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Original article

Handgrip strength cut-off points for identifying French adults at risk of type 2 diabetes

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ABSTRACT

Aim: To identify cut-off points for handgrip strength (HGS) detecting T2D risk among adults in France, and to examine the relationships between absolute and relative HGS and the incidence of T2D.
Methods: Data from 18,519 adults (5096 men) in the NutriNet-Santé cohort, were analyzed. HGS was measured using dynamometry on both hands. Nine indicators were derived, including absolute values and those relative to body weight and BMI. Receiver Operating Characteristic curves and cubic splines were used to assess predictive performance, as well as cut-off points for HGS that maximize this performance. Cox proportional hazards models were used to evaluate associations between reduced HGS and T2D.
Results: Over 9.8 years, 329 incident T2D cases were validated. Absolute HGS showed not associated with T2D risk, whereas higher relative HGS was associated with lower risk (e.g. HR for HGS relative to body weight: 1.30, 95 % CI: 1.07–1.58). Relative HGS showed better discrimination (AUC 0.623–0.675) than absolute HGS ($\leq$ 0.44). Optimal cut-offs were 0.446 kg/kg and 1.086 kg/kg/m^2 (dominant hand), and 0.397 kg/kg and 1.033 kg/kg/m^2 (non-dominant). Low relative HGS was associated with increased risk (HRs 1.42–1.68), consistent across sensitivity, sex, and age analyses.
Conclusions: Relative, but not absolute, handgrip strength is independently associated with T2D incidence and shows modest discriminative ability. Given its simplicity and cost-effectiveness, grip strength may be a useful screening tool in clinical and public health settings.

Introduction

The increasing prevalence of diabetes among adults in both developed and low-income countries has become a major concern for health epidemiologists [1]. T2D results from a complex interplay of lifestyle, environmental, and genetic factors [2]. Its high prevalence is alarming due to increased healthcare use and serious health consequences, including micro- and macrovascular complications (neuropathy, nephropathy, retinopathy, cardiovascular disease), which impair quality of life and lead to greater morbidity and mortality [2–6]. The chronic complications of T2D also create a major economic burden, such as lost productivity and healthcare costs, which in France exceeded €8.5 billion in 2013 [7]. Effective prevention and early screening strategies are therefore essential.

A large body of research has demonstrated an association between low muscle strength, as assessed by handgrip strength (HGS), and an increased risk of developing T2D [8–12]. Increasing muscle strength may reduce the risk of insulin resistance, one of the key factors in the development of T2D [13]. In addition, low HGS has been associated with an increased risk of cardiovascular disease and all-cause mortality [14, 15]. The handgrip test is a simple, acceptable, cost-effective, feasible and scalable measure of muscle strength for clinical and population screening and surveillance. It has moderate to high criterion validity and high to very high reliability [16,17]. The handgrip test is considered as a

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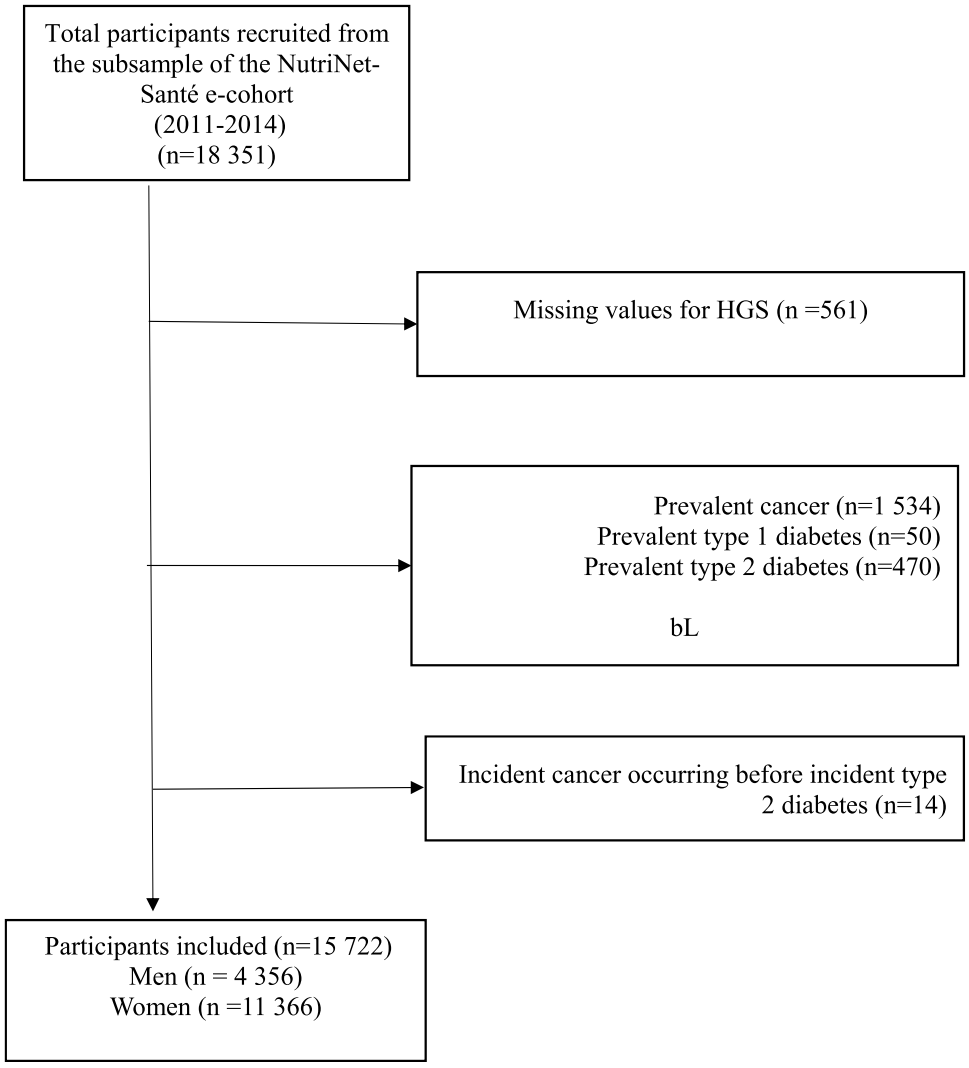


Fig. 1. Participants flowchart of the study.

safe procedure for adult populations, including those with chronic conditions [18]. The handgrip test, using specific thresholds, can serve as a rapid and practical approach for healthcare professionals in the early screening of adults at risk of developing T2D.

In a representative sample of 4066 US adults and older Mexicans [19, 20], the authors identified optimal age- and sex-specific low-strength thresholds for detecting T2D risk. A subsequent study was conducted in a similar cohort of US adults [10]. Importantly, there is significant interregional and ethnic variations in mean HGS values, as shown by data from the multinational Prospective Urban Rural Epidemiology (PURE) study of 125,462 adults from 21 countries [21]. Such findings highlight the need for sex- and age-specific HGS cut-off points to be established for each country [22]. Currently, there are no criterion-referenced norms for HGS predicting T2D in French adults.

The objective of this study was to establish sex-specific HGS cut-off points for identifying of T2D risk in French adults. The secondary objective was to investigate the relationship between absolute and relative HGS and the incidence of T2D.

Methods

Study population: the NutriNet-Santé cohort

This report is based on data collected from a sub-sample of the NutriNet-Santé e-cohort. The NutriNet-Santé study is an ongoing web-based cohort initiated in France in May 2009. The aim of this web-based cohort is to investigate the relationships between nutrition and health and the factors influencing nutrition-related behaviors. Details about the study have been published elsewhere [23]. Volunteers aged ≥15 years complete online questionnaires at baseline and during follow-up. The study complies with the Declaration of Helsinki, and all procedures were approved by the Institutional Review Board of the French Institute of Health and Medical Research (IRB INSERM) and the National Commission on Informatics and Liberty (CNIL). All participants provided informed consent electronically. The study is registered on ClinicalTrials.gov (NCT03335644).

Between 2011 and 2014, a sub-sample of the NutriNet-Santé participants aged ≥18 years participated in an IRB-approved ancillary protocol including clinical and biological assessments (fasting blood glucose, lipids, blood sample, one clinical visit per volunteer). Eighty-two centers across mainland France were involved, and all non-pregnant were invited.

A total of 19,606 volunteers from this subsample agreed to participate. Fifty and 470 were excluded for prevalent type 1 and T2D respectively, and 14 for incident T2D with zero days of follow-up (Fig. 1).

Measurements

Handgrip strength

The Jamar® hydraulic handgrip dynamometer (Sammons Preston Rolyan, Bolingbrook, IL, USA) was used with an adjustable grip. The device is equipped with five different grip positions, each designed to accommodate hand size in five half-inch increments. The dual scale display shows isometric grip force in pounds and kilograms up to 200 pounds or 90 kg, with a peak hold needle that automatically holds the highest reading until reset. The Jamar® hydraulic handgrip dynamometer is considered to be an accurate instrument for measuring HGS, with excellent intra- and inter- reliability [24]. To ensure the accuracy and consistency of the measurements, the device was regularly calibrated in accordance with manufacturer recommendations. Measurements were performed according to the guidelines established by the American Society of Hand Therapists [25]. Participants were seated with their shoulders adducted, elbows flexed at 90 degrees, and forearms in a neutral position. At this point, the investigator lightly supported the base of the dynamometer with one hand, initiating a reset of the peak hold needle to zero. Participants were instructed to apply a gradual and continuous squeeze for a period of two to three seconds, to the extent that they could generate the maximum possible force. The test was performed three times with the right hand, with a one-minute interval between each measurement, and three times with the left hand using the same method. The maximum value, expressed in kilograms, was recorded for each hand. The highest value of all measures was retained as the overall maximal handgrip strength. HGS was also analysed in two relative units: firstly, as the ratio of HGS to body weight (kilograms of HGS divided by kilograms of body weight), and secondly, as the ratio of HGS to body mass index (BMI) (kilograms of HGS divided by BMI).

Ascertainment of incident type 2 diabetes

T2D was ascertained by administering of comprehensive web-based questionnaires. Participants were required to report any significant health events via the annual health questionnaire, the specific health check-up questionnaire, to be completed every six months, or at any other convenient time via a dedicated interface on the study website. In addition, participants were asked to disclose all current medications and treatments via the check-up and annual questionnaires. The data were linked to the French medical-administrative databases, which provide detailed information on the reimbursement of medications and medical consultations. The coverage period ended on March 31th 2024. Details on the identification and validation of the T2D can be found in Appendix S1 (see supplementary materials associated with this article on line).

Covariates

Participants in the NutriNet-Santé study regularly complete web-based questionnaires. At enrolment and then every year or six months, participants are asked to provide information on their sociodemographic and lifestyle characteristics (sex, age, level of educational, smoking status, alcohol consumption, marital status, occupation), health status (personal and family history of disease, medication treatment), dietary intake (using three non-consecutive web-based 24-hour dietary records randomly assigned over a two-week period, including two weekdays and one weekend day), daily physical activity (PA) levels (International Physical Activity Questionnaire – IPAQ short form) and sitting time (hours per week).

In this analysis, the last completed questionnaires of the participants prior to the clinical examination were used, except for dietary intakes. Food consumption and nutrient intakes were calculated as daily averages, based on a minimum of three validated 24-hour dietary records from the two years prior to the clinical examination [26]. Food consumption was recorded in great detail [27]. As described previously, all foods were classified according to the NOVA classification to identify ultra-processed foods (UPF) [28]. Dietary quality was also assessed using the sPNNS-GS2 (Programme National Nutrition Santé Guidelines Score 2), which measures an individual's adherence to the French dietary guidelines including PA [29].

During the clinical examination, anthropometric measurements were performed. Body weight was measured using an electronic scale (Tanita Corp, Tokyo, Japan) with the participants wearing light clothing and no shoes. Height was measured without shoes using a standard medical scale. BMI was calculated as weight/height^2. The World Health Organization (WHO) recommendations were used as the basis for the BMI cut-off points: normal corpulence < 25 kg/m^2, overweight between $\geq$25.0 kg/m^2 and < 30 kg/m^2, and obesity ≥ 30.0 kg/m^2. Waist circumference was measured using a tape measure, with the subject standing and the tape placed horizontally around the waist, mid-way between the last rib and the iliac crest.

Statistical analysis

Nine different HGS indices were obtained, three for each hand: absolute value (in kg), value relative to body weight (expressed in kg/kg), and value relative to BMI (expressed in kg/kg/m^2). The maximum absolute value was also obtained from both hands, from which the maximum value relative to body weight and the maximum value relative to BMI were derived. The present study included participants from the NutriNet-Santé cohort who underwent clinical and biological assessments and who did not have a prevalent diabetes event at the time of assessment. Missing data were handled using multiple imputation by chained equations (MICE) and fully conditional specification to minimize potential bias due to incomplete observations. The imputation model included all covariates, the outcome variable and predictors of missingness, assuming a missing at random mechanism. A total of 10 imputed datasets were created using the mi impute chained command in Stata. Estimates from the imputed datasets were pooled using Rubin's rules to obtain valid statistical inferences.

Descriptive statistics were used to facilitate comparison of the general characteristics of the study population in order to identify any significant differences between men and women. For qualitative variables, results were presented as percentages (%). For quantitative variables, results were presented as means with standard errors of the mean. The normality of the distribution was checked using the Kolmogorov-Smirnov test. Categorical variables were subjected to chi-square tests, while continuous variables were analyzed using the independent Student *t*-test.

Restricted cubic splines with six knots, generated automatically by Stata using the mkspline command, were used to examine the nonlinear associations between the nine measures of handgrip strength and the incidence of T2D. The nine HGS measures were standardized to facilitate comparisons. The reference value was set at 0, to allow interpretation relative to the mean standardized grip strength. The shape of the association was then visualized using the estimated spline coefficients, and non-linearity was assessed using a likelihood ratio test comparing the spline model with a linear model.

Time-to-event analyses were performed on the age scale, using age as the underlying time metric. The predictive performance of the nine grip strength measures was then assessed using the time-dependent area under the receiver operating characteristic (ROC) curve at age 60 years. This was calculated using the stroccurve command in Stata (version 14.2, StataCorp, College Station, TX, USA). ROC analyses for time-dependent outcomes were performed on the nine upper arm strength parameters [30]. The resulting ROC curves and data provide several parameters that facilitate the identification of appropriate thresholds. These include area under the ROC curve (AUC), sensitivity and specificity. The determination of cut-off values for grip strength was achieved by employing the Liu's index. The Liu cut-off points were then utilized for the purpose of dichotomizing the nine HGS variables.

Cox proportional hazards models were used to determine the potential associations between each dichotomized HGS variable and

Table I
Characteristics of enrolled participants included by sex, imputed sample (n = 18,519).

	Men	Women	*P* value
n (%)	5096	13,423	
Age (*years*)	56.9 ± 0.19	52.0 ± 0.11	< 0.001
Height (*cm*)	175 ± 0.09	163 ± 0.05	< 0.001
Weight (*kg*)	77.3 ± 0.17	63.4 ± 0.11	< 0.001
BMI (kg/m^2)	25.3 ± 0.05	24.0 ± 0.04	< 0.001
Waist circumference (*cm*)	90.3 ± 0.15	79.9 ± 0.10	< 0.001
BMI categories (%)			< 0.001
Normal	52.7	68.6	
Overweight	38.1	21.9	
Obese	9.2	9.5	
Educational level (%)			< 0.001
< high school	25.3	18.6	
≤ high school + 3	35.8	48.0	
> high school + 3	38.9	33.4	
Professional activity (%)			< 0.001
Employee, farmer, merchant, artisan, manual	8.6	15.6	
Intermediate profession	23.0	20.7	
Managerial staff	8.9	16.1	
Retired	53.0	34.6	
Unemployed	6.5	13.0	
Smoking status (%)			< 0.001
Actual	5.7	6.9	
Former	56.6	44.6	
Never	37.5	48.4	
Number of packs/years	9.77 ± 0.24	4.65 ± 0.08	< 0.001
Family history diabetes (%)	17.8	21.9	< 0.001
Total energy intake without alcohol (*Kcal/day*)	2214 ± 7.27	1775 ± 3.42	< 0.001
Alcohol consumption (*g/l*)	15.2 ± 0.21	6.76 ± 0.08	< 0.001
sPNNS_GS2	0.34 ± 0.05	2.58 ± 0.03	< 0.001
UPF consumption (%)	15.9 ± 0.001	15.2 ± 0.001	< 0.001
Fasting blood sugar, (g/l)	0.92 ± 0.002	0.88 ± 0.001	
Physical activity level (%)			< 0.001
Low	17.3	20.2	
Moderate	35.8	44.2	
High	46.8	35.6	
Low sedentary behavior (%)	41.1	52.7	< 0.001
Handgrip strength			
Absolute value dominant (*kg*)	44.6 ± 0.12	27.8.2 ± 0.05	< 0.001
Absolute value non-dominant (*kg*)	42.8 ± 0.11	26.3 ± 0.05	< 0.001
Absolute maximal value (kg)	45.6 ± 0.11	28.4 ± 0.05	< 0.001
Relative (to body weight) dominant (*kg/kg*)	0.57 ± 0.002	0.45 ± 0.001	< 0.001
Relative (to body weight) non-dominant (*kg/kg*)	0.56 ± 0.002	0.43 ± 0.001	< 0.001
Relative (to body weight) absolute maximal value (kg/kg)	0.60 ± 0.002	0.46 ± 0.001	< 0.001
Relative (to BMI) dominant ($kg/kg/m^2$)	1.80 ± 0.006	1.19 ± 0.003	< 0.001
Relative (to BMI) non-dominant ($kg/kg/m^2$)	1.72 ± 0.005	1.13 ± 0.003	< 0.001
Relative (to BMI) absolute maximal value ($kg/kg/m^2$)	1.84 ± 0.006	1.22 ± 0.003	< 0.001

Abbreviations: IPAQ, International Physical Activity Questionnaire; sPNNS-GS2, simplified Program National Nutrition Santé - Guidelines Score 2; BMI, body mass index; UPF: ultra-processed food Data are mean ± standard error of the mean or percentages.
Number of observations imputed for the following variables: absolute value of handgrip strength, dominant hand (n = 129) absolute value of handgrip strength, nondominant hand (n = 637), handgrip strength relative to weight, dominant hand (n = 129), handgrip strength relative to weight, nondominant hand (n = 637), handgrip strength relative to BMI, dominant hand (n = 129) handgrip strength relative to BMI, nondominant hand (n = 637), absolute maximal value of handgrip strength (n = 81), absolute maximal value of handgrip strength relative to weight (n = 81), absolute maximal value of handgrip strength relative to BMI (n = 81), number of packs/years (n = 121), sedentary time in hours (n = 588), number of 24 h dietary records (n = 3426), energy intake without alcohol (n = 3426), sPNNS_GS2 (4023) percentage of ultra-processed food intake (n = 3426), alcohol consumption in g/l (n = 3426), IPAQ (n = 453), marital status (n = 238), tobacco smoking (n = 121) professional activity (n = 305).

incident T2D. The results of the Cox analysis are presented as hazard ratios (HRs) with 95 % confidence intervals (CIs) and associated p-values. The assumption of proportional hazards was tested using the Schoenfeld residual method. Participants contributed person-time to the models until the date of T2D diagnosis, date of death, date of last login, or 31 March 2024, whichever occurred first. Seven nested models were constructed, adjusting for baseline covariates. Model 1 was adjusted for age and sex (male, female). Model 2 was further adjusted for BMI as a continuous variable. Model 3 was adjusted for age, sex, BMI, employment status (employees; farmer, merchant, artisan, company, director, manual; intermediate profession; managerial staff; unemployed), educational level (less than high school, ≤ 3 years after high school, ≥ 3 years after high school), monthly household income per consumption unit (continuous), smoking status (current, former, never), number of cigarettes smoked in pack-years (continuous), physical activity (categorical IPAQ variable: high, moderate, low), family history of diabetes, sedentary behaviors (low: < 7 hour/day of sitting time: high: ≥ 7 hour/day of sitting time) and alcohol consumption (in g/day). Model 4 was adjusted as model 3, but BMI was replaced by waist circumference (continuous) to examine whether the observed associations were independent of abdominal obesity. Model 5 was adjusted as model 3, plus the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous). Model 6 was adjusted as model 4, plus the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous). Model 7 was adjusted as model 5, plus baseline fasting blood glucose.

For sensitivity analyses, all models were replicated after excluding incident cases of T2D that occurred during the first year after the clinical and biological measurements.

All statistical tests were two-tailed, and P-values < 0.05 were considered statistically significant. All statistical analyses were performed in Stata®.

Results

The baseline characteristics of the study population are presented in Table I. Men were significantly older, taller, and heavier than women, with higher BMI and waist circumference (all P < 0.001). The prevalence of obesity was higher in women, while the prevalence of overweight was increased in men. Men had greater alcohol and total energy intake, lower diet quality, and higher smoking exposure. As expected, men exhibited markedly higher HGS in all dimensions. Mean absolute HGS in the dominant hand was recorded as 44.6 ± 0.12 kg in men and 27.8 ± 0.05 kg in women (P < 0.001), and the absolute maximal value was 45.6 ± 0.11 kg vs 28.4 ± 0.05 kg. Strength values relative to body weight and BMI were found to be significantly greater in men, both for dominant and non-dominant hands (0.57 ± 0.002 kg/kg vs 0.45 ±

Table II
Associations between standardized HGS and incident T2D in the NutriNet-Santé cohort ($n = 18\,519$).

	Absolute value		Relative to body weight		Relative to BMI	
	HR (95 % CI)	*P*	HR (95 % CI)	*P*	HR (95 % CI)	*P*
Dominant hand						
Model 1	1.03 (0.87 – 1.22)	0.74	2.73 (2.39 – 3.12)	0.001	3.02 (2.58 – 3.53)	0.001
Model 2	1.09 (0.92 – 1.29)	0.31	1.42 (1.20 – 1.69)	0.001	1.45 (1.20 – 1.75)	0.001
Model 3	1.08 (0.90 – 1.29)	0.41	1.37 (1.15 – 1.64)	0.001	1.43 (1.16 – 1.76)	0.001
Model 4	1.00 (0.83 – 1.20)	0.99	1.25 (1.04 – 1.50)	0.017	1.27 (1.02 – 1.57)	0.029
Model 5	1.08 (0.90 – 1.30)	0.40	1.37 (1.15 – 1.64)	0.001	1.43 (1.16 – 1.76)	0.001
Model 6	1.00 (0.84 – 1.20)	0.99	1.25 (1.04 – 1.50)	0.017	1.27 (1.02 – 1.57)	0.03
Model 7	1.03 (0.85 – 1.24)	0.78	1.29 (1.07 – 1.56)	0.009	1.34 (1.08 – 1.67)	0.009
Non dominant hand						
Model 1	1.01 (0.85 – 1.20)	0.88	2.68 (2.34 – 3.08)	0.001	2.95 (2.52 – 3.47)	0.001
Model 2	1.07 (0.91 – 1.27)	0.42	1.39 (1.17 – 1.65)	0.0001	1.42 (1.17 – 1.72)	0.001
Model 3	1.07 (0.89 – 1.28)	0.48	1.33 (1.11 – 1.59)	0.002	1.39 (1.13 – 1.70)	0.002
Model 4	0.99 (0.83 – 1.29)	0.92	1.23 (1.02 – 1.47)	0.028	1.24 (1.01 – 1.54)	0.04
Model 5	1.07 (0.89 – 1.28)	0.89	1.33 (1.11 – 1.59)	0.002	1.39 (1.13 – 1.71)	0.002
Model 6	1.00 (0.83 – 1.19)	0.96	1.23 (1.02 – 1.47)	0.027	1.25 (1.01 – 1.54)	0.04
Model 7	1.04 (0.86 – 1.26)	0.71	1.27 (1.05 – 1.54)	0.01	1.33 (1.06 – 1.66)	0.01
Maximum value						
Model 1	1.01 (0.85 – 1.20)	0.89	2.87 (2.50 – 3.29)	0.001	3.19 (2.71 – 3.74)	0.0001
Model 2	1.09 (0.91 – 1.29)	0.35	1.45 (1.21 – 1.73)	0.001	1.46 (1.20 – 1.78)	0.0001
Model 3	1.08 (0.89 – 1.30)	0.43	1.38 (1.15 – 1.66)	0.001	1.44 (1.17 – 1.79)	0.001
Model 4	0.99 (0.82 – 1.19)	0.89	1.25 (1.03 – 1.50)	0.02	1.26 (1.01 – 1.57)	0.038
Model 5	1.08 (0.90 – 1.30)	0.41	1.38 (1.15 – 1.66)	0.001	1.45 (1.17 – 1.79)	0.001
Model 6	0.99 (0.82 – 1.19)	0.92	1.25 (1.03 – 1.50)	0.02	1.26 (1.01 – 1.57)	0.038
Model 7	1.03 (0.84 – 1.25)	0.79	1.30 (1.07 – 1.58)	0.008	1.35 (1.08 – 1.70)	0.009

Results are for a decrease in 1SD of each handgrip strength variable.
Model 1: adjusted for age and sex.
Model 2: Model 1 + BMI (in kg/m^2).
Model 3: Model 2 + employment status (employees; farmer, merchant, artisan, company, director, manual; intermediate profession; managerial staff; unemployed), educational level (less than high school degree, ≤ 3 years after high school degree, ≥ 3 years after high school degree), monthly household income per consumption unit (continuous), smoking status (actual, former, never), number of smoked cigarettes in pack-years (continuous), physical activity (categorical IPAQ variable: high, moderate, low), family history of diabetes (yes, no), sedentary behaviors (low, high), height (m) and alcohol consumption (in g/day).
Model 4: Model 1 + waist circumference (cm), employment status, educational level (less than high school degree, < 2 y after high school degree, ≥ 2 y after high school degree), monthly household income per consumption unit (continuous), smoking status (never smoked, former smoker, occasional smoker, regular smoker), number of smoked cigarettes in pack-years (continuous), physical activity (categorical IPAQ variable: high, moderate, low), family history of diabetes (yes, no), sedentary behaviors (low, high), height (m) and alcohol consumption (in g/day).
Model 5: Model 3 + the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous).
Model 6: Model 4 + the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous).
Model 7: Model 5 + baseline Fasting blood glucose.

0.001 in women; 1.84 ± 0.006 kg/kg/m^2 vs 1.22 ± 0.003; $P < 0.001$).

During a median follow-up period of 9.8 years, 329 cases of incident T2D were documented among 18,519 participants. No statistically significant interactions were observed by sex or age, indicating that the associations between HGS related indices and T2D risk were consistent across demographic subgroups. Consequently, the further analyses were not stratified according to sex.

The results of the associations between standardized HGS and T2D incidence are presented in Table II. Across all models, absolute HGS was not significantly associated with T2D risk. In contrast, relative HGS (relative to weight or BMI) were consistently and significantly associated with reduced T2D risk. In the fully adjusted model, lower relative HGS to body weight was associated with higher risk of T2D in the dominant (HR = 1.29, 95 % CI: 1.10–1.56), non-dominant hand (HR = 1.27, 95 % CI: 1.05–1.54), and for maximal value (HR = 1.30, 95 % CI: 1.07–1.58). Analogous findings were observed for BMI-related indicators.

To assess the shape of these associations (Fig. 2), restricted cubic spline models were fitted for each HGS indicator. The spline plots revealed flat or null relationships for absolute HGS, but a monotonic inverse association for relative measures across all configurations. Tests for non-linearity were non-significant for most HGS-related indicators, except for strength relative to body weight in the dominant hand ($P = 0.02$), and borderline for the non-dominant hand ($P = 0.08$) and maximal value ($P = 0.06$), suggesting a possible threshold effect at lower HGS strength levels.

To assess the discriminative capacity of HGS variables, time-dependent ROC analyses were conducted at age 60 (Table III). The results indicated that relative HGS outperformed absolute strength across all indicators. The AUC for dominant-hand strength relative to body weight was 0.660 (sensitivity: 64.8 %, specificity: 61.5 %), and 0.623 relative to BMI. For the non-dominant hand, the AUCs were 0.675 and 0.634, respectively. The maximum strength value achieved an AUC of 0.673 (relative to body weight) and 0.632 (relative to BMI). In contrast, AUCs for absolute strength never exceeded 0.44. Optimal cut-off values derived using the Liu method were 0.446 kg/kg and 1.086 kg/kg/m^2 for the dominant hand, and 0.397 kg/kg and 1.033 kg/kg/m^2 for the non-dominant hand.

These thresholds were then used to dichotomize HGS and assess the association between low muscle strength and diabetes risk (Table IV). In age- and sex-adjusted models, low strength—relative to both weight and BMI—was strongly associated with T2D, with HRs above 4.5 for most

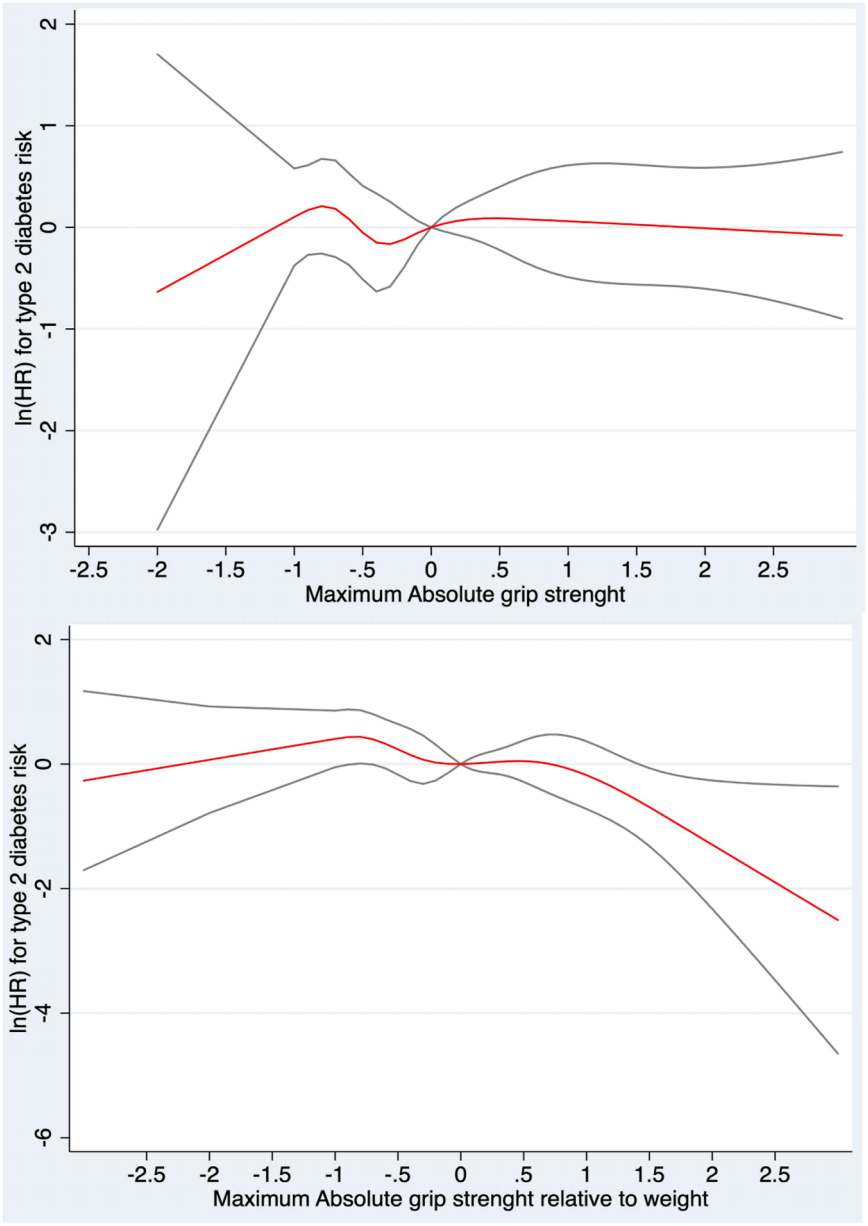


Fig. 2. Restricted cubic spline plots showing the association between grip strength indicators and the risk of incident type 2 diabetes in the NutriNet-Santé cohort (n = 18,519).

The red line represents the log-transformed hazard ratio (ln[HR]) for type 2 diabetes across the range of standardized grip strength values. Grey bands represent the 95 % confidence intervals. Separate plots are shown for absolute and relative grip strength (to weight and to BMI), using the dominant hand, non-dominant hand, and the maximal value.

Tests for linearity: absolute value, dominant hand: $P = 0.73$; relative to weight, dominant hand: 0.02; relative to BMI, dominant hand: $P = 0.11$; absolute value, non-dominant hand: $P = 0.51$; relative to weight, non-dominant hand: 0.08; relative to BMI, non-dominant hand: $P = 0.26$; maximum absolute value, $P = 0.53$; maximum absolute value related to weight, $p = 0.06$; maximum absolute value, relative to BMI, $P = 0.24$.

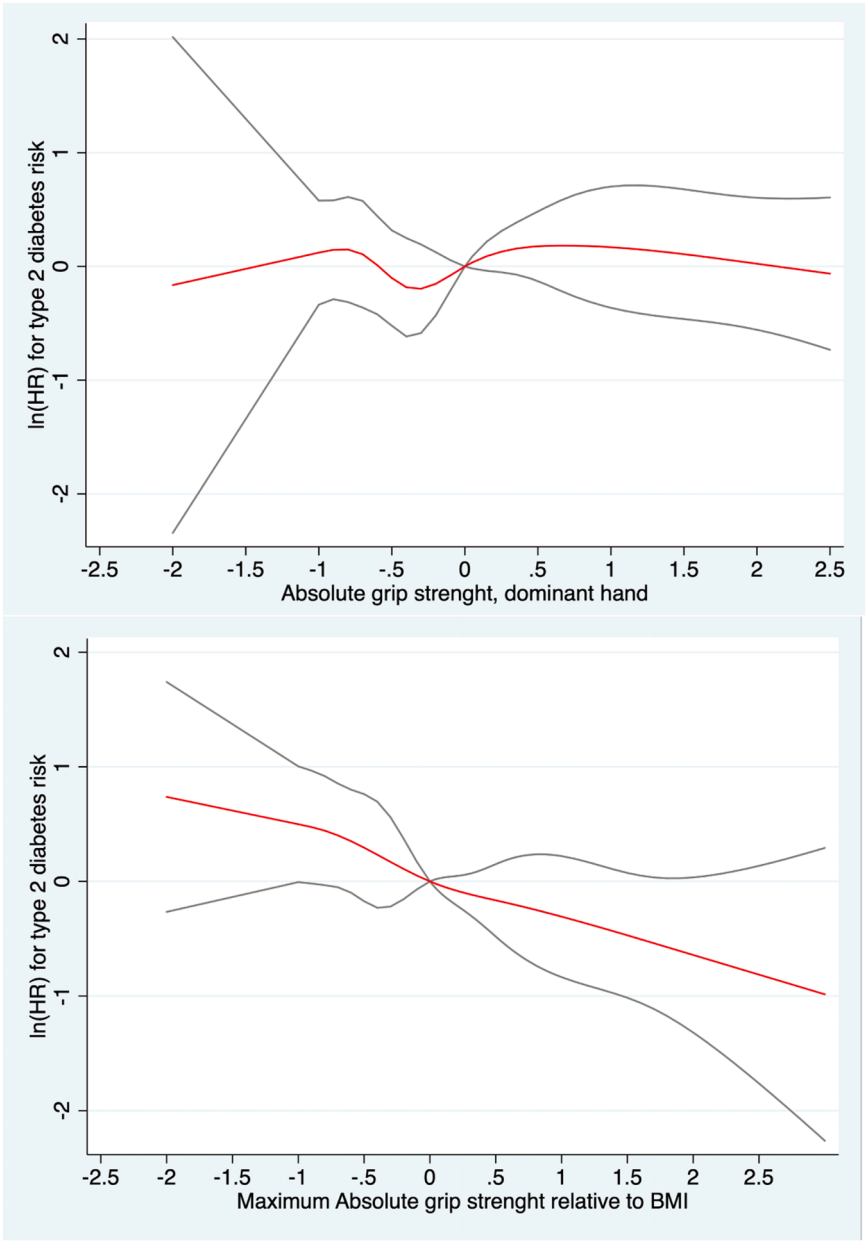
indicators. Following full adjustment, low HGS relative to body weight remained significantly associated with incident T2D across all definitions (HR = 1.62, 95 % CI: 1.20–2.19 for the dominant hand; HR = 1.42, 95 % CI: 1.04–1.92 for the non-dominant hand; HR = 1.68, 95 % CI: 1.24–2.29 for the maximal value). BMI-related low strength also remained significantly associated with risk, albeit with more attenuated associations.

In a subsequent sensitivity analysis, the exclusion of participants diagnosed with T2D within one year of follow-up (incident cases, n = 291), results remained unaltered. Relative HGS remained inversely associated with diabetes risk in fully adjusted models (e.g. maximal value relative to body weight: HR = 1.23, 95 % CI: 1.01–1.49), confirming that findings were not driven by pre-existing but undiagnosed diabetes.

Discussion

Main findings

In a large prospective cohort study in French adults with a 9.8-year follow-up period, a strong association was found for relative, but not absolute, HGS with T2D risk. We are also able to define HGS cut-off



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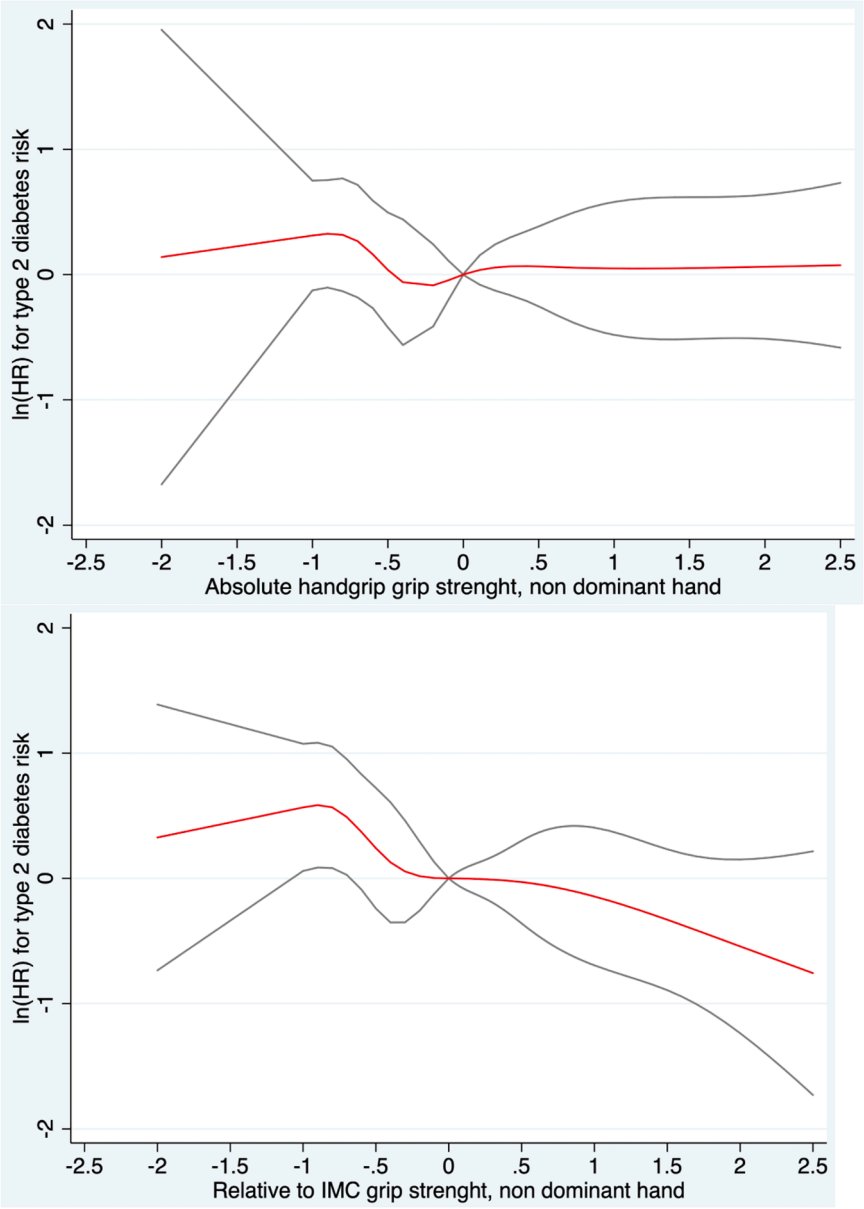
points for identifying T2D risk in this population.

The primary finding is that relative HGS indexed to body weight or BMI, is inversely associated with the risk of developing T2D, independent of established risk factors. In contrast, absolute HGS showed no such association after adjustment for confounders. This supports previous research suggesting that relative muscle strength is a more relevant marker of cardiometabolic health than absolute strength [31–33]. This likely reflects the role of skeletal muscle quality and metabolic efficiency—rather than mass alone—in the development of insulin resistance and T2D [34–36]. Importantly, the association between relative grip strength and T2D risk was not modified by sex or age, suggesting that relative strength could serve as a robust, scalable risk marker across diverse demographic groups.

Clinical thresholds and interpretation

We derived optimal cut-off points for T2D risk using ROC analyses and the Liu method, which simultaneously maximizes sensitivity and specificity. For the dominant hand, optimal thresholds were 0.446 kg/kg and 1.086 kg/kg/m^2; for the non-dominant hand, 0.397 kg/kg and 1.033 kg/kg/m^2. These values provide pragmatic, interpretable thresholds for identifying high-risk individuals using a simple, non-invasive measure. However, since these thresholds were derived and tested within the same dataset, external validation is essential. Future studies should assess the stability of these cut-offs in independent populations and explore their performance across diverse subgroups.

Our findings are consistent with previous studies showing an inverse association between HGS and T2D risk, particularly when HGS is adjusted for body weight or BMI [19,20]. However, the cut-off points identified in our French population are higher than those reported in the US population, underscoring the need for population-specific thresholds [19,20]. Discrepancies in findings may be attributed to methodological issues pertaining to study design (cross-sectional vs prospective). Additionally, differences in demographic characteristics, body composition, and lifestyle factors across populations may explain these variations. This emphasizes the importance of interpreting HGS thresholds



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within the context of the studied population.

Comparison with established risk models and biomarkers

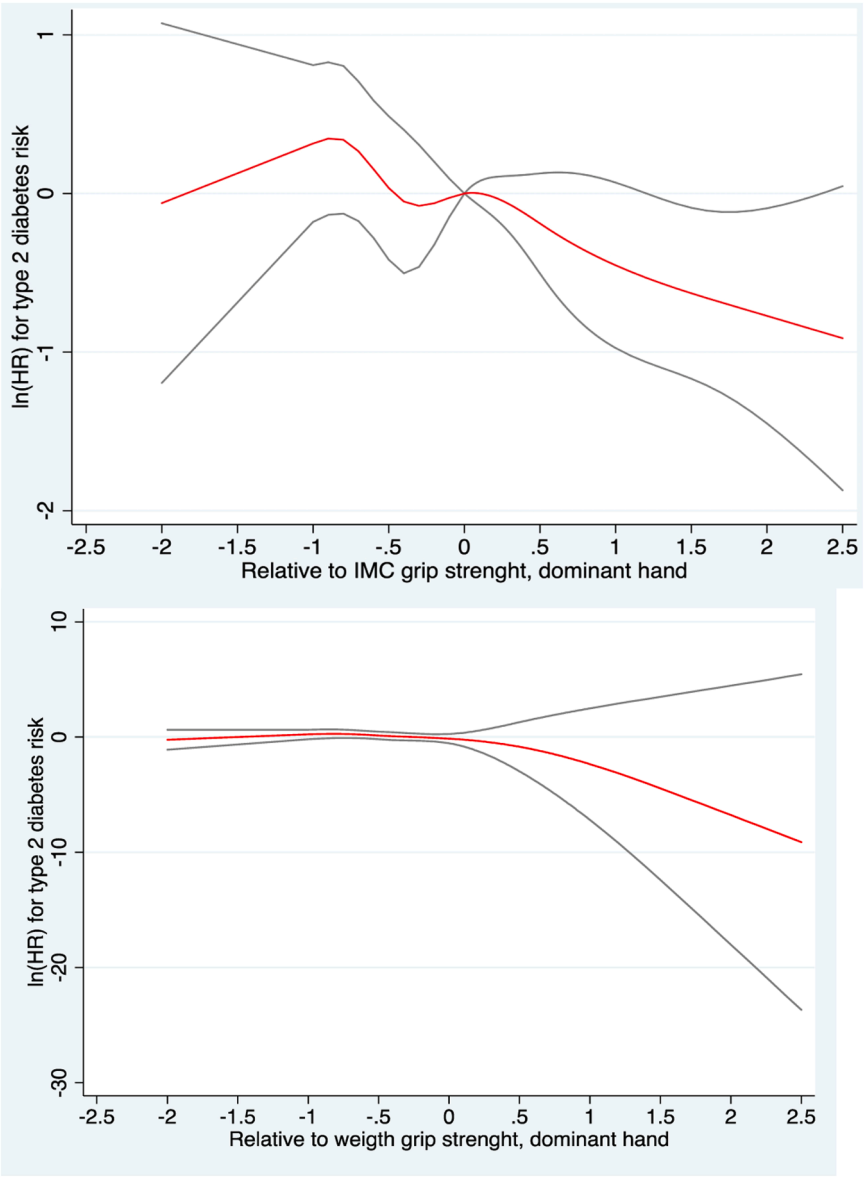
Compared to multifactorial scores such as FINRISK (including demographic data, lifestyle factors, clinical and anthropometric measurements blood sample data) or DESIR (anthropometric and clinical measures, glycemia, lifestyle factors, medical history and medication) whose AUCs typically range from 0.75 to 0.85, HGS indicators perform more modestly [37,38]. Indeed, the AUC values observed for relative handgrip strength (0.623–0.675) indicate only modest discriminative ability for T2D risk. While statistically significant, these values are lower than those reported for established risk scores such as FINRISK, suggesting that HGS alone is not sufficient for high-accuracy screening. Nevertheless, they offer substantial operational advantages: HGS requires only a handheld dynamometer, no fasting, and no laboratory analysis, making it highly deployable in primary care, workplace screening, or public health campaigns.

Relative HGS may also complement biochemical markers like fasting plasma glucose or HbA1c, which reflect short-to-medium term glycemic status. HGS captures a functional-muscular dimension of metabolic health, possibly indicative of early pathophysiological processes such as reduced insulin-stimulated glucose uptake, impaired mitochondrial function, or sarcopenic obesity. Therefore, HGS could serve as an additional marker rather than a standalone tool for T2D risk assessment.

Public health implications

The findings of this study have practical implications for both clinical and public health settings. HGS assessment offers a non-invasive, low-cost, and reliable method for identifying individuals at elevated risk of T2D. Based on the thresholds established in our study, HGS could be used as an early screening tool to guide further evaluation or prompt lifestyle interventions, especially in settings where blood-based metabolic testing is not readily accessible.

In a public health context, integrating HGS measurement into simple screening protocols could help prioritize individuals for follow-up care, making it particularly useful in low-resource environments. Beyond



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clinical use, HGS screening could also support community-based prevention programs, occupational health monitoring, and healthy ageing initiatives.

Furthermore, incorporating HGS values into medical records would allow for longitudinal tracking throughout a patient's life. This would enable healthcare providers to detect early declines in muscular strength that may signal increased metabolic risk, thereby facilitating timely, preventive action.

Strengths and limitations

The current study has several strengths, including its prospective design, the harmonization and standardization of assessment procedures across all centers, and a robust objective methodology for assessing muscular strength. In addition, advanced statistical tools were employed to enhance the interpretation of our findings. For instance, the Liu index was used to determine the optimal cut-off points, as it maximizes both sensitivity and specificity simultaneously. This index is particularly valuable for balancing the trade-off between false positives and false negatives, offering a single threshold value that simplifies clinical decision-making. However, its main limitation is that it assumes equal cost for both types of misclassification, which may not be suitable in all contexts. Moreover, the use of a time-dependent AUC in our analysis represents a significant methodological strength. Unlike the static AUC, which evaluates model performance at a fixed point in time, the time-dependent AUC accounts for the dynamic nature of disease risk over time. This is particularly relevant for predicting chronic conditions like type 2 diabetes, where events may occur at varying intervals and data may be censored. Although this approach provides a more nuanced understanding of predictive performance, it requires careful handling of censored data and can be more complex to interpret than static AUC metrics. Nevertheless, it should be acknowledged that this study is not without limitations. Firstly, it should be noted that participation in the NutriNet-Santé subsample cohort analyzed here and the wider NutriNet-Santé cohort is on a voluntary basis. Consequently, individuals who have chosen to participate in these studies are likely to be healthier than the general population, including a higher proportion of women and individuals with higher levels of education. It is therefore necessary to exercise caution in the generalization of our results, particularly regarding the cut-off points for HGS. Indeed, the thresholds identified in

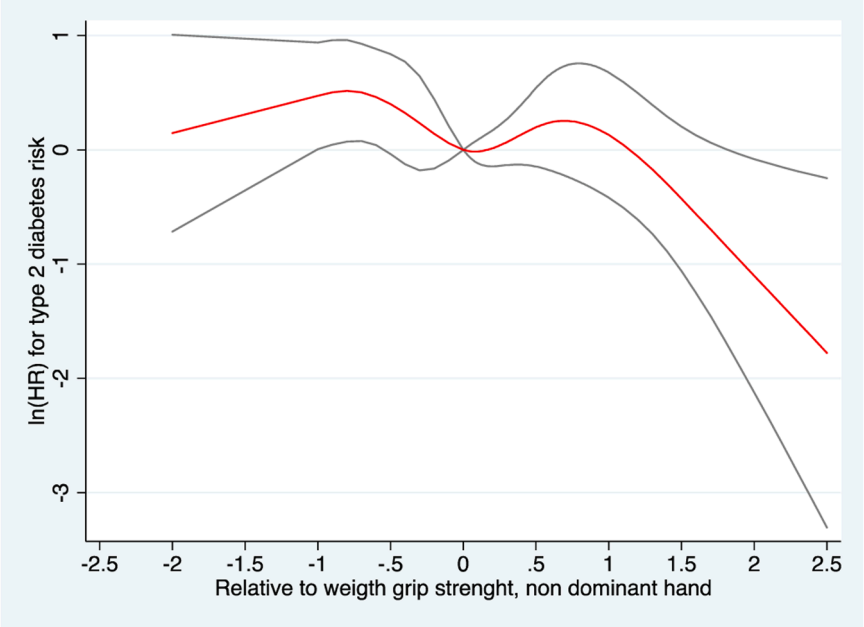

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Table III
ROC-derived cut-off points (Liu index) and diagnostic statistics for handgrip strength for T2D risk prediction in adults, 60 years.

	AUC	cutoff	Sensitivity (%)	Specificity (%)	Low HGS (%)
Dominant hand					
Absolute Handgrip strength	0.425	35	61.4	32.5	-
Relative to weight	0.660	0.446	64.8	61.5	39
Relative to BMI	0.623	1.086	50.1	72.2	27.9
Non-dominant hand					
Absolute Handgrip strength	0.44	31	55.4	40.7	-
Relative to body weight	0.675	0.397	58.8	70.4	27.9
Relative to BMI	0.634	1.033	53.8	71.9	27.4
Maximum value both hands					
Absolute Handgrip strength	0.425	35	61.0	34.1	-
Relative to body weight	0.673	0.447	63.9	64.6	35.6
Relative to BMI	0.632	1.195	58.7	63.8	36.3

our cohort may not directly reflect values in the broader population, as participants are more health-conscious and may have a higher baseline fitness, which could shift reference values upward. Therefore, caution is warranted when applying these cut-offs in different populations or clinical settings. Secondly, the cut-off points established in this study were based on measurements using a single device, the JAMAR® Dynamometer, which is widely regarded as the gold standard for assessing HGS [39,40]. However, the relatively high cost of this device may present a barrier to implementing HGS testing in both clinical and community settings. However, recently, some devices, such as the Camry dynamometer, which are significantly more affordable, have been developed and have demonstrated excellent reliability and validity in comparison to the Jamar dynamometer® [39,40]. Third, the potential inter-operator variability might have influenced our results. However, this bias was minimized through strict standardization of field procedures across the different centers to ensure harmonized data collection. Finally, the observational design of the study precludes the drawing of conclusions regarding the causality of observed relationships.

Future directions

Future research should focus on validating the HGS-based score in larger and more diverse populations, particularly regarding its predictive accuracy compared to established models like FINDRISC and DESIR. In addition, exploring the synergistic potential of combining HGS with other risk factors (e.g., diet, glycemic status, physical activity, family history of diabetes) could enhance the predictive power of T2D risk models.

Conclusion

HGS, relative to body weight or BMI, is independently associated with the incidence of T2D. Although its predictive performance is inferior to that of established clinical risk scores and biomarkers, its simplicity, non-invasiveness, and applicability across age and sex groups make it a promising complementary screening tool. The thresholds derived in this study may help operationalize this tool in both clinical and public health settings. Further validation is required to confirm their utility and to assess whether integrating HGS into broader risk models enhances early detection and prevention of T2D.

Data availability

Researchers from public institutions can submit a request to have access to the data for strict reproducibility analysis (systematically accepted) or for a new collaboration, including information on the institution and a brief description of the project to collaboration@etude-nutrinet-sante.fr. All requests will be reviewed by the steering committee of the NutriNet-Santé study. If the collaboration is accepted, a data access agreement will be necessary and appropriate authorizations from the competent administrative authorities may be needed. In accordance with existing regulations, no personal data will be accessible.

Table IV
Associations between Low handgrip strength (defined using cut-points, Liu method) and incident T2D in the NutriNet-Santé cohort.

Handgrip strength	Relative to body weight		Relative to BMI	
	HR (95 % CI)	*P*	HR (95 % CI)	*P*
Dominant hand				
Model 1	4.36 (3.37 – 5.65)	0.0001	4.78 (3.56 – 6.41)	0.0001
Model 2	1.81 (1.35 – 2.42)	0.0001	1.56 (1.12 – 2.17)	0.008
Model 3	1.71 (1.27 – 2.31)	0.0001	1.47 (1.05 – 2.06)	0.026
Model 4	1.46 (1.08 – 1.98)	0.01	1.26 (0.90 – 1.76)	0.90
Model 5	1.72 (1.28 – 2.31)	0.0001	1.47 (1.05 – 2.06)	0.03
Model 6	1.47 (1.09 – 1.98)	0.01	1.26 (0.90 – 1.76)	0.18
Model 7	1.62 (1.20 – 2.19)	0.002	1.30 (0.92 – 1.82)	0.13
Non dominant hand				
Model 1	4.54 (3.51 – 5.87)	0.0001	5.30 (3.96 – 7.10)	0.0001
Model 2	1.71 (1.27 – 2.31)	0.0001	1.84 (1.32 – 2.55)	0.0001
Model 3	1.57 (1.16 – 2.13)	0.003	1.71 (1.22 – 2.39)	0.002
Model 4	1.35 (1.00 – 1.83)	0.05	1.49 (1.07 – 2.08)	0.02
Model 5	1.58 (1.16 – 2.14)	0.003	1.72 (1.23 – 2.40)	0.002
Model 6	1.36 (1.00 – 1.84)	0.049	1.49 (1.07 – 2.09)	0.02
Model 7	1.42 (1.04 – 1.92)	0.03	1.55 (1.11 – 2.16)	0.01
Maximum value				
Model 1	4.85 (3.74 – 6.30)	0.0001	5.27 (3.91 – 7.12)	0.0001
Model 2	1.92 (1.43 – 2.58)	0.0001	1.86 (1.34 – 2.58)	0.0001
Model 3	1.80 (1.33 – 2.43)	0.0001	1.74 (1.24 – 2.43)	0.001
Model 4	1.53 (1.13 – 2.07)	0.006	1.45 (1.03 – 2.03)	0.03
Model 5	1.81 (1.34 – 2.44)	0.0001	1.74 (1.24 – 2.45)	0.001
Model 6	1.54 (1.14 – 2.08)	0.005	1.46 (1.04 – 2.04)	0.03
Model 7	1.68 (1.24 – 2.29)	0.001	1.55 (1.10 – 2.18)	0.01

Model 1: adjusted for age and sex.
Model 2: Model 1 + BMI (in kg/m^2).
Model 3: Model 2 + employment status (employees; farmer, merchant, artisan, company, director, manual; intermediate profession; managerial staff; unemployed), educational level (less than high school degree, ≤ 3 years after high school degree, ≥ 3 years after high school degree), monthly household income per consumption unit (continuous), smoking status (actual, former, never), number of smoked cigarettes in pack-years (continuous), physical activity (categorical IPAQ variable: high, moderate, low), family history of diabetes (yes, no), sedentary behaviors (low, high), height (m) and alcohol consumption (in g/day).
Model 4: Model 1 + waist circumference (cm), employment status, educational level (less than high school degree, < 2 y after high school degree, ≥ 2 y after high school degree), monthly household income per consumption unit (continuous), smoking status (never smoked, former smoker, occasional smoker, regular smoker), number of smoked cigarettes in pack-years (continuous), physical activity (categorical IPAQ variable: high, moderate, low), family history of diabetes (yes, no), sedentary behaviors (low, high), height (m) and alcohol consumption (in g/day).
Model 5: Model 3 + the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous).
Model 6: Model 4 + the number of 24-h dietary records (continuous), the PNNS-2 score (without PA measurement) and UPF consumption (continuous).
Model 7: Model 5 + baseline Fasting blood glucose.

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CRediT authorship contribution statement

Thi Chi Phuong Nguyen: Writing – original draft, Formal analysis. **Jean-Michel Oppert:** Writing – review & editing, Validation, Methodology. **Laurent Bourhis:** Writing – review & editing, Formal analysis, Data curation. **Alice Bellicha:** Writing – review & editing, Resources. **Bernard Srour:** Writing – review & editing, Resources. **Emmanuelle Kesse-Guyot:** Writing – review & editing, Methodology, Conceptualization. **Serge Hercberg:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Pilar Galan:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Mathilde Touvier:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Léopold K Fezeu:** Writing – review & editing, Validation, Supervision, Formal analysis. **Jérémy Vanhelst:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.diabet.2025.101713.

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