% of baseline activity. This method was chosen owing to the sigmoid shape of the recovery curve having a very protracted deceleration phase before the plateau. Finding a consistent endpoint allowed improved performance on comparisons between patient variables within the linear regression.

Statistical analysis

Descriptive statistics are presented as means with standard deviations (SD) or 95% confidence intervals (CI) for continuous variables. Categorical variables are expressed as frequencies and percentages. To visualize postoperative activity trends, mean daily activity values were calculated for successive time intervals: 0-2, 2-4, 4-6, 6-8, and 8-12 weeks, and 3-6, 6-9, and 9-12 months after surgery. Changes across time were analyzed using the Friedman's two-way ANOVA with Dunn's post hoc comparisons. Regression analysis was performed against short-term postoperative PA levels (days 1-28). Simple linear regression was performed for each variable, along with multiple linear regression to control for confounding and improve prediction accuracy. Owing to the small sample size, the aim of the regression analyses was exploratory, rather than confirmatory, for variables that might be associated with different recovery patterns. Statistical significance was set at $p < 0.05$. Analyses were performed using Microsoft Excel (v16.84) and GraphPad Prism (v10.2.3).

Results

From February to May 2024, a total of 170 patients who underwent breast reconstruction between June 2019 to August 2023 were assessed for study participation (Figure 1). Following eligibility screening, 94 patients met the inclusion criteria, among them 75 provided informed consent, resulting in an enrollment rate of 80%. Android phone users were screened out under the "did not own a smartphone" category (n=13) and there was no significant difference in age. The final analytic cohort comprised 41 patients, including 34 DIEP flap reconstructions, 3 mastectomies, and 4 implant-based reconstructions. Analyses of perioperative recovery trends and predictors of recovery were restricted to the DIEP cohort (n=34), with the other patients' data used for WAM comparison purposes only. During processing, 1 data point out of 379 (1 year–14 postoperative days + 28 preoperative days), on an average (1.21, SD=2.50 days) per patient were removed owing to non-wear/use of the smartphone.

Among the 34 DIEP patients who completed the study, the mean age was 48 years, and almost all had a unilateral, immediate DIEP reconstruction after skin sparing mastectomy and an axillary node biopsy or clearance. Most patients (31/34) were ASA class II and the mean preoperative CCI was 2.6 ± 0.8 (SD) which represents a mild risk of mortality within 10 years. The mean hospital length of stay was 5 (±1) days (Table 1).

Data comparison with wearable activity monitor

The daily postoperative mean activity from WAM, and smartphone-collected data demonstrated a significant

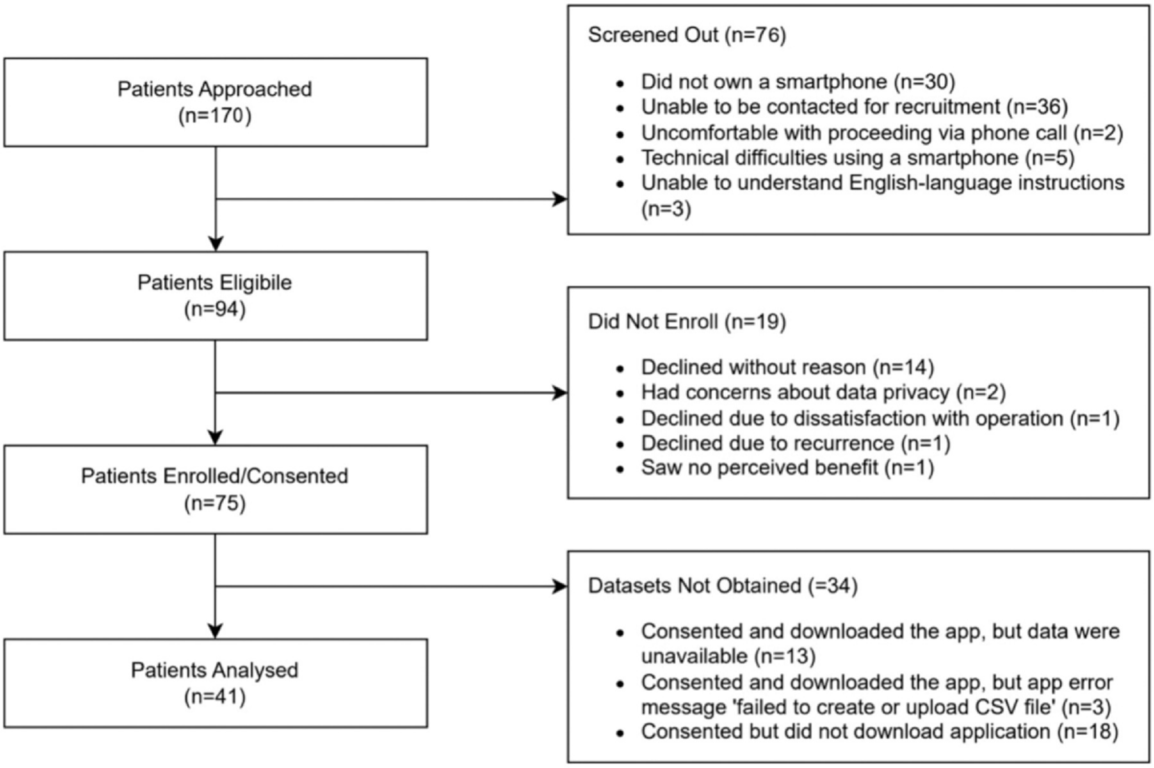

Figure 1 Recruitment of patients for study participation, including screening for eligibility, reasons for exclusion, and barriers to obtaining informed consent for participation.

Table 1 Baseline characteristics of patients undergoing DIEP breast reconstruction (n=34).

Age, years, mean (SD)	48.3 (6.9)
Female sex, *n*	34
Race/Ethnicity, n	
White - British	10
White - Any Other White Background	6
Asian or Asian British - Indian	3
Asian or Asian Background - Pakistani	1
Asian - Any Other Asian Background	2
Other - Any Other Ethnic Group	2
Other - Not Stated	10
Comorbidities, n	
Diabetes	1
Hypertension	2
Previous malignant tumor	3
Smoking status	2
Preoperative CCI	2.6
Preoperative CCI - 10-Year Survival (%)	81
BMI (kg/m^2)	25
Operative details	
ASA Classification, *n*	
Class I	2
Class II	31
Class III	1
Prior chemotherapy, n	
< 6 months preoperatively	13
None or > 6 months preoperatively	21
Prior radiotherapy, n	
< 6 months preoperatively	5
None or > 6 months preoperatively	29
Breast cancer excision procedure, n	
Mastectomy	5
Modified radical mastectomy	1
Skin Sparing Mastectomy	28
Axillary procedure, n	
ALND	11
SLNB	15
None	8
Timing of reconstruction, n	
Immediate	31
Delayed	3
Reconstructive operation laterality, n	
Unilateral	31
Bilateral	3
LYMPHA procedure, *n*	4
Abdominal mesh, *n*	6
Number of drains (mean ± SD)	2.2 (0.5)
Days drains in-situ (mean ± SD)	9.5 (7)
Progressive tension or abdominal quilting sutures, *n*	1
Operative time (minutes) (mean ± SD)	444.9 (89)
Blood loss (mL) (mean ± SD)	345.3 (132)
Final surgical pathology, n	
DCIS	8
IDC	19
ILC	1
IDC and DCIS	3
Risk Reducing Surgery	1
Papillomatosis	1
n/a	2
Stage of malignancy, n	
Stage IA	2
Stage IIA and IIB	16
Stage IIIA and IV	8
Non specified	7
Non-cancerous (BRCA1 or BRCA2)	1
Recovery information	
Return to theater due to postoperative complication, *n*	4
Type of postoperative complication, n	
Flap Failure	1
Hematoma	3
Pneumothorax	1
Pulmonary Embolism	1
Wound Infection	3
Wound Bleeding	1
Emergency department presentations, *n*	8
Hospital LOS (mean ± SD)	5 (1.5)
Adjuvant treatment, n	
Chemotherapy	14
Radiation	8
Hormone therapy	10

n, number; SD, standard deviation; IQR, interquartile range; WAM, wearable activity monitor; PA, physical activity; DIEP flap, deep inferior epigastric perforator artery flap; CCI, Charlson Comorbidity Index; BMI, body mass index; ASA, American Society of Anaesthesiologists; ALND, axillary lymph node dissection; SLNB, sentinel lymph node biopsy; R, right; L, left; BL, bilateral; LYMPHA procedure, lymphatic-venous bypass; DCIS, ductal carcinoma In-situ; IDC, invasive ductal carcinoma; ILC, invasive lobular carcinoma; BRCA1, breast cancer gene 1; BRCA2, breast cancer gene 2; LOS, length of stay in hospital, with the day of surgery being defined as day one. The data are presented as mean values with standard deviations and absolute numbers with corresponding percentages.

association (r=0.6379, p=0.0105), proving concurrent validity (Figure 2).

Recovery analysis

After surgery, there is a sharp decrease in PA followed by a gradual return toward baseline (Figure 3).

Analysis of recovery in DIEP patients (n=34) demonstrated a median return to PA baseline at 27 days (IQR 12, Q1 22, Q3 34 days). During the first 2 weeks postoperation, patients on an average only achieved 18% of their baseline mean daily distance (SD=11%, $p < 0.0001$). This improved to 56% at 2-4 weeks ($p < 0.0001$) and 92% at 4-6 weeks (p=0.2146). By 8-12 weeks postoperation, the mean daily distance reached 107%, but this was not statistically different from baseline (p=0.9999). During 8-12 weeks and 9-12 months postoperation, patients remained roughly at baseline activity levels (Figure 4).

Regression analysis was performed against initial postoperative (days 1-28) PA (Table 2) to explore variables that might be associated with recovery trends. Immediate postoperative reconstruction (β=0.5972, p=0.046) and uncomplicated recovery (no reported complications)

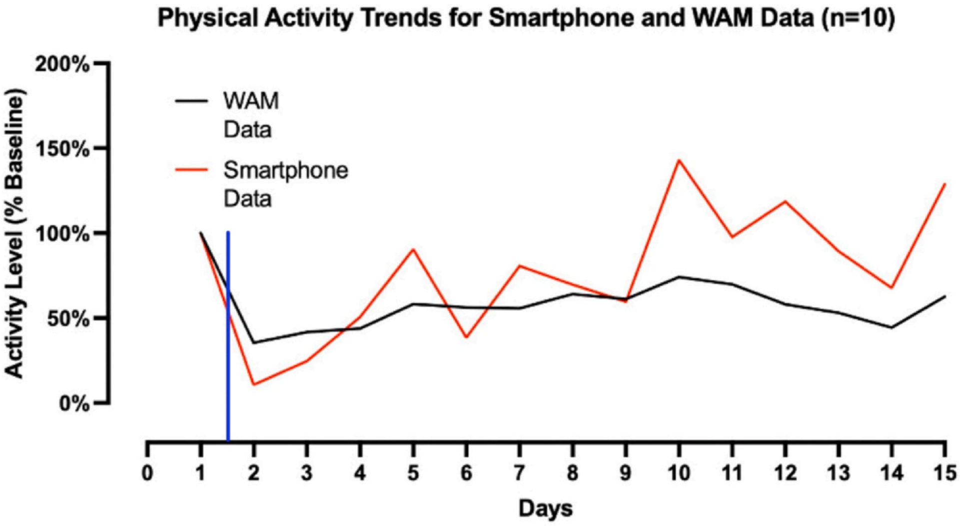

Figure 2 Physical activity for patient wearable activity monitor (WAM) data and smartphone physical activity (PA) Data (n=10). Activity levels are calibrated to baseline PA per patient. WAM data are shown in percentage of average daily signal vector magnitude (SVM), and smartphone data are shown in percentage of mean daily distance walked or run (km/day). Day 1 represents the mean preoperative baseline PA, with days 2–15 representing the 2 weeks of postoperative recovery. The day of operation is marked by the vertical blue line.

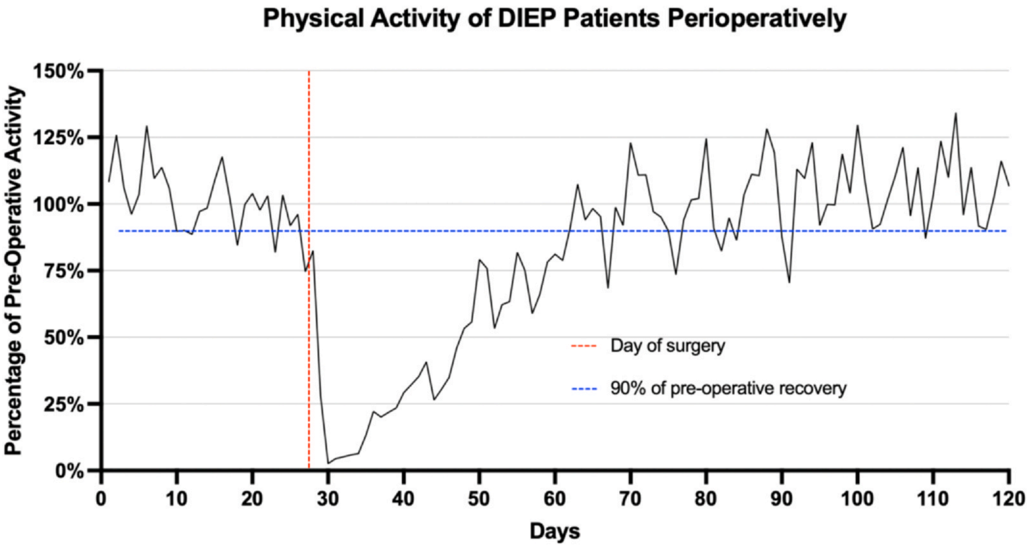

Figure 3 Aggregated physical activity over time in DIEP patients (n=34), relative to baseline PA. The preoperative baseline was calculated as the mean activity during a month (28 days) before surgery. All perioperative values were divided by this baseline.

(β=1.282, p=0.0063) were predictive of higher PA levels in the immediate postoperative period (days 1–28). However, this significance was not retained once analyzed using multivariate regression. None of the variables showed a significant association with long-term recovery.

Discussion

To our knowledge, this is the first study to demonstrate the validity of smartphone-generated PA data to objectively quantify postoperative recovery following DIEP flap breast reconstruction.

Concurrent validity in the perioperative setting was demonstrated by the statistically significant correlation between smartphone PA and WAM data.[10] Where previous work illustrated recovery following DIEP using WAMs, this study extends the literature by significantly increasing the data duration, highlighting smartphone-derived data as a more scalable and cost-efficient alternative.[7,21] Smartphones offer a familiar and accessible tool for patients, eliminating the need for additional devices. This approach can address key limitations of WAMs, including device cost, inconsistent

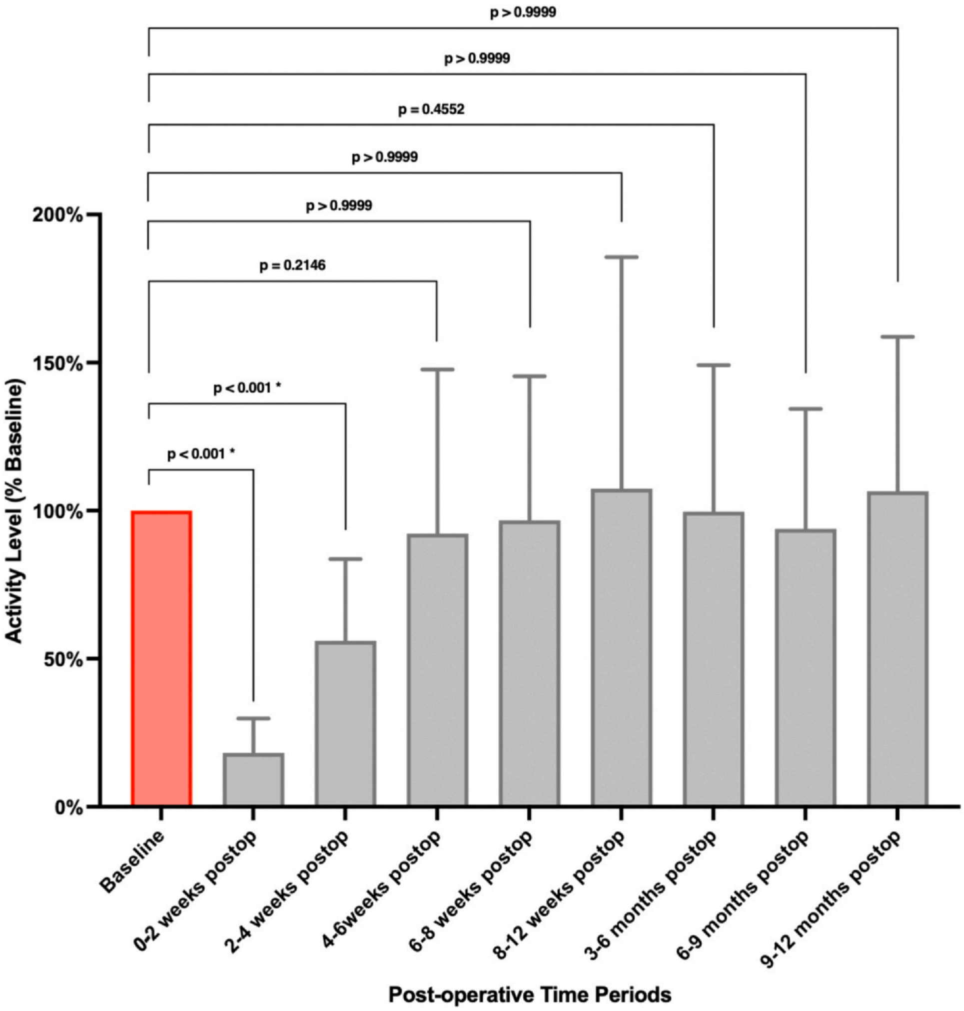

Figure 4 Mean physical activity of DIEP patients: from 1-month preoperative to 12-month postoperative period (n=34). Mean physical activity of patients from 1-month pre-operation to 12-month postoperation with standard deviation bars and associated p-values. Activity levels have been calibrated to baseline PA per patient. * $p < .05$, it indicates statistically significant differences. All significant p-values are highlighted in **bold**.

Table 2 Simple linear regression analysis of patient demographics, operative details and recovery information against mean postoperative % PA of baseline during days 1–28 postoperation.

Variables	Unstandardized ß	95% Confidence interval	p-value
Age	−6.642	−21.75 to 8.463	0.3771
BMI	−6.074	−18.29 to 6.144	0.3181
Smoking	−0.5210	−1.118 to 0.07619	0.0851
Operative details			
ASA	−0.1986	−0.8470 to 0.4498	0.5370
ALND	−0.2934	−1.320 to 0.7336	0.5647
SLNB	0.5979	−0.4766 to 1.672	0.2654
Immediate reconstruction	0.5972	0.009376 to 1.185	**0.0467**
Recovery information			
Return to theater due to post-op complication	−0.5879	−1.267 to 0.09094	0.0873
Emergency department presentations within 1 month	−0.8450	−1.730 to 0.04031	0.0607
No complication	1.282	0.3891 to 2.176	**0.0063**

BMI, body mass index; ASA, American society of anaesthesiologists status; ALND, axillary lymph node dissection, SLNB, sentinel lymph node biopsy; ß, regression coefficient.

$p < 0.05$, it indicates statistically significant differences. All significant p-values are highlighted in **bold**.

compliance and variability across manufacturers and outcome measures, which hinder direct comparisons between studies.[13,15] Smartphones generate large retrospective datasets at no extra cost, offering societal and healthcare savings when applied to remote monitoring.[22] With the vast majority of patients owning and using smartphones as part of their daily lives, this technology can offer a highly accurate depiction of patients' baseline and postoperative physical health status.[23]

The observed reduction in PA during the first two weeks following DIEP was expected, consistent with clinical observations of initial pain, tightness, and weakness at the abdominal donor-site which can restrict the upright posture needed for ambulation.[24] Although the postoperative guidelines encourage walking and commencing light exercises guided by physiotherapy on days 3-5, they discourage strenuous activities for 6-8 weeks postoperation to facilitate wound healing.[25] Consequently, the initially low PA levels that gradually rise in the first 6 postoperative weeks in our cohort likely reflect improvements in physical and mental health, reduction in pain levels, and possibly adherence to clinical recommendations. Patients at our NHS Trust are informed that recovery following DIEP requires approximately 6-8 weeks.[26] Although a previous study (n=17) that used WAMs reported that only 53% of participants achieved preoperative activity levels by week 8 after DIEP,[21] our results showed that 6–8 weeks is a fairly accurate estimate. The observed mean increase in baseline activity to 107% (SD=78%) at 8–12 weeks likely represents a return to preoperative baseline rather than a true improvement beyond baseline. Although this modest elevation could reflect changes in health behaviors following a cancer diagnosis, such as increased motivation to adopt a healthier lifestyle, the data suggest that activity levels stabilize close to 100%, indicating maintenance rather than a sustained increase in activity. It is reassuring that there now exists objective data supporting the return to preoperative activity levels in the mid to long-term periods after breast reconstruction.

Our exploratory univariate analysis demonstrated a positive association to enhanced postoperative recovery with 2 variables: age and immediate (compared to delayed) reconstruction. Immediate reconstruction includes the concomitant mastectomy and axillary surgery, resulting in more invasive surgery and potentially longer operative times that would theoretically reduce PA compared to patients only undergoing delayed reconstruction. However, this association was 1 of 11 tested (without statistical correction), and without evidence in the multivariate analysis; therefore, it may be explained by co-existing patient or disease factors. Differences in baseline activity levels for physical or social reasons can potentially skew the recovery data, given that it is relative to a preoperative baseline. It is also possible that other unmeasured factors, such as patient motivation or social support, contributed to higher PA in the immediate reconstruction group and confounded the univariate relationship.

Smartphone-derived PA provides a reliable and objective measure of postoperative recovery, supplementing the more holistic data gathered using patient-reported outcome measures (PROMs).

If recovery is slower than expected, as measured using a smartphone system, these data could support early intervention. Integrating smartphone-derived PA into a closed-loop system with clinical teams could alert providers when patients are experiencing suboptimal recovery, allowing timely follow-up and targeted interventions such as enhanced physiotherapy or investigation of potential complications. This technology-supported recovery has the potential to improve clinical outcomes and optimize patient safety.[27]

The use of digital health interventions and closed-loop monitoring is being explored in various clinical situations, and so far, it has been feasible and acceptable to patients and clinicians.[15] Broader integration of smartphone PA data with online health platforms could also support virtual follow-ups, reducing the burden of in-person visits while enhancing patient engagement and adherence to recovery plans. Tracking progress during recovery equally enhances patient engagement and often results in improved satisfaction.[28] Overall, leveraging real-time, objective PA metrics could transform postoperative care by enabling personalized, data-driven support throughout recovery.

Limitations

The results of this study should be interpreted in the context of some limitations. The absolute definition of patient recovery after surgery using physical activity data is not yet clearly defined in the literature.[16] Our rationale for using a 90% threshold to define recovery was chosen owing to the protracted tail of the recovery curve and need for attaining a consistent endpoint with which to compare patients in the linear regression analyses. Although 100% of baseline may be more intuitive, the end points were highly variable and did not agree with visual assessment of the data. Furthermore, 10% variation in daily activity or more is common and therefore unlikely to be a clinically meaningful difference to baseline.

The correlation coefficient (r=0.64) between the WAM and smartphone data suggests moderate concurrent validity in our study. This analysis was performed to provide some reassurance that the well-documented validity of smartphone data reported elsewhere extends to the perioperative setting.[20] Although a wrist worn sensor may be more accurate, our method of calibrating postoperative smartphone data to a preoperative baseline should consider the patients' smartphone use/wear behavior. The analysis of processed smartphone data versus raw accelerometry was not intended to be the focus of the study. A formal comparison would benefit from more comparable metrics in a controlled setting.

The assumption that 24 h of inactivity reflected non-wear rather than true inactivity may also have introduced error. The exclusion of periods of implausibly low activity was performed to control data quality, often used in accelerometer research.[19] The number of days removed was minimal and not clustered around clinically significant events such as complications; therefore, no formal sensitivity analysis were performed.

The use of smartphones to measure recovery likely favored younger, more technologically adept patients, reflected in the demographic of our participants with an average age of 48 years (compared to 63 years in the literature).[29] This apparent selection bias limits generalizability to the typical breast reconstruction population, and may have shown a quicker postoperative course. Additionally, the exclusion of Android phone users may have introduced further selection bias; however, from an age perspective, our analysis showed no significant difference in the mean ages of the recruited iPhone patients (n=34, mean=48 years, SD=7.03 years) compared to the excluded Android users (n=13, mean=51 years, SD=8.57 years; p=0.25). An Android version of the software is under development to improve scalability and reduce bias in further studies.

Potential missing or incomplete smartphone data, variations in compliance or smartphone behaviors, and reliance on device-variable sensors may have further affected the accuracy. Importantly, PA data were not combined with qualitative measures such as pain, fatigue, or psychosocial recovery, which could be integrated in future studies. Physical activity is one of the several dimensions of recovery and needs to be interpreted in the context of the patient self-reported experience. Given the variability of the way in which this complex operation can be performed, the generalizability of these findings from a single center, albeit with multiple surgeons, is limited.

The univariate regression analysis was intended to be exclusively exploratory and hypothesis-generating, to identify variables that might be associated with different recovery patterns. Eleven variables were tested with 2 reported as significant; however, without correction for multiple comparisons, there is a higher risk for a false-positive. Regarding the multivariate model, the small sample size limits validity and this was only performed to assess the impact of the confounders. A larger sample size is needed to derive meaningful independent predictors of recovery.

Future directions

Smartphone-derived PA data could be combined with clinical and demographic variables to develop predictive algorithms capable of forecasting recovery trajectories and supporting individualized patient care. Future interventional studies should evaluate whether PA-guided strategies—such as early physiotherapy or tailored activity modifications—can accelerate recovery and improve postoperative outcomes. It would also be valuable to assess the effectiveness of current physiotherapy exercises recommended following DIEP surgery. Integrating smartphone-derived PA data with PROMs could provide a more comprehensive understanding of recovery and quality of life.

Looking ahead, patient-generated smartphone data hold substantial potential for continuous monitoring of recovery and for tailoring surgical recommendations based on individual patient history and procedures. Mobile health solutions can enhance patient education and enable personalized care even in the absence of continuous provider input. Integration of PA monitoring into telemedicine could facilitate virtual follow-ups, reducing the need for in-person visits and streamlining patient-provider communication. Furthermore, when combined with user feedback, smartphone applications are known to increase physical activity—a critical outcome for cancer survivors, who often do not meet the recommended activity levels.[30] Broad adoption of these tools could strengthen adherence, engagement, and overall recovery.

Conclusion

This study demonstrated the validity of smartphone-collected physical activity data as an objective measure of recovery following DIEP breast reconstruction. Using these data, postoperative recovery was quantified and clinical factors impacting recovery were identified. These findings show a significant early decline in activity with return to baseline around 6–8 weeks. These insights may inform preoperative counseling, support the development of personalized postoperative monitoring plans, and in general promote efficient surgical care pathways.

Ethical approval

The study included the recruitment of human participants, with ethical approval granted by the National Research Ethics Committee (Ref: 15/LO/1038).

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Declaration of Competing Interest

The authors have no conflict of interest to declare in relation to this manuscript.

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