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The Future Is Mobile: Pilot Validation Study of Apple Health Metrics in Orthopaedic Trauma

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Abstract

Background: Surgeons often lack objective data on patient functional outcomes, particularly as compared with the patient's baseline. The present study aimed to determine whether gait parameters recorded on Apple iPhones provided longitudinal mobility data following lower-extremity fracture surgery that matched clinical expectations. We hypothesized that iPhones would detect the mobility changes of injury and early recovery, correlate with patient-reported outcome measures, and differentiate nonunion.

Methods: This cross-sectional study included 107 adult patients with lower-extremity fractures who owned iPhones and had at least 6 months of follow-up. Participants shared Apple Health data and completed Patient Reported Outcomes Measurement Information System (PROMIS) surveys. The primary outcome was the daily step count. Four other gait-related parameters were analyzed: walking asymmetry, double support, walking speed, and step length. Mixed-effects models compared mobility parameters at pre-injury, immediate post-injury, and 6-months post-injury time points. Correlations between mobility parameters and PROMIS surveys were assessed. A mixed-effect model evaluated the relationship between step count recovery and surgery for nonunion.

Results: There was a 93% reduction in daily step count from the pre-injury period to the immediate post-injury period (95% confidence interval [CI], –94% to –93%). Other gait parameters also showed increased impairment from pre-injury to post-injury. At 6 months, step count improved sixfold relative to the immediate post-injury period but remained 52% below baseline (95% CI, –55% to –49%). PROMIS Physical Function correlated moderately with step count ($r = 0.42$; 95% CI, 0.25 to 0.57) and weakly with other gait parameters. Patients with a

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The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (<http://links.lww.com/XXXXXXX>).

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known nonunion had a 55% slower recovery of step count than those without a nonunion (95% CI: 44% to 66%).

Conclusions: Apple Health mobility parameters captured changes in mobility following lower-extremity fracture and throughout the subsequent recovery period. These metrics distinguished between patients with and without nonunions, demonstrating their potential usefulness as objective, real-world functional outcome measures. These “digital biomarkers” may aid clinical decision-making and research and could be utilized for the early identification of patients at risk for poor outcomes.

Level of Evidence: Prognostic Level III. See Instructions for Authors for a complete description of levels of evidence.

Orthopaedic surgeons often lack objective data to evaluate patient recovery. This data gap is especially true regarding ambulation and mobility, which patients consider their top priority^{1,2}. Patient-reported outcome measures (PROMs) can sometimes be useful in evaluating functional outcomes, but PROMs in isolation capture mobility information relatively poorly³⁻⁵. In addition, PROMs captured during follow-up visits cannot evaluate mobility progress relative to the patient’s baseline, which is how patients define their mobility goals^{1,6}. While PROMs remain a component of high-value care^{7,8}, they may not be sufficient alone, as they do not reliably capture the mobility information that is important to patients.

The ubiquity of smartphones represents an opportunity to fill this gap. Smartphones can unobtrusively capture real-world mobility data, providing a granular view of how patients function in their daily lives. Platforms like Apple Health, available on the iPhones owned by 61% of U.S. smartphone users, have been validated against gold-standard gait measurement systems^{9,10}. Crucially, because smartphones collect data passively in the background, they capture a patient’s pre-injury baseline mobility. Understanding this patient-specific baseline is key to setting appropriate recovery goals and identifying deviations from expectations.

The present study aimed to evaluate the Apple Health mobility parameters as outcome measures in patients following surgical treatment of a lower-extremity fracture. We assessed whether these parameters captured mobility changes associated with injury and early recovery, correlated with PROMs, and differentiated between patients with and without nonunion requiring reoperation. We hypothesized that iPhone devices would detect mobility changes with injury and recovery, correlate with PROMs, and differentiate nonunion.

Materials and Methods

Study Design and Setting

This was a cross-sectional study of patients who underwent operative treatment of a lower-extremity fracture at a single academic trauma center. Patients were enrolled between November 2023 and May 2024. The university’s institutional review board approved the study.

Participants

Patients were eligible for inclusion if they were ≥ 18 years of age, had a minimum follow-up of 6 months post-injury, had an iPhone with the Apple Health app for ≥ 6 months before the injury, and underwent surgical treatment of a pelvic ring, acetabular, hip, femoral shaft, distal femoral, patellar, tibial plateau, tibial shaft, distal tibial, ankle, or foot fracture. Patients were excluded if they were nonambulatory before injury, had a pathologic fracture, or were unable to consent because of cognitive impairment or a language barrier. The Apple Health platform was utilized for this pilot validation analysis because iPhones are the most common smartphone in the U.S. and because the platform is well validated and always on by default, providing mobility data for patients who have not otherwise configured their device to capture mobility⁹.

Outcomes

The primary outcome was the daily step count, measured by the Apple Health platform on iPhone devices. Secondary outcomes included 4 other Apple Health mobility parameters: walking speed, step length, double support percentage, and asymmetry percentage. Walking speed estimates how quickly a person walks on flat ground. The reference mean $\pm$ standard deviation (SD) for walking speed in ambulatory older adults is $1.30 \pm 0.18 \text{ m/s}$ ¹⁰. Walking step length is the distance between where one foot and the other foot hit the ground while walking, with a reference mean $\pm$ SD of $0.68 \pm 0.08 \text{ m}$ in ambulatory older adults¹⁰. Walking double support percentage represents the percentage of the gait cycle where both feet are on the ground, and the reference mean $\pm$ SD in ambulatory older adults is $28.38\% \pm 3.34\%$ ¹⁰. Walking asymmetry percentage estimates the percentage of time during walking that steps are asymmetric, with increases often occurring as a result of injury or neurodegenerative pathology. Symmetric walking typically had asymmetry percentages below 10% in a reference population¹⁰.

These gait metrics were aggregated for each day by taking the sum (step count) or mean (other gait parameters) of all measurements. Daily aggregate parameters were examined during 3 time points of interest: the pre-injury baseline period (28 days pre-injury), the immediate post-injury period (the first 28 days post-injury), and during the sixth month post-injury (days 152 to 180).

Data Collection

At enrollment, patients exported Apple Health data by tapping “Export All Health Data” under the user profile section of their iPhone’s Apple Health app. The resulting XML file was transferred to a study team’s Apple iPad via Apple AirDrop and uploaded to a secure server. All data recordings of the 5 mobility parameters of interest were extracted from the exported data. Patients also completed a survey regarding their iPhone usage habits, as well as the Patient Reported Outcomes Measurement Information System (PROMIS) computer adaptive tests for Physical Function and Pain Interference (PROMIS Bank v1.2 Physical Function and PROMIS Bank v1.1 Pain Interference). PROMIS is a standardized set of PROMs developed with support from the National Institutes of Health that provides an efficient and precise means of assessing physical, mental, and social health in adults and children^{11,12}. PROMIS has been increasingly utilized in orthopaedic research, given

its potentially lower respondent burden, higher generalizability, and improved psychometric properties relative to some other PROMs^{11,13}.

Demographic and injury data were collected by chart review. The occurrence of unplanned reoperation for nonunion was determined by reviewing the medical record at a minimum of 6 months post-injury. Unplanned reoperation for nonunion was defined as any procedure, not including planned staged procedures, indicated for the treatment of implant breakage or the failure of fracture healing.

Statistical Analysis

A power analysis determined that 103 patients would provide 90% power to detect a 20% drop in step counts, assuming a baseline step count of 5,931 steps with an SD of 3,664 steps¹⁴.

Demographics were summarized with use of descriptive statistics, including proportions for categorical variables and means with SDs for continuous variables.

To evaluate the merits of combining fractures and treatment types, trends in the primary outcome metric (step count) were visually assessed for subgroups involving fracture location, postoperative weight-bearing status, and postoperative walker use (see Appendix Figs. 1, 2, and 3). All subgroups showed sharp declines in daily step count post-injury, with upward recovery trends over 6 months. Subsequent analyses were performed on the entire cohort to maximize generalizability.

For each mobility parameter, 3 mixed-effects linear regression models were fit, all with a random intercept for the subject. First, the immediate post-injury period was compared with the pre-injury baseline. Second, the 6-month time point was compared with the immediate post-injury period. Third, the 6-month time point was compared with the pre-injury baseline. Models were fit both on the nontransformed scale and after a log transformation. For the log-transformed models, the coefficients were exponentiated and then transformed to represent the percentage change in the outcome associated with a 1-unit change in the predictor using the formula: $(\exp[\text{coefficient}] - 1) \times 100$. Pearson correlations were calculated between the most recent 28-day average of each mobility parameter and each PROMIS score. Correlations were interpreted as: 0.00 to 0.09, negligible; 0.10 to 0.39, weak; 0.40 to 0.69, moderate; 0.70 to 0.89, strong; 0.90 to 1.0, very strong¹⁵.

A final mixed-effects model was utilized to assess the relationship between nonunion and the step count recovery trajectory. The outcome was the percentage of the pre-injury step count, calculated by dividing the daily step count on any given recovery day by the mean daily step count during the pre-injury baseline period for each patient. Covariates included age, sex, fracture location, time since injury, nonunion, and a time-nonunion interaction. A significant interaction would indicate that step count distinguished between recovery trajectories for patients who did and did not undergo reoperation for nonunion.

Significance was set at $p < 0.05$, and we did not adjust the alpha for multiple comparisons. All analyses were conducted in R (version 4.3.3; R Foundation for Statistical Computing).

Results

Patient Characteristics

Of the 571 screened patients, 231 were eligible, and 128 were enrolled. Twenty-one enrolled patients were missing adequate mobility data (see Appendix Table I), and the remaining 107 were included in the final analyzed cohort. The mean age was 45 years (SD, 17 years), and 42% of patients were female (Fig. 1, Table I). The median follow-up was 324 days (interquartile range, 210 to 589 days). The most common fracture locations were the tibial plateau (14%), distal femur (13%), and femoral shaft (13%). Fifty-three patients underwent unplanned reoperation, and 21 experienced nonunion requiring reoperation (see Appendix Table II). The average daily step count pre-injury was 4,250 (SD, 3,066).

Mobility Changes After Injury

The average daily step count in the immediate post-injury period was 687 (SD, 852). All 5 Apple Health mobility parameters showed significant changes from pre-injury to post-injury. Step count decreased by 93% (−3,744 steps; 95% confidence interval [CI], −3,916 to −3,573 steps), walking speed decreased by 9% (−0.07 m/s; 95% CI, −0.09 to −0.06 m/s), step length decreased by 6% (−0.03 m; 95% CI, −0.04 to −0.02 m), walking asymmetry increased by 88% (absolute difference, 6%; 95% CI, 5% to 8%), and walking double support increased by 1% (absolute difference, 0%; 95% CI, 0% to 0%) (Figs. 2 and 3, Table II).

Mobility Changes During Recovery

During the sixth month post-injury, the average daily step count was 2,430 (SD, 2,392), representing a 655% increase from the immediate post-injury period (mean change, 1,889 steps; 95% CI, 1,773 to 2,004 steps) but a 52% decrease from pre-injury (mean change, −1,800 steps; 95% CI, −1,963 to −1,637 steps). Walking speed decreased by 4% (−0.05 m/s; 95% CI, −0.06 to −0.03 m/s) and step length decreased by 2% (−0.01 m; 95% CI, −0.02 to −0.00 m) during the first 6 months of recovery, whereas walking asymmetry increased by 45% (absolute difference, 7%; 95% CI, 5% to 10%) and double support time increased by 2% (absolute difference, 1%; 95% CI, 0% to 1%). Compared with pre-injury, walking asymmetry remained 198% higher (absolute difference, 15%; 95% CI, 14% to 16%) and speed remained 15% lower (−0.15 m/s; 95% CI, −0.16 to −0.14 m/s) at 6 months.

Correlations with PROMs

Given conventional criteria for interpreting correlation¹⁵, the PROMIS Physical Function score moderately correlated with daily step count ($r = 0.42$; 95% CI, 0.25 to 0.57) and weakly correlated with walking speed ($r = 0.26$; 95% CI, 0.07 to 0.43), step length ($r = 0.24$; 95% CI, 0.05 to 0.41), double support time ($r = -0.23$; 95% CI, −0.40 to −0.04), and walking asymmetry ($r = -0.29$; 95% CI, −0.45 to −0.10) (see Appendix Table III). The PROMIS Pain Interference score did not significantly correlate with any mobility parameter.

Differentiation of Nonunion Patients

The mixed-effects model estimated that patients who experienced a nonunion had a 55% (95% CI, 44% to 66%) slower step count recovery rate than those without a nonunion (Figs. 4 and 5).

Discussion

This study demonstrated that smartphone-based mobility metrics, particularly the step count, may serve as meaningful outcome measures following surgical treatment of lower-extremity fractures. All 5 Apple Health parameters captured significant decreases in mobility during the immediate post-injury period relative to pre-injury baseline measurements. Step counts also captured early recovery, increasing significantly from the immediate post-injury period to 6 months post-injury while remaining lower than pre-injury levels. All 5 metrics correlated with PROMIS Physical Function scores, but only step count exhibited a moderate or stronger correlation. Notably, patients with nonunions showed a 55% slower recovery in daily step counts compared with those without nonunions, suggesting smartphone-measured step counts correlate with adverse clinical outcomes and may have value in predicting such outcomes.

Returning to baseline mobility is a priority for patients with lower-extremity trauma. Discrete-choice experiments, wherein patients choose between paired hypothetical scenarios, have shown that patients value returning to their baseline mobility level more than reducing long-term pain, reoperation risk, hospital stays, or even modest changes in mortality risk^{1,2,6}. These findings suggest that smartphone-based mobility assessment, with its unique ability to capture a patient-specific pre-injury baseline, aligns well with what matters most to patients. The present study demonstrated that Apple Health metrics captured both acute mobility decline and subsequent recovery, highlighting the potential for these metrics to provide clinically relevant information aligned with patient priorities.

The secondary gait parameters in this study may have tracked recovery less effectively than step counts because of measurement inaccuracies or slower inherent recovery. Werner et al.⁹ found poor to moderate agreement in Apple Health's double support time measurements compared with a reference standard, calling into question the measurement accuracy of this metric in particular. Additionally, these parameters may take longer than 6 months to return to baseline. Studies looking at gait impairments following tibial shaft and plateau fractures showed impairments persisting up to 12 months post-injury^{16,17}. This slower recovery of gait characteristics could explain the lack of significant improvement observed over the initial 6-month period.

The ability of step counts to distinguish patients who developed a nonunion is a novel finding with potential clinical implications. Nonunions are devastating for patients¹⁸ and costly¹⁹ for health-care systems. Whereas current risk prediction tools such as the Nonunion Risk Determination (NURD) score²⁰ rely on clinical variables, incorporating real-time, patient-specific data could enhance prediction accuracy. To our knowledge, the present study is the first to show that passively collected data may correlate with a specific orthopaedic complication like nonunion. Further investigation with a larger cohort of nonunions is

needed to verify whether Apple Health metrics predict nonunions with sufficient sensitivity and specificity to be clinically useful. Nevertheless, with further development, it is conceivable that an algorithm could be deployed to flag patients failing to progress as expected and prompt further evaluation.

This study found weak to moderate correlations between Apple Health mobility parameters and PROMIS scores, seemingly questioning their convergent validity. However, existing literature has consistently shown limited correlation between objective functional measures and PROMs^{3,5}. This discrepancy may partly stem from patients' inaccurate self-assessments of their activity levels²¹. We propose that PROMs and Apple Health parameters measure different, complementary aspects of physical health. PROMs incorporate patient perceptions and expectations, whereas tools like Apple Health may be more useful for comparing treatments between patients and optimizing care over time, given their objective and longitudinal nature.

The present study had several limitations. One limitation was the reliance on Apple's proprietary algorithms and software. Although this reliance on a proprietary product may not be ideal, Apple's metrics have been independently validated⁹, and their use may be a worthwhile trade-off to access the unique strengths of smartphone data, particularly the passive recording of pre-injury baseline function. The sample size, while adequate to evaluate overall pre-injury to post-injury changes, was relatively small for many specific fractures. Grouping diverse fractures may have also limited our ability to assess the performance of Apple Health metrics in specific clinical subgroups. However, combining the data allowed for a more generalizable overall assessment in this pilot study. Inconsistent phone carrying may have introduced error. Our within-patient comparisons helped to partially mitigate this inconsistency, but the accuracy of smartphone-based mobility assessment across different carrying habits and with the use of assistive devices requires further investigation. A small proportion (16%) of initially enrolled patients lacked adequate data, highlighting the need for strategies to improve data capture and develop more scalable collection methods. The minimum follow-up period, while long for a trauma population at 6 months, may have been inadequate to capture the full clinical recovery and may have caused a selection bias toward patients doing more poorly. Future studies with longer follow-up are needed to determine the utility of smartphone mobility metrics in comprehensively characterizing long-term recovery trajectories.

Despite these limitations, the present study provided preliminary evidence for the clinical utility of smartphone mobility metrics. Even without a sophisticated analysis, clinicians could review these metrics on patients' mobile devices to track recovery, inform shared decision-making, and potentially discuss changes in management when recovery plateaus or deviates from expectations. To fully realize this potential, further work is needed to develop streamlined data-collection tools, evaluate how to interpret and discuss these data with patients, and establish the predictive validity of these metrics with comprehensive psychometric evaluation.

Smartphone mobility metrics hold promise as objective measures of real-world function following lower-extremity fracture. These metrics capture meaningful changes in mobility

induced by injury and recovery and can potentially predict the occurrence of complications like nonunion via passively collected data. With further development, these novel “digital biomarkers” hold the potential to help orthopaedic surgeons track their patients’ real-world function, tailor management, and intervene earlier when recovery goes awry.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Disclosure:

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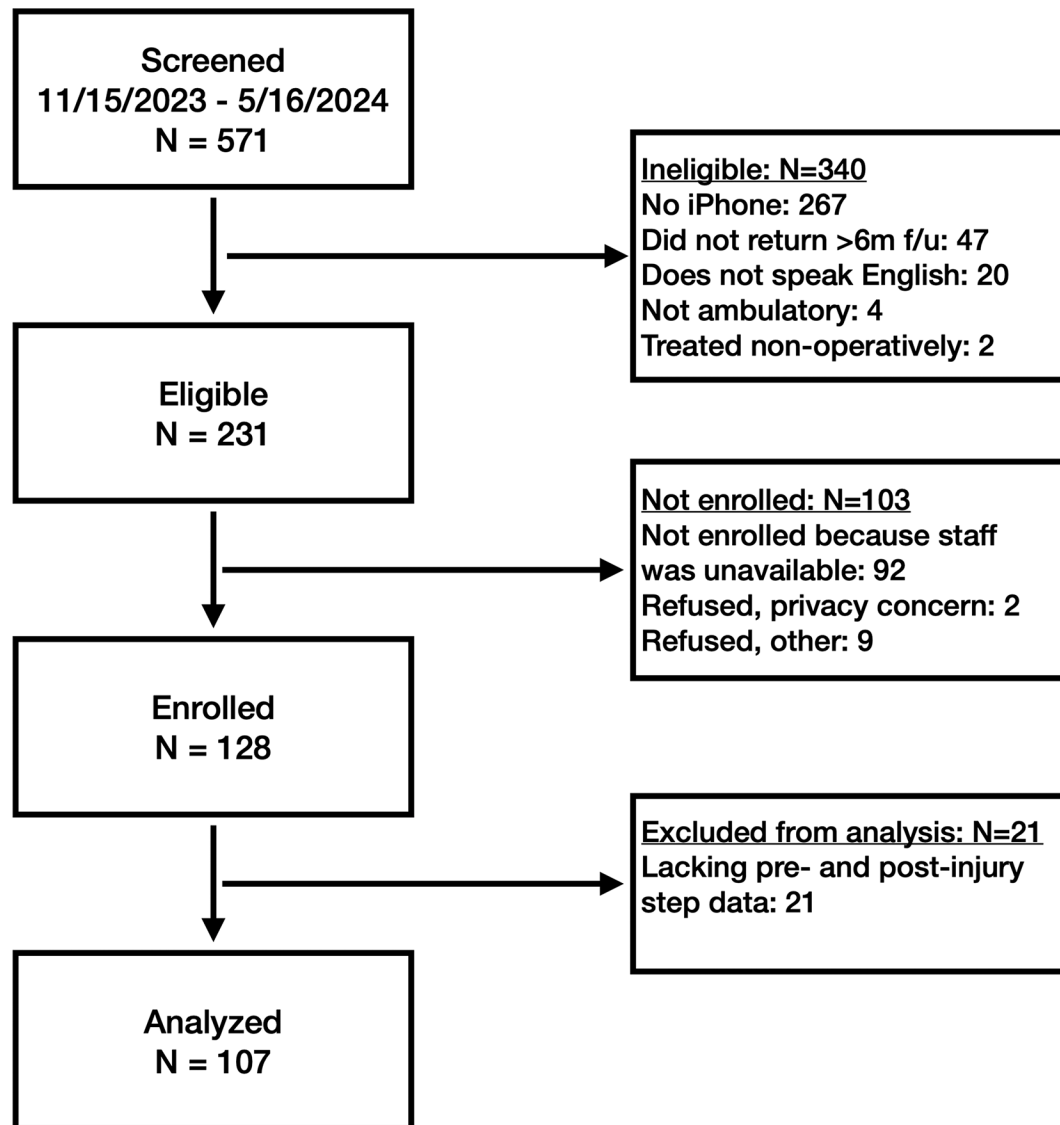


Fig. 1.
CONSORT flow diagram showing study screening and enrollment. f/u = follow-up.

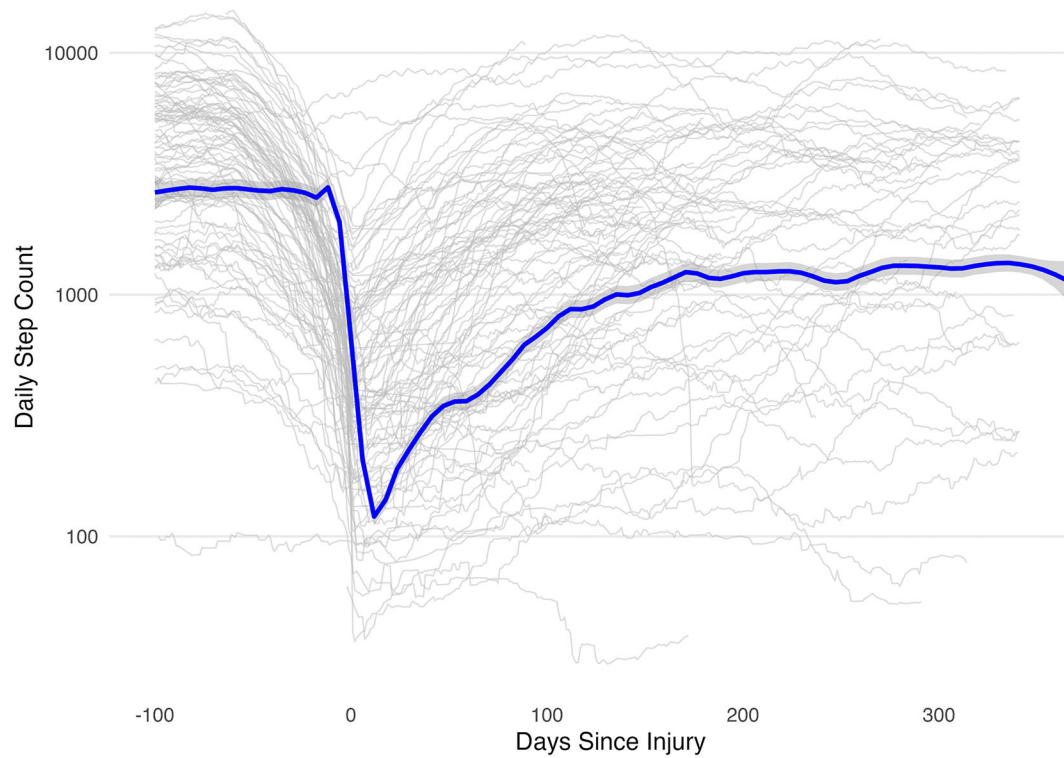


Fig. 2.

Daily step count pre-injury and post-injury for patients with a lower-extremity fracture. Gray lines represent the 30-day rolling average of daily step counts for each patient. The bold line represents a locally estimated scatterplot smoothing curve fitted to the cohort, with the gray shaded area indicating the 95% CI for this curve. The y axis has a log scale.

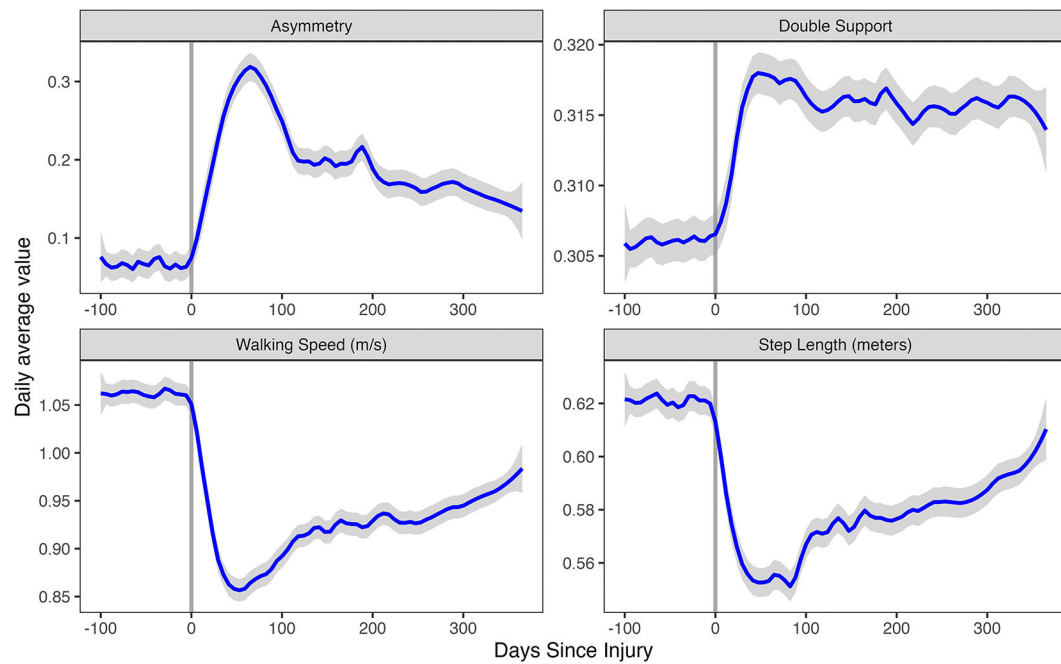


Fig. 3. Walking asymmetry, double support, speed, and step length for patients with a lower-extremity fracture. Bold lines represent locally estimated scatterplot smoothing curves fitted to the cohort, with gray shaded areas indicating the 95% CIs. The units are meters per second for walking speed, meters for step length, and proportions for walking asymmetry and double support.

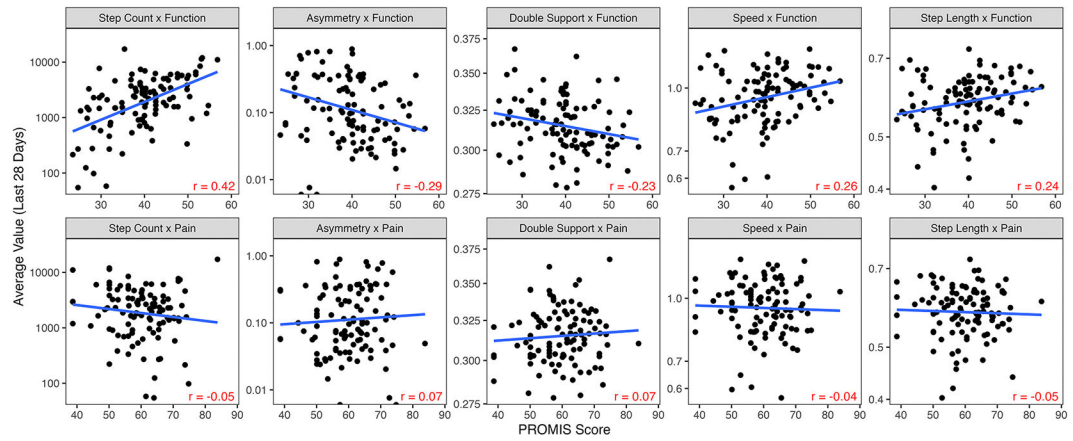


Fig. 4.

Scatterplots showing correlations between the 5 Apple Health mobility parameters and the 2 PROMIS scores (Physical Function and Pain Interference). Bold lines represent linear regression trendlines. The units are steps for step count, meters per second for walking speed, meters for step length, and proportions for walking asymmetry and double support. The y axis has a log scale.

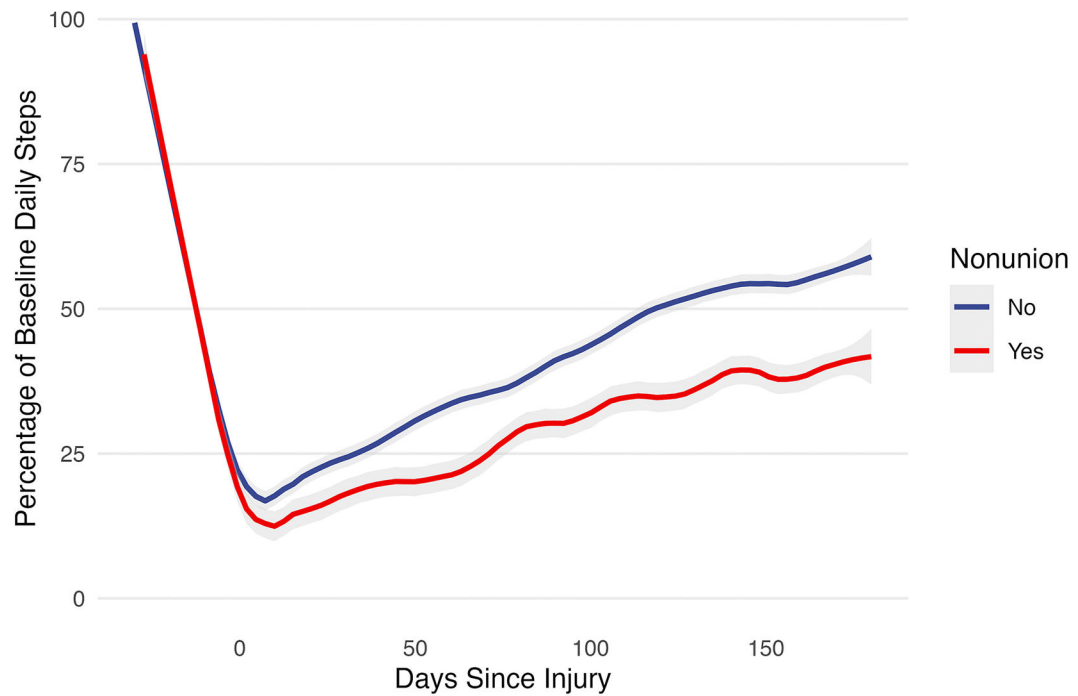


Fig. 5. Percentage of baseline steps stratified by presence or absence of nonunion. Lines represent locally estimated scatterplot smoothing curves, and shaded areas represent 95% CIs. The percentage of baseline daily steps is calculated by dividing the daily step count by the mean step count during the 30 days pre-injury for each patient.

TABLE I

Patient and Injury Characteristics *

Characteristic	Summary Statistics (N = 107)
Age (<i>yr</i>)	45 ± 17
Ethnicity	
Hispanic or Latino	4 (4%)
Not Hispanic or Latino	103 (96%)
Race	
Asian	1 (1%)
Black or African American	39 (36%)
More than 1 race	1 (1%)
White	66 (62%)
Female sex	45 (42%)
Body mass index (<i>kg/m²</i>)	29 ± 7
Presence of diabetes	4 (4%)
Bilateral injuries	21 (20%)
Open fracture	41 (39%)
Fracture location	
Pelvic ring	5 (4.7%)
Acetabulum	12 (11%)
Proximal femur	12 (11%)
Femoral shaft	14 (13%)
Distal femur	14 (13%)
Patella	5 (4.7%)
Tibial plateau	15 (14%)
Tibial shaft	9 (8.4%)
Distal tibia	9 (8.4%)
Ankle (malleolar)	8 (7.5%)
Foot	4 (3.7%)

* Values are given as the mean ± SD or as the count with the percentage in parentheses.

TABLE II
Gait Parameter Comparisons Between Time Points of Interest

Comparison	Mobility Metric	Intercept	Absolute Difference (95% CI)	P Value	Relative Difference (95% CI)	P Value
Immediate post-injury versus pre-injury	Step count (<i>steps</i>)	4,356	-3,744 (-3,916 to -3,573)	<0.001	-93% (-94% to -93%)	<0.001
	Walking asymmetry (%)	8%	6% (5% to 8%)	<0.001	88% (63% to 117%)	<0.001
	Double support (%)	31%	0% (0% to 0%)	<0.001	1% (1% to 1%)	<0.001
	Walking speed (<i>m/s</i>)	1.05	-0.07 (-0.09 to -0.06)	<0.001	-9% (-10% to -7%)	<0.001
	Step length (<i>m</i>)	0.62	-0.03 (-0.04 to -0.02)	<0.001	-6% (-6% to -5%)	<0.001
6 months post-injury versus immediate post-injury	Step count (<i>steps</i>)	601	1,889 (1,773 to 2,004)	<0.001	655% (600% to 714%)	<0.001
	Walking asymmetry (%)	14%	7% (5% to 10%)	<0.001	45% (23% to 70%)	<0.001
	Double support (%)	31%	1% (0% to 1%)	<0.001	2% (1% to 2%)	<0.001
	Walking speed (<i>m/s</i>)	0.97	-0.05 (-0.06 to -0.03)	<0.001	-4% (-6% to -3%)	<0.001
	Step length (<i>m</i>)	0.58	-0.01 (-0.02 to -0.00)	0.005	-2% (-3% to -0%)	0.011
6 months post-injury versus pre-injury	Step count (<i>steps</i>)	4,316	-1,800 (-1,963 to -1,637)	<0.001	-52% (-55% to -49%)	<0.001
	Walking asymmetry (%)	7%	15% (14% to 16%)	<0.001	198% (173% to 226%)	<0.001
	Double support (%)	31%	1% (0% to 1%)	<0.001	3% (3% to 4%)	<0.001
	Walking speed (<i>m/s</i>)	1.05	-0.15 (-0.16 to -0.14)	<0.001	-15% (-16% to -15%)	<0.001
	Step length (<i>m</i>)	0.62	-0.05 (-0.05 to -0.05)	<0.001	-9% (-9% to -8%)	<0.001