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Impact of Weight-Bearing Status on Patient Gait During Fracture Recovery

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Abstract

Introduction: Optimizing weight-bearing can enhance fracture recovery, but measuring the response to weight-bearing protocols has been challenging to continuously and reliably study. We investigated whether smartphone-captured mobility metrics could detect functional differences in patients prescribed either early weight-bearing or delayed weight-bearing after lower extremity fractures.

Methods: We conducted a cohort study, including adult patients with lower extremity fractures treated surgically, ≥ 6 months of follow-up, and an Apple iPhone for ≥ 1 year before injury. Patients with bilateral lower extremity fractures were excluded. Patients were classified as early weight-bearing or delayed weight-bearing. The primary outcome was step count, measured by the Apple

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iPhone Health application, within 12 weeks of injury. Secondary outcomes included walking speed and asymmetry, and an extended observation to 26 weeks postinjury. Between-group differences were estimated using linear mixed-effects models, controlling for preinjury mobility, age, sex, open fracture, and fracture location.

Results: We enrolled 74 patients (mean age, 46 [SD, 19] years; 43% female), with 27 patients in the early weight-bearing group and 47 patients in the delayed weight-bearing group. Within 12 weeks of injury, early weight-bearing patients had markedly more daily steps than delayed weight-bearing patients (mean difference, 1,050 steps per day; 95% confidence interval [CI], 373 to 1,727; $P = 0.002$). Secondary outcomes did not differ between the groups within 12 weeks of injury. However, by 26 weeks after injury, early weight-bearing patients had faster walking speeds (mean difference, 0.13 m/s; 95% CI, 0.04 to 0.22; $P = 0.004$) and less walking asymmetry (mean difference, -12.2%; 95% CI, -21.3% to -3.1%; $P = 0.008$) than delayed weight-bearing patients.

Discussion: Among patients with surgically treated lower extremity fractures, smartphone-collected step counts were higher in early versus delayed weight-bearing patients within 12 weeks of injury. These findings suggest that postoperative weight-bearing protocols affect patient mobility and can be measured continuously and remotely.

Level of Evidence: Level III, Therapeutic

Optimizing postoperative weight-bearing at the appropriate stage of healing is thought to enhance fracture recovery.^{1,2} After intramedullary nailing of a femoral shaft fracture, early weight-bearing is beneficial because it promotes union.^{3,4} By contrast, early weight-bearing might be harmful in periarticular fractures by causing joint subsidence.^{1,5,6} Regardless of its potential effect, weight-bearing in the early postoperative period is challenging to study because it has historically not been measured in a continuous and reliable manner.

Given the absence of highly reliable assessments, it remains unclear if patients prescribed weight-bearing as tolerated actually walk sooner than those prescribed non-weight-bearing or limited weight-bearing. The ubiquity of smartphones equipped with gait sensors and their continuous, passive capture of mobility data offers a viable technique to measure mobility after a lower extremity fracture.^{7,8}

The objective of this research was to assess whether smartphone-collected step count and other mobility measures differed by weight-bearing status among patients surgically treated for a lower extremity fracture. We hypothesized that delayed weight-bearing patients would have fewer daily steps within 12 weeks of injury than early weight-bearing patients.

Methods

Study Design

This retrospective cohort study was conducted at a single academic trauma center from January to May 2024. The study was approved by the University of Maryland, Baltimore, Institutional Review Board, and all patients provided written informed consent before enrollment.

Study Participants

The study included patients aged 18 years and older who had one or more lower extremity fracture (ie, pelvic, hip, femoral shaft, distal femur, tibial plateau, pilon, ankle, or hindfoot fracture), were treated surgically within 7 days of injury, and had completed at least 6 months of clinical follow-up. In addition, participants were required to have used an Apple iPhone for at least 1 year before their injury. Participants were excluded if they had bilateral lower extremity injuries or lacked sufficient mobility data for analysis.

Data Collection

The clinical research team monitored the orthopaedic trauma follow-up appointments to identify patients meeting the study's eligibility criteria. Once informed consent was obtained, the research staff assisted participants in securely exporting their Apple Health data to a secure database. Subsequently, a thorough review of participants' electronic medical records provided demographic details, clinical information (eg, fracture classification, comorbidities), surgical details (eg, fixation techniques, surgical approaches), and postoperative outcomes.

Intervention

The primary variable of interest was weight-bearing status, which was determined based on the postoperative weight-bearing order reported in the medical record and confirmed with 6-week, clinic, follow-up records. Patients were categorized into one of two weight-bearing groups. The early weight-bearing group included patients permitted to bear weight as tolerated within 3 weeks of definitive fixation. The delayed weight-bearing group included patients who were non-weight-bearing, foot-flat weight-bearing, or toe-touch weight-bearing for 6 or more weeks after definitive fixation. These group classifications were selected based on previous weight-bearing studies and local practice.^{1,9,10} The weight-bearing protocol for study participants was determined by the treating surgeon's clinical discretion and hospital-specific protocols. Ten orthopaedic traumatologists contributed patients to the study, with wide weight-bearing practice variation for the included fracture types.

Study Outcomes

The study outcomes were passively collected on the study participants' smartphones. The study restricted eligibility to only patients who use Apple iPhones for several reasons. First, Apple has the largest smartphone market share in the United States, used by 61% of adults. Since 2016, all iPhones come equipped with the Apple Health platform, which continuously measures and records the user's step count and several other gait metrics from day 1 of purchase. These measures have been validated against gold-standard gait analysis techniques both by Apple and independent researchers.^{11,12} Using a single brand of phone and measurement platform avoids cross-platform calibration issues in the analyses.

Average daily step count within 12 weeks of injury was the primary outcome. Step count was captured using the participants' iPhone pedometer to objectively measure the number of steps taken while the patient had the device on them. The device also counts steps

taken while using assistive devices. However, these assistive devices likely influence other mobility parameters, such as walking asymmetry and walking speed.¹¹

The secondary outcomes included walking speed, step length, walking asymmetry, and double support time assessed within 12 weeks of injury. These outcomes and step count were also compared at 2, 6, 12, and 26 weeks after injury. Walking speed was measured in meters per second (m/s), with population averages for comfortable walking speeds ranging from 1.3 to 1.5 m/s.^{13–15} Step length was measured in meters (m) with population norms between 0.55 and 0.88 m.¹⁶ Walking asymmetry is the percentage of the time that steps with one foot are faster or slower than those with the other foot. Values closer to zero indicate better symmetry.¹¹ Asymmetry increases when the individual favors one limb.¹⁷ Double support time is the percentage of the patient's gait cycle with both feet on the ground, with population norms ranging from 20% to 40%.¹¹

We selected mobility within 12 weeks of injury as the primary end point, given the results from several patient preference studies illustrating the priority patients place on early mobility recovery.^{18–20} Additional research has demonstrated the importance of regained mobility within 12 weeks of injury in improving work productivity, further justifying this time point of assessment.²¹

Statistical Analysis

A total sample of 66 patients with a 1:2 early-to-delayed weight-bearing ratio provided at least 80% power to detect between-group differences equal to 75% of the sample SD (ie, Cohen $d = 0.75$) or more with a two-sided alpha of 5%.

The raw data collected on the Apple Health Kit app was preprocessed to smooth out any extreme outliers. With this approach, step count data were aggregated by week and then divided by seven to define average daily values. For walking speed and step length, the weekly 90th percentiles were calculated. For walking asymmetry and double support time, weekly averages were calculated.

The association of early versus delayed weight-bearing with the study outcomes was assessed using linear mixed-effect models. The models were fit with a 3-way interaction for the weight-bearing indicator, time from injury, and the patient's average preinjury mobility for the given parameter calculated using data within the 6 months before the injury. The models also adjusted for age, sex, open fractures, and fracture location. These covariates were selected to address confounding, reflecting the clinical factors known to influence mobility, with the fracture location coded as diaphyseal versus intra-articular based on clinical weight-bearing protocol differences.^{22,23} The dependent variable was a weekly repeated outcome measurement, and a unique subject identifier was included as a random intercept. All continuous independent variables were included as natural splines. As the linear mixed-effect model includes a unique patient intercept and the model adjusts for preinjury data, the estimate is conceptually similar to a paired comparison. The benefits of this approach over the classic paired comparison are that it can handle unbalanced data (eg, skewed or missing pre- or postinjury distributions), it models within-person variation more

explicitly, allows for the inclusion of other covariates (eg, age, fracture location), and better accounts for the nonindependence of repeated measures in the standard errors.

From these models, the study group estimates and between-group differences with 95% confidence intervals (CIs) were estimated at each prespecified time period. The level of significance was 5%. All statistical analyses were done using R Version 4.2.2 (R Foundation for Statistical Computing).

Results

Study Population

A total of 126 patients met the study's inclusion criteria. Of these, 33 patients were excluded due to bilateral injuries, and another 19 patients were excluded due to insufficient Apple Health Kit mobility data for analytical approach. The final study population included 74 patients (mean age, 46 [SD, 19] years; 43% female), with 27 in the early weight-bearing group and 47 in the delayed weight-bearing group. Study participants in the delayed weight-bearing group were more likely to be younger (mean age, 42 vs. 54 years; $P < 0.01$), have an intra-articular fracture (60% vs. 19%; $P < 0.01$), and have polytrauma injuries (43% vs. 19%; $P = 0.04$; Table 1). The most common fracture locations in the sample were femoral shafts (23%) and tibial shafts (20%). In the 6 months before the injury, the average daily step count was 4,446 (SD, 2,996).

Step Count

Daily step counts within 12 weeks of injury were markedly higher in the early weight-bearing group (mean, 1,723; 95% CI, 1,179 to 2,267) compared with the delayed weight-bearing group (mean, 673; 95% CI, 330 to 1,016; mean difference, 1,050; 95% CI, 373 to 1,727; $P = 0.002$; Table 2), based on model-adjusted estimates accounting for preinjury mobility and clinical covariates. As demonstrated in Figure 1A, both groups increased their daily step count until approximately 20 weeks after injury. At this point, the daily step count for the early weight-bearing group asymptotes. By 26 weeks after injury, the daily step count was no longer statistically different between the groups (mean difference, 459; 95% CI, -206 to 1,124; $P = 0.20$; Table 3).

Walking Speed

Within the 12 weeks after injury, walking speed did not markedly differ between the weight-bearing groups (mean difference, 0.04 m/s; 95% CI, 0.05 to 0.13; $P = 0.36$; Table 2). In both groups, walking speed declined from injury to 12 weeks postinjury, presumably due to reduced reliance on walking aids (Figure 1B). By 26 weeks after injury, patients in the early weight-bearing group had faster walking speeds than those in the delayed weight-bearing group (mean difference, 0.13 m/s; 95% CI, 0.04 to 0.22; $P = 0.004$; Table 3).

Step Length

Weight-bearing status was not associated with a difference in step length within 12 weeks of injury (mean difference, 0.02 m; 95% CI, -0.01 to 0.06; $P = 0.19$; Table 2). In both weight-bearing groups, a linear increase in step length from injury to 26 weeks postinjury

was observed (Figure 1C). The between-group difference in step length remained similar at 2, 6, 12, and 26 weeks postinjury (Table 3).

Walking Asymmetry

Walking asymmetry was not statistically different in early weight-bearing or delayed weight-bearing patients during the 12 weeks after injury (mean difference, 1.7%; 95% CI, -8.1% to 11.5%; $P = 0.74$; Table 2). Both groups demonstrated increased walking asymmetry from injury to 6 weeks postinjury, after which walking asymmetry in the delayed weight-bearing group asymptotes and declined in the early weight-bearing group (Figure 1D). By 26 weeks after injury, walking asymmetry was 12.2% lower in early weight-bearing patients than in delayed weight-bearing patients (95% CI, -21.3% to -3.1%; $P = 0.008$; Table 3).

Double Support Time

Double support time within 12 weeks of injury was not statistically different between early and delayed weight-bearing patients (mean difference, 0.1%; 95% CI, -0.7% to 0.4%; $P = 0.69$; Table 2). The overall and between-group double support time estimates remained similar over the 26 weeks after injury (Figure 1E and Table 3).

Discussion

This study of patients with surgically treated lower extremity fractures investigated if mobility data that were passively collected on the patients' smartphones could distinguish gait differences between patients treated with early versus delayed weight-bearing. Using these novel metrics, observation found patients prescribed delayed weight-bearing took more than 1,000 fewer steps per day within 12 weeks of injury compared with patients prescribed early weight-bearing. This result was statistically significant and likely of clinical importance. Differences in the other mobility parameters, including walking speed, step length, walking asymmetry, and double support time, did not reach statistical significance within 12 weeks postinjury. After adjusting for potential confounders, patients in the early weight-bearing group had faster walking speeds with better symmetry than those in the delayed weight-bearing group by 26 weeks postinjury.

The findings suggest that postoperative weight-bearing status appears to be associated with important differences in early step counts. The data presented in Figure 1 indicate that the difference in step count improvement between the two groups is greater than merely a temporal shift due to the weight-bearing restriction. Differences in walking speed and asymmetry were observed 26 weeks after injury. Extensive mobility aid use by the study participants early in the recovery process might have muted the ability to detect notable differences in the other mobility parameters within 12 weeks of injury.

This study's strengths lie in the novel look at the clinical effect of differences in weight-bearing status on early gait. The notable differences observed in step counts between different weight-bearing protocols underscore the potential for such technology to provide valuable insights into patient compliance and recovery expectations. A broad range of fracture patterns were included in this study, with an overlapping distribution between weight-bearing groups. This study feature suggests that the observed association of weight-

bearing status on early step count remains after adjusting for fracture location and severity, enhancing the findings' generalizability. In addition, the analysis used advanced statistical modeling to adjust for potential confounding, incorporating multifactor interaction terms and non-linear splines for continuous variables. These estimates reflect adjustments for each patient's individual preinjury mobility, accounting for baseline differences in a longitudinal framework.

Despite these strengths, several key limitations are observed. For eligibility, the study required patients to have a minimum of 6 months follow-up to adequately observe postfracture recovery. This requirement likely introduces selection bias toward patients with more severe injury and comprised recovery. Second, inclusion was restricted to patients with Apple iPhone devices. This decision was made due to the homogeneity of the Apple system, which has been previously externally validated, allowing decreased variability in sensor systems and more confidence in the validity of the data provided. Finally, inherent baseline differences in early versus delayed weight-bearing patients preclude the ability to infer the clinical benefits or harms with either approach. Although the study controlled for measured confounders, there are limits to the specificity of the measurements. For example, more severe articular injuries may have led to fewer steps, not just the prescribed weight-bearing status.

In conclusion, step count data collected on patients' smartphones differed between early versus delayed weight-bearing patients within 12 weeks of injury but converged by 26 weeks after injury. However, patients allowed earlier weight-bearing showed improvement in other gait characteristics, such as walking speed and walking asymmetry, at 26 weeks. The findings demonstrated that weight-bearing status translates into real-world gait differences in patient gait and can be measured. The novel "digital biomarkers" used in this study show promise to objectively monitor gait post-operatively and demonstrate the feasibility of using smartphone-derived metrics in future prospective studies.

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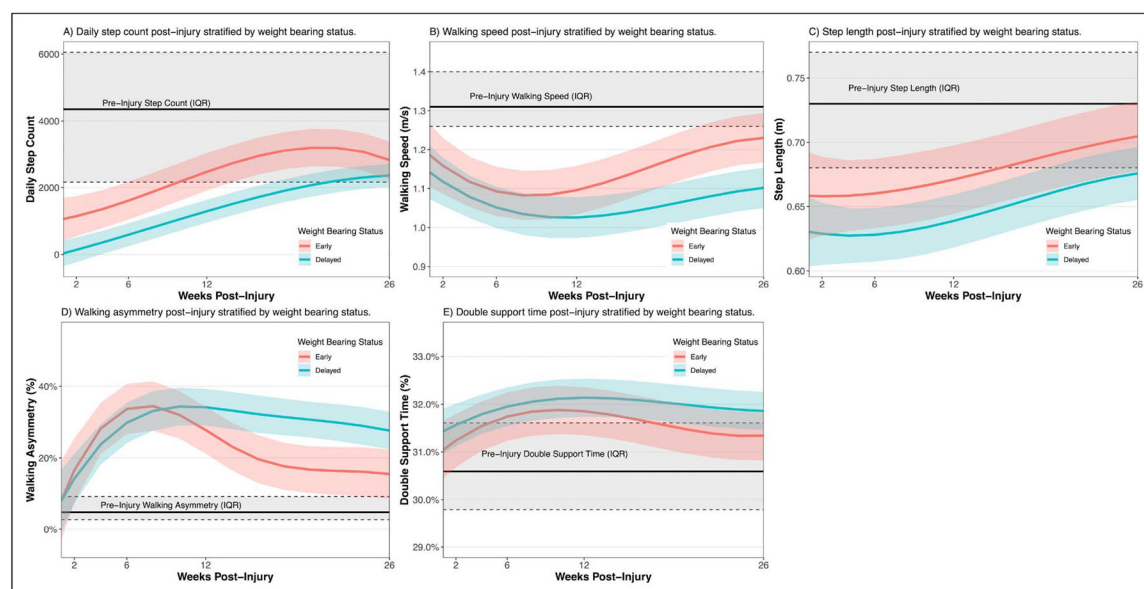


Figure 1.

Graphs showing the association of weight-bearing (early vs. delayed) and postinjury mobility within 26 weeks of injury, (A) daily step count, (B) walking speed, (C) step length, (D) walking asymmetry, and (E) double support time.

Table 1.

Patient Characteristics

Characteristic	Overall (n = 74)	Early Weight-Bearing (n = 27)	Delayed Weight-Bearing (n = 47)	P Value
Age, mean (SD)	46 (19)	54 (20)	42 (16)	<0.01
Sex, female, n (%)	32 (43)	12 (44)	20 (42)	0.87
BMI, mean (SD)	28.6 (6.1)	27.8 (6.2)	29.1 (16.0)	0.39
Diabetes, n (%)	2 (3)	2 (7)	0 (0)	0.06
Smoking status, n (%)	—	—	—	0.45
No	53 (71)	20 (74)	33 (70)	—
Yes	11 (15)	5 (19)	6 (13)	—
Former	10 (14)	2 (7)	8 (17)	—
Drug use, n (%)	—	—	—	0.15
No	53 (72)	23 (89)	30 (64)	—
Yes	16 (22)	3 (11)	13 (28)	—
Former	5 (6)	1 (4)	4 (8)	—
ASA physical status score, n (%)	—	—	—	0.34
I	4 (5)	2 (7)	2 (4)	—
II	38 (51)	15 (56)	23 (49)	—
III	27 (36)	10 (37)	17 (36)	—
IV	6 (8)	0 (0)	5 (11)	—
Area Deprivation Index, mean (SD)	37 (20)	35 (19)	38 (21)	0.66
Polytrauma, n (%)	25 (34)	5 (19)	20 (43)	0.04
Intra-articular, n (%)	33 (45)	5 (19)	28 (60)	<0.01
Fracture types, n (%)				
Pelvic ring	4 (5)	0 (0)	4 (9)	0.57
Acetabulum	8 (11)	0 (0)	8 (17)	0.11
Proximal femur	8 (11)	3 (11)	5 (11)	0.16
Femur shaft	17 (23)	9 (33)	8 (17)	0.02
Distal femur	12 (16)	3 (11)	9 (19)	0.76
Patella	7 (9)	4 (15)	3 (6)	0.21

Characteristic	Overall (n = 74)	Early Weight-Bearing (n = 27)	Delayed Weight-Bearing (n = 47)	P Value
Proximal tibia or fibula	11 (15)	2 (7)	9 (19)	0.28
Tibia or fibular shaft	15 (20)	8 (30)	7 (15)	0.32
Distal tibia or fibula	7 (9)	1 (4)	6 (13)	0.18
Malleolar	8 (11)	1 (4)	7 (15)	0.35
Calcaneus	2 (3)	1 (4)	1 (2)	0.47
Talus	1 (1)	0 (0)	1 (2)	0.99
Preinjury daily steps, mean (SD)	4,446 (2,996)	3,765 (2,865)	4,837 (3,030)	0.14
Preinjury walking speed (m/s), mean (SD)	1.31 (0.14)	1.29 (0.18)	1.32 (0.11)	0.49
Preinjury step length (m), mean (SD)	0.73 (0.07)	0.72 (0.09)	0.73 (0.06)	0.40
Preinjury walking asymmetry (%), mean (SD)	8.1% (9.7%)	9.8% (12.9%)	7.0% (6.9%)	0.25
Double support time (%), mean (SD)	30.7% (1.5%)	30.5% (1.9%)	30.8% (1.3%)	0.54

ASA = American Society of Anesthesiologists, BMI = body mass index.

Table 2.
Association of Weight-Bearing Status With Study Outcomes Measured Within 12 Weeks of Injury

Outcome	Early Weight-Bearing (n = 27)		Delayed Weight-Bearing (n = 47)		Mean Difference (95% CI)	P Value
	Mean (95% CI)		Mean (95% CI)			
Daily step count within 12 weeks of injury	1,723 (1,179–2,267)		673 (330–1,016)		1,050 (373 to 1,727)	0.002
Walking speed (m/s) within 12 weeks of injury	1.10 (1.04–1.17)		1.06 (1.02–1.11)		0.04 (–0.05 to 0.13)	0.36
Step length (m) within 12 weeks of injury	0.66 (0.63–68)		0.64 (0.61–0.66)		0.02 (–0.01 to 0.06)	0.19
Walking asymmetry (%) within 12 weeks of injury	27.5% (19.9%–35.1%)		25.8% (20.5%–31.2%)		1.7% (–8.1% to 11.5%)	0.74
Double support time (%) within 12 weeks of injury	31.8% (31.4%–32.1%)		31.9% (31.5%–32.3%)		–0.1% (–0.7% to 0.4%)	0.69

CI = confidence interval.

All estimates adjust for preinjury mobility, age, sex, open fractures, and fracture location.

Table 3.
Association of Weight-Bearing Status With Study Outcomes Measured at 2, 6, 12, and 26 Weeks after Injury

Outcome	Early Weight-Bearing (n = 27) Mean (95% CI)	Delayed Weight-Bearing (n = 47) Mean (95% CI)	Mean Difference (95% CI)	P Value
Daily step count				
2 weeks postinjury	1,146 (548–1745)	142 (0–512)	1,004 (301 to 1,707)	0.007
6 weeks postinjury	1,612 (1,048–2,176)	592 (249–936)	1,020 (359 to 1,680)	0.004
12 weeks postinjury	2,472 (1,910–3,035)	1,295 (953–1,637)	1,177 (519 to 1,836)	<0.001
26 weeks postinjury	2,824 (2,256–3,393)	2,365 (2,020–2,710)	459 (–206 to 1,124)	0.20
Walking speed (m/s)				
2 weeks postinjury	1.16 (1.09–1.23)	1.12 (1.06–1.18)	0.03 (–0.07 to 0.14)	0.55
6 weeks postinjury	1.09 (1.03–1.16)	1.05 (1.00–1.10)	0.04 (–0.05 to 0.13)	0.40
12 weeks postinjury	1.10 (1.03–1.16)	1.03 (0.97–1.08)	0.07 (–0.02 to 0.16)	0.13
26 weeks postinjury	1.23 (1.17–1.29)	1.10 (1.05–1.15)	0.13 (0.04 to 0.22)	0.004
Step length (m)				
2 weeks postinjury	0.66 (0.63–0.69)	0.63 (0.60–0.65)	0.03 (–0.01 to 0.07)	0.16
6 weeks postinjury	0.66 (0.63–0.69)	0.63 (0.61–0.65)	0.03 (0.00 to 0.07)	0.08
12 weeks postinjury	0.67 (0.64–0.7)	0.64 (0.62–0.66)	0.03 (0.00 to 0.07)	0.08
26 weeks postinjury	0.70 (0.68–0.73)	0.68 (0.66–0.70)	0.03 (–0.01 to 0.06)	0.12
Walking asymmetry (%)				
2 weeks postinjury	16.6% (7.7%–25.4%)	14.2% (7.3%–21.2%)	2.4% (–9.6% to 14.4%)	0.69
6 weeks postinjury	33.7% (26.7%–40.7%)	29.8% (24.2%–35.5%)	3.9% (–5.5% to 13.4%)	0.41
12 weeks postinjury	27.8% (21.2%–34.3%)	34.2% (29.1%–39.3%)	–6.2% (–15.1% to 2.5%)	0.16
26 weeks postinjury	15.5% (8.6%–22.3%)	27.6% (22.4%–32.9%)	–12.2% (–21.3% to –3.1%)	0.008
Double support time (%)				
2 weeks postinjury	31.2% (30.7%–31.8%)	31.6% (31.1%–32.0%)	–0.3% (–1.1% to 0.4%)	0.33
6 weeks postinjury	31.7% (31.2%–32.2%)	32.0% (31.5%–32.4%)	–0.2% (–0.9% to 0.5%)	0.53
12 weeks postinjury	31.9% (31.7%–32.4%)	32.1% (31.7%–32.5%)	–0.3% (–0.9% to 0.4%)	0.48
26 weeks postinjury	31.3% (30.8%–31.9%)	31.9% (31.5%–32.3%)	–0.5% (–1.2% to 0.2%)	0.17

CI = confidence interval.

All estimates are adjusted for preinjury mobility, age, sex, open fractures, and fracture location.