Comparing three wearable accelerometers to measure early activity after cardiac surgery

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ABSTRACT

Objective: Wearable activity monitors can provide detailed data on activity after cardiac surgery and discriminate a patient's risk for hospital-based outcomes. However, comparative data for different monitoring approaches, as well as predictive ability over clinical characteristics, are lacking. In addition, data on specific thresholds of activity are needed. The objective of this study was to compare 3 wearable activity monitors and 1 observational mobility scale in discriminating risk for 3 hospital-based outcomes, and to establish clinically relevant step thresholds.

Methods: Cardiac surgery patients were enrolled between June 2016 and August 2017 in a cohort study. Postoperative activity was measured by 3 accelerometry monitors (StepWatch Ambulation Monitor, Fitbit Charge HR, and ActiGraph GT9X) and 1 nurse-based observation scale. Monitors represent a spectrum of characteristics, including wear location (ankle/wrist), output (activity counts/steps), consumer accessibility, and cost. Primary outcomes were duration of hospitalization >7 days, discharge to a nonhome location, and 30-day readmission.

Results: Data were available from 193 patients (median age 67 years [interquartile range, 58-72]). All postoperative day 2 activity metrics (ie, from StepWatch, Fitbit, ActiGraph, and the observation scale) were independently associated with prolonged hospitalization and discharge to a nonhome location. Only steps as measured by StepWatch was independently associated with 30-day readmission. Overall, StepWatch provided the greatest discrimination (C-statistics 0.71-0.76 for all outcomes). Step thresholds between 250 and 500 steps/day identified between 74% and 96% of patients with any primary outcome.

Conclusions: Data from wearable accelerometers provide additive value in early postoperative risk-stratification for hospital-based outcomes. These results both support and provide guidance for activity-monitoring programs after cardiac surgery. (JTCVS Open 2022;11:176-91)
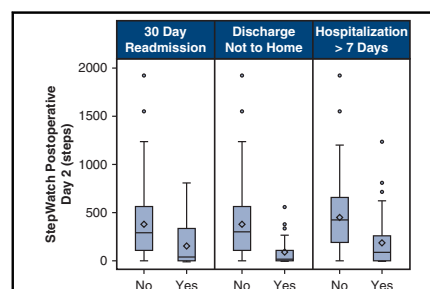
Steps on postoperative day 2 were lower in patients with 3 adverse hospital outcomes.

CENTRAL MESSAGE

Data from wearable accelerometers provide additive value in early postoperative risk-stratification for hospital outcomes. The results provide guidance for activity monitoring after cardiac surgery.

PERSPECTIVE

Increasing postoperative activity is important, and accurate measurement is a key first step. Wearable accelerometers can provide detailed data, but comparison of devices is needed, as well as clinically relevant thresholds (particularly early in recovery). The results provide these comparisons and show that <250-500 steps on day 2 identifies 74%-96% of patients with a hospital-based adverse outcome.

Early ambulation and increased physical activity have long been recognized as important for postoperative recovery,[1] and they are core components of enhanced recovery programs after noncardiac[2] and cardiac surgery.[3] An important part of promoting activity and mobility is accurate and timely patient-level measurement of movement.[4] However, such measurement is difficult in hospital settings, as current measurements are typically limited to observations by staff or patient report, which are often not granular, standardized, or complete.[5] This lack of measurement contributes to what has been characterized an "epidemic of low mobility" in hospitalized patients that may be particularly important for older adults, who are at the greatest risk for impaired mobility and poor functional recovery.[6]

Wearable activity monitors can provide novel and detailed data on activity and mobility after surgery, which could be used to guide clinical care protocols, provide research insights, and display information to patients to increase activity. Scattered reports in noncardiac and cardiac surgical populations at different times of recovery have reported associations of activity and mobility metrics with some postoperative outcomes.[7-11] However, there are a myriad of monitoring devices that can be used, with varying measurement properties and costs.[11] As an alternative to wearable monitors, structured clinical observations of activity and mobility require no extra hardware but provide less granular measurements.[12] For cardiac surgery programs considering all of these options, comprehensive data comparing different monitoring approaches are needed to understand which monitoring approach provides the most clinically relevant information and to establish thresholds of activity and mobility that can be used to target activity after surgery.

To address these questions, we conducted an observational cohort study after cardiac surgery, with measurement of early activity and mobility using 3 different wearable activity monitors and 1 validated nurse-assessed scale (Johns Hopkins Highest Level of Mobility [JH-HLM] scale).[12] The wearable activity monitors were chosen to represent a spectrum of device characteristics, including wear location

(ankle/wrist), type of output (activity counts/step counts), consumer-accessibility, and cost. We hypothesized that measurement of early activity after surgery (ie, postoperative day 2) using wearable accelerometers and/or an observation scale would discriminate risk for hospital-based outcomes (duration of hospitalization, discharge location, and 30-day readmission), even after accounting for other known predictors of these outcomes. We also identified clinically relevant thresholds for number of steps to identify patients at greatest risk for the hospital-based outcomes.

METHODS

The study was approved by the Johns Hopkins Medicine Institutional Review Board (IRB00086547; approved on February 16, 2016). Patients provided written consent at Johns Hopkins in the week before or the day of surgery to be part of a research study, and the consent included distribution of patient information as part of the study.

Study Design, Participants, and Sample Size

This observational cohort study enrolled elective cardiac surgery patients at Johns Hopkins between June 4, 2016, and August 9, 2017. Inclusion criteria were coronary artery bypass graft and/or valve surgery, aortic surgery, and/or myectomy. Exclusion criteria included lung/heart transplant, or planned insertion of a ventricular assist device. Data on a subset of these patients have been published previously.[13]

For sample size determination, we assumed steps of 230 ± 180 and 170 ± 88 in patients discharged to home versus not-home and steps of 510 ± 700 and 220 ± 500 for patients with hospitalization <7 days versus longer, based on previous work.[9] Using these assumptions, a sample size of 176 would provide >80% power for a difference in steps, with significance of $P = .05$.

Activity Measurement

Activity was monitored using 3 devices and 1 nurse observation scale. The devices were (1) StepWatch Activity Monitor (Modus Health), (2) ActiGraph GT9X, and (3) Fitbit Charge HR (Fitbit Inc). Device characteristics are described in Table 1, and all devices can be purchased and are clinically available. For nurse observation, nurses documented the greatest level of mobility observed on their shift using the JH-HLM scale (range, 1-8), with scores 1 to 5 indicating activity that ranges from bed-bound to standing and scores of 6-8 indicating ambulation ≥ 10 steps, ≥ 10 feet, and ≥ 250 feet, respectively. The Fitbit and ActiGraph were placed on the same wrist and the StepWatch was placed on the ankle by 8 AM after surgery. Patients were encouraged to wear devices at all times (except bathing) during hospitalization. Staff visited patients every 1 to 2 days (except weekends) to monitor compliance. For periods of nonwear, staff estimated with patients and nurses the removal time.

Outcome Measurement

Three key outcomes were established before data collection and were duration of hospitalization after surgery, discharge to a nonhome location, and readmission within 30 days of hospital discharge. Duration of hospitalization and discharge location were abstracted from the electronic health record. No patients were institutionalized at baseline. Patients who were discharged to a hotel or with family were considered discharged home. Information on 30-day readmission was abstracted from the health record, which included routine follow-up calls, 1-month clinic appointments, and data from the state health information exchange. Readmission was defined as any overnight stay in a hospital within 30 days of discharge from the initial surgery.

TABLE 1. Characteristics of 3 wearable accelerometers worn by patients

Monitor	Manufacturer	Location of wear	Output	Availability?
StepWatch Activity Monitor	StepWatch; Modus Health LLC	Ankle	Steps	Available by direct order from vendor website
ActiGraph GT9X	ActiGraph LLC	Wrist	Activity counts	Available by direct order from vendor website
Fitbit Charge HR	Fitbit; Fitbit Inc	Wrist	Steps	Easily available to consumers through multiple platforms and the least expensive

Baseline and Perioperative Covariate Data

Patient information was obtained by direct interview and abstraction from the electronic record. Comorbidities, including the logistic European System for Cardiac Operative Risk Evaluation score (logEuroSCORE), were assessed based on information from the medical record and from patient self-report. The logEuroSCORE was chosen because the included variables in this score were potentially important confounding variables based on literature review. The World Health Organization-Disability Assessment Schedule 2.0 (ie, WHO-DAS 2.0)[14] and ability to complete Instrumental Activities of Daily Living were also reported by patients and reflect the time before hospitalization. All patients received a preoperative education packet, as part of usual care, that emphasized the importance of mobility. Clinical protocols targeted out-of-bed to chair on the night of surgery and ambulation 2-3 times daily afterward. Physical and occupational services were available based on nursing screen.

Statistical Analysis

Steps per minute and per day were available from the Fitbit and StepWatch devices, whereas the vector magnitude of activity counts (unit-less quantities of movement across 3 axes) per minute and per day were available from the ActiGraph. Activity metrics on postoperative day 2 were the primary exposure because we were interested in early metrics of activity, and this was the first day with 24-hour data. Devices were considered to be worn if activity was registered between placement and removal, with no documented noncompliance.

Patient characteristics were compared between mobility groups using the Student t test, Wilcoxon rank-sum, χ^2, or Fisher exact tests. Multivariable regression analyses were used to examine the association of mobility metrics with each outcome, adjusting for potentially confounding variables. Duration of hospitalization was analyzed with linear regression with inverse normal transformation. Two sets of outcome-specific adjusted regression models were used. The first set of models used outcome-specific variables defined a priori by the research team based on literature review, supplemented by variables associated with both activity and specific outcomes. The second set of models included variables that were unique to validated outcome-specific prediction models.[15-17] The potentially confounding variables were outcome specific. For duration of hospitalization, the covariates include age, sex, race, logEuroSCORE, bypass time, and intensive care unit (ICU) duration. For discharge location, the covariates include age, sex, race, baseline instrumental activities of daily living, logEuroSCORE, duration of bypass, and ICU duration. For 30-day readmission, the covariates include age, sex, race, baseline instrumental activities of daily living, logEuroSCORE, duration of hospitalization, discharge location, ICU duration, and transfusion of red cell units. Standard model diagnostics were examined to ensure good model fit, including residuals, collinearity and influence measures, and goodness-of-fit tests (Osius and Rojek test) for logistic models and r-squared values for linear models.

The discrimination of activity metrics was examined using outcome-specific receiver operating curves (ROCs), using C-statistics. Nonstandard ROC curves were used since the outcome of interest was less common as activity increased. Duration of hospitalization was categorized using a cut point of 7-days for the ROC analyses. Youden[18] criteria were used to determine step thresholds which maximized sensitivity and specificity. Since ROC curves may be biased when predictor scales are dichotomized or have coarse categorization (JH-HLM) and/or zero values (Fitbit),[19] we also used the "fbroc" package in R with 1000 bootstrapped samples.

SAS, version 9.4 and RStudio, version 1.3.959, were used for main analyses. Missingness for nondevice variables was low (<10%) and considered to be missing at random, thus pairwise and listwise deletion methods were performed. We calculated the proportion of device missingness as the number of patients who wore the device for any portion of day 2 divided by the total number of patients (n = 193). We calculated the proportion of device data missingness as the number of patients with complete data for every minute in postoperative day 2 divided by the number of patients who wore the device for any portion of day 2. Missing minute-level device data were imputed to zero (no movement).

RESULTS

Perioperative and Activity Characteristics

Data were available from 193 patients, with a median age of 67 years (interquartile range [IQR], 58-72). All patients underwent cardiopulmonary bypass with sternotomy during surgery. In total, 47% were inpatients. A patient flow diagram is shown in Figure E1. Patients with low perioperative mobility tended to be women, with lower functional status, greater logEuroSCORE, and longer intubation and intensive care unit duration (Table 2).

The median duration of hospitalization was 7 days (range, 4-48). Overall, 24 (12%) patients were discharged to a nonhome location, and 34 (18%) patients were readmitted within 30 days. All patients (n = 193) had data on duration of hospitalization and discharge location. Five patients were censored for the 30-day readmission outcome because of inadequate postdischarge records. Patient characteristics by each outcome are presented in Tables E1-E3. Patients at risk for all outcomes were older, had greater logEuroSCORE, and longer intensive care unit duration.

Activity on postoperative day 2 was the primary metric of "early activity," since this information is obtained early enough after surgery to be clinically actionable. On postoperative day 2, 98% (n = 189) of patients were wearing at least 1 activity monitor, with 85% (n = 164) wearing all 3 monitors; 96% (185/193) wore the StepWatch, 92% (178/193) wore

TABLE 2. Patient and perioperative characteristics

Characteristic	Overall (n = 193)	Low mobility* (n = 92)	High mobility* (n = 93)	P value
Age, y, median [IQR]	67 [58-72]	67.5 [61-73]	64 [56-72]	.18
Male, no. (%)	158 (81.87)	68 (73.91)	83 (89.25)	.007
White, no. (%)	147 (76.17)	65 (70.65)	74 (79.57)	.16
Living with someone (spouse, family, other), no. (%) (n = 190)	146 (76.84)	77 (84.62)	62 (68.13)	.009
Body mass index, kg/m², median [IQR]	28.3 [24.8-32.1]	27.4 [23.97-31.64]	28.62 [24.98-32.09]	.43
IADL score,† median [IQR], (n = 189)	14 [14-14]	14 [14-14]	14 [14-14]	.05
WHO-DAS 2.0 score,‡ median [IQR], (n = 186)	4 [2-8]	5 [2-10]	3 [1-6]	.004
Difficulty walking long distances				.036
No difficulty, no. (%)	82 (43.62)	30 (33.33)	49 (54.44)	
Mild difficulty, no. (%)	15 (7.98)	8 (8.89)	7 (7.78)	
Moderate difficulty, no. (%)	20 (10.64)	12 (13.33)	6 (6.67)	
Severe difficulty, no. (%)	22 (11.7)	10 (11.11)	11 (12.22)	
Extreme difficulty or cannot do, no. (%)	49 (26.06)	30 (33.33)	17 (18.89)	
Logistic EuroSCORE	2.9 [1.9-5.1]	3.15 [2.1-6.995]	2.69 [1.66-4.1]	.02
Comorbidities				
Previous stroke or TIA, no. (%)	19 (9.84)	10 (10.87)	8 (8.6)	.60
Depression, no. (%)	20 (10.36)	12 (13.04)	7 (7.53)	.22
Hypertension, no. (%)	158 (81.87)	78 (84.78)	74 (79.57)	.35
Congestive heart failure, no. (%)	72 (37.31)	41 (44.57)	29 (31.18)	.06
Peripheral vascular disease, no. (%)	25 (12.95)	12 (13.04)	11 (11.83)	.80
Diabetes, no. (%)	74 (38.34)	39 (42.39)	33 (35.48)	.34
Previous tobacco use, no. (%)	109 (56.48)	54 (58.7)	49 (52.69)	.41
COPD, no. (%)	26 (13.47)	16 (17.39)	10 (10.75)	.19
eGFR, mL/min, mean (SD)	74.31 ± 21.9	71.67 ± 24.1	76.62 ± 19.5	.05
Active alcohol and/or drug use, no. (%)	28 (14.51)	10 (10.87)	17 (18.28)	.15
Medications				
Aspirin, no. (%)	151 (78.24)	73 (79.35)	72 (77.42)	.75
Platelet aggregation inhibitor, no. (%)	40 (20.73)	26 (28.26)	13 (13.98)	.02
Beta blocker, no. (%)	137 (70.98)	67 (72.83)	64 (68.82)	.55
Calcium channel blocker, no. (%)	58 (30.05)	24 (26.09)	30 (32.26)	.36
ACE or ARB, no. (%)	94 (48.70)	41 (44.57)	51 (54.84)	.16
Any anticoagulant (heparin, coumadin, other), no. (%)	81 (41.97)	50 (54.35)	2 (2.15)	.003
Statin, no. (%)	148 (76.68)	74 (80.43)	30 (32.26)	.18
Surgery type				
Isolated CAB, no. (%)	111 (57.51)	57 (61.96)	48 (51.61)	.18
Isolated valve, no. (%)	49 (25.39)	18 (19.57)	30 (32.26)	
CAB + valve, no. (%)	22 (11.40)	13 (14.13)	9 (9.68)	
Other, no. (%)	11 (5.70)	4 (4.35)	6 (6.45)	
Intraoperative intra-aortic balloon pump, no. (%)	26 (13.47)	21 (22.83)	4 (4.3)	<.001
Hemoglobin, g/dL, median [IQR]	9.3 [8.4-10.4]	8.7 [7.9-9.6]	9.8 [8.8-10.9]	<.001
Duration of bypass, min, median [IQR]	104 [77-139]	114 [77-151]	104 [77.5-134]	.41
Intraoperative red blood cell transfusion, units, median [IQR]	0 [0-1]	0 [0-3]	0 [0-0]	.002
Duration of intubation, h, median [IQR]	5.3 [3.7-8.8]	7.25 [4.58-13.5]	4.25 [3.25-6]	<.001
Duration of ICU stay, h, median [IQR]	28.8 [21.8-69.5]	50.625 [26.25-93]	23 [20.25-45]	<.001
Duration of hospital stay before surgery, h, median [IQR]	0 [0-4]	1.5 [0-4.5]	0 [0-3]	.07

IQR, Interquartile range; *IADL*, Instrumental Activities of Daily Living; *WHO-DAS 2.0*, World Health Organization Disability Assessment Schedule 2.0 (12-item); *EuroSCORE*, European System for Cardiac Operative Risk Evaluation score; *TIA*, transient ischemic attack; *COPD*, chronic obstructive pulmonary disease; *eGFR*, estimated glomerular filtration rate; *ACE*, angiotensin-converting enzyme; *ARB*, angiotensin receptor blocker; *CAB*, coronary artery bypass; *ICU*, intensive care unit. *Low and high mobility are defined as based on the median number of steps (as measured by the StepWatch Activity Monitor) on postoperative day 2. StepWatch data was available on 185 patients. †IADL scores range from 0 to 14, with a lower number indicating more difficulty with IADLs. ‡WHO-DAS 2.0 scores range from 0 to 48, with greater scores indicating greater impairment.
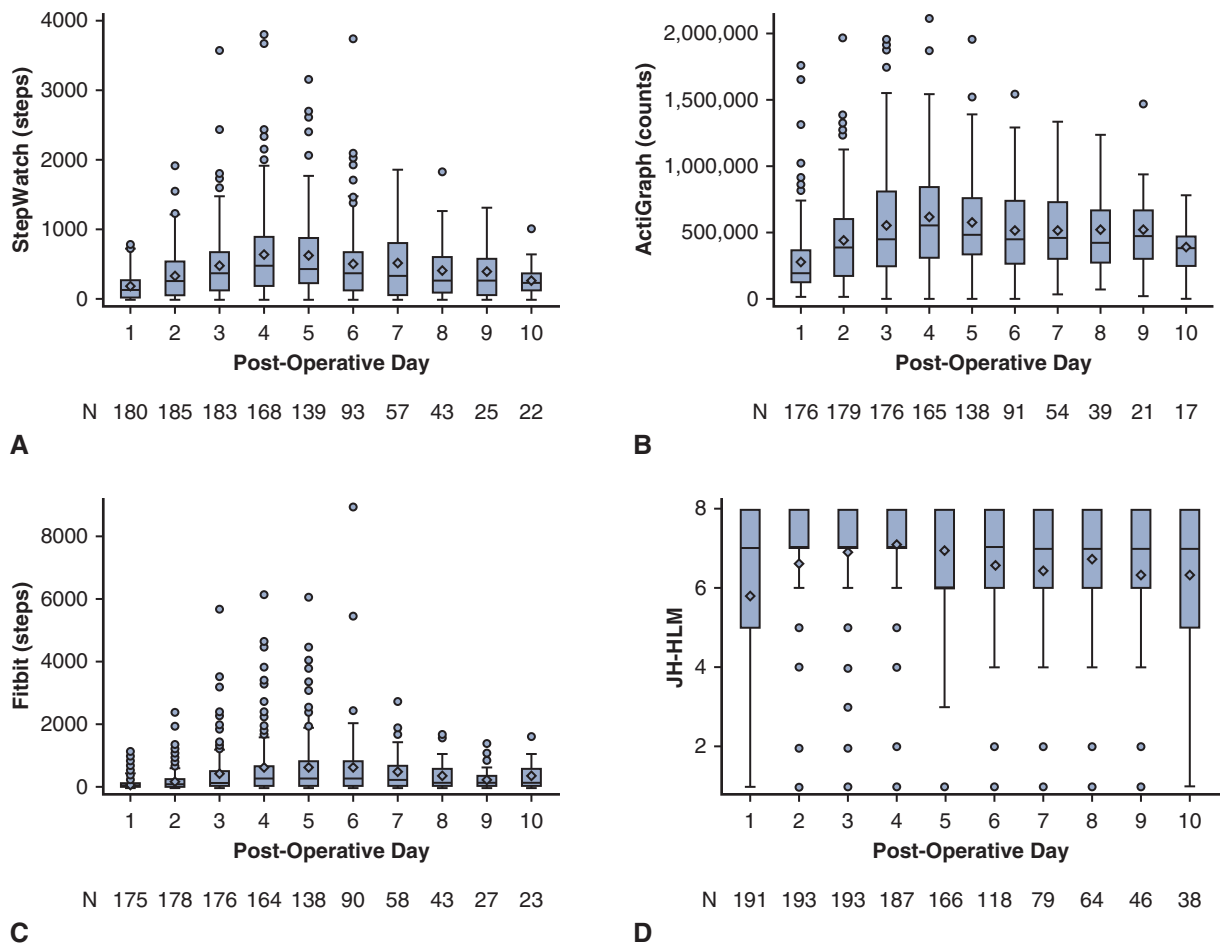
FIGURE 1. Activity and mobility on postoperative days 1-10, as measured by 3 different wearable accelerometers (StepWatch, ActiGraph, Fitbit), and 1clinical observation scale (Johns Hopkins-Highest Level of Mobility [*JH-HLM*]). The distributions of activity on all postoperative days 1-10 are shown for StepWatch Ambulation Monitor (A), ActiGraph (B), Fitbit (C), and the JH-HLM scale (D). A similar pattern of increasing activity from postoperative days 1 through day 5 is observed, regardless of the method of measuring activity. Note that the boxplots reflect only patients in the hospital, and discharges of healthier patients began to occur at approximately day 5, and so the activity of the remaining hospitalized patients decreases after postoperative day 5. The *lower and upper borders of the box* represent the lower and upper quartiles (25th and 75th percentile). The *middle horizontal line* is the median value, and the *diamond* in the box is the mean value. The *lower and upper whiskers* represent 1.5 times the interquartile range. *Open circles* represent outliers. "N" represents the number of patients wearing the monitor on each day.

the Fitbit, and 93% (179/193) wore the ActiGraph. On postoperative day 2, of those who wore the StepWatch 96% (179/185) had data for every minute; for Fitbit, 95% (169/178) had data for every minute, and for ActiGraph, 97% (173/179) had data for every minute. The missing minute data for these patients (n = 9) was often overnight when limited mobility was expected. The median value of activity on postoperative day 2 for each monitor was the following: StepWatch 254 steps (IQR, 62-522) (n = 185), Fitbit 37.5 steps (IQR 0-239) (n = 178), and ActiGraph 392,020 counts (IQR, 173,465-591,368) (n = 179). Median JH-HLM score was 7 (IQR 7-8) (n = 193). Mobility generally increased from postoperative days 2-5 (Figure 1), after

which healthier patients were discharged, so the average mobility for remaining patients decreased through day 10.

Association of Activity Metrics on Postoperative Day 2 and Patient Outcomes

For duration of hospitalization, all metrics of activity on postoperative day 2 were higher in patients who were discharged in <7 days compared with longer (Figure 2). As an example, the median number of StepWatch steps on postoperative day 2 was 424 in patients who were discharged in <7 days, but was 90 in patients with longer hospitalization. All metrics of postoperative day 2 activity (from each approach to activity monitoring) were significantly
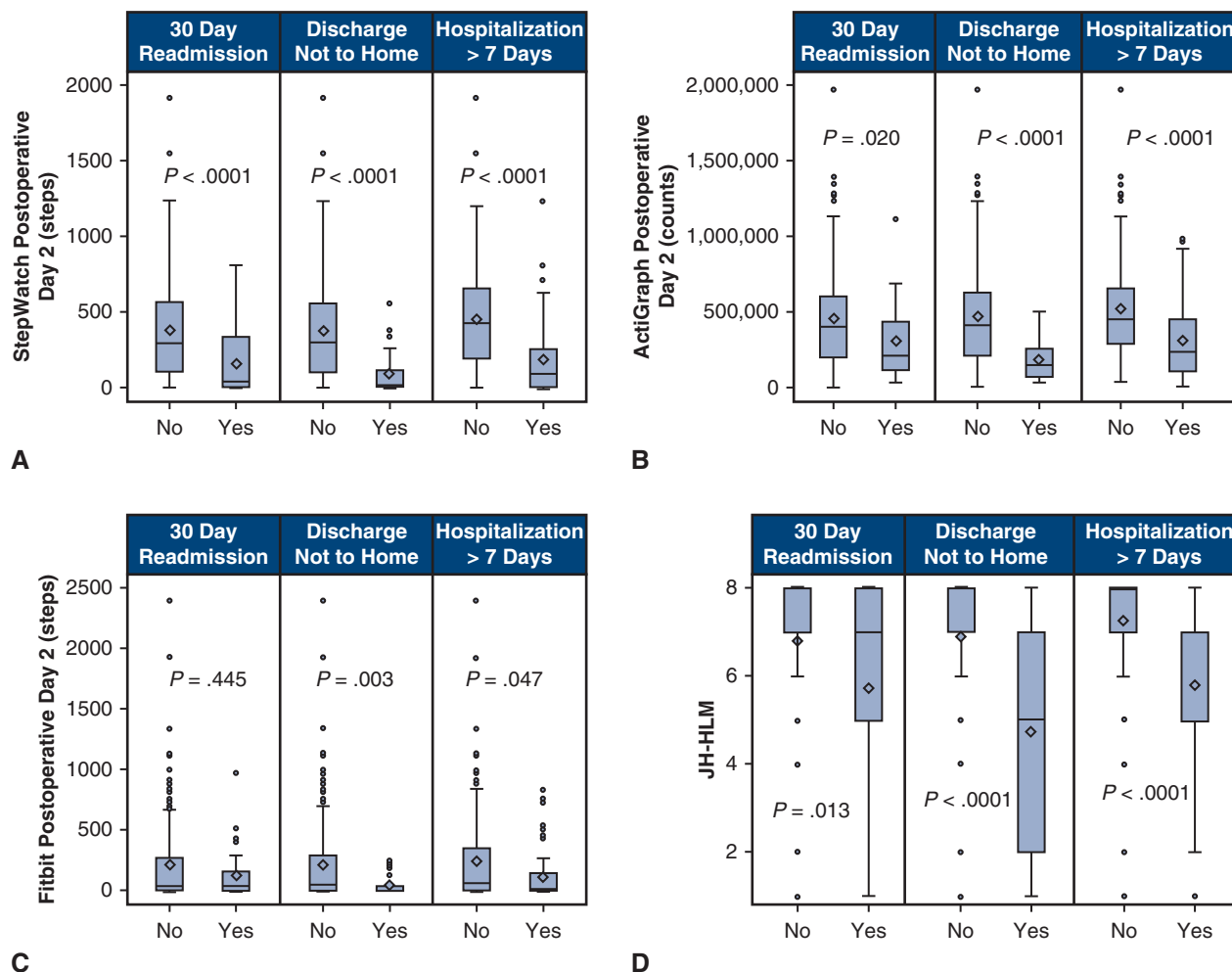
FIGURE 2. Differences in 30-day readmission, discharge location, and duration of hospitalization based on postoperative day 2 activity and mobility. The distributions of postoperative day 2 activity and mobility are shown for patients stratified by 3 outcomes (30-day readmission, discharge to a nonhome location, and duration of hospitalization >7 days). Postoperative day 2 activity is greater in patients with favorable outcomes, regardless of the method of measurement: StepWatch Ambulation Monitor (A), ActiGraph (B), Fitbit (C), and the Johns Hopkins-Highest Level of Mobility (*JH-HLM*) scale (D). However, the strength of the association between early activity and each outcome varies depending on the method of measurement. The *lower and upper borders of the box* represent the lower and upper quartiles (25th and 75th percentile). The *middle horizontal line* is the median value, and the *diamond in the box* is the mean value. The *lower and upper whiskers* represent 1.5 times the interquartile range. *Open circles* represent outliers.

associated with prolonged hospitalization in both unadjusted and 2 adjusted models, including an adjusted model based on validated prediction scores using clinical characteristics[15] (Table 3).

Similarly, for discharge location, all metrics of activity on postoperative day 2 were greater in patients who were discharged home compared with a nonhome location (Figure 2). The median number of StepWatch steps on postoperative day 2 was 298 in patients who were discharged home, but was 14.5 in patients who were discharged to a nonhome location. In regression models, there was a strong association of all metrics of activity on postoperative day 2 with discharge to a nonhome location in both unadjusted and 2 adjusted models, including an adjusted model based

on validated prediction scores using clinical characteristics[16] (Table 3).

However, for 30-day readmission, the results were mixed. In unadjusted models, there were associations between metrics of activity on postoperative day 2 from 3 measurement tools (StepWatch, ActiGraph, and JH-HLM, but not Fitbit) and 30-day readmission. In adjusted models, only steps as measured by StepWatch on postoperative day 2 was independently associated with 30-day readmission (Figure 2 and Table 3).

As post-hoc sensitivity analyses, we examined metrics of mobility on postoperative day 3. The inferences were unchanged for all unadjusted and adjusted models, except the JH-HLM score on postoperative day 3 was newly

TABLE 3. Associations of postoperative day 2 activity with duration of hospitalization, discharge to a nonhome location, and 30-day readmission

	Unadjusted model		Adjusted model #1 (covariates prespecified)*		Adjusted model #2 (covariates from validated risk models)†	
	β-coefficient or Euro SCORE (95% CI)	P value	β-coefficient or physical (95% CI)	P value	β-coefficient or OR (95% CI)	P value
Duration of hospitalization (β-coefficient)‡						
StepWatch, per 100 steps§	−0.14 (−0.18, −0.11)	<.001	−0.08 (−0.12, −0.05)	<.001	−0.09 (−0.13, −0.05)	<.001
Fitbit, per 100 steps‖	−0.09 (−0.13, −0.05)	<.001	−0.06 (−0.09, −0.03)	<.001	−0.06 (−0.10, −0.03)	<.001
ActiGraph, per 50,000 counts¶	−0.06 (−0.08, −0.04)	<.001	−0.03 (−0.05, −0.01)	.003	−0.04 (−0.06, −0.02)	<.001
JH-HLM#	−0.25 (−0.31, −0.18)	<.001	−0.14 (−0.20, −0.08)	<.001	−0.16 (−0.22, −0.09)	<.001
Discharge to a nonhome location vs home location (OR)						
StepWatch, per 100 steps§	0.55 (0.40-0.76)	<.001	0.57 (0.41-0.80)	.001	0.58 (0.40-0.84)	.004
Fitbit, per 100 steps‖	0.63 (0.40-0.98)	.04	0.60 (0.36-0.99)	.04	0.51 (0.26-0.99)	.05
ActiGraph, per 50,000 counts¶	0.76 (0.65-0.89)	<.001	0.74 (0.59-0.92)	.007	0.70 (0.55-0.89)	.003
JH-HLM#	0.65 (0.54-0.78)	<.001	0.69 (0.55-0.87)	.002	0.64 (0.48-0.84)	.002
30-d readmission vs no 30-d readmission (OR)						
StepWatch, per 100 steps§	0.71 (0.59-0.87)	.006	0.8 (0.65-1.00)	.05	0.8 (0.65-0.99)	.04
Fitbit, per 100 steps‖	0.91 (0.78-1.06)	.23	1.00 (0.86-1.17)	.98	0.99 (0.83-1.17)	.87
ActiGraph, per 50,000 counts¶	0.98 (0.97-1.00)	.03	0.99 (0.97-1.01)	.29	0.99 (0.97-1.01)	.24
JH-HLM#	0.79 (0.67-0.93)	.005	0.92 (0.72-1.17)	.51	0.94 (0.76-1.17)	.59

EuroSCORE, European System for Cardiac Operative Risk Evaluation score; *CI*, confidence interval; *OR*, odds ratio; *JH-HLM*, Johns Hopkins-Highest Level of Mobility; *logEuroSCORE*, logistic European System for Cardiac Operative Risk Evaluation score; *ICU*, intensive care unit. *Adjusted for risk factors established a priori by the investigators: (1) For duration of hospitalization, the covariates include age, sex, race, logEuroSCORE, bypass time, ICU duration. R-squared values ranged from 0.38-0.45. (2) For discharge location, the covariates include age, sex, race, baseline instrumental activities of daily living, logEuroSCORE, duration of bypass, ICU duration. *P*-values for goodness of fit were >.9, indicating good fit. (3) For 30-day readmission, the covariates include age, sex, race, baseline instrumental activities of daily living, logEuroSCORE, duration of hospitalization, discharge location, ICU duration, transfusion of red cell units. *P* values for goodness of fit were >.4, indicating good fit. †Adjusted for risk factors from validated outcome-specific prediction models: (1) For duration of hospitalization,[15] the covariates include age, marital status, chronic obstructive pulmonary disease, presence of intra-aortic balloon pump, logEuroSCORE, hemoglobin, major morbidity, transfusion, sex, race. R-squared values ranged from 0.38 to 0.45. (2) For discharge location,[16] the covariates include age, sex, race, marital status, body mass index, peripheral vascular disease, stroke or transient ischemic attack, pulmonary disease, alcohol or drug use, psychiatric disease, operation type. *P*-values for goodness of fit were >.9, indicating good fit. (3) For 30-day readmission,[17] the covariates include race, duration of hospitalization >7 days, severe chronic lung disease, operation, postoperative acute renal failure, age, and sex. *P*-values for goodness of fit were >.6, indicating good fit. ‡Duration of hospitalization is based on an inverse normal transformation, so the coefficients are not interpretable strictly as days. §StepWatch data were available in 185 patients in total. Of these, the regression models used the following patient numbers based on non-missing covariates in models 1 and 2, respectively: duration of hospitalization (n = 183, n = 179), discharge location (n = 179, n = 182), and 30-day readmission (n = 176, n = 180). ‖Fitbit data were available in 178 patients. Of these, the regression models used the following patient numbers based on nonmissing covariates in models 1 and 2 respectively: duration of hospitalization (n = 176, n = 172), discharge location (n = 172, n = 175), and 30-day readmission (n = 169, n = 173). ¶ActiGraph data were available in 179 patients. Of these, the regression models used the following patient numbers based on non-missing covariates in models 1 and 2 respectively: duration of hospitalization (n = 177, n = 173), discharge location (n = 173, n = 177), and 30-day readmission (n = 170, n = 174). #JH-HLM data were available in 193 patients. Of these, the regression models used the following patient numbers based on non-missing covariates in models 1 and 2 respectively: duration of hospitalization (n = 191, n = 187), discharge location (n = 187, n = 190), and 30-day readmission (n = 184, n = 187).

associated with 30-day readmission in one adjusted model. We separately examined whether the addition of complications, baseline difficulty with walking long distances, or inpatient status would change the inferences as compared to the pre-specified adjusted models. The inferences were generally unchanged, with the following exceptions. For StepWatch, the addition of baseline difficulty with walking long distances attenuated the adjusted models with 30-day readmission as an outcome. For Fitbit, the addition of inpatient status attenuated one adjusted model with discharge location as an outcome.

Comparison of Different Methods of Measuring Postoperative Activity

To compare each approach to activity monitoring, outcome-specific ROCs are shown in Figure 3. Taken as a whole, StepWatch provided the highest discrimination (C-statistics 0.71-0.76 for all outcomes). For both duration of hospitalization and 30-day readmission, the greatest discrimination was obtained using steps as derived from StepWatch (C-statistic for hospitalization >7 days 0.74 for StepWatch vs 0.52-0.69 for other metrics, and C-statistic for 30-day readmission 0.71 for StepWatch vs 0.47-0.63 for
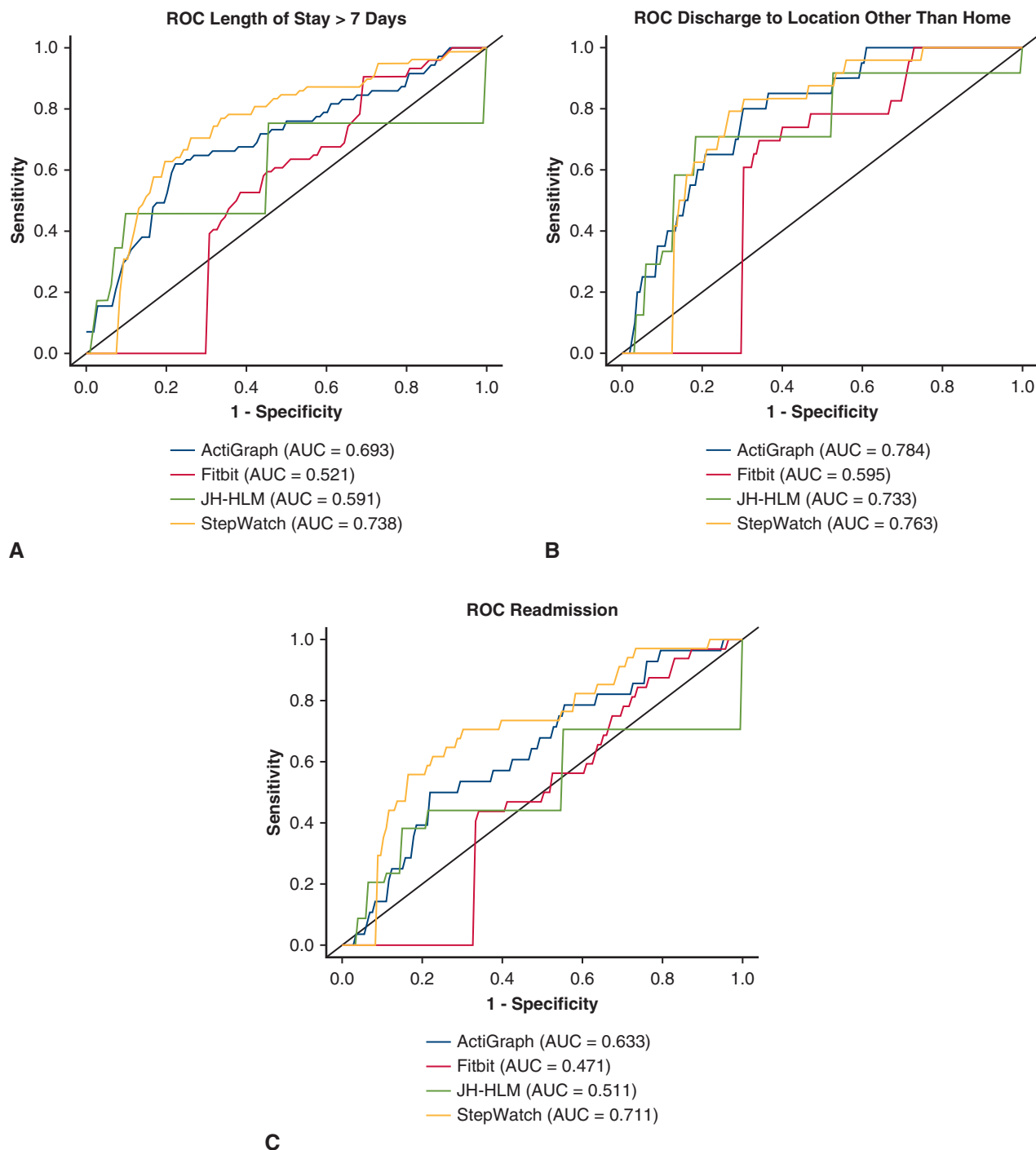
FIGURE 3. Receiver operating curves (*ROCs*). ROCs comparing (A) duration of hospitalization, (B) discharge location, and (C) 30-day readmission by postoperative day 2 activity and mobility as measured by 3 accelerometry devices (StepWatch, Fitbit, ActiGraph) and one clinical observation scale (Johns Hopkins-Highest Level of Mobility [*JH-HLM*]). Taken as a whole, StepWatch provided the highest discrimination (area under the curve [*AUC*] 0.71-0.76 for all outcomes).

other metrics). For discharge location, discrimination was similar for all methods of monitoring activity (C-statistics 0.73-0.78), except for Fitbit (C-statistic 0.60). In a sensitivity analysis of alternate approaches to calculate C-statistics to account for coarse categorizations (JH-HLM scale) and numerous zero values (Fitbit), the C-statistics for StepWatch and ActiGraph were similar, but those for Fitbit and JH-HLM increased slightly (Table E4).

TABLE 4. Sensitivity and specificity for a range of step thresholds on postoperative day 2 for 3 hospital-associated outcomes

Threshold of steps (StepWatch Activity Monitor)	Sensitivity (%)	Specificity (%)
Duration of hospitalization		
>7 d		
100	53	84
250	74	68
500	87	35
750	96	15
Discharge to a nonhome location		
100	71	75
250	83	56
500	96	29
750	100	12
30-d readmission		
100	62	77
250	74	56
500	91	29
750	97	12

Clinically Relevant Thresholds of Steps

Because the StepWatch had the best discrimination and the output of the StepWatch is easily interpretable (eg, steps), a range of StepWatch step thresholds with associated sensitivities and specificities for each outcome were calculated (Table 4). As shown, ambulating for <500 steps on postoperative day 2 (highest quartile) identified approximately 87% to 96% of patients who would eventually have hospitalization >7 days, discharge to a nonhome location, or 30-day readmission, although specificities ranged from approximately 29% to 35%. Using a lower cutoff of <250 steps on postoperative day 2 (median value), 74% to 83% of patients with these eventual outcomes would have been identified, with specificities of 56% to 68%. Overall, step thresholds between 250 and 500 steps/day identified between 74% to 96% of patients with any of the three primary outcomes. The number of steps that maximized sensitivity and specificity for hospitalization >7 days was 217 steps (sensitivity 71%, specificity 74%), for discharge to a nonhome location was 147 steps (sensitivity 83%, specificity 70%), and for 30-day readmission was 159 steps (sensitivity 71%, specificity 70%).

DISCUSSION

Decreased physical activity on postoperative day 2 after cardiac surgery, as measured by several types of wearable activity monitors and a nurse-assessed observation scale, was strongly and independently associated with longer duration of hospitalization and discharge to a nonhome location. For 30-day readmission, only steps as measured by StepWatch was independently associated with this outcome, and the strength of the association was less than for other outcomes. Compared with other approaches to monitoring mobility, steps as measured by StepWatch had the greatest discrimination for duration of hospitalization and 30-day readmission. Steps below a range of 250 to 500 steps on postoperative day 2 had sensitivities between 74% and 96% to identify patients at risk for these 3 outcomes (Figure 4). Taken as a whole, these results support the importance of monitoring activity and mobility after cardiac surgery and provide guidance on optimal monitoring methods and clinically relevant thresholds of steps to identify at-risk patients.

Many patients, especially older adults, experience profoundly low levels of activity and mobility during hospitalization and after surgery,[6] even though activity and mobility in the hospital is well established as important for improving patient outcomes, including delirium-prevention and maintaining function.[20-26] Indeed, activity and mobility are core components of enhanced recovery programs after noncardiac and cardiac surgery.[2,3] Accurate and efficient measurement of activity and mobility is critical, but there is no consensus or mandate for measurement.[5] A primary and important result of this study is that, regardless of how activity is measured (ie, lower vs upper extremity, granular vs coarse measurement), low physical activity early after surgery is consistently associated with longer duration of hospitalization and discharge to a nonhome location, and to a lesser extent 30-day readmission—results that are similar to those reported in a broad range of hospitalized patient populations.[11,27-29] These associations are independent of other important clinical variables from several outcome-specific prediction models; thus, activity and mobility data appear to provide important additive information to clinical characteristics. Notably, in this study, activity and mobility data were obtained early after surgery, which is a more clinically relevant time than later in a hospitalization. In addition, there is substantial evidence in both medical and surgical patients that in-hospital activity and mobility interventions can improve outcomes for hospitalized patients, including reducing costs and use.[22-26] These programs may be particularly important for older adults, who often have reduced physical reserve.

Our results also demonstrate that the accuracy of measuring patient activity varies between devices, each of which has different properties.[30] This information is important for clinicians who are considering different approaches to measure activity and mobility. The StepWatch monitor is worn on the ankle and validated for slow gait speed, which is important in patients using a walker or mobility aid. The research-grade ActiGraph is sensitive to upper-extremity movement and reflects activity beyond ambulation, such as in-bed movement. The Fitbit Charge HR is easily available to consumers and relatively low-cost, so could be worn before or after hospitalization to obtain longitudinal data.
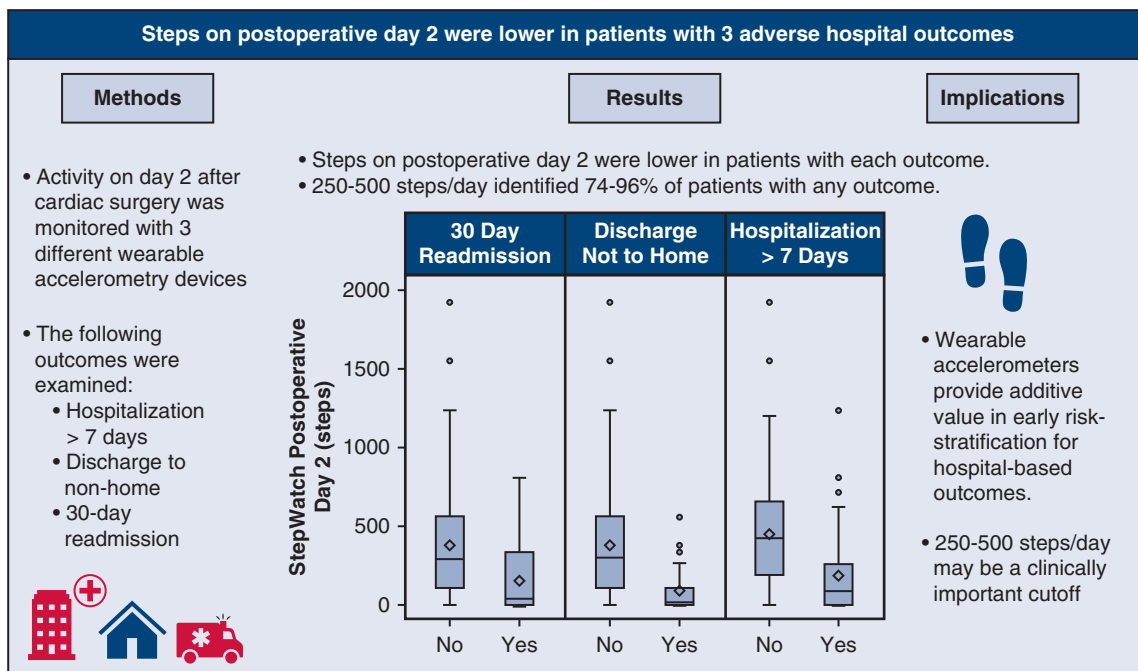
FIGURE 4. Physical activity and mobility were measured after cardiac surgery using wearable accelerometry devices. Steps on postoperative day 2 were lower in patients with 3 adverse hospital outcomes, with 250 to 500 steps/day appearing to be an important cutoff.

By using several different devices in the same patients, the independent and additive information from each device could be compared. Taken as a whole, StepWatch had the best discrimination, and these results highlight the importance of ambulation (since the output of StepWatch is an accurate measure of steps), which likely reflects both patient reserve and ongoing recovery and is an important metric of physical function in older adults. Interestingly, we observed that all metrics of "steps" from wearable activity monitors are not the same. Although both StepWatch and Fitbit report step counts, the outputs were substantially different, with the median steps reported by StepWatch being >5-fold greater than that reported by Fitbit, even in the same patients. The measurement characteristics of Step-Watch (ankle-worn, an algorithm validated in low mobility patients[30]) appear to provide greater discrimination with respect to important outcomes. Clinical scales based on nurse observations are low-cost and easily understandable, but are limited by the need for direct observation, documentation burden, and coarse categorization, which do not assess the full range of activity.[28] Our results suggest that JH-HLM scores were independently associated with duration of hospitalization and discharge location, but not 30-day readmission, and performance on ROC curves were slightly worse for JH-HLM compared with StepWatch.

A significant impediment to improving mobility in hospitalized patients after surgery is lack of consensus on an optimal "dose" of mobility. Our data suggest that thresholds in a range of 250 to 500 steps/day on postoperative day 2

after cardiac surgery have sensitivities between 74% and 96% for all outcomes. However, within this range, the specific thresholds that maximize sensitivity and specificity do vary by outcome. The goal of measuring activity also needs to be considered. For instance, to target resources to all patients at high risk for an outcome (such as 30-day readmission), sensitivity needs to be maximized, at the risk of losing specificity. Since there was overlap in the distribution of steps by outcomes, any threshold will need to balance these concerns. Regardless, our finding that <250 to 500 steps/day is associated with adverse outcomes provides an important threshold that should be validated in other patient populations.

Strengths of this study include the use of 3 separate monitors and an observation scale, a large sample, rigorous consideration of confounding variables, a generalizable cardiac surgery population, and clinically relevant outcomes. There are several limitations to consider. First, although staff frequently assessed device wear, compliance was not verified during every minute, and mobility may be underestimated. Second, as with all observational studies, there is a potential for residual confounding or model overfitting. It also remains unclear if intervening on mobility could improve outcomes. Third, although all monitoring devices are commercially available for medical purchase, there are differences in patient-availability, cost, and ease of data output for the 3 monitors, which may limit the use of some devices. Incorporating monitoring devices into a clinical workflow could also be challenging.

Data from wearable accelerometry monitors early after cardiac surgery provide additive value in identifying patients at risk for prolonged hospitalization, discharge to a nonhome location, and 30-day readmission, and 250 to 500 steps on postoperative day 2 may be a clinically relevant threshold. However, this study is limited because it is observational and incorporating monitoring devices into a clinical workflow could be challenging. Further studies are needed to examine these cutoffs in other populations and to translate this information into individualized mobility-improvement programs.

Conflict of Interest Statement

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Key Words: cardiac surgery, critical care, activity and mobility, accelerometers, physical therapy, older adults, functional status

APPENDIX 1. CARDIAC SURGERY WORKING GROUP

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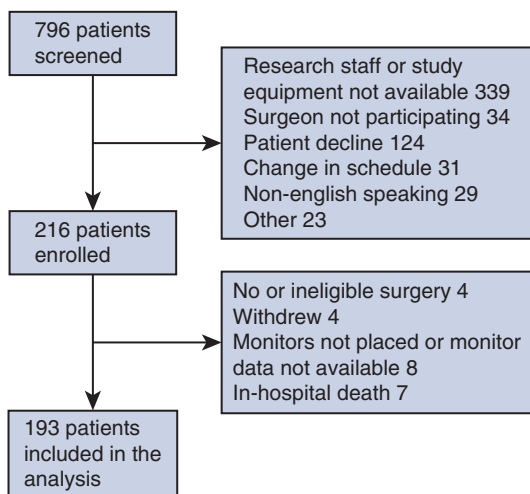
FIGURE E1. Patient flow diagram. The numbers of screened, enrolled, and analyzed patients are described.

TABLE E1. Patient characteristics by duration of hospitalization

Characteristic	Hospitalization ≤7 days N = 112	Hospitalization >7 days N = 81	P value
Age, y, median (IQR)	63 [56.5-69.5]	70 [63-75]	<.001
Male, no. (%)	95 (84.82)	63 (77.78)	.21
White, no. (%)	89 (79.46)	58 (71.6)	.21
Living with someone (spouse, family, other), no. (%)	84 (76.36)	62 (77.5)	.85
Body mass index, kg/m^2, median (IQR)	27.46 [24.74-31.88]	28.75 [24.75-32.48]	.48
IADL score,* median (IQR), (n = 189)	14 [14-14]	14 [14-14]	.26
WHO-DAS score,† median (IQR), (n = 186)	3 [1-6]	5.5 [3-11.5]	<.001
Logistic EuroSCORE	2.22 [1.51-3.96]	4.13 [2.63-8.1]	<.001
Comorbidities			
Previous stroke or TIA, no. (%)	8 (7.14)	11 (13.58)	.14
Depression, no. (%)	6 (5.36)	14 (17.28)	.01
Hypertension, no. (%)	92 (82.14)	66 (81.48)	.91
Congestive heart failure, no. (%)	34 (30.36)	38 (46.91)	.02
Peripheral vascular disease, no. (%)	11 (9.82)	14 (17.28)	.13
Diabetes, no. (%)	38 (33.93)	36 (44.44)	.14
Previous tobacco use, no. (%)	54 (48.21)	55 (67.9)	.01
COPD, no. (%)	12 (10.71)	14 (17.28)	.19
Active alcohol and/or drug use, no. (%)	19 (16.96)	9 (11.11)	.25
Medications			
Aspirin, no. (%)	90 (80.36)	61 (75.31)	.40
Platelet aggregation inhibitor, no. (%)	23 (20.54)	17 (20.99)	.94
Beta blocker, no. (%)	77 (68.75)	60 (74.07)	.42
Calcium channel blocker, no. (%)	36 (32.14)	22 (27.16)	.46
ACE inhibitor or ARB, no. (%)	59 (52.68)	35 (43.21)	.19
Any anticoagulant (heparin, coumadin, other), no. (%)	42 (37.5)	39 (48.15)	.14
Statin, no. (%)	86 (76.79)	62 (76.54)	.97
Surgery type			
Isolated CAB, no. (%)	70 (62.5)	41 (50.62)	.01
Isolated valve, no. (%)	28 (25)	21 (25.93)	
CAB + valve, no. (%)	6 (5.36)	16 (19.75)	
Other, mo. (%)	8 (7.14)	3 (3.7)	
Duration of bypass, min, median (IQR)	98 [73-124]	118 [83-159]	.002
Intraoperative pRBC transfusion, units, median (IQR)	0 [0-0]	0 [0-3]	<.001
Duration of intubation, h, median (IQR)	4.42 [3.33-6.13]	7.5 [4.67-13]	<.001
Intubation at 7 AM on POD2, no. (%)	1 (0.89)	8 (9.88)	.005
Duration of ICU stay, d, median (IQR)	23.25 (20.3-41)	71.5 (38-114.8)	<.001

IQR, Interquartile range; *IADL*, Instrumental Activities of Daily Living; *WHO-DAS*, World Health Organization Disability Assessment Schedule 2.0; *EuroSCORE*, European System for Cardiac Operative Risk Evaluation score; *TIA*, transient ischemic attack; *COPD*, chronic obstructive pulmonary disease, *ACE*, angiotensin-converting enzyme; *ARB*, angiotensin receptor blocker; *CAB*, coronary artery bypass; *pRBC*, packed red blood cells; *POD*, postoperative day; *ICU*, intensive care unit. *IADL scores range from 0 to 14, with a lower number indicating more difficulty with IADLs. †WHO-DAS 2.0 scores range from 0 to 48, with greater scores indicating greater impairment.

TABLE E2. Patient characteristics by discharge location

Characteristic	Discharge to a nonhome location N = 24	Discharge home N = 169	*P* value
Age, y, median (IQR)	74 (70.5-77)	65 (57-71)	.003
Male, no. (%)	19 (79.2)	139 (82.3)	.71
White, no. (%)	15 (62.5)	132 (78.11)	.09
Living with someone (spouse, family, other), no. (%)	16 (69.6)	130 (77.8)	.38
Body mass index, kg/m^2, median (IQR)	28.2 (23.6-31.2)	28.34 (24.8-32.1)	.5
IADL score,* median (IQR), (n = 189)	14 (14-14)	14 (14-14)	.33
WHO-DAS score,† median (IQR), (n = 186)	5 (2.5-11)	4 (2-8)	.14
Logistic EuroSCORE	5.3 (2.5-12.6)	2.8 (1.8-4.5)	<.001
Comorbidities	5 (20.8)	14 (8.3)	.05
Previous stroke or TIA, no. (%)	6 (25)	14 (8.3)	
Depression, no. (%)	23 (95.8)	135 (79.9)	.06
Hypertension, no. (%)	13 (54.2)	59 (34.9)	.07
Congestive heart failure, no. (%)	3 (12.5)	22 (13.0)	.94
Peripheral vascular disease, no. (%)	10 (41.7)	64 (37.9)	.72
Diabetes, no. (%)	15 (62.5)	94 (55.6)	.52
Previous tobacco use, no. (%)	6 (25)	20 (11.8)	.08
COPD, no. (%)	5 (20.8)	14 (8.3)	.05
Active alcohol and/or drug use, no. (%)	1 (4.2)	27 (16.0)	.12
Medications			
Aspirin, no. (%)	20 (83.3)	131 (77.5)	.52
Platelet aggregation inhibitor, no. (%)	6 (25)	34 (20.1)	.58
Beta blocker, no. (%)	20 (83.3)	117 (69.2)	.15
Calcium channel blocker, no. (%)	7 (29.2)	51 (30.2)	.92
ACE inhibitor or ARB, no. (%)	10 (41.7)	84 (49.7)	.46
Any anticoagulant (heparin, coumadin, other), no. (%)	12 (50)	69 (40.8)	.39
Statin, no. (%)	19 (79.2)	129 (76.3)	.76
Surgery type			.40
Isolated CAB, no. (%)	16 (66.7)	95 (56.2)	
Isolated valve, no. (%)	3 (12.5)	46 (27.2)	
CAB + valve, no. (%)	4 (16.7)	18 (10.7)	
Other, no. (%)	1 (4.2)	10 (5.9)	
Duration of bypass, median (IQR), (minutes)	118.5 [97.5-148]	118.5 [97.5-148]	.10
Intraoperative pRBC transfusion, units, median (IQR)	0.5 [0-3]	0 (0-1)	.007
Duration of intubation, h, median (IQR)	11.6 (6.9-16.4)	5 (3.5-7.5)	.006
Intubation at 7 AM on POD2, no. (%)	4 (16.67)	5 (2.96)	.015
Duration of ICU stay, h, median (IQR)	71.4 (47.3-118)	26.5 (21.3-64.8)	<.001

IQR, Interquartile range; *IADL*, Instrumental Activities of Daily Living; *WHO-DAS*, World Health Organization Disability Assessment Schedule 2.0; *EuroSCORE*, European System for Cardiac Operative Risk Evaluation score; *TIA*, transient ischemic attack; *COPD*, chronic obstructive pulmonary disease, *ACE*, angiotensin-converting enzyme; *ARB*, angiotensin receptor blocker; *CAB*, coronary artery bypass; *pRBC*, packed red blood cells; *POD*, postoperative day; *ICU*, intensive care unit. *IADL scores range from 0 to 14 with a lower number indicating more difficulty with IADLs. †WHO-DAS 2.0 scores range from 0 to 48, with greater scores indicating greater impairment.

TABLE E3. Patient characteristics by 30-day readmission

Characteristic	No readmission N = 154	Readmission N = 34	P value
Age, y, median (IQR)	65.5 (57-72)	69.5 (61-75)	.51
Male, no. (%)	132 (85.7)	21 (61.8)	.001
White, no. (%)	119 (77.3)	23 (67.7)	.23
Living with someone (spouse, family, other), no. (%)	113 (74.3)	29 (87.9)	.1
Body mass index, kg/m^2, median (IQR)	28.3 (24.8-32.1)	27.9 (23.9-31.8)	.04
IADL score,* median (IQR), (n = 189)	14 (14-14)	14 (13-14)	<.001
WHO-DAS score,† median (IQR), (n = 186)	4 (1-7)	8 (2-14)	<.001
Logistic EuroSCORE	2.785 (1.87-4.4)	4.185 (1.91-11.53)	<.001
Comorbidities			
Previous stroke or TIA, no. (%)	15 (9.74)	3 (8.82)	.87
Depression, no. (%)	15 (9.74)	4 (11.76)	.72
Hypertension, no. (%)	126 (81.82)	27 (79.41)	.74
Congestive heart failure, no. (%)	50 (32.47)	19 (55.88)	.01
Peripheral vascular disease, no. (%)	21 (13.64)	4 (11.76)	.77
Diabetes, no. (%)	56 (36.36)	16 (47.06)	.25
Previous tobacco use, no. (%)	83 (53.9)	22 (64.71)	.25
COPD, no. (%)	16 (10.39)	8 (23.53)	.04
Active alcohol and/or drug use, no. (%)	24 (15.58)	3 (8.82)	.31
Medications			
Aspirin, no. (%)	116 (75.32)	30 (88.24)	.10
Platelet aggregation inhibitor, no. (%)	30 (19.48)	10 (29.41)	.20
Beta blocker, no. (%)	108 (70.13)	25 (73.53)	.69
Calcium channel blocker, no. (%)	47 (30.52)	9 (26.47)	.64
ACE inhibitor or ARB, no. (%)	80 (51.95)	12 (35.29)	.08
Any anticoagulant (heparin, coumadin, other), no. (%)	58 (37.66)	20 (58.82)	.02
Statin, no. (%)	115 (74.68)	28 (82.35)	.34
Surgery type			.76
Isolated CAB, no. (%)	88 (57.14)	20 (58.82)	
Isolated valve, no. (%)	42 (27.27)	7 (20.59)	
CAB + valve, no. (%)	16 (10.39)	4 (11.76)	
Other, no. (%)	8 (5.19)	3 (8.82)	
Duration of bypass, min, median (IQR)	104 (78-133)	113 (69-156)	.58
Intraoperative pRBC transfusion, units, median (IQR)	0 (0-1)	0 (0-3)	<.001
Duration of intubation, h, median (IQR)	5 (3.5-8.25)	7.13 (4.17-11)	.19
Intubation at 7 AM on POD2, no. (%)	6 (3.9)	3 (8.82)	.22
Duration of ICU stay, h, median (IQR)	27 (21.2-62.8)	69 (26.8-114.8)	<.001

IQR, Interquartile range; *IADL*, Instrumental Activities of Daily Living; *WHO-DAS*, World Health Organization Disability Assessment Schedule 2.0; *EuroSCORE*, European System for Cardiac Operative Risk Evaluation score; *TIA*, transient ischemic attack; *COPD*, chronic obstructive pulmonary disease, *ACE*, angiotensin-converting enzyme; *ARB*, angiotensin receptor blocker; *CAB*, coronary artery bypass; *pRBC*, packed red blood cells; *POD*, postoperative day; *ICU*, intensive care unit. *IADL scores range from 0 to 14 with a lower number indicating more difficulty with IADLs. †WHO-DAS 2.0 scores range from 0 to 48, with greater scores indicating greater impairment.

TABLE E4. Comparing C-statistics using different approaches

Approaches to calculate C-statistic	ActiGraph	StepWatch Ambulation Monitor	Fitbit	Johns Hopkins-Highest Level of Mobility Scale
Duration of hospitalization >7 days				
Method 1*	0.69	0.74	0.53	0.59
Method 2†	0.7	0.75	0.59	0.72
Discharge to a nonhome location				
Method 1*	0.78	0.76	0.595	0.73
Method 2†	0.79	0.78	0.69	0.8
30-d readmission				
Method 1*	0.63	0.71	0.47	0.51
Method 2†	0.64	0.73	0.54	0.63

*Method 1 is calculated using the nrROC package in R to account for the nonstandard relationship between mobility and the outcome of interest (ie, the outcome of interest is more likely with decreasing mobility). †Method 2 is calculated using the fbroc package in R to account for categorical and zero-inflated measurements.