SSM - Population Health 12 (2020) 100644

Contents lists available at ScienceDirect

SSM - Population Health

journal homepage: http://www.elsevier.com/locate/ssmph

Increases in BMI and chronic pain for US adults in midlife, 1992 to 2016

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ARTICLE INFO

Keywords:
Pain
Obesity
Trends
Activity limitations

ABSTRACT

Recent unprecedented increases in mortality and morbidity during midlife are often ascribed to rising despair in the US population. An alternative and less often examined explanation is that these trends reflect, at least in part, the lagged effects of the obesity epidemic. Adults in midlife today are more likely to live with obesity and have a greater cumulative exposure to excess adiposity during their lifetime than any previous generation. Prior work has demonstrated a link between obesity and mortality risk at midlife, but the mechanisms remain unclear. Pain may represent one important pathway linking obesity to mortality trends. Pain is a debilitating condition that has increased significantly over recent decades and is associated with both morbidity and mortality, including suicide and opioid-related mortality. Evidence suggests obesity and pain may be linked, but there is little evidence of an association at the population level. In this paper, we examine to what extent increases in overweight and obesity explain the rising trends in chronic pain observed among middle-aged adults in the US from 1992 to 2016. We assess trends in both mild/moderate nonlimiting pain and severe and/or limiting pain. In doing so, we draw attention to one mechanism through which overweight/obesity may have contributed to recent population health trends. Our analysis found that increases in BMI from 1992 to 2016 may account for up to 20% of the upward trend in mild/moderate nonlimiting pain and 32% of the trend in severe and/or limiting pain for women, and 10% and 19% of the trends respectively for men.

Introduction

There has been considerable attention over recent years to the changing health of US adults during midlife (Case & Deaton, 2015; Woolf et al., 2018). Social scientists have observed several remarkable and potentially interrelated trends, including declines in self-reported mental and physical health along with increases in pain, morbidity, suicide, poisonings, and all-cause mortality (Case & Deaton, 2017; Goldman et al., 2018; Nahin et al., 2019; Woolf & Schoomaker, 2019). While these trends have been consistently documented, researchers remain divided about the underlying factors driving them.

In the context of the opioid epidemic and the discussion of its role in rising morbidity and mortality, scholarship has characterized both the supply-side factors that increased the availability of opioids to middle-aged adults and the demand-side factors that affected this population's economic, social, and health-related vulnerability (Clark & Schumacher, 2017; Dasgupta et al., 2018; Van Zee, 2009). Much of the debate over the role of demand-side factors has focused on a controversial "deaths of despair" argument put forward by Case and Deaton, which suggests that stagnating wages and declines in economic opportunity have driven changes in health during midlife (Case & Deaton, 2017). While the "deaths of despair" narrative has received significant popular and scholarly attention (Masters et al., 2017; Ruhm, 2018; Siddiqi et al., 2019; Soelberg et al., 2017; Venkataramani et al., 2019), Case and Deaton have also suggested that several other demand-side factors could be implicated in these trends, such as increases in obesity (Case & Deaton, 2017), which have received less attention to-date.

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https://doi.org/10.1016/j.ssmph.2020.100644
Received 8 January 2020; Received in revised form 29 July 2020; Accepted 6 August 2020
Available online 10 August 2020

In this paper, we posit that rising population-level trends in obesity are a critical and under-appreciated factor underlying changes in health occurring among adults in the US during midlife. While obesity has previously been linked to a slowdown in the rate of mortality improvement (Preston et al., 2018), the pathways through which obesity operates remain unclear.

One potential pathway that may link obesity to deaths of despair and the broader changes in Americans health during midlife is chronic pain. Obesity is strongly associated with chronic pain, and chronic pain is in turn associated with functional limitations, disability, and many psychological conditions such as depression and anxiety (Gureje et al., 1998) and has been suggested as an important contributor to population-level trends in quality of life, suicide, and opioid-related mortality (Olfson et al., 2017; Petrosky et al., 2018; Stokes et al., 2019). The prevalence of chronic pain has grown steeply over recent decades (Case & Deaton, 2017; Freburger et al., 2009; Grol-Prokopczyk, 2017; Zimmer & Zajacova, 2018), imposing a substantial population health burden in the US. (Institute of Medicine (US) Committee on Advancing Pain Research et al., 2011) The total annual economic costs of chronic pain exceed 600 billion dollars in health care expenses and lost worker productivity (Gaskin & Richard, 2012).

In 2011, the Institute of Medicine (IOM) published a blueprint calling for coordinated action among researchers, policymakers, and health professionals to address the increasing levels of chronic pain in the US. (Institute of Medicine (US) Committee on Advancing Pain Research et al., 2011) The report recommended an increased focus on chronic pain prevention, in particular on stopping progression of acute pain to chronic pain and chronic pain to pain that poses activity limitations. In subsequent years, a comprehensive U.S. National Pain Strategy was developed (Interagency Pain Research Coordinating Committee, 2019). According to this strategy, identifying modifiable risk factors for chronic pain and pain that causes activity limitations remains a national priority for population health research.

Scholars have speculated that obesity may be an underlying factor in rising pain although studies have not systematically examined its role (Zimmer & Zajacova, 2018; Institute of Medicine (US) Committee on Advancing Pain Research et al., 2011). Preliminary evidence suggesting the importance of rising obesity in the increasing prevalence of chronic pain over time is substantial. First, obesity rates have increased over the past several decades, rising from 23% of the adult US population in the early 1990s to 40% in 2015–2016 (Fryar et al., 1960; Hales et al., 2018). Recent birth cohorts are also becoming obese younger and thus are having a greater lifetime exposure to adiposity than prior generations, which could have multiple delayed public health consequences (Lee et al., 2010). Second, obesity is closely associated with numerous painful conditions including osteoarthritis (Grotle et al., 2008), lower back pain (Shiri et al., 2010), and diabetic neuropathy (Shiri et al., 2010). Such associations may relate to the biomechanical effects of excess weight gain as well as obesity's role in creating a pro-inflammatory state (Okifuji & Hare, 2015). A causal association between obesity and chronic pain is also supported by clinical trials and observational studies showing that weight loss can lead to substantial reductions in pain (Christensen et al., 2007; Khoueir et al., 2009; Larsson, 2004; Lim et al., 2010).

Thus, in the present study, we examine the role of increasing obesity in explaining rising trends in chronic pain observed among middle-aged adults in the US from 1992 to 2016. We assess trends in both mild/moderate nonlimiting pain and severe and/or limiting pain. In doing so, we draw attention to one pathway through which obesity may have contributed to the recent population health trends of adults during midlife.

Materials and methods

Data source

We used data from 13 consecutive biennial waves of the Health and Retirement Study (HRS) from 1992 to 2016. The HRS is a nationally representative longitudinal survey of non-institutionalized adults over the age of 50 years in the US. The survey was administered every 2 years with periodic recruitment to refresh samples in 1998, 2004, 2010, and 2016 (Supplementary Fig. 1). At each wave, we restricted our analysis to adults aged 55 to 61. We chose this specific group of middle-aged adults because HRS has followed this age group since 1992, allowing us to examine the rise of pain over a longer period than for other groups. Since item nonresponse was low (0.1%–1.6%), we excluded those with missing data on pain, BMI, or covariates. Participants with a BMI less than 20 kg per meters squared (kg/m^2) were excluded due to potential confounding by diagnosed or preclinical diseases, and individuals with BMI over 70 were also excluded to guard against extreme measurement error. Lastly, adults who reported ever receiving a cancer diagnosis were excluded (Supplementary Fig. 2). The exclusion jointly removed 7595 observations from 60,879 adults aged 55 to 61, yielding the final analytic sample with 53,284 observations (21,356 unique respondents, with each respondent observed for an average of 2.5 waves).

Study design

To estimate and model time trends, we treated sample members in each wave as if they were representative cross-sections of the population. While the validity of this approach could be compromised by selective panel attrition and/or panel conditioning, a previous study (Grol-Prokopczyk, 2017) using the same data found little evidence of pain-related survey attrition. We also evaluated cohort-period curve (Supplementary Fig. 3) for panel conditioning, and found no evidence of such bias. The prevalence of chronic pain in older cohorts, which had undergone multiple waves of survey, was not systematically higher than in newer cohorts.

Exposure and outcome measures

Our exposure variable was time in years since 1992. To be consistent with a prior study using HRS data(Zimmer and Zajacova, 2018), we created a 3-level outcome variable for pain that also considered activity limitations. Participants were asked, "Are you often troubled with pain?" Those who answered yes were asked, "How bad is the pain most of the time: mild, moderate, or severe?" and "Does the pain make it difficult for you to do your usual activities such as household chores or work?" At each wave, participants were then classified as no pain (not troubled by pain), mild/moderate nonlimiting pain (often troubled by pain that was mild or moderate and did not limit respondents' ability to perform usual activities), and severe and/or limiting pain (often troubled by pain that was severe and/or made it difficult to perform activities).

Covariates

BMI was calculated from self-reported weight and height. We transformed BMI to reflect BMI above 25 kg/m^2 by subtracting 25 kg/m^2 (the beginning of the overweight range as defined by the World Health Organization (WHO, 2019)), with values between 20 and 25 kg/m^2 assigned to zero (Preston et al., 2018). Other covariates that might explain the rising trend in chronic pain included the following demographic characteristics: age (Dahlhamer et al., 2018), sex (Fillingim et al., 2009) (male, female), race/ethnicity (Janevic et al., 2017) (non-Hispanic white, non-Hispanic black, Hispanic, other), and nativity (Janevic et al., 2017) (born in US, born outside US). We also measured socioeconomic status (Grol-Prokopczyk, 2017) according to educational

attainment (some college or lower, BA or more) and smoking status (Goesling et al., 2015) (never, former, current). We did not examine depression, mood disorders, arthritis, or other physical conditions as covariates because we hypothesized these conditions may develop on the causal pathway between overweight/obesity and chronic pain (Jantaratnotai et al., 2017; Zis et al., 2147).

Statistical analyses

First, we examined the association between years since 1992 and pain, using multinomial logit models appropriate for our 3-level operationalization of pain (none, mild/moderate nonlimiting, and severe and/or limiting pain). The pain trends were first estimated by controlling only for age to provide a crude estimate of trends from 1992 to 2016. Next, we introduced race/ethnicity and nativity to the base model. In subsequent models, we added education and smoking individually. The final model included all covariates.

Since we were particularly interested in how the trend coefficient changed with the addition of BMI, we assessed each model with and without BMI included. The degree of attenuation in the coefficient for years since 1992 indicates the extent to which the trend in BMI can explain the pain trend. Since our models were non-linear, the Karlson-Holm-Breen (KHB) method was applied to allow accurate decomposition of total effects into direct and indirect effects (Kohler et al., 2011).

We stratified all models by sex. Sex differences in pain and obesity have been routinely observed (Mogil, 2012), and thus we hypothesized that obesity may influence pain trends differently by sex (Flegal, Carroll, Ogden, & Curtin, 2010; Kanter & Caballero, 2012; Zimmer & Zajacova, 2018). Finally, in an additional set of models, we examined if the impact of overweight/obesity on pain trends was consistent across sociodemographic characteristics and smoking status. We again estimated fully adjusted models except that we omitted one of the three covariates (race/ethnicity, education, and smoking status) and instead stratified by this covariate.

Stata statistical software version 15 (StataCorp) was used for all analyses. HRS sampling weights were applied to account for oversampling of demographic groups and attrition, enabling generalizability to the US population aged 55 to 61. Standard errors were also adjusted for intra-individual clustering. As the analyses relied on publicly available, de-identified data, Institutional Review Board approval was not required.

Sensitivity checks

Extensive sensitivity analyses were conducted to verify the robustness of our findings to alternative specifications and procedures. We first tested for non-linear time trends by including higher-order terms for years since 1992 in the full model. To relax the assumption that the impact of BMI on pain was constant over time, we included an interaction term between BMI and time since 1992.

We also examined the sensitivity of results through a number of alternative specifications of BMI. First, we tested a quadratic term for BMI. Second, instead of assigning zero to BMI values in the normal range, we used the original BMI values equal to 20 or higher and its quadratic term. Third, we treated BMI as a categorical variable using the WHO recommended BMI categories of 18.5–24.9 (normal), 25–29.9 (overweight), 30–34.9 (obese I), 35–39.9 (obese II), and $\geq$40 (obese III).

Furthermore, a concern with our cross-sectional study design was that it could overestimate the effects of overweight/obesity on pain because of reverse causality. To assess this potential bias, we first compared results by re-estimating models replacing contemporary BMI measures with BMI lagged 2-years and lagged 4-years. Second, we determined whether baseline pain predicted subsequent BMI trajectories in a longitudinal framework. Third, we examined whether baseline BMI predicted incident pain status (i.e. transitioning from pain-free status at baseline to pain). These latter two investigations are described in the Supplementary Materials.

Results

Between 1992 and 2016, the proportion of US adults aged 55 to 61 with severe and/or limiting pain increased substantially, from 17.6% to 28.3% for females and 13.5% to 22.4% for males. Over the same period, the proportion of middle-aged adults with obesity/overweight increased from 61.4% to 74.9% for women, and 70.9% to 83.2% for men. (Table 1).

Fig. 1 plots the prevalence of overweight/obesity and chronic pain from 1992 to 2016 stratified by sex. Increases in overweight/obesity, mild/moderate nonlimiting pain, and severe and/or limiting pain were all observed. Severe and/or limiting pain was more prevalent than mild/moderate nonlimiting pain and rose more rapidly.

Table 2 presents nested multinomial logit models examining the association of years since 1992 with the prevalence of mild/moderate nonlimiting pain and severe and/or limiting pain versus no pain. For each sex, we estimated 5 models. In each case, we first fit the model without BMI (Col. a) and then added BMI (Col. b). Controlling only for age, the log-odds of reporting mild and severe and/or limiting pain among women increased by 0.024 and 0.027 units per year (Model 1a), respectively, while the log-odds of reporting mild and severe and/or limiting pain among men increased by 0.018 and 0.029 units per year, respectively. In the fully adjusted model, after decomposing total effects by the KHB method, BMI was estimated to account for 20.3% (95% CI 15.8%, 24.9%) of the trend in mild/moderate nonlimiting pain and 32.1% (95% CI 28.2%, 36.0%) of the trend in severe and/or limiting pain for women, and 10.4% (95% CI 5.6%, 15.1%) of the trend in mild/moderate nonlimiting pain and 19.0% (95% CI 15.8%, 22.1%) of the trend in severe and/or limiting pain for men (Model 5). Full models with all coefficients can be found in Supplementary Tables 1 and 2

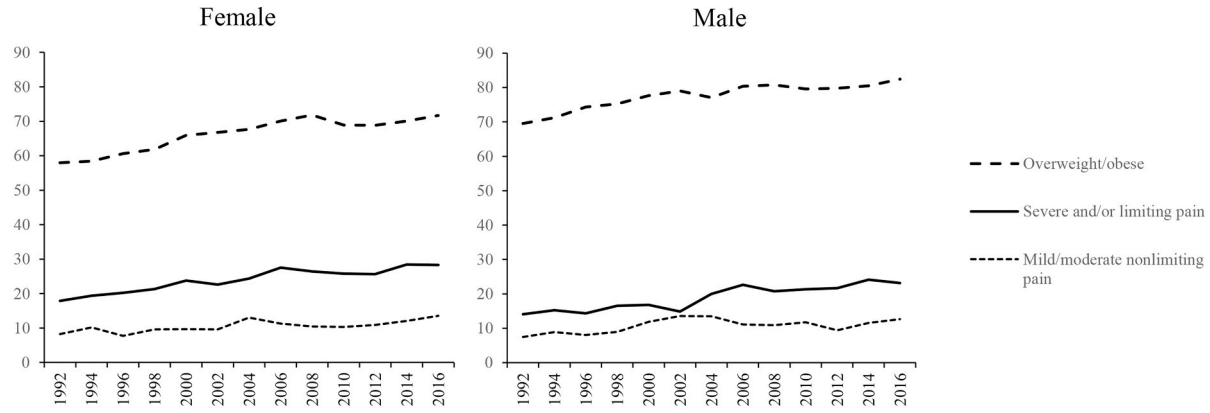
To assess heterogeneity in the role of BMI in rising pain trends, we stratified the regressions by sociodemographic characteristics and smoking status (Table 3). Chronic pain increased in all subgroups. However, the rates of increase varied substantially. While a formal test for differences in the context of the KHB decomposition was not possible, the method does provide estimates with 95% confidence intervals that allow informal comparisons of group differences. Overall, BMI explained a larger proportion of trends in severe and/or limiting pain relative to mild/moderate nonlimiting pain and trends among women than among men. There were no consistent differences in contributions of BMI to pain trends across race/ethnicity groups or by educational attainment, except for severe and/or limiting pain among women. BMI accounted for 34.8% (95% CI 30.2%, 39.3%) of rising severe and/or limiting pain among women with less than a BA education but only 22.6% (95% CI 15.4%, 29.7%) among those with a BA or higher education. Differences by smoking status for severe and/or limiting pain were more substantial. BMI explained 20.7% (95% CI 15.8%, 25.7%) of increases in severe and/or limiting pain among male former smokers and 34.7% (95% CI 27.5%, 41.8%) for female former smokers in comparison to 7.4% (95% CI 4.2%, 10.6%) and 19.7% (95% CI 14.5%, 24.9%) for current smokers.

Auxiliary analyses were conducted to examine to what extent estimates were potentially affected by reverse causality. When contemporary BMI measures were replaced with BMI lagged 2-year and lagged 4-year measures, no meaningful differences were observed (Supplementary Table 3). While pain status at baseline was associated with a higher initial BMI, it was not associated with a faster rate of increase in BMI. In fact, severe and/or limiting pain at baseline was associated with a slower increase in BMI compared to those who have no pain at baseline (Supplementary Table 4). Supplementary Tables 5 and 6 present associations between baseline BMI status and subsequent incident pain for those who were initially pain-free. For females, each unit increase in BMI above 25 was associated with a 0.07 and 0.09 unit increase in the odds of reporting any pain and severe and/or limiting pain, respectively. The

Table 1
Descriptive statistics of the target population of adults aged 55–61 in HRS, 1992 and 2016, N = 53,284[a].

Characteristics	Female				Male			
	1992		2016		1992		2016	
Chronic noncancer pain, %								
No pain	74.0		58.3		79.2		65.2	
Mild/moderate nonlimiting pain	8.4		13.4		7.3		12.4	
Severe and/or limiting pain	17.6		28.3		13.5		22.4	
Overweight/obesity								
Obesity/overweight, %	61.4		74.9		70.9		83.2	
BMI units above 25 kg/m2, mean (sd)	3.1	(4.4)	5.7	(6.3)	2.8	(3.4)	4.8	(5.1)
Age, mean (sd)	57.8	(1.9)	57.8	(2.0)	57.8	(2.0)	57.9	(1.9)
Race/ethnicity, %								
Non-Hispanic white	79.5		70.1		82.7		70.2	
Non-Hispanic black	11.5		13.2		9.6		10.5	
Hispanic	6.6		10.8		5.7		11.4	
Other	2.3		5.8		2.0		7.9	
Nativity								
Born in the US, %	89.7		88.3		91.2		86.4	
Education, %								
Some college or lower	86.2		66.2		77.7		69.6	
BA or more	13.8		33.8		22.3		30.4	
Smoking status, %								
Never	46.3		46.5		26.3		46.0	
Former	30.8		36.9		48.5		34.7	
Current	22.9		16.7		25.2		19.3	
N	2653		2394		2564		2122	

[a] Weighted percent and mean (sd) and unweighted sample size were presented.



* Trends adjusted for age composition.

a. Severe pain refers to severe and/or limiting pain. Mild pain refers to mild/moderate nonlimiting pain

Fig. 1. Trends in the prevalence of overweight/obesity and pain among US adult aged 55–61: HRS 1992 to 2016 *
* Trends adjusted for age composition.
Severe pain refers to severe and/or limiting pain. Mild pain refers to mild/moderate nonlimiting pain.

corresponding numbers were 0.03 and 0.04 for men. Taken together, these results did not support a systematic overestimation of the association between overweight/obesity and chronic pain owing to reverse causality.

We tested for non-linear time trends by including higher-order terms for time since 1992 in the full model. Other than a negative second-degree term for time in the model for men on the outcome of mild/moderate pain (indicating a slight deceleration of the increase in mild/moderate pain over time), no other deviation from linearity was detected. To relax the assumption that the impact of BMI on chronic pain was constant over time, we included an interaction term between BMI and year post-baseline. We found an interaction only for mild/moderate pain among males, which did not alter results materially. In addition, the alternative BMI measures induced little change in the estimated pain trend or reduction in the period trend when accounting for BMI.

Discussion

The rapidly rising prevalence of chronic pain (Case & Deaton, 2017; Freburger et al., 2009; Grol-Prokopczyk, 2017; Nahin et al., 2019; Zimmer & Zajacova, 2018) has contributed substantially to morbidity and mortality in midlife across the US (Case & Deaton, 2017). It has been posited that obesity is an underlying driver of such trends. In this study, we found that rising trends in overweight and obesity were associated with population-level increases in pain from 1992 to 2016, especially increases in severe and/or limiting pain.

Our analysis showed that increases in BMI from 1992 to 2016 may account for up to 20% of the upward trend in mild/moderate nonlimiting pain and 32% of the trend in severe and/or limiting pain for women, and 10% and 19% of the trends respectively for men. The increase in BMI contributed more to trends in severe and/or limiting pain

Table 2
Multinomial logit model predicting chronic pain with and without control for BMI in HRS, 1992–2016, N = 53,284.

Models[a]	Mild/moderate nonlimiting pain			Severe and/or limiting pain		
	Without BMI[b] (a)	With BMI[b] (b)	% Explained by BMI[c] [95% CI]	Without BMI[b] (a)	With BMI[b] (b)	% Explained by BMI[c] [95% CI]
Panel A: Female						
1) Age	0.024	0.020	20.1 [15.6–24.6]	0.027	0.017	38.4 [33.7–43.2]
2) Age + Race + Nativity	0.023	0.019	20.2 [15.7–24.7]	0.025	0.016	38.6 [33.6–43.6]
3) Age + Race + Nativity + Education	0.025	0.021	20.6 [16.1–25.2]	0.033	0.023	31.8 [27.9–35.7]
4) Age + Race + Nativity + Smoking	0.023	0.020	19.6 [15.2–24.0]	0.027	0.018	36.1 [31.4–40.9]
5) Age + Race + Nativity + Education + Smoking[d]	0.025	0.021	20.3 [15.8–24.9]	0.034	0.023	32.1 [28.2–36.0]
Panel B: Male						
1) Age	0.018	0.016	13.9 [8.4–19.5]	0.029	0.022	23.1 [19.3–26.9]
2) Age + Race + Nativity	0.019	0.017	12.9 [7.6–18.2]	0.028	0.021	23.5 [19.6–27.5]
3) Age + Race + Nativity + Education	0.021	0.019	11.1 [6.1–16.0]	0.032	0.026	19.6 [16.2–23.0]
4) Age + Race + Nativity + Smoking	0.021	0.019	12.0 [7.1–16.9]	0.034	0.027	20.9 [17.5–24.3]
5) Age + Race + Nativity + Education + Smoking	0.022	0.020	10.4 [5.6–16.1]	0.036	0.029	19.0 [15.8–22.1]

Abbreviations: BMI, body mass index; CI, confidence interval.

[a] Column (a) and (b) show multinomial logit regression coefficients for a linear time trend. See Supplementary Tables 1 and 2 for the complete regression results.

[b] BMI was transformed to reflect the number of BMI units above 25 kg/m2, with values between 20 and 25 assigned to zero.

[c] % explained was calculated by KHB method.

[d] After adjusting for age, race, nativity, education, and smoking, the coefficient for the mild/moderate nonlimiting pain trend over time was 0.025 among females (i.e. 2.5% annual increase in the odds of reporting mild/moderate nonlimiting pain). After additionally adjustment for BMI, the coefficient dropped to 0.021. Using the KHB method, we then calculated that 20.3% (15.8–24.9%) of the female mild/moderate nonlimiting pain trend was explained by BMI.

Table 3
Multinomial logit model predicting chronic noncancer pain with and without control for BMI in HRS, 1992–2016, stratified by characteristics, N = 53,284.

Model[a]	Mild/moderate nonlimiting pain			Severe and/or limiting pain		
	Without BMI[b] (a)	With BMI[b] (b)	% Explained by BMI[c] [95% CI]	Without BMI[b] (a)	With BMI[b] (b)	% Explained by BMI[c] [95% CI]
Panel A: Female						
By race/ethnicity						
White	0.023	0.019	22.6 [16.2–29.1]	0.037	0.025	32.2 [27.6–36.7]
Black	0.046	0.039	16.3 [10.3–22.2]	0.031	0.022	34.0 [25.4–42.7]
Hispanic	0.018	0.016	15.7 [3.2–28.1]	0.013	0.007	44.7 [25.7–63.8]
By education						
High school or less	0.023	0.019	21.6 [15.9–27.3]	0.032	0.022	34.8 [30.2–39.3]
BA or above	0.033	0.029	15.8 [8.9–22.7]	0.040	0.031	22.6 [15.4–29.7]
By smoking status						
Never smoker[d]	0.025	0.021	19.0 [12.8–25.3]	0.023	0.013	45.2 [37.0–53.5]
Former	0.021	0.016	26.6 [16.8–36.3]	0.034	0.023	34.7 [27.5–41.8]
Current	0.034	0.029	17.7 [8.1–27.4]	0.051	0.042	19.7 [14.5–24.9]
Panel B: Male						
By race/ethnicity						
White	0.019	0.017	12.5 [5.6–15.1]	0.037	0.031	18.8 [15.1–22.5]
Black	0.047	0.046	2.9 [-2.9–8.8]	0.033	0.029	13.9 [7.3–20.5]
Hispanic	0.023	0.021	–	0.037	0.030	17.9 [5.7–30.2]
By education						
High school or less	0.021	0.018	14.0 [8.1–19.8]	0.035	0.028	19.5 [15.8–23.2]
BA or above	0.026	0.025	1.4 [-6.9-9.6]	0.042	0.034	17.5 [11.4–23.6]
By smoking status						
Never smoker	0.019	0.017	10.5 [1.0–20.0]	0.011	0.003	–
Former	0.024	0.022	11.5 [4.3–18.7]	0.040	0.032	20.7 [15.8–25.7]
Current	0.022	0.021	9.2 [0.8–17.6]	0.054	0.050	7.4 [4.2–10.6]

– The % explained was not estimated because the 95% CI for the underlying pain trend was overlapping with 0.

[a] Column (a) and (b) show multinomial logit regression coefficients for a linear time trend. Models controlled for age, sex, race/ethnicity, nativity, education and smoking status.

[b] BMI was transformed to reflect the number of BMI units above 25 kg/m2, with values between 20 and 25 assigned to zero.

[c] % explained was calculated by KHB method.

[d] Sample interpretation: "After adjusting for age, race, nativity, and education, the coefficient for the mild/moderate nonlimiting pain trend over time was 0.025 among female never smokers. After adjusting for BMI, the coefficient dropped to 0.021. Using the KHB method, we then calculated that 19.0% (12.8–25.3%) of the mild/moderate nonlimiting pain trend among female never smokers was explained by individuals having a BMI over 25 kg/m^2

than mild/moderate nonlimiting pain and was a more important factor among women than men. A broad set of biological and psychosocial explanations may account for the sex differences observed in associations of BMI and pain (Fillingim, 2000; Fillingim et al., 2009).

Coupled with existing evidence showing that weight loss can lead to substantial reductions in pain (Larsson, 2004; Christensen et al., 2007), our findings lend support to a causal interpretation of the relationship between BMI and pain. Though much remains to be clarified, an increasing body of evidence illuminates the mechanisms underlying the obesity-pain link such as increased loading on joints and spine (Okifuji & Hare, 2015). Higher levels of BMI are also associated with greater wear-and-tear on knee cartilage (Ding et al., 2005), greater disk

compression force while lifting (Singh et al., 2015), higher risk for degenerative disk disorders (Samartzis et al., 2012), and altered body mechanics and postures (Fabris de Souza et al., 2005). In particular, overloading on lower back, hip, and knee joints may contribute to structural damage and lead to osteroarthritis (McVinnie, 2013).

In addition to the mechanical and structural changes brought on by obesity, studies have identified biochemical mediators as well. As an endocrine organ, adipose tissue produces and releases proinflammatory cytokines and adipokins, which may increase pain (Ronti et al., 2006). Obesity is also associated with leptin, a hormone which may facilitate inflammation and joint damage (Considine, 2005; Vuolteenaho et al., 2014). Depression also acts as an important link between obesity and pain (McVinnie, 2013). Depression and obesity have a bidirectional relationship, meaning that the presence of obesity increases the risk of depression and vice versa (Jantaratnotai et al., 2017). Seretonin depletion, which is involved in the pathophysiology of depression, is known to amplify pain symptoms (Shelton & Miller, 2010). Depression can also contribute to disrupted sleep and activity limitations, which increase pain severity (Harrison et al., 2016). Thus, depression may serve as an additional mechanism through which obesity increases the amount of pain in the US population.

Given the substantial economic and health-related burden of chronic pain, our findings highlight the importance of primary and secondary obesity prevention. Obesity has been increasing in the United States and globally over the past several decades (Finucane et al., 2011; Flegal et al., 2010), driven largely by environmental effects that undermine individual capacity to regulate personal diet and physical activity (Gortmaker et al., 2011). There is emerging consensus on core policy actions to reduce obesity at the population level by reversing systemic and environmental drivers of the obesogenic environment (Hawkes et al., 2013). Examples include nutrition labeling, food taxes or targeted subsidies, restriction of food advertising, regulation of food nutritional quality and availability in schools, and public awareness campaigns (Roberto et al., 2015). An integrated approach that involves regulatory actions from government, increased efforts from industry, health professionals, civil society and individuals is necessary to address the epidemic of obesity effectively, which will in turn reduce the burden of chronic pain in the US population (Gortmaker et al., 2011; Roberto et al., 2015). While obesity appears to be an important factor in the rising prevalence of pain, other factors such as changing social acceptance of pain as a symptom and increases in depression, mood disorders, psychosocial stress, trauma, occupational injury, smoking, and physical inactivity during youth and adulthood may also each play important roles in pain trends and warrant further research (Linton & Shaw, 2011).

Our study had several limitations. First, the estimated role of BMI in rising chronic pain was predicated on a causal relation between BMI and chronic pain. While we found little evidence that the association between overweight/obesity and pain was biased by reverse causality, the relationship between BMI and chronic pain was still subject to the influence of confounding factors such as genes, childhood and early adulthood socioeconomic environment, and behavioral choices at younger age (Hu, 2008). The absence of unobserved and unmeasured factors from our models is likely to bias the estimates of association upwards. On the other hand, residual confounding by smoking could have led us to under-estimate the population-level association of BMI and pain trends. Consistent with this possibility, our findings showed that BMI had less explanatory power among current smokers than among other smoking groups. Second, BMI values were based on self-reported height and weight, which tend to overestimate measured BMI values at the low end of the BMI scale and underestimate BMI values at the high end (Stommel & Schoenborn, 2009). However, correlations between self-reported and measured BMI values are high and similarly predictive of health risks (Stommel & Schoenborn, 2009). Third, the HRS does not probe the duration of chronic pain and therefore the measures used in the present study may not be comparable to other studies, which generally define chronic pain as pain lasting for 3 or 6 months. Nevertheless, given that the measures are consistent across HRS waves, analyses of trends are unlikely to be affected. HRS also does not link chronic pain to particular conditions or site-specific types of chronic pain. Finally, the present study was restricted to US adults aged 55–61 years. Future studies examining the role of BMI in rising pain trend at other ages are needed.

In conclusion, the present study indicated a strong association between the rising prevalence of overweight/obesity and chronic pain among middle-aged adults in the US from 1992 to 2016. The magnitude of the association was stronger for severe and/or limiting pain than for mild/moderate nonlimiting pain and stronger in women as compared to men. Our findings proved consistent across alternative specifications of obesity and did not appear to be a consequence of reverse causality between obesity and pain. The results of the present study highlight the need for integrating obesity prevention and treatment into public health efforts to reduce the burden of chronic pain in the US population. They also call attention to the complex and under-appreciated role of obesity in driving population health trends among US adults during midlife. Further research is needed to examine obesity's contribution to other underlying factors that are commonly associated with deaths of despair and other recent trends in morbidity and mortality.

Ethics statement

This secondary data analysis relied on publicly available, de-identified data from the Health and Retirement Study. Thus, there was no need to obtain ethics approval. To download the data, see instructions in https://hrs.isr.umich.edu/data-products. The computer code used for these analyses is available from the authors upon request.

CRediT authorship contribution statement

Andrew C. Stokes: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Supervision. **Wubin Xie:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **Dielle J. Lundberg:** Conceptualization, Writing - original draft, Writing - review & editing. **Katherine Hempstead:** Conceptualization, Writing - original draft, Writing - review & editing. **Anna Zajacova:** Methodology, Writing - original draft, Writing - review & editing. **Zachary Zimmer:** Writing - original draft, Writing - review & editing. **Dana A. Glei:** Writing - original draft, Writing - review & editing. **Ellen Meara:** Writing - review & editing. **Samuel H. Preston:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

Disclosure and acknowledgments

Research reported in this publication was supported by the Robert Wood Johnson Foundation. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funder. Publication of the study results was not contingent on the sponsor's approval of the manuscript. A. Stokes has reported receiving research funding from Ethcon Inc outside of the submitted work. The other authors declare no conflicts of interest.

The authors would like to thank Dr. Maxine Weinstein for her contributions in reviewing the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2020.100644.

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