Four-Year Increase in Step Cadence Is Associated with Improved Cardiometabolic Health in People with a History of Prediabetes

PHILIP MCBRIDE[1,2], JOSEPH HENSON[1,2], CHARLOTTE L. EDWARDSON[1,2], BENJAMIN MAYLOR[1,2], PADDY C. DEMPSEY[1,2], ALEX V. ROWLANDS[1,2], MELANIE J. DAVIES[1,2], KAMLESH KHUNTI[1,3], and THOMAS YATES[1,2]

[1]Diabetes Research Centre, Health Sciences, College of Life Sciences, University of Leicester, Leicester, UNITED KINGDOM; [2]NIHR Leicester Biomedical Research Centre, Leicester, UNITED KINGDOM; and [3]NIHR Collaboration for Leadership in Applied Health Research and Care East Midlands, University of Leicester and University Hospitals of Leicester NHS Trust, Leicester, UNITED KINGDOM

ABSTRACT

MCBRIDE, P., J. HENSON, C. L. EDWARDSON, B. MAYLOR, P. C. DEMPSEY, A. V. ROWLANDS, M. J. DAVIES, K. KHUNTI, and T. YATES. Four-Year Increase in Step Cadence Is Associated with Improved Cardiometabolic Health in People with a History of Prediabetes. *Med. Sci. Sports Exerc.*, Vol. 55, No. 9, pp. 1601–1609, 2023. **Purpose:** To investigate associations between 4-yr change in step cadence and markers of cardiometabolic health in people with a history of prediabetes and to explore whether these associations are modified by demographic factors. **Methods:** In this prospective cohort study, adults, with a history of prediabetes, were assessed for markers of cardiometabolic health (body mass index, waist circumference, high-density lipoprotein cholesterol [HDL-C], low-density lipoprotein cholesterol [LDL-C], triglycerides, and glycated hemoglobin A1c [HbA1c]), and free-living stepping activity (activPAL3™) at baseline, 1 yr, and 4 yr. Brisk steps per day were defined as the number of steps accumulated at ≥100 steps per minute and slow steps per day as those accumulated at <100 steps per minute; the mean peak stepping cadence during the most active 10 minutes of the day was also derived. Generalized estimating equations examined associations between 4-yr change in step cadence and change in cardiometabolic risk factors, with interactions by sex and ethnicity. **Results:** Seven hundred ninety-four participants were included (age, 59.8 ± 8.9 yr; 48.7% women; 27.1% ethnic minority; total steps per day, 8445 ± 3364; brisk steps per day, 4794 ± 2865; peak 10-min step cadence, 128 ± 10 steps per minute). Beneficial associations were observed between change in brisk steps per day and change in body mass index, waist circumference, HDL-C, and HbA1c. Similar associations were found between peak 10-min step cadence and HDL-C and waist circumference. Interactions by ethnicity revealed change in brisk steps per day and change in peak 10-min step cadence had a stronger association with HbA1c in White Europeans, whereas associations between change in 10-min peak step cadence with measures of adiposity were stronger in South Asians. **Conclusions:** Change in the number of daily steps accumulated at a brisk pace was associated with beneficial change in adiposity, HDL-C, and HbA1c; however, potential benefits may be dependent on ethnicity for outcomes related to HbA1c and adiposity. **Key Words:** ACTIVPAL, WALKING, NONDIABETIC HYPERGLYCEMIA, GAIT, ETHNICITY

Type 2 diabetes mellitus (T2DM) and cardiovascular diseases (CVD) cause some of the most devastating burdens on public health globally (1,2). It has been widely reported that regular participation in physical activity supports the prevention and management of T2DM (3). Beneficial effects of physical activity on insulin-mediated glucose uptake have been observed in healthy individuals, those with a history of prediabetes, and those with diagnosed T2DM (4). Furthermore, physical activity has been shown to be effective in reducing hemoglobin A1c (HbA1c) levels and improving glucose control, insulin sensitivity, and body composition (3,5). In addition to this, studies have demonstrated strong, independent, inverse associations between physical activity and CVD risk (6). For a number of years, research has reported on the potential ethnic and sex differences in the responses to physical activity. For example, innate differences in cardiorespiratory fitness levels and capacity for fat oxidation may be key contributors to ethnic differences in cardiometabolic health and the responses of health markers to changes in physical activity habits (7). In addition, there appear to be differences in the associations between physical activity and all-cause mortality between men and women in specific clinical groups (8).

Address for Correspondence: Philip McBride, M.Sc., Leicester Diabetes Centre, Leicester General Hospital, Leicester, LE5 4PW, United Kingdom; E-mail: ty20@le.ac.uk.

Submitted for publication November 2022.
Accepted for publication March 2023.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/23/5509-1601/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000003180

Despite clear links between physical activity and better health outcomes, international policy efforts to promote regular activity have led to little change in the percentage of adults meeting physical activity guidelines (9). Moreover, during the recent COVID-19 pandemic, there was a significant reduction in physical activity across age groups and sexes (10). In an attempt to improve physical activity uptake and adherence, recent public health campaigns have focused on walking as a preferred choice of physical activity—in particular brisk walking (11). The importance and inherent health benefits associated with stepping activity are widely researched—for example, recent studies and meta-analyses, suggested a steep dose-response association between overall stepping activity and survival, up until a daily volume of between 7000 and 10,000 steps per day, depending on the population, where the risk of mortality was consistently halved compared with those who were less active (~3000–5000 steps per day) (12,13).

Along with overall walking activity, habitual walking pace has also been highlighted as an important predictor of health status (14), with self-reported slow walkers having over twice the risk of premature mortality than brisk walkers (15). Objectively measured brisk walking during free-living activity is typically defined using step cadence, typically accumulation of steps at a cadence ≥100 steps per minute, which is considered indicative of moderate-to-vigorous intensity physical activity (MVPA) (16). In recent years, the association between step cadence with health has become a notable discipline within the field of public health research. Previously, studies have concluded that the accumulation of steps at or above 100 steps per minute has a beneficial association with body mass index (BMI), obesity, T2DM, and overall disease prevalence (16). In addition, there have been studies indicating associations between various cardiometabolic health markers—such as age, BMI, waist circumference (WC), blood pressure, and metabolic syndrome—and peak step cadence over predefined periods (16,17).

Recent large studies have suggested associations between step cadence and mortality are partially or fully mediated by controlling for overall steps per day (12,13,18). However, these studies have focused on mortality in typically healthy individuals with stepping measured at one time point. Further, there is sparse data in general investigating associations between change in stepping behavior and change in cardiometabolic health outcomes. Therefore, the potential associations between step cadence, health status, and the potential health impacts of changing walking behavior, particularly in high-risk populations, such as those with a history of prediabetes, remains unclear. This study aims to investigate the degree to which changes in stepping intensity over a 4-yr period are associated with change in various cardiometabolic risk markers in people with a history of prediabetes recruited from primary care.

RESEARCH DESIGN AND METHODS

Design and procedure. The analysis included data from the "PRomotion Of Physical activity through structured Education with differing Levels of ongoing Support for people at high risk of type 2 diabetes" (PROPELS) study. The study protocol and methods have been published in detail elsewhere (19). Briefly, this multicenter (Leicester and Cambridge, UK) randomized controlled trial investigated the effectiveness of an intervention to support physical activity change and maintenance, delivered at two intervention levels against a control condition, over a 4-yr period, with measures taken at baseline, 1 yr, and 4 yr. Participants were randomized to either: a control group who received a detailed advice leaflet; an intervention group who received the advice leaflet plus a structured educational program followed by annual group maintenance sessions; or an intervention group who received the same package as the first intervention group plus a highly tailored text and phone call service designed to support behavior change and pedometer use. The interventions did not result in sustained changes to behavior at 4 yr (20).

Participants. Participants were identified as having had reported HbA1c (6.0%–6.4% or 42–47.9 mmol·mol^{-1}), fasting glucose (5.5–6.9 mmol·L^{-1}), or 2-h postchallenge blood glucose (7.8–11.1 mmol·L^{-1}), defined as having a history of prediabetes within the last 5 yr documented in their primary care records, and confirmation was sought that they had not been diagnosed with diabetes (19). Other inclusion criteria included being able to communicate in verbal and written English, being free from any condition or limitation that would render participants unable to participate in the study, and the provision of written informed consent. The trial was sponsored by University of Leicester, United Kingdom and ethics approval was granted by NHS National Research Ethics Service, East Midlands Committee (12/EM/0151).

Markers of cardiometabolic health. Markers of cardiometabolic health were measured at baseline, and after 1 and 4 yr. Full details of measurements have been detailed previously (19). HbA1c and lipid profile (triglycerides, HDL-C, and LDL-C) were assessed by venous sampling. Collection and sampling were standardized across research sites. Body weight, body fat percentage, height, and WC were measured to the nearest 0.1 kg, 0.5%, 0.5 cm, and 0.1 cm, respectively. Postcode (to calculate the Index of Multiple Deprivation [IMD]), alcohol intake, and smoking status were assessed through researcher- and self-administered questionnaires. Use of relevant medications (such as blood pressure medication, lipid lowering substances, and metformin) were determined by reviewing a list or packets of currently prescribed medications that participants were asked to bring to each study assessment and were recorded in a consultation with a member of the study team.

Device-assessed physical activity and sedentary behavior. Participants were asked to wear the activPAL3™ device (PAL Technologies, Ltd., Glasgow, UK) 24 h·d^{-1} for 7 d on the midline anterior aspect of the right thigh. The monitor was included as a secondary outcome within the main trial with local activPAL stock and trial delivery team capacity limiting data capture for all recruited individuals at baseline. The initialisation, download, and data cleaning processes have been detailed elsewhere (21). In brief, data were cleaned, processed, and summarized in processing PAL (https://github.

com/UOL-COLS/ProcessingPAL, version 1.3, University of Leicester, Leicester, UK) using the default algorithm thresholds to define a valid day, i.e., <95% of time spent in any one behavior (e.g., standing or sitting), ≥500 step events (1000 steps) and ≥10 h of valid waking hours data (22). Participants were required to have at least three valid days of data to be included in the analysis (23). Output variables of interest included: valid waking wear time; time spent in postures of sitting, standing, and stepping; number of daily steps; and number of daily steps at different thresholds of step cadence, categorized as slow steps per day (<100 steps per minute) or brisk steps per day (≥100 steps per minute) (16). Slow steps per day were bounded at a lower rate of 50 steps per minute and brisk steps per day were bounded at an upper rate of 150 steps per minute to avoid very slow or fast frequencies of stepping that are unlikely to represent purposeful walking activity (24).

When discussing peak step cadence, frequently used techniques report on the accumulation of steps over a predefined epoch or across a walking event; this has the effect of diluting the true peak by averaging across the epoch or the duration of the event and has been criticized for measuring step accumulation as opposed to step cadence (25,26). In contrast, by assigning a step cadence to each stepping event within the activPAL event file, we ensure the accurate capture of instantaneous cadences as opposed to an average of steps across a period (26). The mean peak step cadence variable for the most active 10 min of the day was created in STATA by using the activPAL event files and then matching the valid waking wear times identified from Processing PAL (code available on request): the mean step cadence. Briefly, the code generates these step cadence variables by: 1) assigning a cadence (step per event interval*60*2) to each stepping event within the event file; 2) step cadence for each stepping event is sorted by ascending order; 3) time intervals (not continuous) are collated in accordance with the period of interest (10 min); 4) the average step cadence in the period is identified as the mean.

Statistical analysis. Given that there was no difference between groups in physical activity at 4 yr (20), the PROPELS data were analyzed as a single cohort for the purposes of this study. The flow of participants in this analysis is shown in Supplemental Figure 1 (see Supplemental Digital Content, http://links.lww.com/MSS/C846). Associations between change in the step cadence (exposure) variables and change in the markers of cardiometabolic health (outcome) variables were explored using generalized estimating equations accounting for repeated measures using an exchangeable correlation matrix. Models were conducted across two levels (baseline to 1 yr and 1 to 4 yr), allowing all change values to be included in the analysis over the 4-yr period. Models were restricted to complete case analysis, meaning only participants with complete data for all variables were included. Interaction terms for measurement period were tested in the models described below to confirm associations of interest were consistent across the different measurement periods and suitable for pooling within a repeated measures analysis. Coefficients can therefore be interpreted as the association between change in exposure and outcome variables within the 4-yr study period. Models were adjusted for baseline values of each level for both the outcome and exposure variable, change in wear time, randomization group, age, sex, ethnicity (White European, South Asian, other), employment status (employed, part-time employed, retired, other), IMD, and time varying covariates, smoking status (smoker, previous smoker, never smoked), alcohol consumption (units per day), history of previous CVD (yes/no), blood pressure medication (yes/no), and lipid lowering medication (yes/no). In addition, models were mutually adjusted for change in number of slow steps per day (when brisk steps per day and peak 10-min are the exposure variable) or change in number of brisk steps per day (when slow steps per day is the exposure variable) to assess their independent associations. An acyclic diagram showing the associations under study can be found in Supplemental Figure 2 (see Supplemental Digital Content, http://links.lww.com/MSS/C846). Further adjustment for overall steps per day was not attempted due to multicollinearity between change in total steps per day with brisk steps per day or slow steps per day within this population ($r > 0.50$). However, to provide additional context for the results on stepping intensity, we also repeated the analysis for total steps per day without adjustment for brisk or slow steps. Supplementary models were also run without mutual adjustment for brisk and slow steps per day and for the main model plus change in WC to investigate whether associations were independent of changes to adiposity. For descriptive purposes, change in brisk steps per day from baseline were also categorized as high increasers (>1000 steps per day increase), moderate increasers (1–1000 steps per day increase), moderate decreasers (1–1000 steps per day decrease), and high decreasers (>1000 steps per day decrease), which broadly reflected quartiles with data split at the 27th, 52nd, and 75th percentiles. For context, 1000 brisk steps equate to around 10 min of brisk walking (27).

Interaction terms were explored to assess whether associations with slow or brisk steps per day were modified by ethnicity or sex. Significant interactions were then stratified by categories. For interactions and stratification by ethnicity, participants with "other" ethnicities were excluded due to low numbers, meaning data could not be fitted to the models.

An additional sensitivity analysis was conducted where missing data were replaced with multiple imputations across five data sets. Missing data were imputed using the fully conditional specification (FCS) method, an iterative Markov chain Monte Carlo method for when the pattern of missing data is arbitrary. The FCS method fits a univariate model using all other available variables in the model as predictors and then imputes missing values.

To aid interpretation, results are presented as both standardized and nonstandardized beta coefficients (95% confidence interval [CI]) per 1000 steps per day for slow and brisk steps per day and per 10 steps per minute for peak step cadence. All data were analyzed using IBM SPSS Statistics (version 24.0). A P value <0.05 was considered statistically significant for the main effects and interactions.

RESULTS

From a total of 1366 participants recruited to the study, 794 participants (age = 60 ± 9 yr; 51.3% male; 72.9% White European [WE], 21.9% South Asians [SA], 5.2% other ethnicities) had valid activPAL data at baseline and at least one follow-up period (1 and 4 yr) and were included in this analysis. Models therefore analyzed participants who had data at all time points alongside participants who had data at baseline and 1-yr follow-up (but not 4 yr), and participants with 1-yr and 4-yr follow-up (but not baseline). Participant characteristics at each measurement period (baseline, 1 yr, and 4 yr) are displayed in Table 1 and baseline characteristics stratified by treatment group in Supplemental Table 1 (see Supplemental Digital Content, Baseline participant characteristics stratified by randomization group, http://links.lww.com/MSS/C846). Participants averaged 15.8 ± 1.2 $h \cdot d^{-1}$ of valid waking wear time, 8445 ± 3364 steps per day, of which 4794 ± 2865 were brisk steps per day. There were no substantial differences between characteristics of participants included and excluded due to missing data (data shown in Supplemental Table 2, Supplemental Digital Content, Baseline characteristics of participants excluded due to missing data, http://links.lww.com/MSS/C846).

TABLE 1. Participant characteristics.

	Baseline (*n* = 794)	1-yr (*n* = 791)	4-yr (*n* = 749)
Fixed variables		*n* [%] of participants	
Ethnicity			
White European	579 [72.9%]	574 [72.6%]	556 [74.2%]
South Asian	174 [21.9%]	171 [21.6%]	149 [19.9%]
Other ethnicities	41 [5.2%]	46 [5.8%]	44 [5.9%]
Sex			
Male	407 [51.3%]	409 [51.7%]	386 [51.5%]
Female	387 [48.7%]	382 [48.3%]	363 [48.5%]
History of cardiovascular disease	100 [12.6%]	128 [16.2%]	121 [16.1%]
Employment			
Full-time	288 [36.3%]	270 [34.1%]	208 [27.8%]
Part-time	146 [18.4%]	140 [17.7%]	123 [16.4%]
Retired	275 [34.6%]	320 [40.5%]	363 [48.4%]
Unemployed or other	85 [10.7%]	61 [7.7%]	55 [7.4%]
		Mean ± SD	
Social deprivation (IMD decile)	5.8 ± 3.0	5.8 ± 2.9	5.8 ± 2.8
Time-varying variables		*n* [%] of participants	
Lipid lowering substances	237 [29.9%]	246 [31.1%]	286 [38.2%]
Blood pressure medication	295 [37.2%]	308 [38.9%]	305 [40.7%]
Smoking status			
Nonsmokers	443 [55.8%]	448 [56.6%]	404 [53.9%]
Ex-smokers	288 [36.3%]	287 [36.3%]	257 [34.3%]
Current smokers	62 [7.8%]	56 [7.1%]	47 [6.3%]
		Mean ± SD	
Alcohol (units per day)	3.7 ± 5.9	3.8 ± 5.5	3.7 ± 5.8
Weight (kg)	81.0 ± 17.3	81.1 ± 17.7	80.0 ± 18.1
BMI ($kg \cdot m^{-2}$)	29.0 ± 5.4	29.0 ± 5.5	28.8 ± 5.6
WC (cm)	98.3 ± 13.9	98.2 ± 13.9	99.6 ± 14.0
HDL ($mmol \cdot L^{-1}$)	1.5 ± 0.4	1.5 ± 0.5	1.5 ± 0.5
LDL ($mmol \cdot L^{-1}$)	3.0 ± 0.9	2.9 ± 0.9	2.7 ± 0.9
Triglycerides ($mmol \cdot L^{-1}$)	1.6 ± 1.1	1.6 ± 1.1	1.6 ± 0.9
HbA1c (%) [$mmol \cdot mol^{-1}$]	5.8 ± 0.3 [40.7 ± 3.5]	5.9 ± 0.3 [41.3 ± 3.4]	6.0 ± 0.4 [41.6 ± 4.7]
activPAL valid waking wear time ($h \cdot d^{-1}$)	15.8 ± 1.2	15.4 ± 2.6	15.4 ± 2.5
Steps per day	8445 ± 3364	8626 ± 3798	8422 ± 3962
Slow steps per day	2401 ± 1286	2408 ± 1334	2386 ± 1312
Brisk steps per day	4794 ± 2865	5018 ± 3126	4900 ± 3286
Peak 10-min step cadence (steps per minute)	127.8 ± 10.1	128.0 ± 10.6	127.1 ± 10.5

Slow and brisk steps. Associations between change in overall, slow, and brisk steps per day with change in markers of cardiometabolic health are presented in Table 2. Change in total steps per day was associated with change in BMI, WC, HDL-C, and HbA1c. However, when separated by and mutually adjusted for stepping intensity, associations were largely only maintained for change in brisk steps where every 1000 steps per day change was associated with a change in BMI (−0.09 $kg \cdot m^{-2}$; 95% CI, −0.15 to −0.04), WC (−0.25 cm; 95% CI, −0.43 to −0.06), HDL-C (0.015 $mmol \cdot L^{-1}$; 95% CI, 0.008–0.021), and HbA1c (−0.010%; 95% CI, −0.019 to −0.001) (Table 2). Standardized associations are displayed in Figure 1. Further adjustment of markers of cardiometabolic health for change in WC did not change the overall pattern of results with associations persisting nor did the removal of mutual adjustment for brisk and slow steps per day (Supplemental Table 3, Supplemental Digital Content, Nonstandardized associations between change in step cadence variables and change in cardiometabolic health outcomes, http://links.lww.com/MSS/C846). In contrast, slow steps were only associated with change in BMI (−0.16 $kg \cdot m^{-2}$ per 1000 steps per day; 95% CI, −0.28 to −0.05).

When analyzed categorically, change in brisk steps per day showed broadly dose-related associations with change in markers of cardiometabolic health. Compared with high decreasers, high increasers had 0.29 $kg \cdot m^{-2}$ (0.03–0.55) lower BMI (Fig. 2, panel A) and 0.06 $mmol \cdot L^{-1}$ (−0.09 to −0.02) and higher HDL-C (Fig. 2, panel C). HbA1c increased in all groups, but the largest increase occurs in the high decreasers, 0.11% (0.07–0.15), being 0.04% (0.01–0.08) different to high increasers (Fig. 2; panel D).

Peak step cadence. Associations between change in peak stepping cadence variables and change in markers of cardiometabolic health are presented in Figure 1 (nonstandardized coefficients shown in Table 2). In the whole cohort, there were associations between change in 10-min peak step cadence variables and change in BMI (−0.02 $kg \cdot m^{-2}$; 95% CI, −0.04 to 0.00), WC (−0.09 cm per 10 steps; 95% CI, −0.16 to −0.03), and HDL-C (0.004 $mmol \cdot L^{-1}$; 95% CI, 0.002–0.006). Further adjustment with markers of cardiometabolic health for change in WC did not change the overall pattern of results with association persisting; nor did the removal of mutual adjustment for brisk and slow steps per day (Supplemental Table 3, Supplemental Digital Content, http://links.lww.com/MSS/C846).

Ethnicity and sex interactions. Interaction analyses suggested some differences between ethnicities (Supplemental Table 4, Supplemental Digital Content, Interaction *P* values for associations between change in step cadence variables and change in cardiometabolic health outcomes, http://links.lww.com/MSS/C846) for brisk steps. Stratified results are presented in Supplemental Figure 3 (see Supplemental Digital Content, http://links.lww.com/MSS/C846) (nonstandardized coefficients shown in Supplemental Table 5, Supplemental Digital Content, Nonstandardized associations between change in step cadence variables and change in cardiometabolic health

APPLIED SCIENCES

TABLE 2. Nonstandardized associations between change in step cadence variables and change in markers of cardiometabolic health.

	Change in BMI ($kg \cdot m^{-2}$), $n = 794$	*P*	Change in WC (cm), $n = 787$	*P*	Change in HDL-C ($mmol \cdot L^{-1}$), $n = 786$	*P*	Change in LDL-C ($mmol \cdot L^{-1}$), $n = 775$	*P*	Change in Triglycerides ($mmol \cdot L^{-1}$), $n = 790$	*P*	Change in HbA1c (%) [$mmol \cdot mol^{-1}$], $n = 790$	*P*
Change in Overall steps per day (per 1000 steps)	**−0.10 (−0.14, −0.06)**	**<0.001**	**−0.27 (−0.41, −0.12)**	**<0.001**	**0.013 (0.008, 0.019)**	**<0.001**	0.009 (−0.006, 0.025)	0.241	0.00 (−0.02, 0.03)	0.711	**−0.008 (−0.015, 0.00) [−0.08 (−0.16, −0.01)]**	**0.031**
Change in Slow steps per day (per 1000 steps)[a]	**−0.16 (−0.28, −0.05)**	**0.007**	−0.38 (−0.80, 0.04)	0.073	0.008 (−0.004, 0.021)	0.188	−0.003 (−0.047, 0.041)	0.895	−0.046 (−0.125, 0.034)	0.260	−0.002 (−0.018, 0.013) [−0.02 (−0.18, 0.15)]	0.846
Change in Brisk steps per day (per 1000 steps)[a]	**−0.09 (−0.15, −0.04)**	**0.001**	**−0.25 (−0.43, −0.06)**	**0.009**	**0.015 (0.008, 0.021)**	**<0.001**	0.014 (−0.006, 0.035)	0.175	0.020 (−0.010, 0.050)	0.190	**−0.010 (−0.019, −0.001) [−0.11 (−0.21, −0.01)]**	**0.029**
Change in Peak 10-min Step Cadence (per 10 steps)[a]	**−0.02 (−0.04, 0.00)**	**0.049**	**−0.09 (−0.16, −0.03)**	**0.005**	**0.004 (0.002, 0.006)**	**<0.001**	0.002 (−0.004, 0.008)	0.547	−0.003 (−0.013, 0.007)	0.527	−0.002 (−0.004, 0.000) [−0.02 (−0.05, 0.00)]	0.080

Bold highlights statistically significant associations.
Adjusted for baseline value for both the outcome and exposure variable, change in activPAL valid waking wear time, group, age, sex, ethnicity (White, South Asian, other), deprivation, employment (employed, part-time employed, retired, other), smoking status, alcohol (drinks per day), previous CVD (yes/no), blood pressure medication (yes/no), lipid lowering medication (yes/no).
[a]Plus mutual adjustment for baseline and change in slow steps per day (when brisk steps per day or peak 10-min step cadence is the exposure variable) or baseline and change in brisk steps per day (when slow steps per day is the exposure variable).

outcomes, http://links.lww.com/MSS/C846). Associations in SA were observed between change in 10-min peak step cadence and change in BMI (−0.08 $kg \cdot m^{-2}$; −0.11 to −0.05). No associations were observed in WE.

A significant association was found for change in overall steps per day (−0.010%; −0.018 to −0.002), brisk steps per day (−0.013%; −0.023 to −0.002) and change in peak 10-min step cadence (−0.003%; −0.006 to 0.000) with change in HbA1c in WE, but not in SA.

Results revealed a significant association between change in brisk steps per day and change in LDL-C for males (0.029 $mmol \cdot L^{-1}$; 95% CI, 0.002–0.057) but not females (see Supplemental Table 6, Supplemental Digital Content, Nonstandardized associations between change in step cadence variables and change in cardiometabolic health outcomes stratified by sex, http://links.lww.com/MSS/C846).

Multiple imputations for missing data did not change the overall interpretation of BMI, WC, HDL-C, LDL-C, triglycerides, or HbA1c (see Supplemental Table 7, Supplemental Digital Content, Nonstandardized associations between change in step cadence variables and change in cardiometabolic health outcomes with multiple imputations for missing data, http://links.lww.com/MSS/C846).

DISCUSSION

To our knowledge, the present study is the first to investigate the associations between change in stepping behaviors and change in markers of cardiometabolic health in people with a high risk for T2DM. We show that although increases in overall stepping over a 4-yr period had a beneficial association with adiposity, HDL-C, and HbA1c in people with a history of prediabetes, these associations were only maintained for brisk steps when analyzed by and mutually adjusted for stepping intensity. In addition, increases in average steps per minute for 10-min peak step cadence was associated with improvements in adiposity and HDL-C. Changes in slow steps per day were not associated with changes to markers of cardiometabolic health, apart from BMI. When results were stratified by ethnicity, a stronger association was seen between 10-min peak step cadence and adiposity in SA than in WE. Conversely, a stronger association between increase in brisk steps per day and 10-min peak step cadence and change in HbA1c was seen in WE compared with SA.

Our study using accelerometer measured stepping behavior provides new prospective evidence in support of the importance of brisk stepping for cardiometabolic health. Previous evidence using self-reported measures has found faster habitual walking pace to be a stronger predictor of survival and longer telomere length than overall physical activity volume or other lifestyle factors (14,16,28,29). However, recent research using objectively measured stepping cadence at a single time point within the general populations have been more equivocal, with some or all of the association of brisk stepping with health outcomes attenuated after adjustment for overall stepping volume (12,13,18), emphasizing the need for

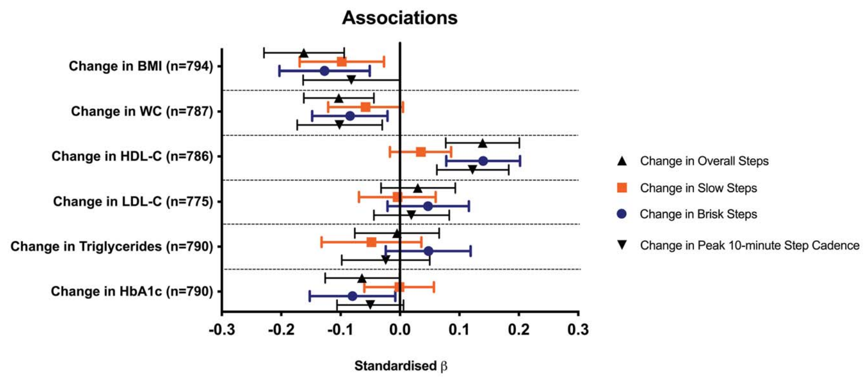

FIGURE 1—Standardized associations between change in slow and brisk steps per day and change in cardiometabolic health outcomes. Data shown as standardized difference (per SD) in the outcome per 1000 steps per day change in overall, slow, and brisk steps per day and per 10 steps per minute change in peak 10-min step cadence. Data adjusted for baseline value for both the dependant and exposure variable, change in activPAL waking wear time, group, age, sex, ethnicity (White, South Asian, other), deprivation, employment (employed, part-time employed, retired, other), smoking, alcohol (drinks per week), previous CVD (yes/no), blood pressure medication (yes/no), lipid lowering medication (yes/no), mutual adjustment for baseline and change in slow steps per day (when brisk steps per day or peak 10-min step cadence is the exposure variable) or baseline and change in brisk steps per day (when slow steps per day is the exposure variable).

further research. Here we show that a stronger more consistent pattern of health benefits is observed with 4-yr changes to brisk steps per day than for slow steps per day in those with a history of prediabetes. This finding supports the continued emphasis on MVPA within recent updated physical activity guidelines in the United States (30), United Kingdom (31), and internationally (32).

The associations between 4-yr change in brisk steps per day and change in HDL-C were consistent across the different metrics of walking intensity employed. Early intervention studies investigating how the introduction of a brisk walking program influences lipid profiles showed beneficial changes to HDL-C after 12 wk of increased brisk walking (33). More recently, a 1-yr lifestyle intervention aimed at increasing overall and brisk stepping demonstrated that brisk walking lasting ≥10 min was significantly associated with an increase in HDL-C (34). The results of the present study support these findings and provide new evidence that longer-term changes to brisk walking may be beneficial for improving lipid profile. In the present study, the difference in change in HDL-C between those that decreased their brisk steps per day by over 1000 steps per day versus those that increased by over 1000 steps per day was 0.06 $mmol \cdot L^{-1}$ (−0.09, −0.02 $mmol \cdot L^{-1}$). Previous research has suggested that 0.05 $mmol \cdot L^{-1}$ equates

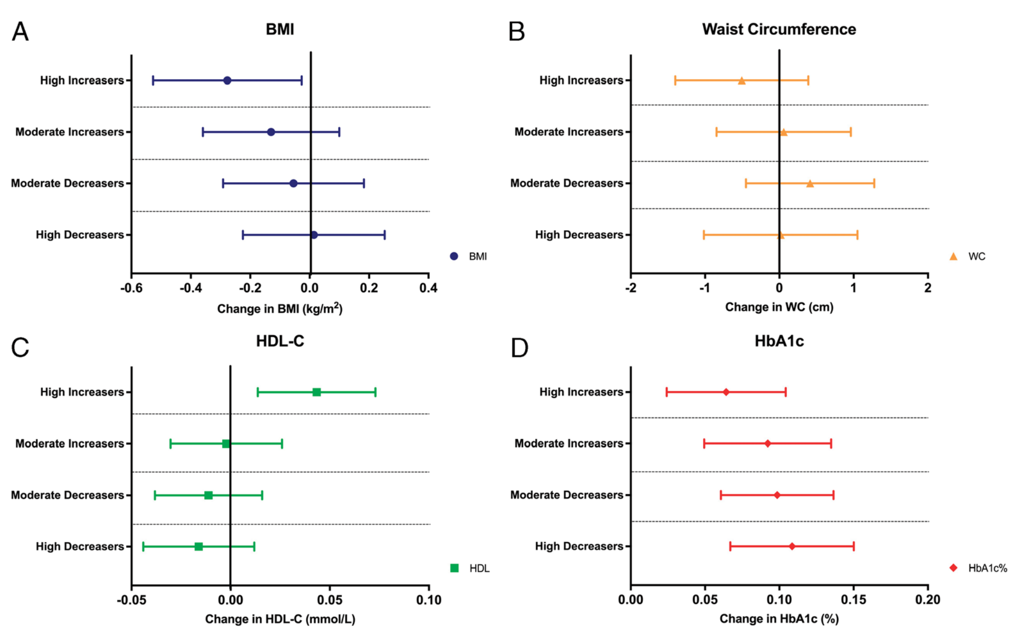

FIGURE 2—Group differences in change in markers of cardiometabolic health (Panel A BMI, Panel B waist circumference, Panel C HDL-C, Panel D HbA1c) and change in brisk steps per day. Data points represent mean change (95% CI). Adjusted for baseline value for both the dependant and exposure variable, change in activPAL waking wear time, group, age, sex, ethnicity (White, South Asian, other), deprivation, employment (employed, part-time employed, retired, other), smoking, alcohol (drinks per week), previous CVD (yes/no), blood pressure medication (yes/no), lipid lowering medication (yes/no), and mutual adjustment for baseline and change in slow steps per day. High Increasers >1000 brisk steps per day increase. Moderate Increasers 0–999 brisk steps per day increase. Moderate Decreasers 1–999 brisk steps per day decrease. High Decreasers >1000 brisk steps per day decrease.

to the minimum clinically important difference in HDL-C (35), with a difference of 0.06 mmol·L^{-1} shown to be associated with a 3% to 6% difference in the relative risk of CVD mortality in women and men (36).

This analysis also identified an association between a 4-yr change in brisk steps per day and reduction in HbA1c. This supports data from the NHANES cohort, which reported an association between physical activity and HbA1c in people at risk for T2DM, which was stronger when a higher percentage of overall activity came from MVPA (37). Similarly, the present study identified associations between 4-yr change in several step cadence variables and change in BMI and WC, which extends observations from previous cross-sectional associations (38). However, changes in HbA1c and adiposity between those that increased and decreased their brisk steps per day were relatively modest and below the threshold for clinical significance (39). Nonetheless, there was a dose-related association between categorical change in brisk steps per day and change in HbA1c; and in this high-risk population, any action to reverse or slow the trajectory of worsening cardiometabolic health over time could have important public health benefits.

When the data were stratified by ethnicity, an increase in brisk steps per day and average peak step cadence for 10-min resulted in a reduction in HbA1c in WE, but not in SA. Conversely, there were stronger associations between peak 10-min step cadence and adiposity in SA than in WE. Previous, cross-sectional analysis of the PROPELS cohort highlighted that SA engaged in less MVPA and took fewer steps per day at baseline than WE (40). Different patterns of baseline activity, fitness, and relative intensity of physical activity may help explain differences in the health benefits of increasing brisk steps per day. However, it is notable that the results for HbA1c are in contrast to previous experimental research showing reductions in insulin resistance in response to acute exercise sessions are greater in SA than in WE (41). Similarly, acute responses of postprandial insulin to breaking up prolonged sitting with bouts of walking have previously been reported as being greater in SA than in WE (42). This suggests that further research is required to determine how acute and chronic adaptions to physical activity may differ by, or be optimized in, different ethnic groups. This is particularly important for walking, which is one of the most universally popular forms of physical activity across different ethnicities and cultures (43).

Strengths and limitations. There are several notable strengths of the present study. To the best of our knowledge, this is the first analysis to investigate the associations between change in metrics for stepping activity and change in markers of cardiometabolic health in people with a history of prediabetes. Further, the inclusion of a population that was predominantly recruited from primary care with coded HbA1c or glucose values highlighting a history of prediabetes makes these results reflective of people currently being referred to diabetes prevention programs. A further strength of this study is the use of the activPAL device to calculate step cadence. The activPAL has previously been found to be highly accurate in determining step cadence at speeds ≥0.5 m·s^{-1} (44). In addition, it is important to note the high proportion of study participants representing ethnic minority groups, specifically SA. However, the study is also limited by various factors. This is secondary data analysis of a trial that was designed for a different research question. The duration and requirements of the original trial may have deterred some people from taking part. For example, both the overall (8445 steps per day) and number of brisk steps (4794 steps per day) at baseline were relatively high. Therefore, the generalizability of the findings to less active populations requires further research. There was also loss of data due to reduced capacity for activPAL placement within the study or through participant drop-out. However, multiple imputations did not result in meaningful change to the overall pattern of results. Furthermore, as the PROPELS intervention did not elicit meaningful change to stepping behavior after 4 yr (20), the cohort was combined and analyzed as an observational study. Therefore, causation between change in stepping behavior and change in cardiometabolic health cannot be established and residual or unmeasured confounding cannot be discounted.

CONCLUSIONS

This study found that when change in total steps over a 4-yr period were split out by intensity (brisk steps per day and slow steps per day), only increases in brisk steps per day were associated with beneficial changes to a range of cardiometabolic health markers in people with a history of prediabetes. These findings highlight the need to further explore the benefits of promoting brisk stepping as part of a healthy lifestyle. Further to this, the differences in the strength of associations between WE and SA for changes in brisk steps per day and peak stepping cadence and changes in adiposity and HbA1c suggest that behavioral interventions may need to be tailored to suit responses of different ethnic groups.

The authors would like to thank the participants for their time and commitment. The authors would also like to thank the PROPELS investigators (particularly Professor Simon Griffin, Professor Laura Gray, Prof Stephen Sutton, Dr Helen Eborall, Dr Wendy Hardeman) and the PROPELS study management and administrative team for their time and effort in making the PROPELS study possible and for data collection. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

K. K. and T. Y. were joint PIs for the original RCT. T. Y. and C. L. E. had the idea for the article. P. M. and T. Y. drafted the first version of the article. C. L. E. and P. M. processed the activPAL data. P. M. and J. H. analyzed all the data. All the authors contributed to the interpretation of the data, reviewed and edited the article, and approved the final article.

This study was funded by the National Institute for Health Research Health Technology Assessment (HTA) Programme (HTA 09/162/02). The research was also supported by the NIHR Leicester Biomedical Research Centre (which is a partnership between University Hospitals of Leicester NHS Trust, Loughborough University and the University of Leicester) and the National Institute for Health Research Applied Research Collaboration–East Midlands (NIHR ARC–EM). The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR or the Department of Health.

The costs of the intervention were supported by the NHS Leicester City Clinical Commissioning Group, NHS West Leicestershire Clinical Commissioning Group, NHS East Leicestershire and Rutland Clinical Commissioning Group and NHS England.

APPLIED SCIENCES

REFERENCES

1. Zhou B, Lu Y, Hajifathalian K, et al. Worldwide trends in diabetes since 1980: a pooled analysis of 751 population-based studies with 4.4 million participants. *Lancet*. 2016;387(10027):1513–30.
2. Roth GA, Mensah GA, Johnson CO, et al. Global burden of cardiovascular diseases and risk factors, 1990-2019: update from the GBD 2019 study. *J Am Coll Cardiol*. 2020;76(25):2982–3021.
3. Colberg SR, Sigal RJ, Yardley JE, et al. Physical activity/exercise and diabetes: a position statement of the American Diabetes Association. *Diabetes Care*. 2016;39(11):2065–79.
4. Dela F, Prats C, Helge JW. Exercise interventions to prevent and manage type 2 diabetes: physiological mechanisms. *Med Sport Sci*. 2014;60:36–47.
5. Avery L, Flynn D, van Wersch A, Sniehotta FF, Trenell MI. Changing physical activity behavior in type 2 diabetes: a systematic review and meta-analysis of behavioral interventions. *Diabetes Care*. 2012; 35(12):2681–9.
6. Wahid A, Manek N, Nichols M, et al. Quantifying the association between physical activity and cardiovascular disease and diabetes: a systematic review and meta-analysis. *J Am Heart Assoc*. 2016;5(9):e002495.
7. Gill JMR, Celis-Morales CA, Ghouri N. Physical activity, ethnicity and cardio-metabolic health: does one size fit all? *Atherosclerosis*. 2014;232(2):319–33.
8. Molsted S, Eidemak I, Aadahl M. Sex difference in the association between physical activity and all-cause mortality in ambulatory patients with chronic kidney disease. *Int J Environ Res Public Health*. 2021;18(7):3698.
9. Scholes S. *Health Survey for England 2016: Physical Activity in Adults*. London: NHS Digital; 2017.
10. Wunsch K, Kienberger K, Niessner C. Changes in physical activity patterns due to the Covid-19 pandemic: a systematic review and meta-analysis. *Int J Environ Res Public Health*. 2022; 19(4):2250.
11. Public Health England. Focus on brisk walking, not just 10,000 steps, say health experts 2018 [cited 2021 4th December]. Available from: https://www.gov.uk/government/news/focus-on-brisk-walking-not-just-10000-steps-say-health-experts.
12. Saint-Maurice PF, Troiano RP, Bassett DR Jr, et al. Association of daily step count and step intensity with mortality among US adults. *JAMA*. 2020;323(12):1151–60.
13. Paluch AE, Bajpai S, Bassett DR, et al. Daily steps and all-cause mortality: a meta-analysis of 15 international cohorts. *Lancet Public Health*. 2022;7(3):e219–28.
14. Argyridou S, Zaccardi F, Davies MJ, Khunti K, Yates T. Walking pace improves all-cause and cardiovascular mortality risk prediction: a UK biobank prognostic study. *Eur J Prev Cardiol*. 2020;27(10): 1036–44.
15. Yates T, Zaccardi F, Dhalwani NN, et al. Association of walking pace and handgrip strength with all-cause, cardiovascular, and cancer mortality: a UK Biobank observational study. *Eur Heart J*. 2017;38(43): 3232–40.
16. Tudor-Locke C, Han H, Aguiar EJ, et al. How fast is fast enough? Walking cadence (steps/min) as a practical estimate of intensity in adults: a narrative review. *Br J Sports Med*. 2018;52(12):776–88.
17. Adams B, Fidler K, Demoes N, et al. Cardiometabolic thresholds for peak 30-min cadence and steps/day. *PLoS One*. 2019;14(8): e0219933.
18. Lee IM, Shiroma EJ, Kamada M, Bassett DR, Matthews CE, Buring JE. Association of step volume and intensity with all-cause mortality in older women. *JAMA Intern Med*. 2019;179(8):1105–12.
19. Yates T, Griffin S, Bodicoat DH, et al. PRomotion of physical activity through structured education with differing levels of ongoing support for people at high risk of type 2 diabetes (PROPELS): study protocol for a randomized controlled trial. *Trials*. 2015;16:289.
20. Khunti K, Griffin S, Brennan A, et al. Behavioural interventions to promote physical activity in a multiethnic population at high risk of diabetes: PROPELS three-arm RCT. *Health Technol Assess*. 2021; 25(77):1–190.
21. Edwardson CL, Winkler EAH, Bodicoat DH, et al. Considerations when using the activPAL monitor in field-based research with adult populations. *J Sport Health Sci*. 2017;6(2):162–78.
22. Winkler EAH, Bodicoat DH, Healy GN, et al. Identifying adults' valid waking wear time by automated estimation in activPAL data collected with a 24 h wear protocol. *Physiol Meas*. 2016;37(10): 1653–68.
23. Kang M, Kim Y, Rowe DA. Measurement considerations of peak stepping cadence measures using National Health and Nutrition Examination Survey 2005–2006. *J Phys Act Health*. 2016;13(1):44–52.
24. Tudor-Locke C, Camhi SM, Leonardi C, et al. Patterns of adult stepping cadence in the 2005–2006 NHANES. *Prev Med*. 2011;53(3):178–81.
25. Granat M, Clarke C, Holdsworth R, Stansfield B, Dall P. Quantifying the cadence of free-living walking using event-based analysis. *Gait Posture*. 2015;42(1):85–90.
26. Stansfield B, Clarke C, Dall P, Godwin J, Holdsworth R, Granat M. True cadence and step accumulation are not equivalent: the effect of intermittent claudication on free-living cadence. *Gait Posture*. 2015; 41(2):414–9.
27. Tudor-Locke C, Craig CL, Brown WJ, et al. How many steps/day are enough? For adults. *Int J Behav Nutr Phys Act*. 2011;8:79.
28. Zaccardi F, Franks PW, Dudbridge F, Davies MJ, Khunti K, Yates T. Mortality risk comparing walking pace to handgrip strength and a healthy lifestyle: a UK Biobank study. *Eur J Prev Cardiol*. 2021; 28(7):704–12.
29. Dempsey PC, Musicha C, Rowlands AV, et al. Investigation of a UK biobank cohort reveals causal associations of self-reported walking pace with telomere length. *Commun Biol*. 2022;5(1):381.
30. Piercy KL, Troiano RP, Ballard RM, et al. The physical activity guidelines for Americans. *JAMA*. 2018;320(19):2020–8.
31. Department of Health and Social Care, , Care DoHaS. In: *UK Chief Medical Officers' Physical Activity Guidelines*. London: UK Government; 2019.
32. Bull FC, Al-Ansari SS, Biddle S, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *Br J Sports Med*. 2020;54(24):1451–62.
33. Hardman AE, Hudson A. Brisk walking and serum lipid and lipoprotein variables in previously sedentary women—effect of 12 weeks of regular brisk walking followed by 12 weeks of detraining. *Br J Sports Med*. 1994;28(4):261–6.
34. Kim J, Tanabe K, Yoshizawa Y, Yokoyama N, Suga Y, Kuno S. Lifestyle-based physical activity intervention for one year improves metabolic syndrome in overweight male employees. *Tohoku J Exp Med*. 2013;229(1):11–7.
35. Zhou YL, Zhang YG, Zhang R, et al. Population diversity of cardiovascular outcome trials and real-world patients with diabetes in a Chinese tertiary hospital. *Chin Med J*. 2021;134(11):1317–23.
36. Cooney MT, Dudina A, De Bacquer D, et al. HDL cholesterol protects against cardiovascular disease in both genders, at all ages and at all levels of risk. *Atherosclerosis*. 2009;206(2):611–6.
37. Gay JL, Buchner DM, Schmidt MD. Dose-response association of physical activity with HbA1c: intensity and bout length. *Prev Med*. 2016;86:58–63.
38. Tudor-Locke C, Schuna JM Jr, Han HO, et al. Step-based physical activity metrics and cardiometabolic risk: NHANES 2005-2006. *Med Sci Sports Exerc*. 2017;49(2):283–91.
39. Goldenberg JZ, Day A, Brinkworth GD, et al. Efficacy and safety of low and very low carbohydrate diets for type 2 diabetes remission: systematic review and meta-analysis of published and unpublished randomized trial data. *BMJ*. 2021;372:m4743.
40. Biddle GJH, Edwardson CL, Rowlands AV, et al. Differences in objectively measured physical activity and sedentary behaviour between white Europeans and South Asians recruited from primary

care: cross-sectional analysis of the PROPELS trial. *BMC Public Health*. 2019;19(1):95.
41. Sargeant JA, Jelleyman C, Coull NA, et al. Improvements in glycemic control after acute moderate-intensity continuous or high-intensity interval exercise are greater in South Asians than white Europeans with nondiabetic hyperglycemia: a randomized crossover study. *Diabetes Care*. 2021;44(1):201–9.
42. Yates T, Edwardson CL, Celis-Morales C, et al. Metabolic effects of breaking prolonged sitting with standing or light walking in older South Asians and white Europeans: a randomized acute study. *J Gerontol A Biol Sci Med Sci*. 2020;75(1):139–46.
43. Office of the Surgeon General. Publications and Reports of the Surgeon General. *Step It Up! The Surgeon General's Call to Action to Promote Walking and Walkable Communities*. Washington, DC: US Department of Health and Human Services; 2015.
44. Stansfield B, Hajarnis M, Sudarshan R. Characteristics of very slow stepping in healthy adults and validity of the activPAL3™ activity monitor in detecting these steps. *Med Eng Phys*. 2015;37(1):42–7.