The Changing Relationship between Bodyweight and Longevity in High- and Low-Income Countries

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Preliminary draft

Abstract

Bodyweight has been rising around the world for centuries, first reducing chronic malnutrition, and more recently, leading to obesity and chronic diseases. However, standard bodyweight measures (overweight and obese, for example) fail to reflect technological progress - and in particular, progress that disproportionately promotes longevity at higher bodyweights (as well as differences in access to it). This paper builds on the pioneering work of Hans Waaler (1983) and Robert Fogel (1994) to empirically estimate how technological progress, and differential access to it, have fundamentally transformed the relationship between body mass index (BMI) and longevity in high-, middle-, and low-income countries. Importantly, we show that the combined effect of technological progress and access to it across countries is so profound that the share of national populations above mortality-minimizing bodyweight is not clearly greater in countries with higher overweight and obesity rates (as traditionally defined) - and in fact, a larger share of low-income country populations can be unhealthily heavy.

Keywords: Waaler curves, Health technology, Mortality, Obesity

Bodyweight has been rising around the world for centuries. Since the time of the Second Agricultural Revolution, innovation in agricultural has reduced the real price of calories (Ankli 1980, Clark 2003), fueling increases in human stature (Fogel 1994, Fogel and Costa 1997, Floud et al. 2011). Early gains in bodyweight reduced chronic malnutrition, promoting immune resilience and raising life expectancy dramatically in Western nations (Fogel and Costa 1997, Sen 1981, Dreze and Sen 2013). However, the continued rise in bodyweight - and obesity - has more recently been treated with alarm because of accompanying chronic disease morbidity and mortality (Fontaine et al., 2003; Yach et al., 2006; Popkin et al., 2004; Ebbeling et al. 2002). And in lower-income countries today, which confront a "double burden" - that is, the simultaneous existence of both undernutrition and obesity - rising bodyweight is a mixed blessing, helping some and harming others (Shrimpton et al., 2012; Strauss, 1998; Biswas et al., 2020). Altogether, roughly 2 billion people globally today are considered overweight or obese, a number projected to continue rising (Roberto et al., 2015).

Clinically, whether or not a particular bodyweight is healthy for an individual patient is a complex question that involves more than just weight and height. For example, body mass index (BMI - the ratio of weight in kilograms to height in meters-squared) does not discriminate well between fat and muscle mass (Heitmann et al., 2000; Ortega et al., 2016), nor does it identify an underlying case of metabolic syndrome.[1] At the population level, however, BMI continues to be a widely measured and used summary statistic. According to the World Health Organization (WHO), for adults, a BMI less than 18.5 indicates underweight, between 18.5 and 25 indicates normal weight, between 25 and 30 indicates overweight, and 30 or above indicates obesity (WHO 2006; Onis et al. 2007). Increases in BMI above 25 or 30 are therefore considered markers of deteriorating health (Di Angelantonio et al., 2016).[2]

There are several important problems with this approach. First, these BMI thresholds are somewhat arbitrarily chosen. Second, they may not reflect genotypic differences across populations in which the distribution of body fat varies (WHO, 2000; Mehta et al., Nakagami et al., 2003; 2003; Bodicoat et al., 2014). Third, and importantly, technology is changing - and in particular, changing in response to population anthropometrics in ways that promote longevity among those considered overweight or obese. A number of studies now find that BMI in the overweight range is not associated with an increased mortality risk (Flegal et al., 2013; Chen et al., 2009; Gu et al., 2006), particularly among the elderly

[1] By contrast, Woolcott et al. (2018) have recently developed a Relative Fat Mass (RFM) measure, which is easier to implement than other more direct body fat estimation methods.

[2] [add footnote on different BMI thresholds for different countries - 23 instead of 25 for Indonesia, for example]

(Winter et al., 2014; Berraho et al., 2010). Moreover, there is considerable inequality across countries in access to new technologies that promote longevity at higher bodyweights.

A potentially superior approach to relying on fixed thresholds, pioneered by Hans Waaler (1984) and promoted by Nobel laureate Robert Fogel (1994) and Fogel and Costa (1997), uses iso-mortality curves as key tool for understanding the changing population health consequences of anthropometric status. Estimated using detailed data containing information both on anthropometric status and mortality risk, iso-mortality curves - or Waaler surfaces - relate mortality to height and weight in a way that circumvents these problems. They do not impose bright-line thresholds on the joint distribution of height and weight. Instead, they can be estimated separately for different populations, and importantly, their shape and location reflect the change role of technological progress - and access to health technologies - over time in moderating the relationship between anthropometric status and longevity.

Thanks to pioneering data collection efforts in recent years, in this paper we re-estimate iso-mortality Waaler curves in three different contemporary environments, relating height and weight to longevity in the United States (a high-income country), Mexico (a middle-income country), and Indonesia (a lower-income country) with detailed individual-level data. These countries represent different technological regimes, broadly defined, for longevity at different heights and weights - and varying access to these health technologies. They also provide an update to Fogel's (1994) estimates (obtained using a sample of 50-64 year-old Norwegians observed between 1963 and 1975) by using more contemporary data - data reflecting technological progress in recent decades that has disproportionately focused on obesity-related chronic diseases. The data requirements for doing so are stringent; few representative surveys both measure individuals' anthropometric characteristics and follow the same individuals over time, recording subsequent deaths. We use individual-level panel data collected in directly comparable ways between 2001 and 2016 through the Health and Retirement Study (HRS) in the U.S., the Mexican Health and Aging Study (MHAS) in Mexico, and the Indonesian Family Life Survey (IFLS) in Indonesia to study adult populations at the ages at which chronic diseases commonly emerge (ages 50-79).

To set the stage, Supplement Figure A1 first shows how average combinations of weight and height at middle and older ages (50-79) in these three countries (the U.S., Mexico, and Indonesia) have changed in recent decades (from 1975 to 2014) relative to the original Waaler surface minimum risk curve estimated by Waaler (1983) and Fogel (1994). This minimum risk curve shows the bodyweight that minimizes mortality risk for each height (i.e., it is the set of bodyweights that minimizes mortality risk across the

height distribution, with increasing mortality risk at bodyweights both to the left and right of the curve) - in this case, estimated using a sample of Norwegians observed between 1963 and 1975. In the United States, average stature (or height) has generally remaining constant over time, while average bodyweight has increased - starting to the right of Fogel's minimum risk curve, and systematically moving further above it by 2014 (reflecting the well-known increase in obesity in the U.S.). In Mexico and Indonesia, average stature has steadily risen over time, and average bodyweight has as well - in Mexico, starting near the minimum risk curve and rising above it over time, and in Indonesia, moving towards it (but still remaining below as of 2014). These are national averages, masking underlying heterogeneity in their distribution, which we consider below.

Figure 1 then presents contemporary Waaler surface estimates (age-adjusted) for the United States, Mexico, and Indonesia, separately for men and women in each country. The colored curves represent level sets of mortality risk, spaced in equal increments/decrements of absolute risk. Each panel also shows a corresponding minimum risk curve, again denoting the set of bodyweights that minimizes mortality risk across the height distribution. Reflecting both technological differences and varying access to health technology, the location and shape of these Waaler surfaces differ considerably across countries (and between women and men).[3] Arguably the largest difference is between the Indonesian Waaler surfaces and those estimated for the U.S. and Mexican populations (both for women and men). The Indonesian minimum risk curve reflects an absolute mortality risk above those for the U.S. and Mexico - but perhaps more strikingly, at all heights, mortality risk for Indonesian women and men is minimized at much lower bodyweights across the height distribution.

To facilitate comparisons across each country's Waaler surfaces (and corresponding differences in the relationship between BMI and mortality risk), Figure 2 next shows minimum risk curves corresponding to the Waaler surfaces in Figure 1 (as well as Fogel's original minimum risk curve estimated using the 1963-1975 Norwegian sample). For a given height, among both men and women, the weight that minimizes mortality risk is lowest in Indonesia - substantially higher in Mexico, and higher yet in the U.S. For example, for a male 6 feet tall ($\sim$ 1.83 meters), the minimum mortality weights in kilograms are 64 (in Indonesia), 89 (in Mexico), and 88 (in the U.S.), corresponding to BMIs of 19.1, 26.6 and

[3]Because we focus our analyses on mortality over a 4-year period, it should not reflect the recently debated "obesity paradox" which some attribute to weight prior to death (Banack and Stokes, 2017; Di Angelantonio et al., 2016; Kalantar-Zadeh, 2014; Romero-Corral et al., 2006). Our analysis examine height and weight (BMI) today, in year y, and probability of death during year y+4 - but exclude deaths occurring in years y+1 through y+3, minimizing the role of weight loss in the years prior to death.

26.3, respectively. These differences across countries are present, but less pronounced, for women: for example, for a female 5 feet 8 inches tall (1.73 meters), the corresponding minimum mortality weights are 69, 76, and 80, with corresponding BMIs of 23.1, 25.4 and 26.7, respectively. Notably, relative to a BMI of 25 (the WHO threshold for overweight), these minimum risk bodyweights are consistently lower in Indonesia, and substantially higher in Mexico and the U.S.

Because Figure 2 does not consider the actual distribution of anthropometric status in these three populations, we then focus on how the joint distributions of height and weight in each relate to their corresponding contemporary minimum-risk curves. Specifically, Figures 3-5 show heat maps of these joint distributions for men and women in each country using 5x5 unit cells (in millimeters of height and in kilograms of weight) along with the corresponding minimum risk curves. In all cases, national populations are distributed both above and below their minimum risk curves - but notably, population shares above the minimum risk curve are not clearly greater in a country with a higher obesity rate like the U.S. (30% among men) than in countries with lower obesity rate like Indonesia or Mexico (2% and 19%, respectively).

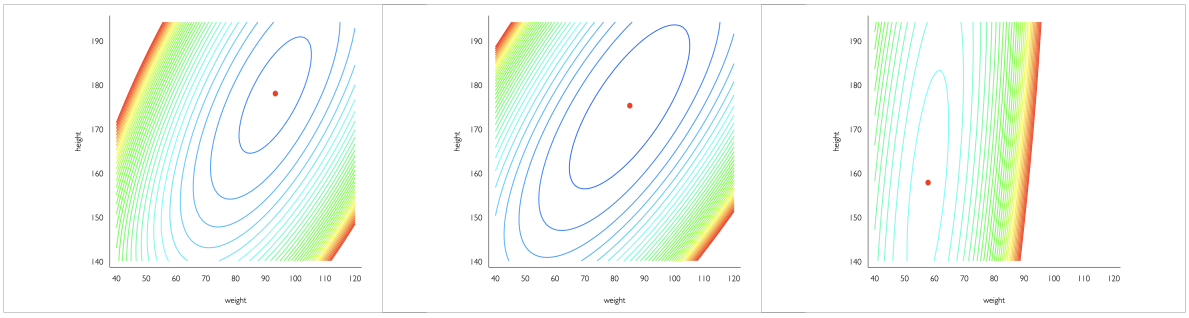
To formalize these points, Figures 3-5 also show the implied number of averted deaths over a 4-year horizon if all individuals in each population were to move to her/his minimum risk bodyweight (holding height constant). These averted deaths, weighted to obtain implied national totals, are shown for each height row to the left of the minimum risk curve for those gaining weight and to the right of the curve for those losing weight. Finally, for each country, we compute ratios of the share of each national population above mortality-minimizing bodyweight to the share of each national population considered overweight by contemporary standards (BMI>25 in the US and Mexico, and BMI>23 in Indonesia). If contemporary standards defining unhealthily high bodyweights matched bodyweights above mortality-minimizing levels, thess ratios would be 100% for each country. Instead, we find them to be 52.6% in the United States, 56.8% in Mexico, and 124.4% in Indonesia. These results suggest that contemporary standards do not accurately capture mortality risk associated with bodyweight. Perhaps more importantly, they also suggest that technological progress promoting longevity at higher bodyweight - and access to these technologies - varies so profoundly across countries that a larger share adult Indonesians are above their mortality-minimizing bodyweights than are adult Americans and Mexicans (despite considerably higher overweight population shares in the US and Mexico measured by contemporary standards).

Health-specific technological change over time has been dramatic. In the past half-century, it has

focused particularly on the emerging population health needs of wealthy countries, fundamentally transforming the relationship between bodyweight and longevity. Moreover, access to these technologies varies greatly across higher- and lower-income countries, leading to marked differences in the bodyweights that maximize health (or minimize mortality risk). Current bodyweight classification standards such as "overweight" (BMI 25-30) and "obese" (BMI 30+) do not reflect the moderating role of this technological progress or differences in access to health technology. Incorporating the changing role of technology, and variation in access to it, is critical for understanding the population health implications of changing anthropometric status around the world. In some cases, higher bodyweights may not unambiguously

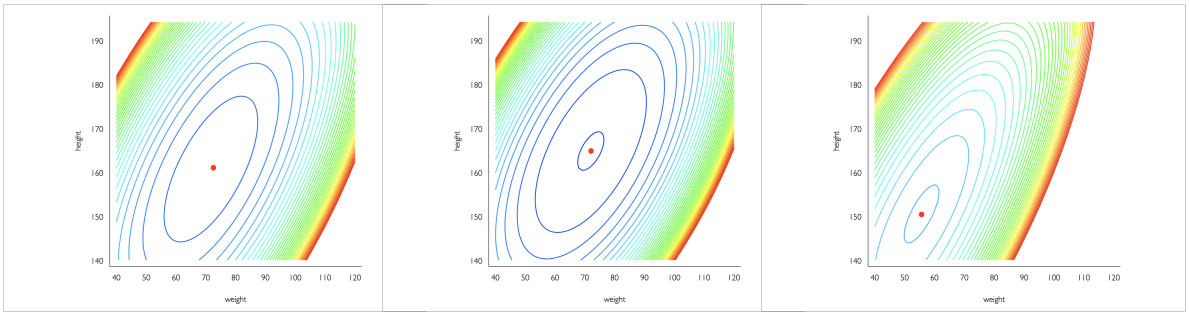
Figure 1: Waaler iso-mortality curves by gender and country

Men



USA Mexico Indonesia

Women



USA Mexico Indonesia

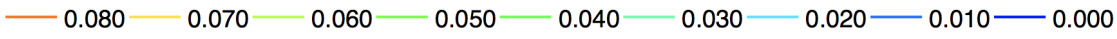


Figure 2: Waaler minimum mortality probability curve by gender and country

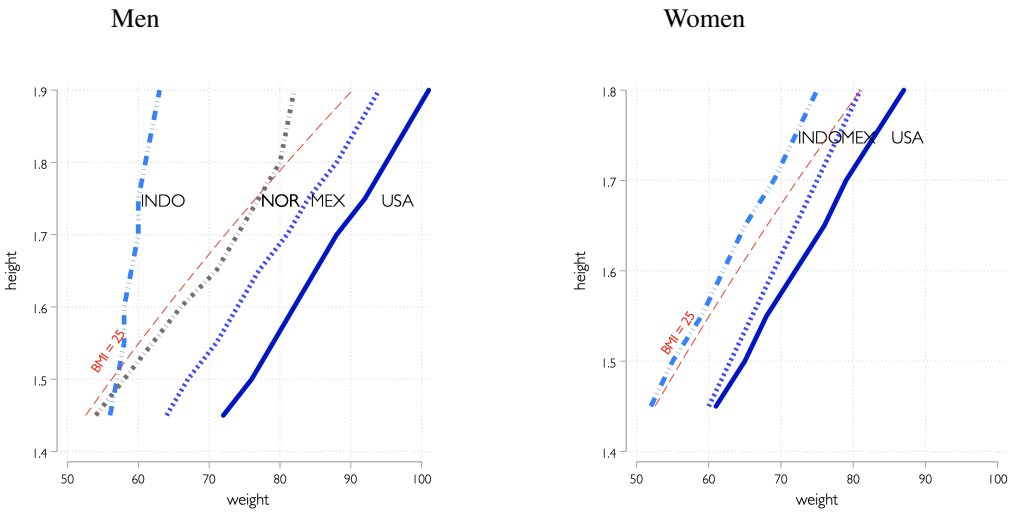


Figure 3: Number of lives saved by moving to optimum weight in the USA



Figure 4: Number of lives saved by moving to optimum weight in Mexico

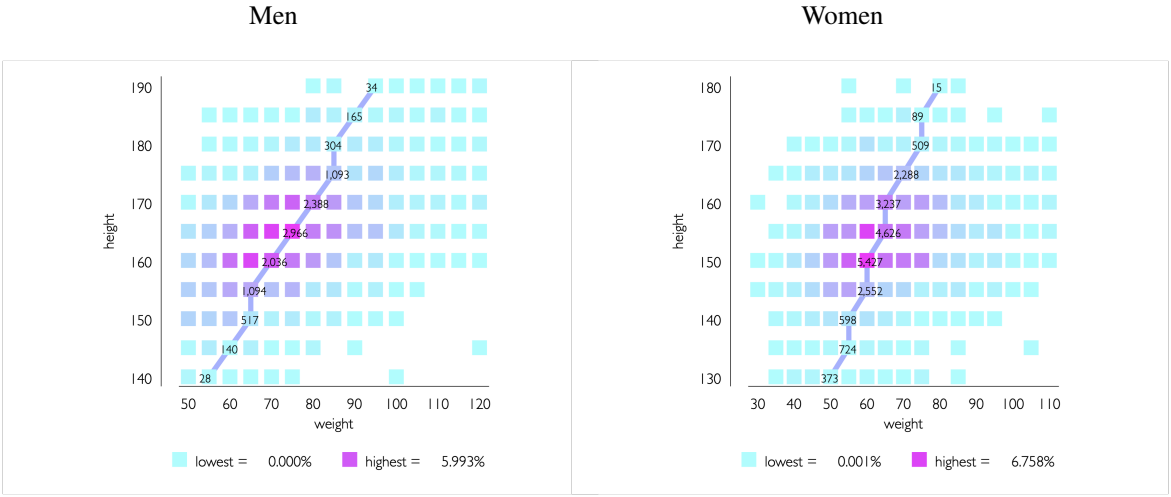
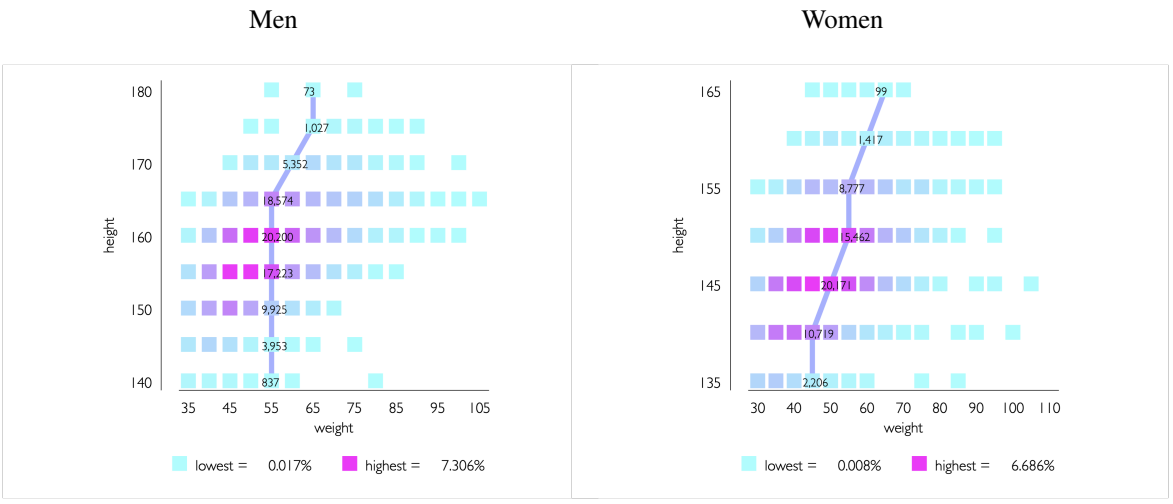


Figure 5: Number of lives saved by moving to optimum weight in Indonesia



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A Supplement

A.1 Data sources

We use individual-level longitudinal datasets which contain information on height, weight, and mortality for USA, Mexico and Indonesia.

The data sources used for the analysis are the Health and Retirement Survey (HRS) for the United States, the corresponding Mexican Health and Aging Study (MHAS) for Mexico, and Indonesian Family Life Survey (IFLS) from RAND for Indonesia. In particular we use the harmonized versions of the USA and Mexican, both coming from the Gateway to Global Aging platform. The HRS and the MHAS data are multipurpose, longitudinal household surveys, representing the population aged 50 years or older. The samples include age-eligible persons and their spouses or partners (regardless of age). Also the Indonesian IFLS represents a multidisciplinary, longitudinal household survey, where the age range is wider, sampling individuals aged 26 and older. Over the years IFLS has been redesigned to collect data on health and retirement behavior comparable to the HRS family of surveys. The data in all the three surveys is self-reported, and provides information on a wide range of dimensions. We focus on anthropometric measures, health conditions, socioeconomic status, education and demographic characteristics, including death episodes and their dates. The data allow continuous cross-sectional descriptions of the underlying populations, longitudinal studies of given cohorts over a substantial periods of time, and research on cross-cohort trends. Table A1 presents the main features of the three data sources.

A.2 Data selection

The HRS and the MHAS focus on aging populations aged 50 and more.We apply a comparable age restriction to the the IFLS, using samples of men and women aged 50-79. By way of comparison, Fogel (1994) uses a different age range, 50-64 year-olds, based on data collected by Waaler (1984) combining information of anthropometric measures obtained from the State Mass Miniature Xray Examination carried out between 1963 and 1975 in Norway, with the death register of the Central Bureau of Statistics registered between 1963 and 1979. We allow for a wider observation window, on the one hand, in order to base our analysis on larger sample sizes, and on the other hand, in order to account for life expectancy gains experienced in the recent decades.

Table A1: Data sources

	USA HRS	**Mexico MHAS**	**Indonesia IFLS**
Waves	2000/01, 2002/03, 2004/05, 2006/07, 2008/09, 2010/11, 2012/13, 2014/15 , 2016/17	2000/01, 2002/03, 2012/13, 2014/15	2000, 2007/2008, 2014/15
Survey type	Household level, Longitudinal , Self-reported	Household level, Longitudinal , Self-reported	Household level, Longitudinal , Self-reported
Target population	Age 50+	Age 50+	All ages (26+)
Characteristics	Around 44,000 individuals	Around 15,000 individuals	Around 33,000 individuals, with above 90% re-contact rate each year, the survey sample represented about 83% of the Indonesian population, and as the population aged, it turned comparable to HRS style data collections

We construct 6 data samples, referring to the three countries analyzed for male and female respondents separately. We first pool all available information on respondents aged 50-79 ever present in all available survey waves conducted between 2001 and 2016 for each country and gender separately. The three data sources are collected in waves scattered in different points in time. Table A1 presents the recent available waves. The HRS data are collected every second year and we employ the nine waves available from 2000/01 through 2016/17. The MHAS data collection was less homogeneous in time, with a substantial time interval between the second and the third wave, delivering 4 waves of observation. Finally, the IFLS data were collected in three waves in the period considered.

We exploit the longitudinal nature of the data and trace the respondents over time. We apply to each data source a procedure of rectangularization, where we fill in the data relative to years between two subsequent waves. We use tracking files available in each wave of each data source in order to collect the information on the status of individuals across subsequent waves. For years in which the data collection did not take place, we interpolate the missing information on weight and height at the individual level with a nearest neighbourhood imputation, based on the nearest data available. We also reconstruct individual age. The procedure is carried out for each individual until their death of their attrition from the sample. In each wave we retrieve the status of each individual form the tracking files and in particular, we exploit the information on whether an individual died. Each tracking file reports retrospectively death years of

all individuals interviewed in the preceding wave who died after the last interview.

For each data source we thus end up with a longitudinal dataset relative to years 2001-2016. We subsequently divide the data in gender specific samples and eventually end up with 6 unbalanced panels, where the unbalance comes from both new 50-year-olds joining the survey, as well as individuals dying or leaving the sample or becoming older than 79 years of age. The descriptive statistics on the variables and data samples constructed are presented in table A2.

Table A2: Descriptive statistics

	HRS - USA		MHAS - Mexico		IFLS - Indonesia	
	Men	Women	Men	Women	Men	Women
Raw data						
	2001-2016		2001 - 2015		2001 - 2014	
Age (years)	62	63	61	61	60	61
Weight (kg)	90	75	74	66	56	51
Height (cm)	177	163	166	156	160	149
BMI	28	28	27	27	22	23
Disease	.62	.58	.42	.57	.05	.07
Death	0.013	0.010	0.008	0.006	0.013	0.001
N	76.254	96,719	25,133	30,004	9,509	11,490
Rectangularized data						
	2001-2012		2001 - 2011		2001 - 2010	
Age (years)	62	63	61	61	60	61
Weight (kg)	90	75	74	66	55	49
Height (cm)	177	163	166	156	160	148
BMI	28	28	27	27	22	23
Disease	.61	.57	.43	.61	.02	.02
Death	0.013	0.010	0.010	0.007	0.023	0.017
N	115,309	144,577	70,999	83,747	28,849	33,731

Notes: The statistics in the first panel refer to raw data relative to the waves carried out, while the second panel refers to rectangularized filling in for the periods where the data collection was not carried out.

Unlike Fogel (1994), and as a consequence Waaler (1984), the longitudinal rectangularized data allows us to control for the time lag between the moment of death and that of the measurement of weight and height. In fact, time to death is associated with the onset and rate of weight loss, in addition to chronological age (**?**). Several studies suggest that pre-existing occult disease might be a significant confounder for elevated mortality at lower levels of body mass index (BMI), thus recommending eliminating subjects who die during the very first years of follow-up (**?**). In order to account for the issue of unintentional weight loss as a marker for fast health deterioration, in our core specification we exclude weight and height measurements in three years before the death year. This homogenous temporal separation for all three countries and gender groups is likely to improve consistency and comparability of the findings.

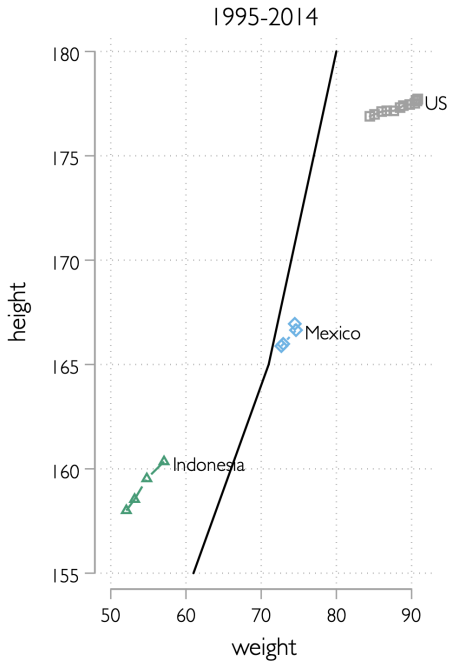
Finally, due to the presence of outliers and measurement errors, we perform a data cleaning procedure,

where we discard the bottom and top percentile of BMI distribution for each data sample. Additionally, in order to reinforce the precision of the estimates, in the case of the MHAS and the IFLS data, we top code the first and last percentile of the weight and height distribution.

A.3 Body weight evolution

Figure A1 pictures population average heights and weights trend for males (ages: 50 - 79), as measured in HRS, MHAS and IFLS data, for the United States, Mexico and Indonesia, respectively. This minimum risk curve shows the bodyweight that minimizes mortality risk for each height (i.e., it is the set of bodyweights that minimizes mortality risk across the height distribution, with increasing mortality risk at bodyweights both to the left and right of the curve) - in this case, estimated using the 1963-1975 Norwegian sample. In the United States, average stature (or height) has generally remaining constant over time, while average bodyweight has increased - starting to the right of Fogel's minimum risk curve, and systematically moving further above it by 2014 (reflecting the well-known increase in obesity in the U.S.). In Mexico and Indonesia, average stature has steadily risen over time, and average bodyweight has as well - in Mexico, starting near the minimum risk curve and rising above it over time, and in Indonesia, moving towards it (but still remaining below by 2014).

Figure A1: Population average heights and weights trend and Waaler's minimum mortality risk curve for elderly males (ages: 50 - 79) - Source: HRS, MHAS and IFLS data



A.4 Methods

Following Fogel (1994), we fit the iso-mortality curves in relation to weight and height. Unlike Fogel (1994), we exploit the individual level data and estimate the probability of dying in relation to individual weight and height combinations, controlling for age and education. In all cases, we examine the data separately for men and women treating each year as though it were an independent cross-section. We estimate a probit cubic response surface, with weights and heights products of maximum 2nd order. In particular we for each dataset and gender subsample, we estimate the the following risk-height-weight relationship:

$$Death_{it} = \alpha + \beta_1 H_{it-4} + \beta_2 H_{it-4}^2 + \gamma_1 W_{it-4} + \gamma_2 W_{it-4}^2 + \delta W_{it-4} * H_{it-4} + \lambda Age_{it} + \epsilon_{it} \quad (1)$$

where an event of $Death_{it}$ stands for an event of death of individual i in period t, H_{it-4} and W_{it-4} are Height in meters and and weight in kilogrammes measure on the fourth year before the event of death, with their squared terms and the interaction term. Finally, Age_{it} is age in years, while ϵ_{it} is a standard idiosyncratic error term. The estimates are computed using sampling weights. Table A3 presents probit coefficient estimates of the six models respectively.

Table A3: Probit estimates

	HRS - USA		MHAS - Mexico		IFLS - Indonesia	
	Men	Women	Men	Women	Men	Women
weight	0.0258	0.0323**	0.0344	0.0770	-0.0391	0.0453
	(0.0194)	(0.0162)	(0.0629)	(0.1035)	(0.0569)	(0.0504)
weight*weight	0.0004***	0.0003***	0.0003*	0.0005	0.0006***	0.0005***
	(0.0000)	(0.0000)	(0.0002)	(0.0003)	(0.0002)	(0.0001)
height	-0.1024*	-0.0701	-0.0830	-0.3642*	-0.0028	-0.0824
	(0.0538)	(0.0467)	(0.1002)	(0.1935)	(0.1229)	(0.1289)
height*height	0.0004***	0.0003**	0.0004	0.0014*	0.0000	0.0004
	(0.0002)	(0.0002)	(0.0004)	(0.0008)	(0.0004)	(0.0005)
weight*height	-0.0005***	-0.0005***	-0.0005	-0.0009	-0.0007*	-0.0007*
	(0.0001)	(0.0001)	(0.0005)	(0.0009)	(0.0004)	(0.0004)
age	0.0358***	0.0365***	0.0479***	0.0389***	0.0300***	0.0307***
	(0.0015)	(0.0016)	(0.0027)	(0.0039)	(0.0021)	(0.0021)
R2						
N	97857	105690	56723	59580	28603	35484

Standard errors reported in parenthesis, are clustered at the individual level, * p<0.05, ** p<0.01, *** p<0.001

The coefficient estimates for each data source and gender are subsequently employed to perform a

prediction of individual mortality risk based on a smooth grid of each height/weight combination in intervals proportioned to whole centimeters and kilograms. The education and age are set at the sample mean.

We then plot 3 dimensional surfaces graphs relating weights and heights combination to the relative mortality risk prediction in Figure 1 in the body of the text. The figures are structured as heat maps, where red tones signal higher mortality probability levels.

Additionally, based on the predicted values, we retrieve minimum risk lines. The minimum-risk lines are defined by the locus (Weight, Height) pairs such that for any given Height, the chosen Weight minimizes the mortality risk. In practice, for each 5-centimeter interval of Height, we determine the Weight corresponding to the lowest mortality risk. The results are presented in the body of the text.

A.5 Mortality reduction computation

Given the minimum mortality risk lines, we compute estimates of the potential mortality reduction under the assumption that all individuals reach the optimal weight. The exercise foresees a simulation where the weight of individuals in each 5-centimeter height interval is moved to the optimal level as defined by our estimates present in Figure 2. In order to construct figure 3, we first summarize the underlying population for each country and gender separately in terms of their weight and height. The background of figures 3-5 can be read as two-dimensional histograms in which the frequencies of combinations of binned heights and weights are displayed as rectangular field using a color gradient. The bins pool individuals falling into the combination of each 5-centimeter height interval and 5-kilogramme weight interval. The colors range from light blue to dark purple and describe lowest to highest relative frequencies, respectively. The estimates presented in this section refer to population sizes in the last year of the survey available. Using the population sampling weights available in each of the data, in 2016 in the USA the population aged 50-79 amounted to 44 mln of men and 48 mln of women; in 2014 Mexico population was equal to 9.9 mln of women and to 9.5 mln of men; finally, in Indonesia the population corresponded to 19.6 mln of men and 20.1 mln of women. While the HRS and the MHAS study is representative at the national level, the estimates for Indonesia refer to the IFLS study population, which consists of 13 major Indonesian provinces, representing 83% of the overall Indonesian population.

In order to compute the number of individuals whose lives could be saved if their weight, given their

height was shifted to the optimum, we compare two sets of predictions based on our model estimates (Table A3). The first set is the one relative to the actual weights and heights, while the second set simulates the mortality predictions, imputing to individuals their optimum weight, given their height. The final step of the exercise is the quantification of deaths in the first and in the second scenario and computation of the avoidable mortality. The numbers of individuals saved for each 5-centimeter bin of height are superimposed on each height interval in proximity to the minimum-risk line.