Health inequalities and inequities by age: Stability for the Health Utilities Index and divergence for the Frailty Index

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\textit{ABSTRACT}

Successful aging is an important policy goal in an aging society. A key indicator of successful aging of a population is whether health inequalities (differences) and inequities (unfair differences) in the population increase or decrease with age. This study investigates how health inequalities and inequities differ across age groups in the Canadian population within the equity framework of equal opportunity for health, using two popular measures of health, the Health Utilities Index Mark 3 (HUI) and the Frailty Index (FI). We use the 2009-10 Canadian Health Measures Survey. We first quantify the degree of health inequality by calculating the Gini coefficient for the distributions of the HUI and the FI within three age groups (20–44, 45–64, and 65–79 years). We then identify sources of health inequality by using regression models and decomposing inequality into ethically acceptable and unacceptable components. We finally quantify the degree of health inequity by calculating the Gini coefficient for each health measure and each age group after standardizing for fairness. We find that the magnitudes of inequality and inequity in the HUI and the FI in each of the three age groups are policy relevant. The magnitude and age-related dynamics of health inequality and inequity depend on the choice of the health measures. In all three age groups, inequality and inequity in health measured by the HUI are larger than those measured by the FI. Across the three age groups, inequality and inequity are stable in the HUI but divergent in the FI. This study contributes to the methodological development to support policies for successful aging. Examination of alternative notions of health captured by the HUI and the FI contributes to the exploration of how the fair distribution of each aspect of health may characterize a successfully aging population.

\textbf{1. Introduction}

Faced with aging populations, countries around the world strive to foster successful aging (World Health Organization, 2015). What constitutes successful aging – sometimes also referred to as healthy aging or optimal aging – is often debated, but health is indisputably an essential component of successful aging (Depp & Jeste, 2006; Rowe & Kahn, 1997). While successful aging is most commonly framed at the individual level, it can also be framed from a population perspective, which introduces a new consideration: equity in the distribution of health within a population. A successfully aging population has both a good overall level of health and a fair distribution of health (World Health Organization, 2015). Thus, when viewed from a population perspective, a key indicator of successful aging is whether health inequalities (i.e., differences) and inequities (i.e., unfair differences) in the population increase or decrease over the life course. Achieving health equity is a widely endorsed health policy goal in many countries (Marmot, 2010; WHO Commission on Social Determinants of Health, 2008), and it applies importantly as a population ages.

Aging is more than chronological age, and two conceptions of aging predict how aging might drive health inequalities over the life course. In the first conception, aging is a process of health deterioration leading to death. Because all individuals have to die at some point and each cohort has a maximum lifespan, the deterioration process would lead to a decrease in health inequalities as a population – or more precisely, a cohort – increases in chronological age. In this conception, aging thus acts as a leveler of health inequalities, predicting convergence over the life course (Quesnel-Vallée, Willson, & Reiter-Campeau, 2015). In the

\textsuperscript{⁎} Our study used data collected from human subjects by Statistics Canada. The data were publicly available and legally accessible by following strict disclosure protocols according to the Statistics Canada Act. Thus, this study was exempt from the research ethics board review based on Article 2.2(a) of the Tri-council Policy Statement, Ethical conduct for research involving humans (TCPS2 2014) http://www.pre.ethics.gc.ca/eng/policy-politique/initiatives/tcps2-eptc2/Default/.

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second conception, aging is exposure to insults that accumulate over time. Differences in exposure to insults early in life likely have cumulative effects over time, leading to an increase in health inequalities as a cohort adds chronological age (Dannefer, 2003). In this conception, aging thus acts as an amplifier of health inequalities, predicting divergence over the life course.

How these two conceptions of aging drive health inequalities over the life course is more complicated. It depends on whether one considers the deterioration and accumulation processes as unfair or fair. If one considers as unfair the mechanism through which differential deterioration occurs for different people, then, the expected convergence of health inequalities over the life course indicates convergence of health inequalities over the life course. Aging acts as a leveler of health inequities and health inequalities. Analogously, if one considers the accumulation process as unfair, then, the expected divergence of health inequalities over the life course suggests divergence of health inequalities as well. Aging in this case acts as an amplifier of health inequities and health inequalities. Diverse views exist as to whether to consider the deterioration and accumulation processes as unfair or fair. For example, if, following Phelan and Link, the accumulation process is driven by social conditions that influence access to critical, flexible resources (e.g., money, power, and prestige) (Link & Phelan, 1995; Phelan, Link, & Tehranifar, 2010), and these social conditions are unfair determinants of health, the accumulation process is unfair. Alternatively, if one subscribes to the view that personal choices are an unfair source of health inequality (Roemer, 1995; Segall, 2010), and personal choices importantly influence the deterioration process and accumulation processes, both processes would be fair. In this case, convergence (divergence) of health inequalities would not necessarily indicate convergence (divergence) of health inequalities.

Available empirical studies investigating equity and age-related dynamics of health distributions have focused almost exclusively on issues of health and socioeconomic status (Read, Grundy, & Foverskov, 2016). Such studies typically describe the bivariate relationship between health and a socioeconomic indicator (e.g., income, education, or occupation) by age, on the assumption that these social inequalities in health are inequitable. Empirical evidence is mixed, without a clear pattern of findings across a range of health measures, socioeconomic indicators, populations, types of data, and study periods. For example, in studies using longitudinal data from Europe (Stolz, Mayerl, Waxenegger, Räsly, & Freidl, 2017), England (Marshall, Nazrro, Tampubolon, & Vanhoutte, 2015), and the United States (Yang & Lee, 2010), socioeconomic inequalities in health (measured by the Frailty Index (Rockwood & Mitnitski, 2007; Searle, Mitnitski, Gahbauer, Gill, & Rockwood, 2008)) variously diverged, converged, or remained constant across age groups. While socioeconomic status is unquestionably a critical element of health inequality, it is only one element (Fleurbaey & Schokkaert, 2009). To assess why socioeconomic status is a key element and what other elements to consider, we need an ethical framework that allows us to elaborate what constitutes unfair or ethically problematic differences in health (Segall, 2010; Whitehead, 1991; Braveman, Arkin, Orleans, Proctor, & Plough, 2017; Daniels, 2008; Hausman, 2009; Norheim & Asada, 2009; Ruger, 2010; Venkatapram, 2011). It is important to understand how health inequality more broadly conceived changes as a population ages.

A central contribution of this study is the explicit incorporation of an ethical framework in the investigation of age-related dynamics of health distributions. This study investigates how health inequalities and inequities differ among age groups in the Canadian population, using a methodological approach that explicitly and transparently accommodates alternative definitions of health inequality (Asada, Hurley, Norheim, & Johri, 2014; Asada, Hurley, Norheim, & Johri, 2015). For this study, we adopt the equity framework of equal opportunity for health. This framework originates in a philosophical theory of justice, often referred to as luck egalitarianism, which regards as unfair health inequalities due to factors beyond individuals’ control, and as fair inequalities those that result from individuals’ choices (Roemer, 1995; Segall, 2010; Fleurbaey, 2008; Kanbur & Wagstaff, 2016). We adopt this framework for two reasons. First, equal opportunity for health has been gaining increasing attention in recent years in both scholarly and policy audiences (Roemer, 1995; Segall, 2010; Fleurbaey, 2008; Kanbur & Wagstaff, 2016), and substantial effort has been devoted to developing empirical approaches to implement this framework (Fleurbaey & Schokkaert, 2009, 2012; García-Gómez, Schokkaert, Van Ourti, & Bago d’Uva, 2015; García-Gómez, Schokkaert, & Van Ourti, 2013; Jusot, Tubeuf, & Trannon, 2013; Rosa Dias, 2009; Rosa Dias, 2010; Trannon, Tubeuf, Jusot, & Devaux, 2010). Second, conceptually, equal opportunity for health embeds a life-course perspective. Many childhood exposures and experiences considered beyond the control of an individual can have lifelong health consequences, while the range of determinants originating in individual choices increases through adulthood. Bringing a life-course perspective in empirical implementation may be informative for further development of this framework. While we adopt the equity framework of equal opportunity for health in this paper, our work is not intended to advocate exclusively for this framework. Rather, we argue for a transparent incorporation of an explicit ethical perspective of health equity beyond the focus on socioeconomic status alone. Our sensitivity analysis suggests that key findings in this paper also hold for at least one other currently debated alternative equity definition, policy amenability, which argues that health inequalities rooted in factors that are amenable to policy intervention are unfair (Norheim & Asada, 2009).

Another central contribution of this study is the use of well-validated and widely-applied measures of health—the Health Utilities Index (HUI) and the Frailty Index (FI)—in the examination of age-related dynamics of health distributions. The HUI and the FI capture health in different ways: The HUI is a measure of health-related quality of life that reflects community-based preferences (Horsman, Furlong, Feeny, & Torrance, 2002), while the FI is an indicator of frailty based on the aggregation of deficits with no weights reflecting any type of preference (Rockwood & Mitnitski, 2007; Searle et al., 2008). We highlight alternative notions of health these measures capture as a potentially important driving force of differences in the magnitude of inequality and inequity and their age-related dynamics between the HUI and FI observed in this study. The examination of alternative notions of health captured by the HUI and the FI contributes to the exploration of how the fair distribution of each aspect of health may characterize a successfully aging population.

2. Methods

2.1. General analytic approach

This study adopts an analytic approach that we previously developed (Asada et al., 2014; Asada et al., 2015). This approach incorporates, in an explicit and transparent manner, alternative definitions of health inequality into the measurement of inequality, as described below. See Appendix 1 for technical details.

Step 1. Measuring health inequality

The first step uses an inequality index to quantify variation in observed health across individuals. In principle, one can use any suitable univariate inequality index. In this application, we use the widely applied Gini coefficient (see below) (Sen, 1997; Smits & Monden, 2009).

Step 2. Understanding sources of health inequality

The second step identifies sources of health inequality both statistically and normatively. The statistical analysis seeks to explain as much variation in health as possible with the data at hand, while the normative examination calls for ethical judgment as to which sources of
health inequality are ethically acceptable (“legitimate” (Fleurbaey & Schokkaert, 2009, 2012)) or unacceptable (“illegitimate” (Fleurbaey & Schokkaert, 2009, 2012)). The ethical judgments in this study are guided by the view of equal opportunity for health. We carry out three tasks in this step: modeling health using multiple regression; classifying variables as legitimate or illegitimate; and decomposing inequality into legitimate and illegitimate components.

Modeling health

We use regression analysis to quantify the association between health and its determinants. The determinants fall into four categories: biological endowments (biological attributes that a person is born with); social background (social attributes that a person is born into or acquires later in life that often influence the possession of resources of diverse instrumental value for life in general); health-affecting behaviors; and social support.

Classifying variables as legitimate and illegitimate

Next, we classify each variable as a legitimate or illegitimate source of health according to our chosen definition of inequity, equal opportunity for health. This classification process requires judgment. “Individual control” is a key dividing line to decide the ethical status of determinants of health according to the view of equal opportunity for health: determinants beyond the control of the individual are illegitimate; determinants under the control of the individual are legitimate. As shown in Table 1, we classify age and health behavior variables as legitimate and all other variables as illegitimate. We treat age as legitimate, because, although it is not under individual control, aging is a universally shared process among all persons (Daniels, 1988). We acknowledge that health behaviors are not solely under individual control as they are also influenced by an individual’s circumstances. We accommodate this by estimating the effects of health behavior variables on health conditional on social background and social support variables. Depending on the nature of the health variable, we classify the variable “sex” as biological sex (in the FI model) or as gender, representing social background (in the HUI model).

Classifications like this are at the heart of defining health inequity and often generate heated debate as the legitimate-illegitimate classification of a variable is often not clear-cut. For example, the variable “sex” can capture both biological sex and gender. Whether one engages in health damaging behaviors or how much education one obtains, is influenced both by personal decisions and circumstances. There is no consensus regarding all aspects of such classifications. The strength of our analytic approach is to make assumptions transparent and explicit, and the ability to test the sensitivity of the results to alternative classifications of determinants.

Decomposing inequality into legitimate and illegitimate components

Finally, we decompose observed health inequality into its legitimate and illegitimate components. To do so, we use a regression-based inequality decomposition method (Cowell & Fiorio, 2011). This method enables us to quantify the proportion of health inequality explained by each variable and the proportion of health inequality left unexplained (i.e., residuals). Summarizing this result based on the legitimate-illegitimate classification above, we estimate proportional contribution as follows:

\[
\text{Observed health} = \text{Legitimate} + \text{Illegitimate} + \text{Unexplained}
\]  

Step 3. Measuring health inequality

The final step estimates the unfair distribution of health across individuals in the population. To estimate unfair health, we use a well-established method, fairness-standardization (Fleurbaey & Schokkaert, 2009, 2012), which removes the influence of the fair component attributable to legitimate determinants. This standardization leaves inequity due only to unfair sources and constitutes the distribution of inequitable health in the population.

In this study, we use the indirect fairness-standardization method, which reflects the view that health inequalities due to factors beyond individual control are unfair and should be compensated by society (often referred to as the principle of compensation (Fleurbaey & Schokkaert, 2009, 2012; Brunori & Peragine, 2011)). Specifically, for each individual we predict fair health by allowing only the legitimate variables to influence the predictions. We purge the influence of illegitimate variables by holding their values at the mean during prediction:

\[
\text{Fair health}_i = \text{Legitimate}_i + \text{Illegitimate}_i
\]

We then calculate unfair health by subtracting the estimate of fair health from the observed health and adding the mean health of the population:

\[
\text{Unfair health}_i = \text{Observed health}_i - \text{Fair health}_i + \text{Mean health}
\]

The addition of the mean health of the population ensures that the distributions of the observed health and the unfair health have the same mean value (O’Donnell, van Doorslaer, Wagstaff, & Lindelow, 2007). As Eq. (3) shows, our formulation of indirect standardization implicitly considers the unexplained component as an unfair source of inequality.

The amount of inequality (i.e., inequality in the distribution of unfair health) is then measured by applying the same index as in Step 1 to the distribution of unfair health, in our case, the Gini coefficient.

2.2. Data

We use cycle 2 (2009-10) of the Canadian Health Measures Survey (CHMS), a cross-sectional, comprehensive health survey conducted by Statistics Canada (Statistics Canada, 2012). The CHMS collects information regarding health status, health behavior, demographic, socioeconomic status, and housing and environmental characteristics through self-reported household questionnaires and direct health

| Table 1 |
| --- |
| Legitimate-illegitimate classification of variables according to the view of equal opportunity for health. |
| Variable category | Illegitimate determinant | Legitimate determinant |
| --- | --- | --- |
| Biological endowment | Sex (for FI), family medical history | Age |
| Social background | Sex (for HUI), visible minority status, immigrant status, province, education, income | Recreational drug (light and heavy)*, sleep, STD, alcohol, BMI, sedentary activity, physical activity |
| Health behaviour | Sense of community belonging, leisure activity | |
| Social support | |

FI: Frailty Index; HUI: Health Utilities Index; STD: sexually transmitted disease; BMI: body mass index

* Light recreational drugs include marijuana, cannabis, or hashish, and heavy recreational drugs include prescription, street, or injected drugs.
assessments at mobile examination centers (MEC). The target population is non-institutionalized household residents aged 3 to 79 years in 10 provinces and 3 territories in Canada. The CHMS uses a complex sampling design with multiple sampling units (MEC sites, households, and respondents) and stratification by age group.

The CHMS cycle 2 is well suited for this study for two reasons. First, its diverse data on determinants of health allow detailed examination of sources of inequalities. Second, its rich information regarding health status enables comparison of inequalities using different measures of health. Specifically, cycle 2, unlike other cycles, includes the HUI. In addition, the detailed information on health status, assessed both physically and by self-report, supports the construction of the Frailty Index.

The original sample size of the CHMS cycle 2 is 6395. The overall response rate, considering response rates at multiple stages of sampling, is 55.5%. For our study, we exclude observations that are younger than 20 years old (n = 2742). After further excluding observations with missing values of variables used in the analysis and observations with the HUI score less than or equal to zero, the final sample size is 3430.

2.3. Variables

Measures of health (dependent variables)

We use two measures of health: The Health Utilities Index Mark 3 (HUI) and the Frailty Index (FI).

The HUI is a generic health-related quality of life measure that assesses the respondent’s functional status in eight dimensions (vision, hearing, speech, mobility, dexterity, emotion, cognition, and pain) and converts his or her functional status into a health-related quality-of-life score based on preferences of the general public over functional health states (Horsman et al., 2003). The observed distribution of HUI scores in the full sample ranges from -0.360 to 1.000 on a scale in which 0.000 represents being dead, 1.000 represents full health, and negative scores indicate health states worse than dead. Previous studies suggest a difference of 0.03 or greater as meaningful or important — a difference large enough to justify a recommendation for an intervention to achieve such an increment in health (Horsman et al., 2003; Drummond, 2001).

We use only observations with zero or positive HUI scores because the Gini coefficient allows only non-negative values for the variable being analyzed (Chen, Tsaur, & Rbai, 1982).

The Frailty Index (FI) is based on the aggregation of deficits (Rockwood & Mitnitski, 2007; Searle et al., 2008). The FI counts 30 or more non-specific “deficits in health.” These deficits can be symptoms, signs, diseases, disabilities, or laboratory-assessed abnormalities. The FI is a ratio of the number of deficits present to the total number of deficits considered (e.g., 10/30 = 0.330), where an FI of 0.000 indicates the absence of any deficit, and 1.000 indicates the full expression of deficits. Validation of the FI has shown that, regardless of the number and specific types of deficits used, the index follows a continuous, gamma distribution; the rate of deficit increase is about 0.300 per year; and deficits aggregate up until about 0.700 (Rockwood & Mitnitski, 2007; Searle et al., 2008). We constructed our FI using 46 variables ranging from laboratory tests to self-reported function and chronic conditions available in the CHMS (Appendix 2), selected based on the criteria recommended in the literature (Rockwood & Mitnitski, 2007; Searle et al., 2008). Previous studies use a difference of 0.02–0.03 or greater as meaningful as it typically indicates a change in response categories in one of the variables used to construct the FI (Fallah et al., 2011). This difference is also equivalent to the annual deficit increase rate.

We transform the FI into the “flipped” FI (FFI), 1 – FI, whereby 0.000 represents the full expression of deficits, and 1.000 represents the absence of any deficit. We use the FFI, instead of the FI so that for both the HUI and frailty larger values indicate better health, and smaller values indicate worse health, which facilitates comparison of analyses based on these two measures and use of the Gini coefficient to measure inequality and inequity (see below).

Determinants (independent variables)

We use a number of variables known to be associated with these two health measures, as listed in Table 1.

2.4. Index of inequality and inequity

We use the Gini coefficient to quantify the degree of inequality and inequity in the distributions of the HUI and the FFI (see Appendix 3 for technical details). The Gini coefficient is widely used in the income inequality literature (Sen, 1997) and has also been applied to the distribution of health (Smits & Monden, 2009). The Gini coefficient applied to distributions of the HUI and the FFI can be interpreted from a policy perspective: twice the value of the Gini coefficient multiplied the population mean indicates the expected mean difference between two randomly selected persons in the population (Atkinson, 2013). We consider the degree of inequality or inequity to be policy relevant when a difference in the Gini coefficient is greater than the aforementioned, minimally policy-relevant values of the HUI (0.03) and the FFI (0.02). For example, if the Gini coefficient for the HUI distribution is 0.098 and the mean HUI is 0.869, the expected mean difference in the HUI between two randomly selected persons in the population would be 0.170 (=2×0.098×0.869), which is greater than the minimally policy-relevant value of the HUI of 0.03, hence, the Gini coefficient of 0.098 is policy relevant.

2.5. Analysis

The analysis follows the three steps in the general analytic framework described above for each of the HUI and FFI separately. To model health in the second step, we use Ordinary Least Squares (OLS) regression. Modeling the HUI is challenging due to its skewed distribution and the ceiling effect. The literature is inconclusive as to the best statistical methods to model the distribution of the HUI (Huang et al., 2008; Li & Fu, 2009; Pullenayegum et al., 2010; Sullivan & Ghushchyan, 2006). In the absence of a clear recommendation, we opt to use OLS for ease of interpretation. We start with the same set of independent variables for both measures of health. For each health measure, we retain variables that remained statistically significant at the 5% level. We report inequality, inequity, and inequality decomposition results for the full sample and separately by age group.

All analyses are weighted using the sample weights provided by the CHMS. To estimate standard errors accounting for the CHMS’s complex survey design, we use a bootstrap method with bootstrap weights provided by Statistics Canada. We consider p < 0.05 as statistically significant. Stata 14 is used for all analyses (StataCorp, 2015).

3. Results

3.1. Sample characteristics

Our CHMS sample of non-institutionalized household residents in Canada aged 20–79 in 2009-10 had a mean HUI of 0.869 (95% Confidence Interval [CI]: 0.855, 0.883) and a mean FFI of 0.870 (95% CI: 0.866, 0.875) (Table 2). The HUI and the FFI vary largely in expected directions by sample characteristics. Of note, how the mean HUI and the mean FFI differ by age group indicates potentially different relationships between age and these two measures of health: The mean HUI does not differ statistically significantly across the three age groups, while the mean FFI is statistically significantly lower in older age groups. In addition, the confidence intervals for the mean HUI are much larger than those for the mean FFI in all age groups.

3.2. Health inequality

As measured by the Gini coefficient, inequality in the distributions of HUI and FFI differs markedly. The Gini for the FFI (0.046; 95% CI:
## Table 2
Sample characteristics.

| Variable                        | Mean HUI (95%CI) | Mean FFI (95%CI) |
|---------------------------------|-----------------|-----------------|
| Total sample (N)                |                 |                 |
| 3430                            | 0.869 (0.855, 0.883) | 0.870 (0.866, 0.875) |
| Age (%)                         |                 |                 |
| 20–44 years                     | 0.886 (0.874, 0.899) | 0.908 (0.904, 0.913) |
| 45–64 years                     | 0.856 (0.836, 0.877) | 0.852 (0.844, 0.859) |
| 65–79 years                     | 0.847 (0.827, 0.867) | 0.795 (0.787, 0.803) |
| Sex (%)                         |                 |                 |
| Male                            | 0.877 (0.861, 0.893) | 0.873 (0.868, 0.878) |
| Female                          | 0.861 (0.842, 0.880) | 0.868 (0.862, 0.874) |
| Presence of family medical history (%) |         |                 |
| Yes                             | 0.865 (0.852, 0.878) | 0.861 (0.856, 0.867) |
| No                              | 0.882 (0.855, 0.908) | 0.900 (0.894, 0.906) |
| Visible minority status (%)     |                 |                 |
| Non-white, non-Aboriginal       | 0.893 (0.878, 0.907) | 0.865 (0.879, 0.901) |
| White or Aboriginal             | 0.863 (0.844, 0.881) | 0.890 (0.860, 0.870) |
| Immigration status (%)          |                 |                 |
| Non-immigrant                  | 0.863 (0.844, 0.883) | 0.867 (0.861, 0.874) |
| Immigrant (less than 5 years)   | 0.926 (0.895, 0.963) | 0.919 (0.907, 0.931) |
| Immigrant (5–9 years)           | 0.924 (0.902, 0.946) | 0.915 (0.909, 0.922) |
| Immigrant (10–19 years)         | 0.865 (0.834, 0.897) | 0.890 (0.883, 0.898) |
| Immigrant (longer than 20 years)| 0.865 (0.844, 0.887) | 0.845 (0.834, 0.856) |
| Province (%)                    |                 |                 |
| Ontario                         | 0.865 (0.838, 0.892) | 0.870 (0.863, 0.877) |
| Atlantic                        | 0.874 (0.870, 0.878) | 0.858 (0.841, 0.876) |
| Quebec                          | 0.891 (0.863, 0.919) | 0.875 (0.867, 0.883) |
| Prairies                        | 0.857 (0.829, 0.886) | 0.872 (0.861, 0.883) |
| British Columbia                | 0.855 (0.827, 0.883) | 0.868 (0.856, 0.881) |
| Education (%)                   |                 |                 |
| Less than high school graduate  | 0.821 (0.786, 0.857) | 0.826 (0.813, 0.839) |
| High school graduate            | 0.872 (0.844, 0.900) | 0.864 (0.856, 0.872) |
| Some post-secondary/trade certificate | 0.856 (0.793, 0.879) | 0.875 (0.867, 0.884) |
| College/university certificate  | 0.880 (0.864, 0.896) | 0.870 (0.861, 0.878) |
| Bachelor's degree               | 0.910 (0.894, 0.926) | 0.894 (0.889, 0.899) |
| Degree higher than Bachelor's degree | 0.901 (0.876, 0.927) | 0.888 (0.869, 0.908) |
| Income (%)                      |                 |                 |
| Lowest/low middle 40%           | 0.814 (0.753, 0.874) | 0.858 (0.839, 0.877) |
| Middle 20%                      | 0.811 (0.752, 0.871) | 0.855 (0.842, 0.867) |
| Upper middle 20%                | 0.861 (0.837, 0.885) | 0.861 (0.851, 0.871) |
| Highest 20%                     | 0.895 (0.878, 0.912) | 0.881 (0.876, 0.886) |
| Tried recreational drug (light) in lifetime (%) yes | | |
| Yes                             | 0.867 (0.850, 0.884) | 0.879 (0.871, 0.887) |
| No                              | 0.871 (0.856, 0.887) | 0.861 (0.855, 0.867) |
| Tried recreational drug (heavy) in life time (%) | | |
| Yes                             | 0.826 (0.778, 0.874) | 0.871 (0.854, 0.889) |
| No                              | 0.876 (0.861, 0.891) | 0.870 (0.866, 0.874) |
| Sleep (%)                       |                 |                 |
| Normal sleep (6–8 h)            | 0.886 (0.874, 0.897) | 0.876 (0.871, 0.881) |
| Short sleep (less than 6 h)     | 0.812 (0.769, 0.855) | 0.828 (0.807, 0.848) |
| Long sleep (more than 6 h)      | 0.795 (0.725, 0.866) | 0.864 (0.850, 0.879) |
| Have diagnosed with sexually transmitted (%) | | |
| Yes                             | 0.817 (0.772, 0.863) | 0.865 (0.849, 0.881) |
| No                              | 0.873 (0.859, 0.887) | 0.871 (0.866, 0.875) |
| Alcohol drink (%)               |                 |                 |
| Never drank                     | 0.888 (0.864, 0.911) | 0.878 (0.861, 0.896) |
| Former drinker                  | 0.777 (0.735, 0.820) | 0.844 (0.826, 0.862) |
| Occasional drinker              | 0.839 (0.808, 0.870) | 0.861 (0.851, 0.871) |
| Regular drinker                 | 0.888 (0.866, 0.910) | 0.877 (0.873, 0.881) |
| Regular heavy drinker           | 0.888 (0.866, 0.910) | 0.867 (0.854, 0.880) |
| Body Mass Index (%)             |                 |                 |
| Normal weight                   | 0.876 (0.856, 0.896) | 0.902 (0.895, 0.908) |
| Underweight                     | 0.821 (0.770, 0.871) | 0.842 (0.813, 0.871) |
| Overweight                      | 0.896 (0.885, 0.907) | 0.874 (0.869, 0.878) |
| Obese                           | 0.827 (0.804, 0.849) | 0.824 (0.817, 0.830) |
| Sedentary activity (per week, %) |                 |                 |
| Less than 10 h                  | 0.892 (0.866, 0.918) | 0.890 (0.879, 0.900) |
| 10–29 h                         | 0.893 (0.878, 0.908) | 0.877 (0.871, 0.883) |
| 30–44 h                         | 0.859 (0.837, 0.881) | 0.855 (0.846, 0.864) |
| More than 45 h                  | 0.773 (0.731, 0.815) | 0.851 (0.840, 0.863) |

(continued on next page)
The Gini coefficients suggest that if we were to take two persons at random among Canadian adults, the expected difference in their HUI would be 0.170 and in their FFI would be 0.080, both of which are greater than the minimally policy-relevant differences (Appendix 4).

The degree of inequality by age is stable for the HUI but diverges for the FFI (Fig. 1). The Gini coefficients for the HUI in the three age groups are not statistically significantly different from each other (p < 0.05). For the FFI, the Gini coefficient for those aged 20–44 years (0.029; 95% CI: 0.026, 0.031) is statistically significantly smaller than the Gini coefficient for those aged 45–64 years (0.044; 95% CI: 0.041, 0.047), which, in turn, is statistically significantly smaller than the Gini coefficient for those aged 65–79 years (0.060; 95% CI: 0.054, 0.065) (Appendix 4). The amounts of inequality in general health as measured by the HUI and the FFI in all three age groups exceed the minimally policy-relevant differences (Appendix 4).

3.3. Sources of health inequality

Modeling health

The fit of the OLS model varies between the HUI and the FFI (adjusted R²: 0.172 and 0.472, respectively) (Table 3). Among biological endowment variables, age remains statistically significant in the final HUI and FFI models, although the coefficients for the age categories show stronger effects for the FFI than the HUI. Sex is not statistically significant in the final HUI and FFI models, and family medical history is only in the FFI model. Similar socioeconomic background variables (province, education, and income) are important in both models. There is more variation across the two models regarding the importance of health behaviour variables (sexually transmitted disease and alcohol are statistically significant only in the HUI model, while heavy recreational drug and physical activity are statistically significant only in the FFI model). Estimated coefficients are in the expected directions.

Illegitimate, legitimate, and unexplained components of health inequality

Fig. 2 reports the extent to which illegitimate, legitimate, and unexplained components contribute to inequality in the HUI and the FFI. For the full sample of all ages, for both health measures, illegitimate inequality is relatively small (6% and 9% of inequality in the HUI and the FFI, respectively). The amount of unexplained inequality varies noticeably between them (83% for the HUI and 53% for the FFI), corresponding to the fit to the regression models. For the FFI, age drives much of the explanatory power of the model, explaining 21% of inequality in the FFI. No single variable dominates for explaining inequality in the HUI; each variable explains less than 5% of inequality in the HUI. Fig. 2 also shows how the contribution of these illegitimate, legitimate, and unexplained components differs by age group for both the HUI and the FFI. The contribution of the illegitimate component is larger in older age groups for both health measures.

3.4. Health inequity

The degree of inequity in the HUI and the FFI differs appreciably. In Fig. 1, white markers show estimates of inequity measured by the

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**Table 2 (continued)**

| Physical activity (%) | Mean HUI (95%CI) | Mean FFI (95%CI) |
|-----------------------|------------------|------------------|
| Infrequent            | 0.827 (0.790, 0.865) | 0.845 (0.840, 0.867) |
| Occasional            | 0.849 (0.809, 0.890) | 0.868 (0.858, 0.879) |
| Regular               | 0.888 (0.878, 0.897) | 0.876 (0.871, 0.881) |
| Sense of belonging to local community (%) |        |        |
| Very weak             | 0.776 (0.700, 0.853) | 0.861 (0.846, 0.876) |
| Weak                  | 0.861 (0.833, 0.890) | 0.878 (0.872, 0.885) |
| Somewhat strong       | 0.887 (0.874, 0.900) | 0.871 (0.867, 0.876) |
| Very strong           | 0.878 (0.855, 0.901) | 0.860 (0.849, 0.871) |
| Leisure activity (in the past month, %) |        |        |
| Yes                   | 0.873 (0.856, 0.890) | 0.880 (0.871, 0.889) |
| No                    | 0.867 (0.849, 0.884) | 0.865 (0.860, 0.870) |

HUI: Health Utilities Index; FFI: “Flipped” Frailty Index (FFI=1 − FI)

Proportions and the HUI and FFI means are weighted.

CI: 0.026, 0.031) is statistically significantly smaller than the Gini coefficient for those aged 45–64 years (0.044; 95% CI: 0.041, 0.047), which, in turn, is statistically significantly smaller than the Gini coefficient for those aged 65–79 years (0.060; 95% CI: 0.054, 0.065) (Appendix 4). The amounts of inequality in general health as measured by the HUI and the FFI in all three age groups exceed the minimally policy-relevant differences (Appendix 4).

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Fig. 1. Inequality and inequity in the HUI and the FFI, all ages and by age group. HUI: Health Utilities Index; FFI: “Flipped” Frailty Index (FFI=1 − FI).
Table 3

Regression model results.

|                    | HUI Coefficient (95% CI) | p-value | FFI Coefficient (95% CI) | p-value |
|--------------------|--------------------------|---------|--------------------------|---------|
| Age (ref: 20–44 years) | 0.010                    | 0.000   | 0.016                    | 0.000   |
| 45–64 years        | −0.034 (−0.057, −0.011)  | 0.003   | −0.043 (−0.056, −0.036)  | 0.000   |
| 65–79 years        | −0.020 (−0.051, 0.011)   | 0.196   | −0.085 (−0.096, −0.075)  | 0.000   |
| Presence of family medical history (ref: no) |                      |         | −0.016 (−0.023, −0.009)  | 0.000   |
| Immigration status (ref: non-immigrant) |                      |         | 0.027 (0.013, 0.041)     | 0.000   |
| Immigrant (less than 5 years) |                     |         | 0.012 (−0.001, 0.025)    | 0.065   |
| Immigrant (5–9 years) |                          |         | 0.015 (0.000, 0.031)     | 0.054   |
| Immigrant (10–19 years) |                         |         | 0.009 (−0.022, 0.004)    | 0.169   |
| Immigrant (longer than 20 years) |                        |         | 0.036                   | 0.000   |
| Province (ref: Ontario) |                     |         | 0.025 (0.000, 0.051)     | 0.050   |
| Atlantic |                        |         | 0.005 (−0.009, 0.020)    | 0.490   |
| Quebec |                         |         | 0.020 (0.013, 0.027)     | 0.000   |
| Prairies |                    |         | 0.002 (−0.009, 0.013)    | 0.770   |
| British Columbia |                       |         | −0.004 (−0.013, 0.004)   | 0.301   |
| Education (ref: less than high school graduate) |               |         | 0.092                   | 0.000   |
| High school graduate |                  |         | 0.024 (0.013, 0.035)     | 0.000   |
| Some post-secondary/trade certificate |                    |         | 0.024 (0.016, 0.032)     | 0.000   |
| College/university certificate |                   |         | 0.020 (0.010, 0.030)     | 0.000   |
| Bachelor's degree |                         |         | 0.004                   | 0.000   |
| Degree higher than Bachelor's degree |                     |         | 0.035 (0.018, 0.052)     | 0.000   |
| Income (ref: lowest/lower middle 40%) |                   |         | 0.110                   | 0.000   |
| Middle 20% |                     |         | 0.078                   | 0.037   |
| Upper middle 20% |                         |         | 0.122                   | 0.005   |
| Highest 20% |                       |         | 0.099                   | 0.001   |
| Tripped recreational drug (heavy) in life time (ref: no) |                       |         | −0.014 (−0.027, −0.001)  | 0.034   |
| Sleep (ref: normal sleep [6–8 h]) |                  |         | 0.000                   | 0.000   |
| Short sleep (less than 6 h) (ref) |                     |         | 0.011                   | 0.000   |
| Long sleep (more than 6 h) |                       |         | 0.068                   | 0.601   |
| Have diagnosed with STD (ref: no) |                     |         | −0.021 (−0.031, −0.015)  | 0.010   |
| Alcohol drink (ref: never drank) |                    |         | 0.009                   | 0.000   |
| Former drinker |                         |         | 0.000                   | 0.000   |
| Occasional drinker |                        |         | 0.000                   | 0.000   |
| Regular drinker |                          |         | 0.000                   | 0.000   |
| Regular heavy drinker |                      |         | 0.000                   | 0.000   |
| BMI (ref: normal weight) |                     |         | 0.000                   | 0.000   |
| Underweight |                       |         | 0.073                   | 0.000   |
| Overweight |                        |         | −0.055 (−0.079, −0.031)  | 0.000   |
| Obese |                          |         | −0.060 (−0.065, −0.054)  | 0.000   |
| Sedentary activity (per week) (ref: less than 10 hours) |                 |         | 0.001                   | 0.000   |
| 10–29 h |                          |         | −0.006 (−0.013, 0.000)   | 0.061   |
| 30–44 h |                          |         | −0.010 (−0.018, −0.002)  | 0.018   |
| Physical activity (ref: infrequent) |                    |         | −0.018 (−0.025, −0.011)  | 0.000   |
| Occasional |                        |         | 0.004                   | 0.004   |
| Regular |                         |         | 0.000                   | 0.615   |
| Sense of belonging to local community (ref: very weak) |                 |         | 0.003                   | 0.006   |
| Weak |                            |         | 0.059 (−0.006, 0.123)    | 0.075   |
| Somewhat strong |                        |         | 0.087 (0.031, 0.143)     | 0.002   |
| Very strong |                         |         | 0.080 (0.019, 0.141)     | 0.011   |
| Constant |                        |         | 0.799 (0.723, 0.874)     | 0.885 (0.865, 0.905) |
| Adjusted R-square |                 |         | 0.172                   | 0.472   |
| Sample size |                       |         | 3430                   | 3430    |

HUI: Health Utilities Index; FFI: “Flipped” Frailty Index (IFI = 1 − FFI); CI: Confidence interval; STD: sexually transmitted disease; BMI: body mass index

Table reports variables that are statistically significant at the 5% level in the HUI and/or the FFI model.

indirect standardization. The Gini coefficients for the indirectly-standardized FFI by age (white squares) show divergence, while those for unfair HUI by age (white circles) are stable. The Gini coefficient for the indirectly-standardized FFI among those aged 20–44 years (0.025; 95% CI: 0.023, 0.027) is statistically significantly smaller than that for those aged 45–64 years (0.038; 95% CI: 0.036, 0.040), which, in turn, is statistically significantly smaller than that for those aged 65–79 years (0.053; 95% CI: 0.049, 0.057) (Appendix 4). The magnitudes of these differences in the Gini coefficient across the age groups are policy relevant.

4. Discussion

Understanding the dynamics of health inequalities and inequities over the life course is critical to support successful aging of a population. This study contributes to this understanding in two ways: first, by explicitly adopting a framework of health equity, moving beyond bivariate associations between health and socioeconomic status; and second, by using two widely-applied measures of health, the HUI and the FFI. Our main findings are twofold. First, the magnitudes of inequality and inequity in health measured both by the HUI and the FFI in each of the three age groups (20–44, 45–64, and 65–79 years) are policy relevant. Second, the age-related dynamics of health inequalities and inequities depend on the choice of the health measures. In all three
age groups, inequality and inequity in general health measured by the HUI are larger than those measured by the FFI. Across the three age groups, inequality and inequity are stable in the HUI but divergent in the FFI.

Equal opportunity for health, the definition of health inequity used in our analysis, suits well the examination of age-related dynamics of health inequity. It can incorporate many socioeconomic indicators considered ethically and policy relevant together in a coherent framework, and it naturally prompts us to think about health inequity in a dynamic, life-course perspective. From the view of equal opportunity for health, early life circumstances during childhood, which can have long-standing health effects, are beyond the control of an individual and are therefore unfair sources of health inequalities. Hence, they justify social interventions. As one grows into adulthood, however, it is possible to postulate that health is increasingly influenced by individual choices, which may result in a decrease in health inequity.

While equal opportunity for health may be suited for the investigation of the dynamics of health inequities among olders persons, competing definitions of health inequity also exist. To test the robustness of key conclusions of this study to our choice of health equity definition, we also applied our methodology to an alternative health equity definition, policy amenability, which considers as unfair health inequalities due to factors amenable to policy intervention (data not shown) (Norheim & Asada, 2009). Using policy amenability as the definition of health equity did not alter our key conclusions. This is consistent with other work, which has found that, while the distinction between inequality and inequity is important (i.e., estimates of the amount of inequity can differ substantially from the amount of inequality), differences among inequity estimates generated by alternative equity definitions tend to be small given our limited ability to explain inequalities empirically (Asada et al., 2014; Asada et al., 2015). Thus, whether one subscribes to the view of equal opportunity for health or of policy amenability, the magnitude of health inequity during adulthood is worthy of attention.

When implementing an equity perspective in the context of aging, a question worthy of further attention is whether to treat the variable “age” as legitimate or illegitimate. This study considered the variable “age” legitimate, or more precisely, differences in health solely influenced by age differences between the three age groups (20–44, 45–64, and 65–79 years) as legitimate. As in most data, the variable “age” in our data means chronological age, with which we could, in principle, capture the two aging processes, the deterioration and/or accumulation processes. Our rationale to treat the variable “age” as legitimate is based on our view that whichever aging process is captured by the variable “age,” it is fair because it is a shared, universal phenomenon (Daniels, 1988). We acknowledge that our view is one of many, and it is vitally important to explore further as to how to conceptualize aging and how to characterize its unfairness or fairness in equity analysis in aging. This is particularly so when using the FFI given its strong relationship with the variable “age,” as exemplified in our decomposition analysis in which the variable “age” explained inequality in the FFI (21%) far more than for the HUI (less than 1%).

To implement the view of equal opportunity for health, we opted for the indirect fairness-standardization method. This is one of the several fairness-standardization methods discussed in the literature (Fleurbaey & Schokkaert, 2009, 2012; Brunori & Peragine, 2011). The selection of a fairness-standardization method involves two decisions: (1) the choice between direct standardization (also referred to as direct unfairness) and indirect standardization (also referred to as fairness gap) (Fleurbaey & Schokkaert, 2009, 2012); and (2) the treatment of the unexplained inequality (Fleurbaey & Schokkaert, 2012). Both of these decisions are as ethical as they are technical (Asada et al., 2015; Fleurbaey & Schokkaert, 2012). The choice of the indirect or direct standardization method in the context of equal opportunity for health implies the ethical judgment as to whether society should compensate for health inequalities due to factors beyond individual control (known

Fig. 2. Unexplained, illegitimate, and legitimate components of inequality in the HUI and the FFI, all age ages. HUI: Health Utilities Index; FFI: “Flipped” Frailty Index (FFI=1 – FI). Numbers in the bars are % contribution to inequality.
as the principle of compensation, reflected in indirect standardization) or society should not compensate for health inequalities due to factors within individual control (known as the principle of reward, reflected in direct standardization) (Fleurbaey & Schokkaert, 2009, 2012; Bruno & Peragine, 2011). The literature shows that the indirect and direct standardization methods support the same ethical judgment (i.e., the principles of compensation and reward are equivalent) if and only if factors within individual control are not influenced by factors beyond individual control (Fleurbaey & Schokkaert, 2009, 2012; Bruno & Peragine, 2011). Because ample evidence suggests that factors beyond individual control, such as social origin, do indeed influence personal choices, e.g., smoking behaviours (Pampel, Krueger, & Denney, 2010), the indirect and direct standardization methods lead to different assessments of inequity. In this study, we opted for the principle of compensation, reflected in indirect standardization.

The treatment of unexplained inequality – whether to consider unexplained inequality as fair or unfair – is another ethical question, for which the literature offers varying fairness judgments without a definitive view (Asada et al., 2015; Fleurbaey & Schokkaert, 2012). When unexplained inequality is relatively large as in this study (83% for the HUI and 53% for the FFI), the treatment of unexplained inequality has an important empirical implication: the magnitude of inequity would be considerably smaller when considering unexplained inequality as fair than when treating it as unfair. Unexplained inequality likely consists of both purely random noise and systematic variations, and in our models the latter likely includes interactions between factors within and beyond individual control. Sensitivity analysis testing interaction terms in the HUI and FFI models suggested our limited ability to capture such interactions: By adding interaction terms, adjusted R² increased only 0.050 for the HUI model and 0.018 for the FFI model. While they did not explain a large amount of variation, interactions between social background and health behaviour variables were more often statistically significant in the HUI model than in the FFI model. The decomposition analysis using the models with interaction terms showed, for every age group, the unexplained component was much larger for the HUI (> 10% increase) than the FFI (< 10% increase) once the interaction terms were removed (data not shown). In our models, thus, unmeasured and measured interactions between factors within and beyond individual control largely remain in the unexplained component. Because we consider the influence of social background on health behaviour as unfair, in this study we treated unexplained inequality as unfair.

Our choice of the principle of compensation and our treatment of unexplained inequality as unfair are conventional. In addition, sensitivity analysis using the direct standardization (therefore supporting the principle of reward) and treating unexplained inequality as fair yielded similar results in terms of the age-related dynamics of health inequity. Though the estimates based on the direct standardization produced smaller degrees of inequity than those reported in this paper (due to the treatment of relatively large unexplained inequality as fair), the magnitudes of inequity were still policy relevant (Appendix 4).

In the examination of age-related dynamics of health inequalities and inequities, our study demonstrates that the choice of the measure of health matters and that health inequality and inequity analysis results differ depending on the choice. Inequality and inequity measured by the HUI are larger than those measured by the FFI in each of the three age groups. Across the age groups, inequality and inequity measured by the HUI are stable, while those measured by the FFI diverge. Stability in inequality in the HUI we found is not consistent with the two previous studies that report divergent inequality by age in a Canadian general population using the same outcome measure (Prus, 2007; van Kippersluis, Van Ourt, O’Donnell, & van Doorslaer, 2009). It is possible that divergent inequality by age in 1994 and 2001 have become stable in 2009, or the discrepancy may be partly due to small differences in study samples, including the age cut-off of 79 years in our sample. We cannot compare our FFI results to existing studies using frailty as they have examined age-related dynamics of health inequalities related to socioeconomic status alone (Stolz et al., 2017; Marshall et al., 2015; Yang & Lee, 2010). These studies have reported divergence, convergence, and stability without a consistent pattern.

To examine why inequality and inequity results differ between the HUI and the FFI, we first note the moderate correlation between the two outcomes in our data (Pearson correlation coefficient: 0.42). In addition, the distributions of HUI and FFI differ noticeably in their shape. These observations suggest that the HUI and the FI differ in important ways, and this difference may be the key to understand our results.

The HUI and the FI embody different notions of health. The HUI focuses exclusively on tangible functional limitations in eight dimensions (vision, hearing, speech, mobility, dexterity, emotion, cognition, and pain) (Horsman et al., 2003), whereas the FI incorporates further aspects, including chronic conditions and physiological states that may or may not have a contemporaneous impact on function (Appendix 2) (Rockwood & Mitnitski, 2007; Searle et al., 2008). Thus, it is possible for a person who has many deficits that have not yet manifested as functional limitations to be considered as frail despite few visible or conscious functional limitations. In essence, the FI measures more “latent” aspects of health, while the HUI measures their manifestation in the selected dimensions of function. The broader and more elemental aspects of health captured in the FI may explain divergent inequality in the FFI and stable inequality in the HUI that we observed. Furthermore, compensation that a person makes to maintain a certain functional level may have also accounted for the study results. Take an example of the first two levels (among five) of the pain dimension of the HUI: Level 1 “free of pain and discomfort” and Level 2 “mild to moderate pain that prevents no activities.” (Horsman et al., 2003) Level 1 would capture persons who are free of pain and discomfort through various compensation strategies, including the use of medication and changes in activities. A need for such compensation would be invisible in the HUI, while it is likely to be detected through asymptomatic aspects of health incorporated in the FI. Another important difference between the HUI and the FI is how their respective health composites are aggregated. The HUI aggregates the eight dimensions of health using community-based preferences, which are average preferences of individuals drawn from the community regarding the relative importance of these functional dimensions (Horsman et al., 2003). The FI, on the other hand, counts each deficit equally in aggregating all deficits it includes (Rockwood & Mitnitski, 2007; Searle et al., 2008). It is, thus, possible for a deaf person who is otherwise in excellent health to be considered as having a severe functional limitation yet not be frail. This incorporation of the community-based preferences in the HUI might explain the larger magnitude of inequality and inequity in the HUI than the FFI that we observed in every age group.

The contrast between these two measures of health prompts a question of whether aging influence on the HUI and the FI reflects the deterioration or accumulation process. The FI is sometimes referred to as a measure of “biological aging,” (Stolz et al., 2017) implying the deterioration process of aging, thus, inequalities in the FI are assumed to converge over the life course (Stolz et al., 2017). However, both the deterioration and accumulation processes are biological, and “biological aging” does not equate to the former. The FI, more precisely, is a measure of deficits, only some of which are biologically based (e.g., clinical or laboratory tests). In fact, the construct of the FI appears to support that aging influence on the FI reflects the accumulation process. The FI counts a number of deficits, and studies plotting trajectories of the FI within individuals as they increase chronological age show deficit accumulation in general, though repairs are possible (Mitnitski, Song, & Rockwood, 2012; Mitnitski & Rockwood, 2016). Aging then is expected to act as an amplifier of inequalities in health measured by the FI, which corroborate our results. The construct of the HUI, on the other hand, does not clearly point to the deterioration or accumulation process.

In summary, careful examination of what each of the HUI and the FI...
is measuring defies a simple explanation for age-related dynamics of overall level of health and its distribution in a population. Such dynamics are likely to differ depending on what aspect of health we are measuring. To inform policies for successful aging, it is critical to consider the choice of the measure of health not merely as a technical and data-driven question but as a societal question of how the fair distribution of different aspects of health may characterize a successfully aging population. This paper uncovered many intricate issues through the application of a comprehensive equity perspective beyond a focus solely on socioeconomic status and the use of two measures of health. As populations age, extending the examination of health inequalities and inequities in the context of aging populations, as this paper did, can contribute to the methodological development to support policies for successful aging.

Appendix 1. Technical explanation of analytical steps

Step 1: Measuring health inequality

Our approach begins by quantifying observed variation in health. Specifically, using individual-level data, we use an inequality index to quantify the extent of inequality in the distribution of observed health across individuals in the population. In principle, one can use any inequality index as long as it applies to univariate distribution. In this application, we use the Gini coefficient.

Arithmetically, the Gini coefficient ($G$) takes many forms, and the following is one expression:

$$ G = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{|y_i - y_j|}{n^2 \mu} $$

(A1)

where the population of interest holds $n$ people, $y_i$ is the health of individual $i$, $y_j$ is the health of individual $j$ and the mean level of health in the population is $\mu$.

Step 2: Understanding sources of health inequality

The second step examines sources of health inequality both statistically and normatively. The statistical analysis seeks to explain as much variation in health as possible with the data at hand, while the normative examination calls for ethical judgment as to which sources of health inequality are ethically acceptable ("legitimate" (Fleurbaey & Schokkaert, 2009, 2012)) or unacceptable ("illegitimate" (Fleurbaey & Schokkaert, 2009, 2012)). The ethical judgments in this study are guided by the view of equal opportunity for health. We carry out three tasks in this step: (1) modeling health using multiple regression; (2) classifying variables as legitimate or illegitimate; and (3) decomposing inequality into legitimate and illegitimate components.

(1). Modeling health

Using the same individual-level data as Step 1, separately for the HUI and the FFI, we explain variation in observed health by estimating a regression model of the following form (modified from Fleurbaey and Schokkaert (Fleurbaey & Schokkaert, 2009, 2012)):

$$ y_i = \alpha + \beta M_i + \gamma S_i + \delta P_i + \eta Z_i + \epsilon_i $$

(A2)

where $y_i$ is the observed health for individual $i$, $M_i$ is a vector of biological endowments (age and family medical history). We enter age as a categorical variable, to account for non-parametric (non-linear) relationships between age and health; we use the same age categories as for the stratification used in the measurement of health inequality and inequity (see below). $S_i$ is a vector of social background – social attributes that a person is born to (visible minority status) or acquires later in life (immigrant status, education, province of residence) that often influence the possession of resources of diverse instrumental value for life in general (income). $P_i$ is a vector of health behaviours, $Z_i$ is a vector of social support available to a person (sense of belonging to local community, leisure activity), and $\epsilon_i$ is an error term. Depending on the nature of the health variable, we classify the variable "sex" as biological sex, representing biological endowments, $M_i$ (in the FFI model) or as gender, representing social background, $S_i$ (in the HUI model).

(2). Classifying variables as legitimate and illegitimate

For each model of health, we will classify each variable included in the model as a legitimate or illegitimate source of health according to our chosen definition of inequity, equal opportunity for health. This classification process requires judgment. “Individual control” is a key dividing line to decide the ethical status of determinants of health according to the view of equal opportunity for health: determinants beyond the control of the individual are illegitimate; determinants under the control of the individual are legitimate.

With the necessary legitimate-illegitimate distinction of explanatory factors, we can rewrite Eq. (A2) as follows:

$$ y_i = \xi + \tau X_i + \upsilon W_i + \epsilon_i $$

(A3)

where $y_i$ is the observed health for individual $i$, $X_i$ is a vector of legitimate factors, $W_i$ is a vector of illegitimate factors, and $\epsilon_i$ is an error term.

We classify age and health behaviour variables as legitimate ($X_i$) and all other variables as illegitimate ($W_i$). We treat age as legitimate, because, although it is not under individual control, aging is a universally shared process among all persons (Daniels, 1988). We acknowledge that health behaviors are not solely under individual control as they are also influenced by an individual’s circumstances. We accommodate this by estimating the effects of health behaviour variables on health conditional on social background and social support variables.

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(3). Decomposing inequality into ethically acceptable and unacceptable components

After making the legitimate-illegitimate judgment, using a regression-based inequality decomposition method (Cowell & Fiorio, 2011), we estimate to what degree inequality in the observed health is legitimate or illegitimate. Using the same individual-level dataset, we start by estimating an equation in the following form:

\[ y_i = \xi + \psi K_i + \varepsilon_i \]  

(A4)

where \( y_i \) is the observed health for individual \( i \), and \( K_i \) is a vector of all variables included in the Eq. (A2). Let \( k_j \) be each variable included in the model (e.g., \( j = \) age, income, sleep, leisure activity, etc.). The regression-based inequality decomposition identifies the proportional contribution of each variable \( k_j \) to health inequity as follows:

\[ S_j = \frac{\text{cov}(K_j, y_i)}{\text{var}(y_i)} \]  

(A5)

where \( \Sigma S_j = 1 \) From this result, we can obtain the proportion of the total variation in the observed health explained by legitimate variables and illegitimate variables as well as the proportion of the total variation in the observed health that is unexplained by either legitimate or illegitimate variables in the model.

This decomposition rule does not depend on the choice of inequality index. The regression-based inequality decomposition method is akin to the widely used Concentration Index decomposition by attributes. The difference is that the Concentration Index decomposition breaks down bivariate health inequality (e.g., income-related health inequality) by variable, while the regression-based inequality method decomposes health inequality by variable.

Step 3: Measuring health inequity

The final step quantifies the unfair distribution of health across individuals in the population. To estimate unfair health, we use a well-established method, fairness-standardization (Fleurbaey & Schokkaert, 2009, 2012), which removes the influence of the fair component attributable to legitimate determinants. This standardization leaves inequality due only to unfair sources and constitutes the distribution of inequitable health in the population.

In this study, we use the indirect fairness-standardization method, which reflects the view that health inequalities due to factors beyond individual control are unfair and should be compensated by society (often referred to as the principle of compensation (Fleurbaey & Schokkaert, 2009, 2012; Brunori & Peragine, 2011)). Specifically, for each individual we predict fair health by allowing only the legitimate variables to influence the predictions. We purge the influence of illegitimate variables by holding their values at the mean (expressed with the bar in the equation) during prediction:

\[ \hat{y}_{i,\text{fair}} = \xi + \bar{X} + \bar{\varepsilon} \]  

(A6)

We then calculate unfair health by subtracting the estimate of fair health from the observed health and adding the mean health of the population:

\[ \hat{y}_{i,\text{indirect-unfair}} = y_i - \hat{y}_{i,\text{fair}} + \bar{y} \]  

(A7)

where \( \bar{y} \) is the mean health of the study population. This addition of \( \bar{y} \) ensures that the distributions of the observed health and the unfair health have the same mean value (O'Donnell et al., 2007). As \( y_i \) in Eq. (A7) includes the error term, \( \varepsilon_i \), the indirect standardization we use in this study considers the unexplained component as an unfair source of inequality.

The amount of inequity (i.e., inequality in the distribution of unfair health) is then measured by applying the same index as in Step 1 to the distribution of unfair health. Despite the use of the same mathematical index, the measure here is an index of inequity, as opposed to simply inequality, as it quantifies the distribution of unfair health.

In our analysis, we measure the amount of inequity for the full sample and separately for each of the three age groups (20–44, 45–64, and 65–79 years). We use different mean values in the indirect standardization depending on the sample within which we measure the amount of inequity. Specifically, for the full sample, the mean values, \( \bar{W} \) in Eq. (A6) and \( \bar{y} \) in Eq. (A7), are those of the full sample. For a specific age group, the mean values are those specific to that age group. In addition, because all observations in a specific age group have the same age category, the variable "age" is dropped from Eq. (A6) in age group-specific analysis.
Appendix 2. Variables used to construct the Frailty Index

The selection of the 46 variables listed below was based on the criteria recommended in the literature (Rockwood et al., 2007; Searle et al., 2008): (1) a deficit must be associated with health status; (2) a deficit's prevalence must generally increase with age; (3) a deficit should not saturate too early; (4) deficits as a group must cover a range of systems; and (5) the same deficits must be used for within-person comparisons.

| Variable                        | Cut-off point                                                                 |
|---------------------------------|-------------------------------------------------------------------------------|
| General health                  |                                                                              |
| Self-perceived health rating    | 0 = excellent<br>0.25 = very good<br>0.5 = good<br>0.75 = fair<br>1.0 = poor |
| Change in health status         | 0 = Much better now than 1 year ago; somewhat better now than 1 year ago; about the same as 1 year ago<br>1 = somewhat worse now than 1 year ago; much worse now than 1 year ago |
| Function                        |                                                                              |
| Pain                            | 0 = no pain or discomfort<br>0.25 = pain prevents no activities<br>0.5 = pain prevents a few activities<br>0.75 = pain prevents some activities<br>1.0 = pain prevents most activities |
| Vision                          | 0 = no visual problems<br>0.25 = problems corrected by lenses<br>0.75 = problem seeing distance – not corrected; problem seeing close – not corrected; problem close & distance – not corrected<br>1.0 = no sight at all |
| Hearing                         | 0 = no hearing problems<br>0.25 = problem hearing in group – corrected; problem hearing in group & individual – corrected<br>0.75 = problem hearing in group – not corrected; problem hearing in group & individual – not corrected<br>1.0 = no hearing |
| Mobility                        | 0 = no mobility problem<br>0.25 = problem – no aid required<br>0.75 = problem – requires mechanical support, wheelchair or help from people<br>1.0 = cannot walk |
| Activity of Daily Living (ADL)  |                                                                              |
| Simple chores make short of breath | 0 = no<br>1 = yes |
| Other                           |                                                                              |
| Body mass index                 | 0 = normal weight<br>0.5 = overweight<br>1 = underweight/obese |
| Waist circumference norms       | 0 = excellent<br>0.25 = very good<br>0.5 = good<br>0.75 = fair<br>1.0 = needs improvement |
| Falls                           | 0 = no<br>1 = yes |
| Cough regularly                 | 0 = no<br>1 = yes |
| Cough up phlegm regularly       | 0 = no<br>1 = yes |
| Heart condition limiting physical activity | 0 = no<br>1 = yes |
| Chest pain with physical activity | 0 = no<br>1 = yes |
| Chest pain not during physical activity | 0 = no<br>1 = yes |
Sleeping problems

| Rating   | Description                  |
|----------|------------------------------|
| 0        | never                        |
| 0.25     | rarely                       |
| 0.5      | sometimes                    |
| 0.75     | most of the time             |
| 1.0      | all the time                 |

Chronic Conditions

| Condition                                                                 | Rating   | Description                                                                 |
|---------------------------------------------------------------------------|----------|-----------------------------------------------------------------------------|
| Arthritis or rheumatism                                                  | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Back problems excluding arthritis or fibromyalgia                        | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Osteoporosis                                                              | 0        | no; not applicable (respondents younger than 40 years old)                  |
|                                                                           | 1        | yes                                                                         |
| Bone or joint problems                                                   | 0        | no; not applicable (people who don't have any chronic condition that may prevent them from participating in tests) |
|                                                                           | 1        | yes                                                                         |
| Fibromyalgia                                                              | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| High blood pressure                                                      | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Blood cholesterol                                                        | 0        | no; not applicable (people who don't have their blood cholesterol measured) |
|                                                                           | 1        | yes                                                                         |
| Chronic bronchitis, emphysema, or chronic obstructive pulmonary disease  | 0        | no; not applicable (respondents younger than 30 years old)                  |
|                                                                           | 1        | yes, have either chronic bronchitis, emphysema, or chronic pulmonary disease |
| Heart disease                                                             | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Heart attack                                                              | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Diabetes                                                                  | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Cancer (based on ccc_72)                                                 | 0        | no                                                                          |
|                                                                           | 1        | yes (either had cancer or currently has cancer)                             |
| Effects of stroke                                                        | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Kidney disease/weak or failing kidneys                                    | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Liver disease                                                             | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |
| Thyroid disease                                                           | 0        | no                                                                          |
|                                                                           | 1        | yes                                                                         |

Lab tests

| Category                                      | Description                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------------|
| Grip strength                                 | 1 = Male: underweight or normal weight and grip strength less than 59 kg  |
|                                              | overweight and grip strength less than 61 kg                                |
|                                              | obese and grip strength less than 65 kg                                    |
|                                              | 1 = Female: underweight or normal weight and grip strength less than 35 kg |
|                                              | overweight and grip strength less than 37 kg                                |
|                                              | obese and grip strength less than 43 kg                                    |
|                                              | 0 = otherwise                                                               |
| Heart rate at rest                           | 0 = average heart rate at rest between 60 and 99 bpm                        |
|                                              | 1 = average heart rate at rest less than 60 bpm or greater than 99 bpm     |
| Systolic blood pressure                      | 0 = systolic blood pressure less than 120 mmHg                             |
|                                              | 0.5 = systolic blood pressure between 120 and 139 mmHg                     |
|                                              | 1.0 = systolic blood pressure greater than 139 mmHg                       |
| Folate, red blood cells                      | 0 = between 60 and 99 nmol/L of folate, red blood cell                      |
|                                              | 1 = less than 60 nmol/L and greater than 99 nmol/L of folate, red blood cell |
| Red blood cell count                         | 0 = between 3.93 and 5.69 10^-12 cells/L of red blood cell                 |
|                                              | 1 = less than 3.93 10^-12 cells/L and greater than 5.69 10^-12 cells/L of red blood cell |
| Hemoglobin                                   | 0 = Male: between 135 and 180 g/L of hemoglobin                             |
|                                              | Female: between 120 and 160 g/L of hemoglobin                              |
|                                              | 1 = Male: less than 135 g/L and greater than 180 g/L of hemoglobin         |
|                                              | Female: less than 120 g/L and greater than 160 g/L of hemoglobin           |
| Mean corpuscular volume                      | 0 = between 80 and 96 fl of mean corpuscular volume                         |
|                                              | 1 = less than 80 fl and greater than 96 fl of mean corpuscular volume      |
| Creatinine                                   | 0 = between 53 and 106 μmol/L of creatinine                                |
|                                              | 1 = less than 53 μmol/L and greater than 106 μmol/L of creatinine          |
Ferritin
- Male: between 20 and 200 μg/L of ferritin
- Female: between 15 and 150 μg/L of ferritin

Platelet count
- Male: less than 20 μg/L and greater than 200 μg/L of ferritin
- Female: less than 15 μg/L and greater than 150 μg/L of ferritin

Potassium
- Male: less than 3.8 mmol/L and greater than 5 mmol/L of potassium
- Female: less than 3.8 mmol/L and greater than 5 mmol/L of potassium

Sodium
- Male: less than 136 mmol/L and greater than 142 mmol/L of sodium
- Female: less than 136 mmol/L and greater than 142 mmol/L of sodium

High-density lipoprotein cholesterol
- Male: less than 1 mmol/L of high-density lipoprotein cholesterol
- Female: less than 1.3 mmol/L of high-density lipoprotein cholesterol
- Male: between 1 and 1.3 mmol/L of high-density lipoprotein cholesterol
- Female: between 1.3 and 1.5 mmol/L of high-density lipoprotein cholesterol
- Male: greater than 1.3 mmol/L of high-density lipoprotein cholesterol
- Female: greater than 1.5 mmol/L of high-density lipoprotein cholesterol

Urea
- Male: less than 2.9 mmol/L and greater than 8.2 mmol/L of urea
- Female: less than 2.9 mmol/L and greater than 8.2 mmol/L of urea

**Appendix 3. Modified Gini coefficient**

Applied to an unbounded ratio-scale variable, such as income, the Gini coefficient takes values between zero (perfectly equal distribution) and one (most unequal). Applied to a bounded cardinal variable, such as the HUI and the FFI, the maximum and minimum values of the Gini coefficient are influenced by the mean (Erreygers & Van Ourti, 2011; Kjellsson & Gerdtham, 2013). This means that the Gini coefficients for the HUI and FFI across age groups reflect both the magnitude of inequality and inequity and the declining mean of the HUI and FFI in older age groups. The literature offers three alternative indices to resolve this issue, and the simplest is the modified Gini coefficient (Erreygers & Van Ourti, 2011; Kjellsson & Gerdtham, 2013).

Gini coefficient: \( G = \frac{2}{n^2 \mu_h} \sum_{i=1}^{n} z_i h_i \)

Modified Gini coefficient: \( G^* = \frac{2}{n^2 (\mu_h - a_h)} \sum_{i=1}^{n} z_i h_i \)

Where, \( n \) is the number of individuals in a given population, \( \mu_h \) is the mean health of the population, \( z_i \) is a vector indicating ranking of individual \( i \) according to his/her health, and \( h_i \) is the health of individual \( i \), and \( a_h \) is the lower bound of the health variable.

When \( a_h = 0 \): \( G^* = \frac{2}{n^2 (\mu_h - 0)} \sum_{i=1}^{n} z_i h_i = \frac{2}{n^2 \mu_h} \sum_{i=1}^{n} z_i h_i = G \)

This means that, because the lower bound of the HUI and FFI, the two variables used in our analyses, is zero, modified Gini coefficient is identical to Gini coefficient. It is thus appropriate to use the Gini coefficient as is for the HUI and FFI, bounded cardinal health variables.
Appendix 4. Degree of inequality and inequity in the HUI and the FFI, all ages and by age group

|                | HUI                          | FFI                          |
|----------------|------------------------------|------------------------------|
|                | Mean                        | Gini (95% CI)                | Expected mean difference* | Mean                        | Gini (95% CI)                | Expected mean difference* |
| **Inequality** |                              |                              |                           |                            |                              |                           |
| All ages       | 0.869 (0.855, 0.883)         | 0.098 (0.086, 0.110)         | 0.170                     | 0.870 (0.866, 0.875)       | 0.046 (0.044, 0.048)         | 0.080                     |
| 20–44 years    | 0.886 (0.874, 0.899)         | 0.088 (0.077, 0.100)         | 0.156                     | 0.908 (0.904, 0.911)       | 0.029 (0.026, 0.031)         | 0.053                     |
| 45–64 years    | 0.856 (0.836, 0.877)         | 0.105 (0.088, 0.122)         | 0.180                     | 0.852 (0.844, 0.859)       | 0.044 (0.041, 0.047)         | 0.075                     |
| 65–79 years    | 0.847 (0.827, 0.867)         | 0.106 (0.091, 0.122)         | 0.180                     | 0.795 (0.787, 0.803)       | 0.060 (0.054, 0.065)         | 0.095                     |
| **Inequity (indirect)** |                              |                              |                           |                            |                              |                           |
| All ages       | 0.866 (0.855, 0.878)         | 0.091 (0.081, 0.100)         | 0.158                     | 0.866 (0.862, 0.869)       | 0.035 (0.033, 0.036)         | 0.061                     |
| 20–44 years    | 0.889 (0.879, 0.900)         | 0.078 (0.068, 0.089)         | 0.139                     | 0.906 (0.902, 0.910)       | 0.025 (0.023, 0.027)         | 0.045                     |
| 45–64 years    | 0.850 (0.831, 0.868)         | 0.099 (0.085, 0.114)         | 0.168                     | 0.848 (0.842, 0.854)       | 0.038 (0.036, 0.040)         | 0.064                     |
| 65–79 years    | 0.836 (0.817, 0.854)         | 0.102 (0.089, 0.116)         | 0.171                     | 0.797 (0.788, 0.805)       | 0.053 (0.049, 0.057)         | 0.084                     |
| **Inequity (direct)** |                              |                              |                           |                            |                              |                           |
| All ages       | 0.869 (0.866, 0.872)         | 0.027 (0.026, 0.028)         | 0.047                     | 0.870 (0.869, 0.872)       | 0.010 (0.010, 0.011)         | 0.017                     |
| 20–44 years    | 0.886 (0.883, 0.889)         | 0.028 (0.027, 0.030)         | 0.050                     | 0.908 (0.906, 0.909)       | 0.007 (0.006, 0.007)         | 0.013                     |
| 45–64 years    | 0.856 (0.851, 0.861)         | 0.033 (0.030, 0.036)         | 0.056                     | 0.852 (0.849, 0.855)       | 0.016 (0.015, 0.017)         | 0.027                     |
| 65–79 years    | 0.847 (0.841, 0.852)         | 0.038 (0.035, 0.040)         | 0.064                     | 0.795 (0.792, 0.798)       | 0.019 (0.018, 0.021)         | 0.030                     |

HUI: Health Utilities Index; FFI: "Flipped" Frailty Index (FFI = 1 – FI); CI: Confidence interval.
*Expected mean difference is the average difference in the HUI (or the FFI) between two randomly selected persons from the population. It is calculated as twice the Gini coefficient multiplied by the mean.
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