

# Deficit accumulation, plantar pressure-time loading and contact timing in community-dwelling older adults with type 2 diabetes: a cross-sectional study with exploratory foot-risk stratification

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## Research Article

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# Abstract

## Background

Frailty is associated with impaired mobility in older adults, but whether greater deficit accumulation is reflected in plantar pressure-time loading and contact timing among older adults with type 2 diabetes remains unclear. We examined these associations and explored them across diabetic foot-risk strata.

## Methods

This community-based cross-sectional study, conducted from September 2025 through March 2026, included 810 adults aged  $\geq 60$  years with type 2 diabetes. FI33 was used for descriptive stratification; FI30, excluding BMI, diabetes duration and HbA1c, was the continuous exposure. Dynamic plantar pressure was measured using Footscan. The primary outcome was total regional pressure-time integral (T-PTI), defined as the sum of PTI across 20 bilateral plantar regions. Timing outcomes were relative medial-heel, lateral-heel and midfoot contact times, foot-flat phase (FFP), and forefoot push-off phase (FFPOP). HC3-robust linear regression adjusted for age, sex, BMI, diabetes duration, HbA1c and loss of protective sensation. Benjamini-Hochberg correction was applied. Operational IWGDF-based foot-risk strata were evaluated using stratified and interaction analyses.

## Results

Each 0.10 increase in FI30 was associated with 5.12% higher T-PTI (95% CI 1.01%–9.40%;  $q = 0.0171$ ). Relative medial-heel, lateral-heel and midfoot contact times were 1.79, 1.55 and 1.58 percentage points longer, respectively ( $q = 0.0012$ ,  $0.0034$  and  $0.0045$ ), whereas FFPOP was 1.51 percentage points shorter ( $q = 0.0036$ ). FFP was 1.68 percentage points longer ( $q = 0.0232$ ), but was less robust in sensitivity analyses. Associations were directionally consistent in risk 0 and risk  $\geq 1$ , with generally larger estimates among participants with at-risk feet; interaction tests did not indicate clear heterogeneity.

## Conclusions

Greater deficit accumulation was associated with higher plantar pressure-time exposure, prolonged relative heel and midfoot contact, and shorter forefoot push-off in community-dwelling older adults with type 2 diabetes. Frailty-related systemic vulnerability and diabetic foot risk may provide complementary information, while dynamic plantar loading may provide candidate outcomes for prospective gait and exercise studies.

## Background

Frailty reflects reduced multisystem physiological reserve and increased vulnerability to adverse outcomes after health stressors in later life [1]. Among older adults with diabetes, frailty is common and is associated with mortality, hospitalization, disability and impaired mobility [2]. Mobility impairment is central to the clinical expression of frailty and may include slower walking, reduced balance control and altered gait adaptability. In older adults with type 2 diabetes, these age-related functional limitations coexist with diabetes-related sensorimotor and foot-specific constraints on walking. Understanding whether accumulated health deficits are reflected in foot-ground interaction may therefore provide a biomechanical perspective on functional vulnerability in this population.

The deficit-accumulation approach conceptualizes frailty as the proportion of health deficits present in an individual [3, 4]. When a frailty index is constructed from an existing dataset, transparent specification of deficit selection, coding, missingness and construct characteristics is essential [5]. Routine clinical and laboratory variables can contribute to deficit-accumulation indices [6, 7], but the resulting research construct depends on the variables available. Frailty measured in this way is not simply a marker of one disease or organ system; rather, it summarizes accumulated vulnerability across multiple health domains.

Frailty has been associated with slower gait and alterations in spatiotemporal and kinematic characteristics [8, 9]. Direct evidence linking frailty to plantar biomechanics is much more limited. In a small study of institutionalized older adults, frail participants differed from pre-frail participants in rearfoot relative contact time [10]. In type 2 diabetes, loss of protective sensation and peripheral neuropathy may independently alter gait, muscle activation and dynamic plantar-pressure patterns [11–13]. Thus, an older person with type 2 diabetes may simultaneously experience systemic functional vulnerability related to frailty and local foot vulnerability related to diabetic foot-risk factors. How these dimensions are expressed during walking remains insufficiently understood.

Plantar biomechanics can be characterized using complementary measures. Peak plantar pressure represents an instantaneous maximum, whereas pressure-time integral (PTI) incorporates both pressure magnitude and contact duration and therefore provides a pressure-time measure of plantar loading within stance [14]. The additional information provided by PTI alongside peak pressure is context-dependent, and both measures are influenced by walking conditions, speed and measurement protocol [14–17]. Regional relative contact time adds a temporal dimension by describing how contact is distributed across stance. Foot-flat and forefoot push-off phases further characterize progression from rearfoot loading toward terminal forefoot contact [18]. Measurement protocol and repeated trials can influence plantar-pressure reliability [19]. Although elevated plantar pressure has been associated with diabetic foot ulceration, its predictive performance is limited and no universal critical threshold has been established [20, 21]. Together, pressure-time and timing measures may identify a dynamic plantar phenotype that is not evident from peak pressure alone.

Diabetic foot-risk stratification captures a different dimension of vulnerability. In the IWGDF 2023 system, risk 0 denotes neither loss of protective sensation (LOPS) nor peripheral arterial disease (PAD);

risk 1 denotes LOPS or PAD; risk 2 denotes LOPS plus PAD, LOPS plus foot deformity, or PAD plus foot deformity; and risk 3 denotes LOPS or PAD together with a history of foot ulceration, lower-extremity amputation, or end-stage renal disease [11]. In the present community screening dataset, the available IWGDF-based categories were operational screening classifications because ankle-brachial index and vascular imaging were not available. Frailty and diabetic foot-risk status therefore operate at different conceptual levels: one reflects generalized deficit accumulation, whereas the other identifies established local foot-risk conditions. Whether frailty-related plantar biomechanical differences become more apparent when local foot vulnerability is also present has not been well characterized.

We therefore examined the association of continuous FI30 with T-PTI, medial-heel, lateral-heel and midfoot relative contact time, and reconstructed foot-flat and forefoot push-off phases in community-dwelling older adults with type 2 diabetes. As a secondary exploratory objective, we examined these associations in participants with operational IWGDF risk 0 and those with at-risk feet (risk  $\geq 1$ ), and further described estimates across risk 0, 1 and 2. Because these subgroup analyses were exploratory, differences in within-stratum statistical significance were not interpreted as evidence of heterogeneity without support from formal interaction tests.

## Methods

### Study design, setting and participants

This community-based cross-sectional study was conducted from September 2025 through March 2026 at Sijing Community Health Service Center and its affiliated subcenters in Songjiang District, Shanghai, China. Reporting followed the STROBE guidance for cross-sectional studies [22]. Clinical trial number: not applicable.

Participants were recruited consecutively during community health examinations and diabetic-foot risk screening conducted within the prespecified study period. Inclusion criteria were: age  $\geq 60$  years; previously diagnosed type 2 diabetes, with diabetes status confirmed against contemporary diagnostic criteria when required [23]; community dwelling; ability to understand the study procedures; and ability to stand independently and safely complete natural walking plantar-pressure testing. Exclusion criteria were: active foot ulcer, foot infection or acute Charcot neuro-osteoarthropathy; previous lower-limb or foot amputation, or severe foot deformity preventing standardized walking and plantar-pressure testing; recent lower-limb fracture or surgery, an acute cardiovascular or cerebrovascular event, or another acute illness clearly affecting gait or testing safety; or another condition preventing comprehension of the testing procedure or safe independent walking. Less severe foot deformity was not an exclusion criterion if standardized testing could be completed safely.

Because recruitment covered all eligible participants available during the fixed screening period, no formal a priori sample-size target was used to terminate recruitment. Statistical precision is presented using effect estimates and 95% confidence intervals.

## Clinical variables and diabetic foot-risk assessment

Demographic and clinical variables were obtained from the standardized screening questionnaire and from clinical and biochemical measurements collected within the community screening program. Variables included age, sex, height, weight, BMI, diabetes duration, HbA1c, fasting plasma glucose, blood pressure, lipids and chronic disease history. The analytical file did not contain a separate variable for the interval between laboratory testing and Footscan assessment; therefore, no narrower timing assumption was imposed.

LOPS was screened by trained staff using a 10-g monofilament applied perpendicularly to the hallux pulp and the first and fifth metatarsal heads until it bent into a C shape for approximately 1–2 seconds. Participants kept their eyes closed and reported whether pressure was perceived; failure to perceive pressure at any tested site was classified as LOPS. The archived field protocol did not document a fixed number of repeated or sham applications, and none is inferred. Dorsalis pedis pulse, intermittent claudication/rest-pain screening, callus, foot deformity, previous ulceration, amputation history and end-stage renal disease were also recorded.

For exploratory stratification, the existing dataset variable based on IWGDF risk logic was used as an operational foot-risk classification. Using the available screening fields, risk 0 represented neither identified LOPS nor PAD-related screening evidence; risk 1 represented LOPS or PAD-related screening evidence alone; risk 2 represented LOPS together with PAD-related screening evidence, or either LOPS/PAD-related screening evidence together with foot deformity; and risk 3 represented LOPS or PAD-related screening evidence together with a major prior foot complication or end-stage renal disease. Because ankle-brachial index and vascular imaging were unavailable, these are IWGDF-based operational screening categories rather than vascular-confirmed classifications. Risk  $\geq 1$  was considered an at-risk foot category. The single risk-3 participant was retained in the binary risk  $\geq 1$  grouping but excluded from the separate risk-level stratified regressions.

## Frailty assessment and construct audit

Frailty was quantified using the deficit-accumulation approach [3–5]. FI33 comprised 33 deficits spanning lifestyle, activity/function, chronic conditions, diabetes/metabolic characteristics, urinalysis and hematological measures. Each deficit was scored from 0 (no deficit) to 1 (maximal deficit), with intermediate values for graded variables. FI33 was calculated as the sum of available deficit scores divided by the number of available items. At least 27 of 33 items were required; participants in the analytical cohort had 32–33 available items. End-stage renal disease was collected clinically but was not part of the final 33-item index. Plantar-pressure measures, loss of protective sensation (LOPS), callus, foot deformity and ulcer-related variables were excluded from FI33 to avoid incorporating the biomechanical or foot-risk pathway into the exposure. Detailed items and scoring rules are provided in Additional file 1: Table S1.

FI33 categories were defined operationally for descriptive analysis as low ( $< 0.10$ ), intermediate ( $0.10$  to  $< 0.25$ ) and high ( $\geq 0.25$ ). These categories are research strata rather than validated diagnostic cut points for this study-specific index. For regression analyses, FI30 was derived from FI33 by removing BMI, diabetes duration and HbA1c because these variables were entered separately as covariates. The denominator was the number of available retained items. FI30 was modeled continuously, with effects expressed per 0.10 increase.

Because FI33 was constructed from an existing screening dataset, we performed a construct audit consistent with recommended FI-development checks [5]. We examined item-level missingness, prevalence of non-zero deficits, association with age, inter-item Spearman correlations and the balance of represented health domains. An exploratory 31-item structural audit index was also calculated after removing one variable from each of the two item pairs with Spearman correlations greater than 0.70. This audit assessed structural redundancy only and did not replace FI33 or FI30 in the main biomechanical models. Laboratory-based frailty indices have precedent, but their composition requires transparent reporting [6, 7].

## Dynamic plantar-pressure assessment

Dynamic plantar pressure was assessed using a footscan pressure-platform system (RSscan International, Olen, Belgium) with footscan 6.7 software. The platform measured 2,096 x 472 x 18 mm, incorporated 16,384 resistive sensors, sampled at 125 Hz and had a pressure range of 0-200 N/cm<sup>2</sup>. The software divided each foot into 10 anatomical regions: hallux, toes 2–5, metatarsals 1–5, midfoot, medial heel and lateral heel. Repeatability of Footscan loading measures has been reported previously [15].

Participants wore thin socks without shoes and walked at a self-selected comfortable pace. Practice walks preceded formal testing. Walking speed was not provided in the Footscan export used for this study and was therefore not directly recorded or available for covariate adjustment. Body weight and foot information were entered before individualized calibration. Three dynamic walking records were obtained per participant. A valid record required identifiable bilateral footprints within the effective sensing area, successful 10-region segmentation, and continuous heel-to-forefoot progression without obvious stopping, crossing, marked acceleration/deceleration or deliberate platform targeting. Invalid trials were repeated. After quality review, valid records were averaged in footscan 6.7 and the participant-level exported averages were used for analysis. Prior protocol studies indicate that step protocol and repeated trials can influence plantar-pressure reliability [19].

## Outcome construction

Regional exported variables included Start Time and End Time (ms), percentage contact, Max P (N/cm<sup>2</sup>), Time Max P (ms), Load rate, Impulse (N s/cm<sup>2</sup>), Contact area (cm<sup>2</sup>), Active Contact area (cm<sup>2</sup>) and the

maximum peak sensor value in area (N/cm<sup>2</sup>). For this study, the Footscan-exported Impulse variable was treated as regional pressure-time integral (PTI), because it is a pressure-time quantity expressed in N s/cm<sup>2</sup>.

The principal pressure-time outcome was total regional pressure-time integral (T-PTI), calculated as the sum of regional PTI across all 20 bilateral plantar regions. T-PTI was expressed in N s/cm<sup>2</sup> and was natural-log transformed for regression analysis. Complete T-PTI required all 20 regional PTI values. Because the values were summed across segmented regions, T-PTI was interpreted as a total regional pressure-time measure rather than a force-time integral.

For each foot, stance duration was reconstructed as the latest regional End Time minus the earliest regional Start Time. Regional relative contact time was  $100 \times \text{regional contact duration} / \text{ipsilateral stance duration}$ ; bilateral same-region values were averaged when both feet were available. The focused regional timing outcomes were medial-heel, lateral-heel and midfoot relative contact time.

Rollover timing was reconstructed from regional summary times rather than measured using motion capture. Full forefoot contact was defined as the latest Start Time among M1-M5; heel-off as the later End Time of the medial and lateral heel regions; and last foot contact as the latest regional End Time. Relative foot-flat phase (FFP) was  $100 \times (\text{heel-off} - \text{full forefoot contact}) / \text{stance}$ ; forefoot push-off phase (FFPOP) was  $100 \times (\text{last foot contact} - \text{heel-off}) / \text{stance}$ . Sequences were retained only when  $\text{first contact} \leq \text{first metatarsal contact} \leq \text{full metatarsal contact} \leq \text{heel-off} \leq \text{last contact}$  and stance was positive. Five left-foot sequences and no right-foot sequences failed this check; bilateral phase values were averaged only when both feet passed QC. These outcomes are therefore reconstructed timing proxies, not direct measures of ankle power or propulsion. Detailed outcome definitions and analysis samples are provided in Additional file 1: Table S2.

## Regional PTI completeness

The original workbook distinguished explicit numerical zeros from blank Footscan Impulse fields used to derive regional PTI. Across 16,200 expected regional fields, 15,869 were non-zero values, 220 were explicit zeros and 111 were blank, affecting 94 participants. Explicit zeros were retained as observed values, whereas blank fields were retained as missing and were not recoded to zero. Complete 20-region PTI data were available for 716 participants; two had missing diabetes duration, leaving 714 in the fully adjusted T-PTI model. Additional file 1: Tables S3A-S3C and Figure S1 present region-specific completeness and the missingness analysis.

## Statistical analysis

Continuous variables are presented as median [Q1, Q3] and categorical variables as n (%). Kruskal-Wallis tests were used for descriptive continuous-variable comparisons and Pearson chi-square or Monte Carlo Fisher exact tests for categorical comparisons where appropriate. To avoid circular inference, between-group P values were not displayed for FI33 itself, FI30, or variables that contributed directly to FI33 (BMI,

diabetes duration, HbA1c, fasting plasma glucose, ADL, hypertension, coronary heart disease, stroke and hyperlipidemia).

FI30 was analyzed continuously. Four full-sample linear regression specifications were fitted: M0, FI30 alone; M1, FI30 plus age and sex; M2, M1 plus BMI; and M3, M2 plus diabetes duration, HbA1c and LOPS. M3 was the principal fully adjusted model. HC3 heteroscedasticity-consistent standard errors were used; confidence intervals and P values were based on residual-degrees-of-freedom t inference. T-PTI was natural-log transformed, and coefficients were back-transformed to percentage change per 0.10 increase in FI30; timing outcomes are reported as percentage-point changes.

Six biomechanical outcomes were selected for focused manuscript analysis after exploratory evaluation: T-PTI, medial-heel relative contact time, lateral-heel relative contact time, midfoot relative contact time, FFP and FFPOP. Benjamini-Hochberg false-discovery-rate adjustment [24] was applied across these six outcomes separately within each model. Because the focused set was selected after exploratory analysis rather than prospectively preregistered, the resulting q values apply to this six-outcome set and the findings are interpreted as hypothesis-generating.

Exploratory foot-risk analyses first compared operational IWGDF risk 0 with risk  $\geq 1$ . Within each stratum, models adjusted for age, sex, BMI, diabetes duration and HbA1c. LOPS was not included in the primary stratified models because it contributes to the definition of foot-risk status and is structurally absent in risk 0. Formal effect modification was evaluated in the full sample by adding an FI30 x at-risk-foot-status interaction term to the same covariate set; BH adjustment was applied across the six interaction tests. A further exploratory analysis examined risk 0, 1 and 2 separately, excluding the single risk-3 participant. For each outcome, an omnibus FI30 x categorical-risk interaction and an FI30 x ordinal-risk interaction were tested, with BH adjustment across the six tests in each interaction family. Stratum-specific P values were not used to infer between-stratum differences.

Sensitivity analyses added callus status to M3, replaced FI30 by ordinal FI33 categories, trimmed the upper and lower 1% of each outcome, and assessed nonlinearity with restricted cubic splines. Exploratory outcomes were retained in a separate family. Missing data were not imputed; models used outcome-specific complete cases. A supplementary logistic regression assessed whether having at least one blank regional PTI field was associated with FI30 after adjustment for age, sex, BMI, diabetes duration, HbA1c and LOPS.

All statistical analyses were performed in R version 4.6.0.

During the preparation of this work the authors used ChatGPT to improve readability, enhance language and assist with translation. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Results

# Participant characteristics

A total of 928 individuals were screened. Forty-five did not meet the eligibility criteria, leaving 883 eligible participants. Of these, 14 did not complete the study procedures: five did not attend the scheduled test and could not subsequently be reached, and nine withdrew because of prolonged on-site waiting. Among the 869 participants who completed study procedures, 37 were excluded after data linkage and quality control because frailty information was insufficient to calculate the FI, and 22 because Footscan records were missing or failed quality control. The overall analytical cohort therefore comprised 810 participants (Fig. 1). Outcome-specific analyses used all eligible observations with complete data for the corresponding outcome and covariates.

The recruitment flow was 928 screened, 118 excluded and 810 included. Exclusions comprised 45 individuals who did not meet eligibility criteria, 37 with missing or non-calculable frailty information, 22 with missing or invalid Footscan assessments, and 14 other exclusions. Outcome-specific branches overlap. M3 included 714 participants for T-PTI, 808 for regional relative contact-time analyses and 803 for reconstructed rollover analyses.

The final analytical cohort included 810 community-dwelling older adults with type 2 diabetes: 82 (10.1%) in the low-FI33 group, 577 (71.2%) in the intermediate group and 151 (18.6%) in the high group. Median age was 71 years [Q1, Q3: 67, 74], and 392 participants (48.4%) were men. LOPS was present in 29.9% overall and in 28.0%, 30.5% and 28.5% of the low-, intermediate- and high-FI33 groups, respectively ( $P = 0.827$ ). The operational foot-risk distribution was risk 0 in 423 participants (52.2%), risk 1 in 135 (16.7%), risk 2 in 251 (31.0%) and risk 3 in 1 (0.1%); the distribution did not differ across FI33 groups ( $P = 0.870$ ). Other participant characteristics are shown in Table 1.

Table 1  
Participant characteristics according to FI33 category

| Characteristic                 | Overall<br>N = 810              | Low<br>n = 82                  | Intermediate<br>n = 577         | High<br>n = 151                 | P           |
|--------------------------------|---------------------------------|--------------------------------|---------------------------------|---------------------------------|-------------|
| Age, years                     | 71.00 [67.00, 74.00]<br>n = 810 | 70.00 [66.00, 74.00]<br>n = 82 | 70.00 [67.00, 74.00]<br>n = 577 | 72.00 [67.00, 74.00]<br>n = 151 | 0.2132      |
| BMI, kg/m2                     | 24.22 [22.04, 26.37]<br>n = 810 | 23.32 [21.69, 24.43]<br>n = 82 | 24.22 [22.03, 26.31]<br>n = 577 | 25.07 [22.65, 27.35]<br>n = 151 | -           |
| Diabetes duration, years       | 9.00 [3.00, 16.00]<br>n = 808   | 3.00 [1.00, 6.00]<br>n = 82    | 8.00 [3.00, 16.00]<br>n = 576   | 12.00 [8.00, 20.00]<br>n = 150  | -           |
| HbA1c, %                       | 6.60 [6.00, 7.30]<br>n = 810    | 6.00 [5.70, 6.50]<br>n = 82    | 6.60 [6.00, 7.20]<br>n = 577    | 7.40 [6.60, 8.30]<br>n = 151    | -           |
| FI30                           | 0.17 [0.12, 0.22]<br>n = 810    | 0.07 [0.05, 0.08]<br>n = 82    | 0.16 [0.13, 0.20]<br>n = 577    | 0.26 [0.24, 0.28]<br>n = 151    | -           |
| FI33                           | 0.18 [0.14, 0.24]<br>n = 810    | 0.08 [0.06, 0.09]<br>n = 82    | 0.18 [0.14, 0.21]<br>n = 577    | 0.28 [0.26, 0.31]<br>n = 151    | -           |
| Education, years               | 9.00 [8.00, 12.00]<br>n = 798   | 9.00 [9.00, 12.00]<br>n = 81   | 9.00 [7.00, 12.00]<br>n = 570   | 9.00 [6.00, 12.00]<br>n = 147   | 0.0756      |
| Fasting plasma glucose, mmol/L | 7.25 [6.24, 8.45]<br>n = 810    | 6.33 [5.62, 6.92]<br>n = 82    | 7.19 [6.20, 8.26]<br>n = 577    | 8.16 [7.16, 9.52]<br>n = 151    | -           |
| ADL score                      | 14.00 [14.00, 14.00]<br>n = 798 | 14.00 [14.00, 14.00]<br>n = 81 | 14.00 [14.00, 14.00]<br>n = 566 | 14.00 [14.00, 14.00]<br>n = 151 | -           |
| Male sex                       | 392/810<br>(48.4%)              | 59/82<br>(72.0%)               | 273/577<br>(47.3%)              | 60/151<br>(39.7%)               | <<br>0.0001 |

| <b>Characteristic</b>        | <b>Overall<br/>N = 810</b> | <b>Low<br/>n = 82</b> | <b>Intermediate<br/>n = 577</b> | <b>High<br/>n = 151</b> | <b>P</b> |
|------------------------------|----------------------------|-----------------------|---------------------------------|-------------------------|----------|
| Hypertension                 | 528/810<br>(65.2%)         | 27/82<br>(32.9%)      | 380/577<br>(65.9%)              | 121/151<br>(80.1%)      | -        |
| Coronary heart disease       | 121/810<br>(14.9%)         | 3/82 (3.7%)           | 77/577 (13.3%)                  | 41/151<br>(27.2%)       | -        |
| Stroke                       | 92/810<br>(11.4%)          | 3/82 (3.7%)           | 57/577 (9.9%)                   | 32/151<br>(21.2%)       | -        |
| Hyperlipidemia               | 241/810<br>(29.8%)         | 9/82<br>(11.0%)       | 156/577<br>(27.0%)              | 76/151<br>(50.3%)       | -        |
| Loss of protective sensation | 242/810<br>(29.9%)         | 23/82<br>(28.0%)      | 176/577<br>(30.5%)              | 43/151<br>(28.5%)       | 0.8270   |
| Callus                       | 726/810<br>(89.6%)         | 77/82<br>(93.9%)      | 514/577<br>(89.1%)              | 135/151<br>(89.4%)      | 0.4055   |
| Any foot deformity           | 414/810<br>(51.1%)         | 39/82<br>(47.6%)      | 295/577<br>(51.1%)              | 80/151<br>(53.0%)       | 0.7317   |
| Foot-risk category 0         | 423/810<br>(52.2%)         | 41/82<br>(50.0%)      | 305/577<br>(52.9%)              | 77/151<br>(51.0%)       | 0.8702   |
| Foot-risk category 1         | 135/810<br>(16.7%)         | 17/82<br>(20.7%)      | 91/577 (15.8%)                  | 27/151<br>(17.9%)       | -        |
| Foot-risk category 2         | 251/810<br>(31.0%)         | 24/82<br>(29.3%)      | 180/577<br>(31.2%)              | 47/151<br>(31.1%)       | -        |
| Foot-risk category 3         | 1/810 (0.1%)               | 0/82 (0.0%)           | 1/577 (0.2%)                    | 0/151 (0.0%)            | -        |

Continuous data are median [Q1, Q3] with available n; categorical data are count/available n (%). FI33 groups are < 0.10, 0.10 to < 0.25 and ≥ 0.25. BMI, diabetes duration, HbA1c, fasting plasma glucose, ADL, hypertension, coronary heart disease, stroke and hyperlipidemia are components of FI33; between-group P values are not shown for these variables to avoid circular inference. FI30 and FI33 are likewise not tested across FI33-defined groups. The foot-risk P value is one omnibus test across all four IWGDF-based operational categories. Because ABI or vascular imaging was not available, these categories are screening classifications rather than vascular-confirmed IWGDF diagnoses. Abbreviations: ABI, ankle-brachial index; ADL, activities of daily living; BMI, body mass index; FI30/FI33, 30-item/33-item frailty index; HbA1c, glycated haemoglobin; IWGDF, International Working Group on the Diabetic Foot; Q1/Q3, first/third quartile.

Complete bilateral PTI data for all 20 plantar regions were available in 716 participants, of whom 714 entered the fully adjusted T-PTI model. The fully adjusted regional relative contact-time and reconstructed rollover models included 808 and 803 participants, respectively. Outcome completeness and regional missingness are detailed in Additional file 1: Tables S3A-S3C. Descriptive plantar

biomechanical characteristics by FI33 category are shown in Table 2. Corresponding distributions by FI33 category are shown in Additional file 1: Figure S2.

Table 2  
Plantar biomechanical characteristics according to FI33 category

| Outcome                                           | Overall                              | Low                                 | Intermediate                         | High                                 | P      |
|---------------------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|--------|
| Total regional PTI (T-PTI), N s/cm <sup>2</sup>   | 19.45 [15.60, 24.60]<br>n = 716      | 17.85 [15.50, 21.88]<br>n = 74      | 19.30 [15.70, 24.60]<br>n = 506      | 20.75 [16.58, 26.73]<br>n = 136      | 0.0303 |
| Stance duration, ms                               | 1110.35 [928.90, 1390.25]<br>n = 810 | 1066.12 [928.24, 1288.35]<br>n = 82 | 1106.50 [921.60, 1386.00]<br>n = 577 | 1136.15 [945.38, 1419.47]<br>n = 151 | 0.2881 |
| Medial heel relative CT, %                        | 70.41 [64.53, 75.82]<br>n = 810      | 68.90 [63.37, 73.69]<br>n = 82      | 70.10 [64.44, 75.65]<br>n = 577      | 72.43 [65.95, 77.49]<br>n = 151      | 0.0093 |
| Lateral heel relative CT, %                       | 69.97 [64.02, 75.40]<br>n = 810      | 69.04 [63.53, 73.60]<br>n = 82      | 69.58 [63.89, 74.97]<br>n = 577      | 71.65 [65.52, 77.00]<br>n = 151      | 0.0234 |
| Midfoot relative CT, %                            | 71.20 [65.23, 76.96]<br>n = 810      | 68.98 [63.88, 74.04]<br>n = 82      | 71.06 [65.09, 76.93]<br>n = 577      | 72.94 [67.15, 77.80]<br>n = 151      | 0.0049 |
| Foot-flat phase, %                                | 56.20 [47.46, 63.95]<br>n = 805      | 52.43 [46.35, 61.03]<br>n = 82      | 56.45 [47.24, 63.48]<br>n = 572      | 56.95 [48.48, 66.45]<br>n = 151      | 0.0441 |
| Forefoot push-off phase, %                        | 28.38 [22.64, 34.20]<br>n = 805      | 30.32 [24.51, 35.88]<br>n = 82      | 28.79 [22.82, 34.15]<br>n = 572      | 26.68 [21.64, 32.68]<br>n = 151      | 0.0236 |
| Maximum regional peak pressure, N/cm <sup>2</sup> | 3.80 [3.15, 4.65]<br>n = 810         | 3.67 [3.15, 4.35]<br>n = 82         | 3.80 [3.15, 4.65]<br>n = 577         | 3.85 [3.25, 4.65]<br>n = 151         | 0.4389 |

Values are median [Q1, Q3]. P values are descriptive Kruskal-Wallis tests without multiplicity adjustment. Timing measures and maximum regional peak pressure are averaged between feet. T-PTI is the sum of regional PTI across the complete set of 20 bilateral plantar regions and is expressed in N s/cm<sup>2</sup>. Rollover measures are reconstructed timing proxies. Abbreviations: CT, contact time; PTI, pressure-time integral; T-PTI, total regional pressure-time integral.

## FI33 construct audit

Missingness was below 5% for every FI33 item, and the prevalence of non-zero deficits ranged from 1.73% to 68.94%, within the prespecified screening range for FI items [5]. Mean FI33 was 0.188 (SD 0.071), median 0.184 and range 0-0.447; within the restricted age range of 62–88 years, the association between FI33 and age was weak (Spearman rho = 0.053).

Two item pairs had Spearman correlations > 0.70: total cholesterol with LDL and urinary sediment red blood cells with urine occult blood. An exploratory FI31 formed by removing one item from each pair remained highly correlated with FI33 (Spearman rho = 0.981; Pearson r = 0.983). Urinalysis and hematology items constituted a relatively large proportion of FI33; full construct-audit results are provided in Additional file 1: Tables S4A-S4B.

## **Associations between FI30 and plantar biomechanical outcomes**

In the fully adjusted M3 model, higher FI30 was associated with greater total regional pressure-time exposure and altered plantar contact timing (Table 3; Fig. 2). Each 0.10 increase in FI30 was associated with a 5.12% increase in T-PTI (95% CI 1.01%-9.40%; P = 0.0143; q = 0.0171; n = 714), with a consistent direction of association across M0-M3.

Table 3  
Associations between FI30 and focused biomechanical outcomes

| <b>Outcome / effect unit</b>  | <b>Model</b> | <b>N</b> | <b>Effect [95% CI]</b> | <b>P</b> | <b>BH q</b> |
|-------------------------------|--------------|----------|------------------------|----------|-------------|
| T-PTI (%)                     | M0           | 716      | 6.75 [2.85, 10.80]     | 0.0006   | 0.0007      |
| T-PTI (%)                     | M1           | 716      | 7.26 [3.31, 11.37]     | 0.0003   | 0.0003      |
| T-PTI (%)                     | M2           | 716      | 5.24 [1.27, 9.36]      | 0.0093   | 0.0093      |
| T-PTI (%)                     | M3           | 714      | 5.12 [1.01, 9.40]      | 0.0143   | 0.0171      |
| Medial heel relative CT (pp)  | M0           | 810      | 1.77 [0.92, 2.62]      | < 0.0001 | 0.0001      |
| Medial heel relative CT (pp)  | M1           | 810      | 1.85 [0.98, 2.71]      | < 0.0001 | < 0.0001    |
| Medial heel relative CT (pp)  | M2           | 810      | 1.77 [0.88, 2.65]      | < 0.0001 | 0.0006      |
| Medial heel relative CT (pp)  | M3           | 808      | 1.79 [0.85, 2.73]      | 0.0002   | 0.0012      |
| Lateral heel relative CT (pp) | M0           | 810      | 1.55 [0.70, 2.41]      | 0.0004   | 0.0006      |
| Lateral heel relative CT (pp) | M1           | 810      | 1.66 [0.80, 2.52]      | 0.0002   | 0.0003      |
| Lateral heel relative CT (pp) | M2           | 810      | 1.61 [0.73, 2.49]      | 0.0004   | 0.0010      |
| Lateral heel relative CT (pp) | M3           | 808      | 1.55 [0.62, 2.49]      | 0.0011   | 0.0034      |
| Midfoot relative CT (pp)      | M0           | 810      | 1.98 [1.07, 2.89]      | < 0.0001 | 0.0001      |
| Midfoot relative CT (pp)      | M1           | 810      | 2.02 [1.08, 2.96]      | < 0.0001 | < 0.0001    |
| Midfoot relative CT (pp)      | M2           | 810      | 1.54 [0.57, 2.51]      | 0.0019   | 0.0028      |
| Midfoot relative CT (pp)      | M3           | 808      | 1.58 [0.54, 2.63]      | 0.0030   | 0.0045      |
| Foot-flat phase (pp)          | M0           | 805      | 1.99 [0.66, 3.32]      | 0.0034   | 0.0034      |
| Foot-flat phase (pp)          | M1           | 805      | 2.12 [0.77, 3.47]      | 0.0022   | 0.0022      |
| Foot-flat phase (pp)          | M2           | 805      | 1.89 [0.51, 3.27]      | 0.0075   | 0.0090      |
| Foot-flat phase (pp)          | M3           | 803      | 1.68 [0.23, 3.12]      | 0.0232   | 0.0232      |
| Forefoot push-off phase (pp)  | M0           | 805      | -1.63 [-2.49, -0.78]   | 0.0002   | 0.0004      |
| Forefoot push-off phase (pp)  | M1           | 805      | -1.68 [-2.55, -0.81]   | 0.0002   | 0.0003      |
| Forefoot push-off phase (pp)  | M2           | 805      | -1.60 [-2.50, -0.70]   | 0.0005   | 0.0010      |
| Forefoot push-off phase (pp)  | M3           | 803      | -1.51 [-2.46, -0.56]   | 0.0018   | 0.0036      |

Effects are per 0.10 increase in FI30. T-PTI was log transformed and is reported as percentage change; timing effects are percentage-point changes (pp). M0: unadjusted; M1: age and sex; M2: M1 plus BMI; M3: M2 plus diabetes duration, HbA1c and LOPS. Confidence intervals and P values use HC3 standard

errors and residual-df t inference. BH q values are calculated across the six focused outcomes separately within each model. The focused outcomes were selected after exploratory evaluation; findings are hypothesis-generating. Abbreviations: BH, Benjamini-Hochberg; CI, confidence interval; FI30, 30-item frailty index; HbA1c, glycated haemoglobin; LOPS, loss of protective sensation; pp, percentage points; T-PTI, total regional pressure-time integral.

Adjusted M3 effects and 95% confidence intervals per 0.10 increase in FI30. The T-PTI effect is reported as percentage change after back-transformation of the log-scale coefficient; timing effects are percentage-point changes. M3 adjusts for age, sex, BMI, diabetes duration, HbA1c and LOPS. BH q values are calculated across the six focused outcomes. The focused outcomes were selected after exploratory evaluation.

For timing outcomes, each 0.10 increase in FI30 was associated with 1.79 percentage points longer medial-heel relative contact time (95% CI 0.85–2.73;  $P = 0.0002$ ;  $q = 0.0012$ ), 1.55 points longer lateral-heel relative contact time (95% CI 0.62–2.49;  $P = 0.0011$ ;  $q = 0.0034$ ), and 1.58 points longer midfoot relative contact time (95% CI 0.54–2.63;  $P = 0.0030$ ;  $q = 0.0045$ ). FFP was 1.68 percentage points longer (95% CI 0.23–3.12;  $P = 0.0232$ ;  $q = 0.0232$ ), whereas FFPOP was 1.51 points shorter (95% CI -2.46 to -0.56;  $P = 0.0018$ ;  $q = 0.0036$ ).

## Exploratory diabetic foot-risk stratification

The direction of the FI30 associations with T-PTI, medial-heel, lateral-heel and midfoot relative contact time, FFP and FFPOP was broadly consistent in operational risk 0 and risk  $\geq 1$ , with generally larger point estimates in risk  $\geq 1$  (Fig. 3; Additional file 1: Table S5A). Per 0.10 increase in FI30, T-PTI increased by 3.51% (95% CI -2.01% to 9.35%) in risk 0 and 6.38% (95% CI 0.17%-12.96%) in risk  $\geq 1$ ; FFPOP decreased by 0.67 percentage points (95% CI -1.99 to 0.64) and 2.30 points (95% CI -3.72 to -0.88), respectively. Medial-heel, lateral-heel and midfoot relative contact time and FFP showed the same general between-stratum pattern.

Adjusted effects and 95% confidence intervals per 0.10 increase in FI30 are shown separately for operational IWGDF risk 0 and risk  $\geq 1$ . T-PTI is reported as percentage change after back-transformation; timing outcomes are percentage-point changes. Stratified models adjust for age, sex, BMI, diabetes duration and HbA1c. Formal FI30 x at-risk-foot interaction tests, rather than within-stratum P values, were used to assess heterogeneity; interaction P values ranged from 0.082 to 0.586 and all BH-adjusted q values were  $\geq 0.188$ . These analyses are exploratory.

Formal FI30 x at-risk-foot interaction tests did not show clear effect heterogeneity; interaction P values ranged from 0.082 to 0.586 and all Benjamini-Hochberg-adjusted q values were  $\geq 0.188$ . When operational risk 0, 1 and 2 were examined separately, the T-PTI estimates were + 3.51%, + 4.34% and + 8.21%, respectively, and the FFPOP estimates were - 0.67, -2.03 and - 2.57 percentage points. Point estimates for medial-heel, lateral-heel and midfoot relative contact time and FFP were also generally

largest in risk 2, while categorical and ordinal interaction tests did not show statistical heterogeneity (Additional file 1: Table S5B and Figure S3).

## Sensitivity and exploratory analyses

The main T-PTI association remained similar after additional adjustment for callus status (+ 5.16%, 95% CI 1.00%-9.49%;  $P = 0.0147$ ) and after trimming the upper and lower 1% of the outcome distribution (+ 4.27%, 95% CI 0.40%-8.30%;  $P = 0.0305$ ). When ordinal FI33 categories replaced continuous FI30, the direction remained positive but the 95% CI included zero (+ 3.59%, 95% CI -1.49%-8.94%;  $P = 0.1687$ ). Medial-heel, lateral-heel and midfoot relative contact-time findings were generally stable across sensitivity analyses. FFP was more sensitive to trimming and ordinal FI33 modelling; FFPOP remained directionally consistent, although its ordinal FI33 confidence interval included zero. Restricted cubic splines did not show clear evidence of nonlinearity for T-PTI, FFP or FFPOP (Additional file 1: Tables S6A-S6D and Figures S4-S6).

In exploratory analyses, maximum regional peak pressure was not clearly associated with FI30 (+ 0.69%, 95% CI -2.44%-3.91%;  $P = 0.6708$ ). Stance duration increased by 61.78 ms per 0.10 increase in FI30 (95% CI 5.58-117.99;  $P = 0.0313$ ), but this did not remain statistically significant after multiplicity correction ( $q = 0.3066$ ). Complete exploratory results are shown in Additional file 1: Table S7.

## Discussion

In this community-based study of 810 older adults with type 2 diabetes, greater deficit accumulation was associated with higher T-PTI, longer relative medial-heel, lateral-heel and midfoot contact, and a shorter forefoot push-off phase. FFP also increased with FI30, although this association was less robust in some sensitivity analyses. Taken together, the findings indicate that frailty-related functional differences may extend beyond conventional spatiotemporal gait characteristics to the magnitude of plantar pressure-time exposure and the temporal organization of load transfer within stance.

A central finding was the stable positive association between FI30 and T-PTI, whereas maximum regional peak pressure did not show the same pattern. These metrics capture different aspects of plantar loading: peak pressure reflects the instantaneous maximum at a local region, whereas PTI integrates pressure magnitude over contact duration [14]. Greater deficit accumulation may therefore be expressed more strongly through the duration and accumulation of plantar loading than through generalized elevation of local pressure peaks. This extends previous frailty research, which has largely focused on gait speed, step length, cadence and support-time characteristics [8, 9], by showing that systemic vulnerability may also be reflected in how plantar load is sustained and organized during walking.

The timing findings complement the T-PTI result. Higher FI30 was associated with longer relative heel and midfoot contact and a shorter FFPOP, indicating a reorganization of plantar contact timing within stance. Pinloche et al. reported significantly longer relative rearfoot contact time in frail than in pre-frail older adults [10], which is directionally consistent with the present heel-contact findings. In the larger

community-dwelling T2DM sample studied here, the accompanying prolongation of midfoot contact and shortening of the forefoot push-off phase further suggest that frailty-related plantar biomechanical differences may be particularly evident in rollover timing and load-transfer organization. Slower or more cautious transfer of load could plausibly relate to lower strength, balance reserve and gait adaptability, although the present study did not directly measure these mechanisms. Future studies that synchronously measure gait speed, step length, cadence, support time, lower-limb strength and ankle kinematics could clarify the relative contributions of gait strategy and motor control to T-PTI and contact-timing changes.

Diabetic foot-risk status adds a complementary local dimension. IWGDF risk stratification is based primarily on local sensory, vascular and structural factors such as LOPS, PAD, foot deformity and previous foot complications [11], whereas the FI captures multi-system deficit accumulation and overall health reserve. In this study, FI30 associations were directionally similar across operational risk strata, but point estimates were generally larger among participants with at-risk feet and were often largest in risk 2. This pattern across both pressure-time exposure and timing outcomes suggests that local foot vulnerability may be an important clinical context for interpreting frailty-related plantar biomechanics. Formal interaction tests, however, did not show clear statistical heterogeneity, so FI and foot-risk status are best viewed here as complementary dimensions rather than as demonstrated effect modifiers.

This interpretation is relevant to emerging epidemiological evidence. In a UK primary-care cohort of 186,473 people with type 2 diabetes, greater electronic frailty was associated with higher rates of subsequent diabetic foot ulceration and mortality [25], and a 2025 NHANES analysis also reported an association between frailty and diabetic foot ulceration [26]. These studies establish a population-level link but do not identify the functional pathway. The present findings suggest a candidate intermediate phenotype: even before active ulceration, greater systemic deficit accumulation may be accompanied by altered plantar pressure-time exposure and contact timing. Whether these biomechanical characteristics contribute to subsequent callus progression, pre-ulcerative lesions, ulceration or functional decline requires prospective testing.

The findings have direct implications for subsequent assessment and intervention research. Plantar biomechanical evaluation in older adults with diabetes may benefit from considering T-PTI and contact timing alongside peak pressure, because these measures capture sustained loading and load-transfer timing that are not represented by an instantaneous maximum alone. Synchronizing plantar-pressure testing with gait speed, step length, cadence, support time, strength and balance measures would support a more integrated framework linking systemic function, gait strategy and plantar biomechanics. If confirmed longitudinally, T-PTI and contact-timing measures could also serve as candidate mechanistic outcomes for gait and exercise interventions that target load transfer, stance-time organization and overall walking function.

Strengths of this study include the relatively large community-based T2DM sample, continuous FI30 modelling, joint analysis of pressure-time exposure and plantar contact timing, explicit handling of

regional PTI zeros and missing values, HC3 robust inference, multiplicity adjustment, and formal interaction testing rather than comparison of subgroup P values. The study-specific FI was also subjected to a construct audit, and negative exploratory findings were retained to improve analytical transparency.

Several limitations should be considered. The cross-sectional design precludes inference about temporal sequence or causality. Participants were required to complete natural walking plantar-pressure testing, limiting generalizability to people with severe mobility impairment or severe active foot disease. The operational foot-risk classification was based on community screening variables and lacked objective vascular testing with ABI, TBI or arterial Doppler assessment. Walking speed, step length, cadence, lower-limb strength and ankle kinematics were not measured, limiting mechanistic interpretation of pressure-time and contact-timing differences. Bilateral averaging may also obscure clinically relevant asymmetry. Finally, several outcomes and foot-risk stratified analyses were exploratory and should be confirmed in independent and prospective samples.

## Conclusions

In community-dwelling older adults with type 2 diabetes, greater deficit accumulation was associated with higher total regional pressure-time integral, longer relative heel and midfoot contact, and a shorter forefoot push-off phase. These findings indicate that frailty-related functional differences may be expressed through both plantar pressure-time exposure and the temporal organization of load transfer within stance.

Associations were directionally consistent across diabetic foot-risk strata, with relatively larger point estimates in higher-risk groups, while formal interaction tests did not show clear effect heterogeneity. Frailty-related systemic vulnerability and diabetic foot-risk-related local vulnerability may therefore provide complementary information, and dynamic plantar pressure and contact timing may characterize their biomechanical expression during walking.

These findings provide a basis for prospective research frameworks integrating frailty, gait and plantar biomechanics, and for evaluating T-PTI and contact-timing measures as candidate outcomes in gait and exercise interventions.

## Abbreviations

ADL  
activities of daily living  
BH  
Benjamini-Hochberg  
BMI  
body mass index  
CI

confidence interval  
FI  
frailty index  
FI30  
modified 30-deficit frailty index  
FI33  
33-deficit frailty index  
FFP  
foot-flat phase  
FFPOP  
forefoot push-off phase  
IWGDF  
International Working Group on the Diabetic Foot  
LOPS  
loss of protective sensation  
M1-M5  
first to fifth metatarsal regions  
OR  
odds ratio  
PAD  
peripheral arterial disease  
PTI  
pressure-time integral  
QC  
quality control  
T2DM  
type 2 diabetes mellitus  
T-PTI  
total regional pressure-time integral.

## **Declarations**

## **Ethics approval and consent to participate**

The study protocol was approved by the Ethics Committee of Huadong Hospital Affiliated to Fudan University (protocol no. 2025K333; approval no. 20250132) and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent before participation.

## **Consent for publication**

Not applicable. The manuscript contains no identifiable individual participant information.

## Competing interests

The authors declare that they have no competing interests.

## Additional file

Additional file 1 (.docx): Supplementary Tables S1-S7 and Figures S1-S6. This file provides frailty-index construction and construct-audit diagnostics, PTI outcome definitions, sensitivity analyses, IWGDF-based stratified and interaction analyses, regional PTI completeness, exploratory outcomes, model diagnostics and supplementary figures.

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## Author Contribution

JB and ZB conceptualized the study. SZ and JB developed the methodology. YZ, AD, SZ, YW, FZ, WQ, and YM conducted the investigation and data collection. SZ curated the data, performed the formal analyses, and drafted the original manuscript. JB and ZB supervised the work and critically reviewed and edited the manuscript. All authors read and approved the final manuscript and agree to be accountable for the work.

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## Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available because of participant confidentiality but are available from the corresponding author on reasonable request.

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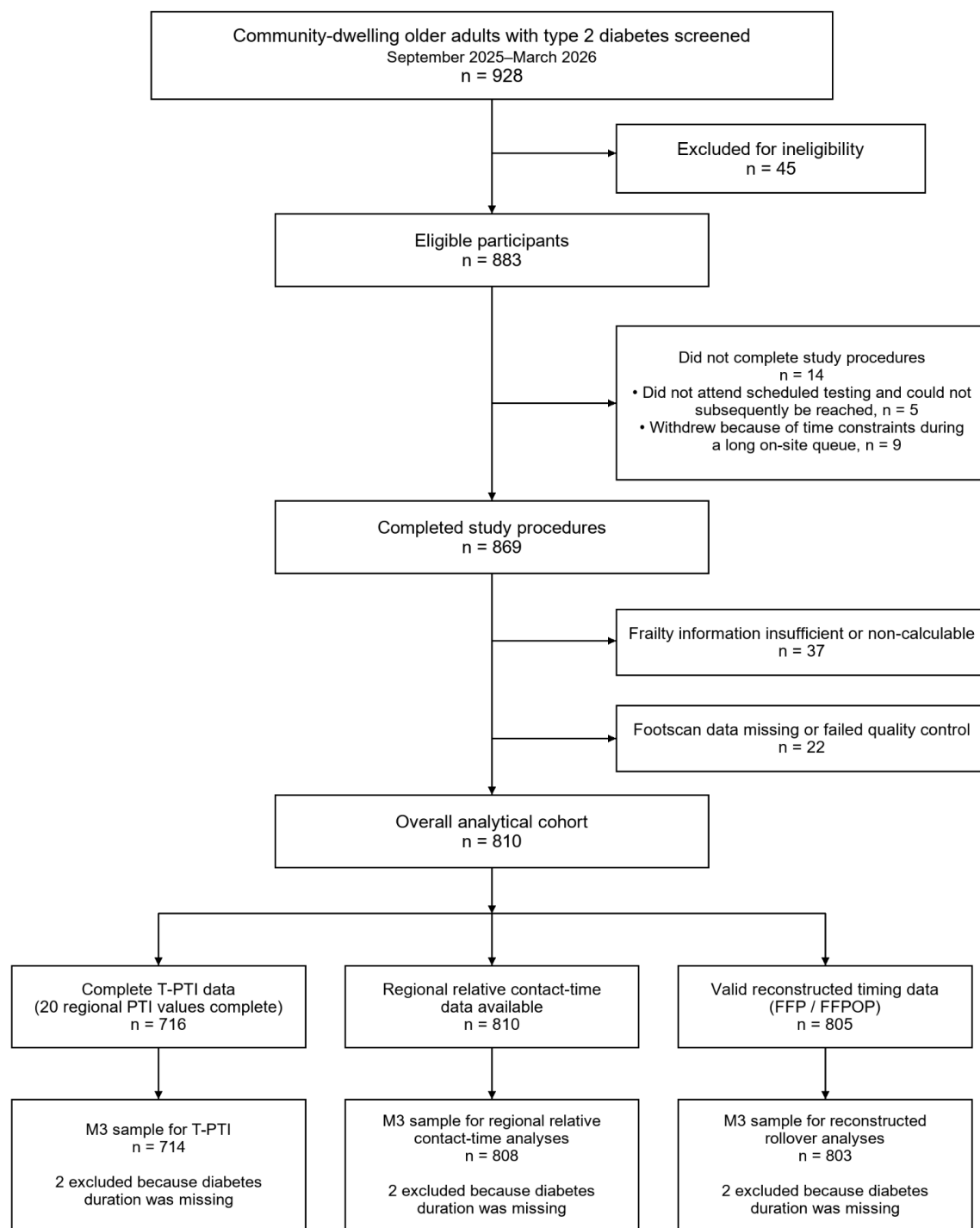
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## Figures



Outcome-specific branches overlap. T-PTI = total regional pressure-time integral; FFP = foot-flat phase; FFPOP = forefoot push-off phase; M3 = fully adjusted model.

**Figure 1**

Participant flow and analysis samples

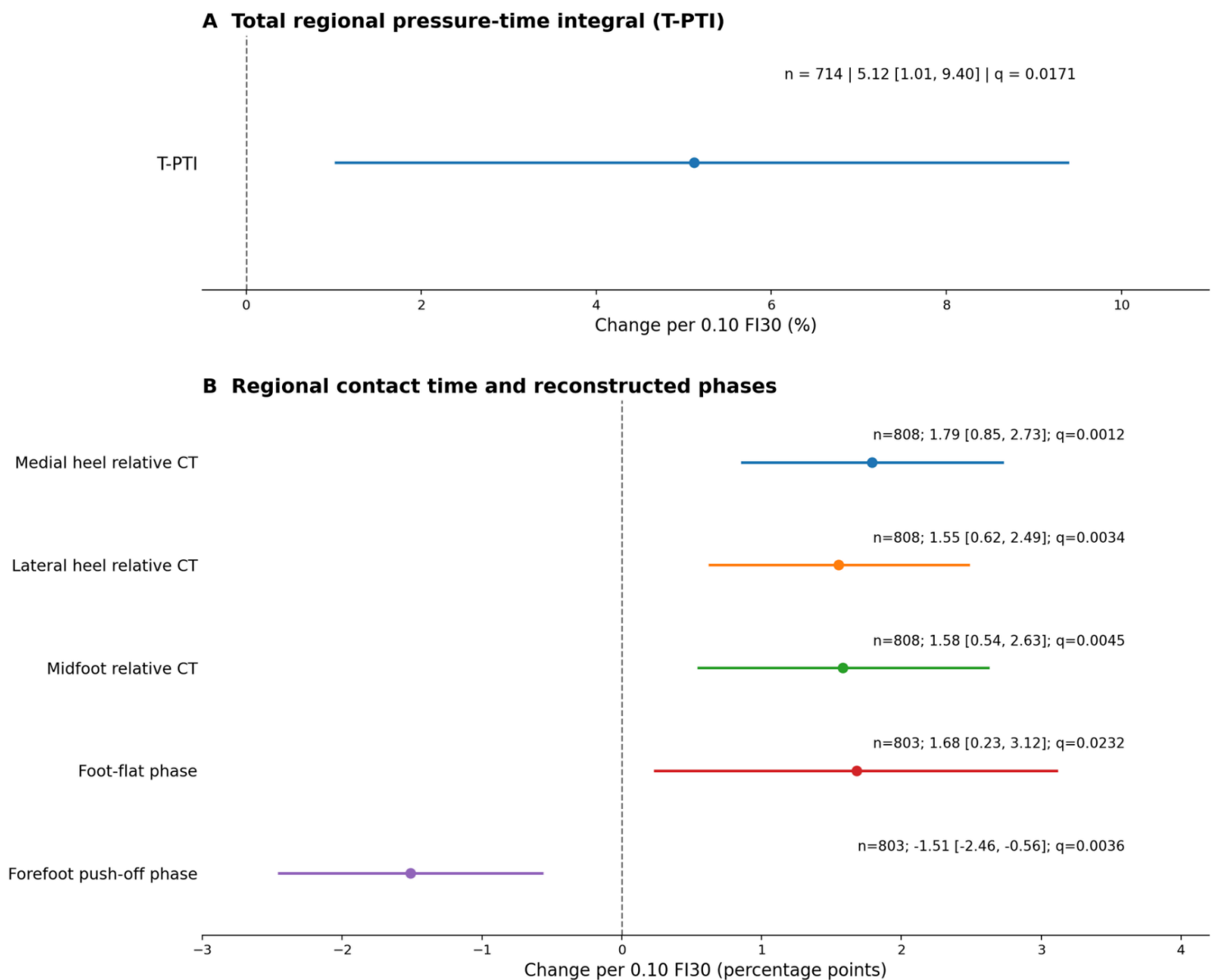


**Figure 2**

Associations between FI30 and focused biomechanical outcomes

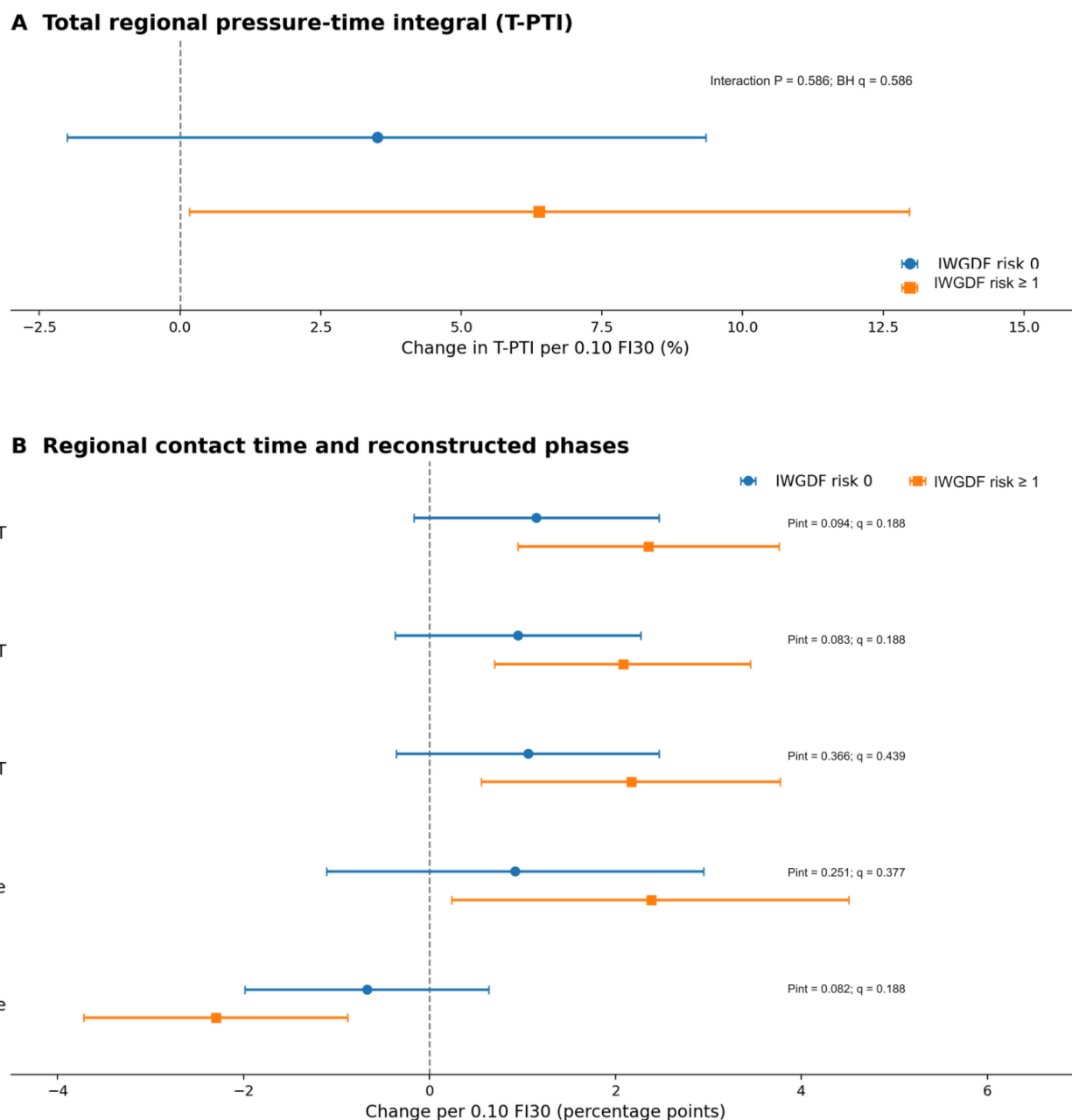


**Figure 3**

Exploratory FI30 associations by IWGDF-based at-risk foot status

## Supplementary Files

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- [STROBEChecklist.docx](#)