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The impact of non-pharmaceutical interventions on COVID-19 transmission and its effect on life expectancy in two European regions

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Abstract

Background In response to the rapid global transmission of COVID-19, governments worldwide enacted lockdowns and other non-pharmaceutical interventions (NPI) to control the disease. In this study, we aim to quantify the influence of NPIs on the transmission of COVID-19 within selected European regions, specifically Spain (including the Basque Country) and Italy (including Tuscany), during the period of February to December 2020, which predates the initiation of COVID-19 vaccinations. We investigate potential correlations and associations between the implementation of NPIs, changes in COVID-19 transmission rates, and alterations in life expectancy across different age and sex categories from the year 2019 to 2020.

Methods We use a Susceptible-Hospitalized-Asymptomatic/Mild-Recovered-Deceased (SHARD) ordinary differential equations model to analyze COVID-19 dynamics in the studied regions. The model calibration process was performed with empirical data on hospitalization and death to estimate the weekly transmission and death rates. To quantify reductions in life expectancy, we used established survival analysis techniques.

Results The SHARD model effectively captures multiple waves of COVID-19, accurately representing peaks and aligning with the instantaneous reproduction number. Our analysis reveals a 66-78% reduction in transmission rates during the initial set of NPIs in March 2020, followed by a 34-55% reduction during the subsequent NPIs in October 2020. Additionally, the elderly and individuals with comorbidities experienced the most pronounced reductions in life expectancy.

Conclusions Our model calibration approach provides a valuable tool for evaluating the effectiveness of interventions across multiple waves of an epidemic. By applying this method to COVID-19 dynamics, we have demonstrated the capacity to quantify the impact of non-pharmaceutical interventions (NPIs) on transmission rates. These findings offer practical insights into the effectiveness of NPIs in mitigating COVID-19 spread and contribute to the broader understanding of epidemic control strategies.

Keywords COVID-19, Lockdown, Non-pharmaceutical interventions, NPIs, Epidemiological models, Effective reproduction number, Life expectancy

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Background

The coronavirus disease 2019 (COVID-19), caused by SARS-CoV-2 was first identified in China in 2020 [1]. The virus spread rapidly around the world and was declared a pandemic by the World Health Organization (WHO) in March 2020 [2, 3]. As of August 16, 2023, over 769 million cases were confirmed with around 7 million deaths, a global case fatality ratio of approximately 1% [1, 4].

The clinical presentation of COVID-19 varies from person to person. While some individuals may remain asymptomatic, others may experience mild symptoms such as coughing, headaches, or loss of smell or taste. However, in some cases, the disease can progress to severe or critical symptoms that require hospitalization. Age and pre-existing health conditions enhance disease severity [5] and as a result of high mortality rates among the elderly, the average life expectancy in many countries has decreased [6, 7].

COVID-19 vaccines became globally available and began to be administered in December 2020. These vaccines were initially prioritized for the elderly and individuals with underlying health conditions, resulting in reduced disease severity among the infected [2]. As a result, governments were able to gradually ease intervention measures [8]. By May 2023, the World Health Organization declared an end to the international public health emergency status of COVID-19, attributed to a significant decline in COVID-19 deaths and hospitalizations [9]. However, the global risk assessment remains elevated, with the potential for new variants to emerge due to uneven vaccination distribution [10].

With the unprecedented global health burden, countries worldwide have implemented extreme measures to control the transmission of COVID-19, from lockdowns to mask-wearing mandates [11]. During the initial months of the pandemic, Spain and Italy were among the countries that were most heavily affected, as highlighted in the study by Ceylan [12]. By the end of 2020, Spain had reported 1,156 COVID-19 deaths per million inhabitants, while Italy had reported 1,248 deaths per million inhabitants, reflecting some of the highest rates in the world [13, 14].

In this study, we perform a retrospective assessment of the impact of lockdown measures on COVID-19 transmission during the initial phase of the pandemic, from February to December 2020, prior to vaccine implementation. We achieve this by calibrating a Susceptible-Hospitalized-Asymptomatic/Mild-Recovered-Deceased (*SHARD*) model, which effectively captures the distinctions between mild and severe infections. Our calibration process involves fitting the *SHARD* model to COVID-19 hospitalization and death data from Spain and Italy, as well as two comparable regions from each country: the Basque Country and Tuscany. Our analysis is expanded to estimate the changes in life expectancy after the first year of the epidemic.

Mathematical modeling of COVID-19 interventions

There has been a surge of studies in the epidemiological modeling of COVID-19 since its emergence. Reviews of the literature on COVID-19 modeling highlight the critical role of modeling in estimating transmission rates, quantifying disease severity and burden, forecasting trends with and without interventions, and assessing the cost-effectiveness of those interventions [11, 15–17]. Modeling continues to provide insights into public health response in decision-making in regions of major transmission [18–22].

Since the initial stages of the pandemic, modeling studies estimating the essential features of COVID-19 such as transmission rates and projected peaks have suggested that strict countermeasures such as national lockdowns and social distancing measures were essential to reduce the spread of the disease [23–25]. In Spain, studies have shown the effects of COVID-19 control measures on transmission through the evolution of the instantaneous and effective reproduction number [26–28]. Likewise, by modeling the spatiotemporal distribution of infections, Giuliani et al. (2020) [29] found evidence that strict control measures implemented in some Italian provinces interrupted the spread to nearby areas, underlining the need for effective and homogeneous enforcement of control measures at the national level. Recognizing the transient nature of the disease, studies have also introduced time-varying parameters to calibrate their models and accurately predict cases [30–33].

COVID-19 responses

Within the European region, both Spain and Italy were considered to be the epicenters of COVID-19 in the early stages of the pandemic. In Italy, the first documented COVID-19 case was notified in the latter part of February 2020 [34], though the virus might have appeared as early as January 2020 [35]. A rapid surge in cases quickly overwhelmed hospitals, leading to an influx of critically ill patients. In response, schools, universities, and local events were promptly suspended, and travel restrictions were imposed. By March 9, 2020, Italy implemented a nationwide lockdown [36, 37].

The extreme lockdown strategy led to a significant decrease in cases and hospitalizations, enabling the Italian government to ease the restrictions on May 4, 2020 [38]. Nonetheless, another wave of infections started to emerge in October 2020, triggering a new set of restrictions including the use of masks, social distancing, and limitations on gatherings [39]. In November 2020, the

Italian government introduced a system of color-coded regional lockdowns based on the level of risk, although these measures were potentially less strict than the initial ones [40, 41]. For instance, on November 11, 2020, the region of Tuscany in central Italy was categorized as having a medium-risk level (orange), followed by a high-risk level (red) designation on November 15, 2020. This continued until December 4, 2020, when the risk level reverted to orange until the end of 2020.

Spain experienced a comparable pattern of cases and corresponding measures. Official data documented cases and hospitalizations as early as January 2020 [13]. However, it was not until March 14, 2020, after several weeks of a rapid surge in hospitalizations, that the government declared a state of alarm and implemented mandatory home confinement. This measure was complemented by the closure of restaurants, schools, universities, and various other non-essential establishments [42, 43]. A de-escalation of the restrictions began on April 28. By June 21, the state of alarm was lifted and international borders were opened. However, in October 2020, in response to the emergence of a third wave of cases, a new state of alarm was imposed [44]. This subsequent set of measures was comparatively milder than the initial one, encompassing curfew enforcement and restrictions on social gatherings. The decision concerning border control was delegated to the regional governments.

The Basque Country, an autonomous region in the northern part of Spain, implemented the same set of measures as recommended by the Spanish government [45]. In contrast to Italy and its Tuscany region, which encountered only two waves of infections in 2020, Spain and the Basque Country region have experienced three distinct waves of infections during the specified period. The first wave emerged as an initial outbreak in March and abated by May, followed by subsequent waves from July to October and from October to December.

Shifts in life expectancy due to COVID-19

Numerous studies have investigated the decline in average life expectancy during the year 2020. Aburto et al. (2021) [7] reported substantial reductions in life expectancy at birth across 27 of the 29 assessed countries, including Spain and Italy. This decline was primarily attributed to increased mortality among individuals aged 60 and above, along with documented COVID-19 deaths. Similarly, Islam et al. [46] found that the pandemic resulted in a reduction in life expectancy in 37 upper-middle and high-income countries, causing an excess loss of more than 28 million years of life in 2020.

Spain experienced an estimated overall decrease of 0.9 to 1.6 years in average life expectancy, while Italy encountered a loss of 1 to 1.72 years [46, 47]. Additionally, COVID-19 disproportionately impacted various demographic groups, with the elderly and men exhibiting higher rates of hospitalizations and deaths [48–50]. These disparities could potentially have led to uneven declines in life expectancy.

Aims of the current study

In this study, we assess the impact of the initial lockdown and subsequent Non-Pharmaceutical Intervention (NPI) measures in Spain, Italy, and two specific regions within each country: the Basque Country and Tuscany. These two countries were particularly vulnerable due to their higher life expectancy and median age, factors associated with increased COVID-19 mortality rates [51].

We develop a Susceptible-Hospitalized-Asymptomatic/Mild-Recovered-Deceased (*SHARD*) model to analyze hospitalization and mortality data, allowing us to observe changes in transmission rates before and after the implementation of NPIs. Our analysis is complemented by observations of the instantaneous reproduction number, enhancing the robustness of our methodology. Additionally, we also assess the changes in life expectancy during the initial year of the pandemic across various age groups and genders in Spain and Italy.

Methods

The *SHARD* model

The epidemiological *SHARD* model is constructed using a system of ordinary differential equations to capture the dynamics of COVID-19. This model is parameterized based on empirical data concerning hospitalizations and deaths described in the Model calibration section.

Upon infection, susceptible individuals (S) can either develop severe symptoms leading to hospitalization (H) or experience a mild/asymptomatic infection (A). In this context, η represents the fraction of infected individuals who are hospitalized, while $1 - \eta$ refers to the proportion of infected individuals who exhibit mild or no symptoms. Hospitalized individuals transmit the virus to susceptible individuals at a rate β, whereas individuals with mild or no symptoms infect others at a rate of $\phi\beta$. It is assumed that $\phi > 1$, indicating that mild/asymptomatic individuals have a higher transmission rate compared to those who are hospitalized, mainly due to their increased mobility and interactions. After infection, all individuals either recover (R) or die (D) at rates γ and μ, respectively. The cumulative count of hospitalizations (C_H) is recorded and used for model fitting. Figure 1 provides an overview of the individuals' flow within this model described by the equation system (1).

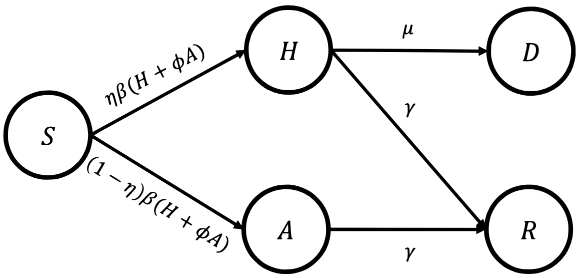

Fig. 1 Diagram for the *SHARD* model. The arrows indicate the progression from the susceptible (*S*) compartment to the hospitalized (*H*), mild and asymptomatic (*A*), recovered (*R*), and deceased (*D*) compartments

$$\begin{cases} \dot{S} = -\beta \dfrac{S}{N}(H+\phi A), \quad S(0) \geq 0, \\ \dot{H} = \eta\beta \dfrac{S}{N}(H+\phi A) - (\gamma+\mu)H, \quad H(0) \geq 0, \\ \dot{A} = (1-\eta)\beta \dfrac{S}{N}(H+\phi A) - \gamma A, \quad A(0) \geq 0, \\ \dot{R} = \gamma(H+A), \quad R(0) \geq 0, \\ \dot{D} = \mu H, \quad D(0) \geq 0. \\ \dot{C_H} = \eta\beta \dfrac{S}{N}(H+\phi A), \quad C_H(0) \geq 0. \end{cases} \tag{1}$$

The model's robustness and analytical characteristics have been validated through multiple extensions exploring different aspects of COVID-19 control responses [33, 52], growth rates and reproductive numbers [53], dynamics in the subcritical regime [54], vaccination [19, 55], spatial [56] and network dynamics [57, 58].

The initial time ($t = 0$) is February 24, 2020 for Spain, Italy, and Tuscany, and March 1, 2020 for the Basque Country, the earliest available data for the region [49]. The total populations ($N = S + H + A + R + D$) were assumed to be constant for all settings. Except for Spain, we also assumed that no one had recovered yet from the disease at the initial time ($R(0) = 0$). For Spain, we estimated the initial number of recovered based on the cumulative number of detected cases and hospitalizations 8 days before February 24. The initial number of hospitalized ($H(0)$), cumulative hospitalized ($C_H(0)$) and deaths ($D(0)$) were taken from the available data. The recovery rate (γ) is fixed at 0.125 based on an average recovery period of 8 days [48]. We assumed that the proportion hospitalized (η) is 0.05 and that the relative infectiousness of mild and asymptomatic individuals is 1.6, based on robust calibration results for the Basque Country [33]. The estimation of the initial number of mild/asymptomatic individuals ($A(0)$, as well as the parameters β and μ, is discussed in the Model calibration section. Table 1 summarizes the parameters and initial state values for each setting.

Model calibration

For this study, we used epidemiological COVID-19 data on hospitalizations and deaths retrieved from the Centro Nacional de Epidemiologia (CNE) [13] for Spain, the Basque Health Service (Osakidetza) [49] for the Basque Country, and the Istituto Superiore di Sanità (ISS) [62] for Italy and Tuscany.

To calibrate the model, we divided the epidemiological year into weekly intervals and used available data on the number of reported hospitalizations and deaths from each study region. This approach allowed the *SHARD* model to effectively capture the multiple infection waves that occurred in 2020 across Spain, Italy, the Basque Country, and Tuscany. Within this framework, we estimated both the transmission rate (β) and the death rate (μ) for each week throughout the year 2020. Additionally, during the estimation process for the first week, we determined the initial number of mild and asymptomatic individuals ($A(0)$). To ensure that the last day of the last week falls on December 31, 2020, we added four days in the first calibration interval for Spain, Italy, and Tuscany and five days in the first interval for the Basque Country.

In our analysis, we employed the `fminsearchbnd` function within `MATLAB 2022b` to iteratively determine parameter values that minimized the squared error between the model's predictions and the actual data for cumulative hospitalizations ($\eta\beta S(H + \phi A)/N$) and deaths ($\mu H$). Given the relatively higher order of magnitude of the number of hospitalizations, we assigned an additional weight to estimate death data by proportionally weighting it based on the disparity between the mean values of the two datasets. A pseudocode detailing the model calibration process is provided in section 3 of the Additional File.

For the optimization process, we defined the lower and upper boundaries for β and μ as 0 and 1, respectively. For the initial number of mild/asymptomatic individuals ($A(0)$), the boundaries were set between 1 and 20,000. Our initial guesses for β, μ, and $A(0)$ were 0.1, 0.025, and 1,000, respectively. The outcomes obtained from the model's solution, as well as the estimated values for β and μ, were carried forward as the initial state values and initial guesses for subsequent weekly estimations.

Computing the instantaneous reproduction number

The instantaneous reproduction number, R_t, defined as the average number of secondary cases produced by one infected individual at time t is a key metric for evaluating the transmissibility of infectious diseases. The value of R_t is useful to quantify if the incidence

Table 1 Values and description of parameters and initial state values for the *SHARD* model for Spain, Italy, the Basque Country and Tuscany

Parameter	Description	Value	Unit	Source
β	Transmission rate	fitted	1/day	
ϕ	Relative infectiousness of mild/asymptomatic	1.6	none	[33]
η	Proportion hospitalized	0.050	none	[33]
γ	Recovery rate	0.125	1/day	[48]
μ	Death rate due to COVID-19	fitted	1/day	
State values	**Spain**			
N	Total population	47 332 614	individuals	[59]
$H(0)$	Initial hospitalized	242	individuals	[13]
$A(0)$	Initial mild or asymptomatic	fitted	individuals	
$R(0)$	Initial recovered	630	individuals	[13]
$D(0)$	Initial deceased	1	individuals	[13]
$S(0)$	Initial susceptible	$N - H(0) - A(0) - R(0) - D(0)$	individuals	
$C_H(0)$	Initial cumulative hospitalized	856	individuals	[13]
	Italy			
N	Total population	59 438 851	individuals	[60]
$H(0)$	Initial hospitalized	190	individuals	[14]
$A(0)$	Initial mild or asymptomatic	fitted	individuals	
$R(0)$	Initial recovered	0	individuals	assumed
$D(0)$	Initial deceased	7	individuals	[14]
$S(0)$	Initial susceptible	$N - H(0) - A(0) - R(0) - D(0)$	individuals	
$C_H(0)$	Initial cumulative hospitalized	190	individuals	[14]
	Basque Country, Spain			
N	Total population	2 199 711	individuals	[61]
$H(0)$	Initial hospitalized	3	individuals	[49]
$A(0)$	Initial mild or asymptomatic	fitted	individuals	
$R(0)$	Initial recovered	0	individuals	assumed
$D(0)$	Initial deceased	0	individuals	[49]
$S(0)$	Initial susceptible	$N - H(0) - A(0) - R(0) - D(0)$	individuals	
$C_H(0)$	Initial cumulative hospitalized	3	individuals	[49]
	Tuscany, Italy			
N	Total population	3 692 555	individuals	[61]
$H(0)$	Initial hospitalized	2	individuals	[49]
$A(0)$	Initial mild or asymptomatic	fitted	individuals	
$R(0)$	Initial recovered	0	individuals	assumed
$D(0)$	Initial deceased	0	individuals	[49]
$S(0)$	Initial susceptible	$N - H(0) - A(0) - R(0) - D(0)$	individuals	
$C_H(0)$	Initial cumulative hospitalized	2	individuals	[49]

is decreasing ($R_t < 1$), growing ($R_t > 1$), or plateauing ($R_t = 1$), and can be used to evaluate the impact of control interventions in real time [17]. Several methods have been proposed to estimate R_t using only incidence time series [63–66].

Let I_t represent the incidence at calendar time t, and let the discretized probability distribution of the generation interval be denoted as g_s. Employing the renewal equation approach as outlined in Fraser et al. (2007) [65], the instantaneous reproduction number can be expressed as

$$R_t = \frac{I_t}{\sum_{s=1}^{t} g_s I_{t-s}} = \frac{I_t}{\Lambda_t}. \tag{2}$$

The denominator Λ_t in (2) quantifies the total number of active cases. Hence, R_t is the ratio of new secondary cases produced by the actual total active cases [63].

Drawing from the definition in Eq. (2), Cori et al. [64] made the assumption that

$$\mathbb{E}(I_t|I_{t-1},...,I_2,I_1) = R_t\Lambda_t, \tag{3}$$

where $\mathbb{E}(\cdot)$ denotes the expectation function, and

$$I_t|I_{t-1},...,I_2,I_1 \sim Po(R_t\Lambda_t) \tag{4}$$

indicating that the conditional incidence I_t given previous incidences follows a Poisson distribution. Given that incidence time series often exhibit overdispersion in data, a natural refinement of the Poisson model is to consider a more generalized count data model, such as the Negative Binomial. In this context, we adopt a recently developed approach [63] to enhance the estimation of R_t by augmenting the Poisson sampling model with an autoregressive prior for the logarithm of observed R_t values. This transformation yields a dynamic linear model, which in conjunction with Bayesian updating, enables a filtering-type inference for the sequence of $log(R_t)$ (for detailed insights, refer to [63]).

Evaluating the life expectancy before and during COVID-19 pandemic

Our evaluation of changes in life expectancy was conducted using the methodology outlined by Román et al. [67]. This approach involves deriving the life expectancy function by using the mortality rate across all ages and causes of death. The mortality rate is calculated as the ratio of the number of deaths to the population within each age group. We performed this analysis for the populations of Spain, Italy, the Basque Country, and Tuscany for the years of 2019 and 2020.

To obtain the necessary data, we accessed information from the Spanish National Statistics Institute (INE) [68], the National Statistics Institute of Italy (ISTAT) [14], and the Basque Statistics Institute (EUSTAT) [61]. The data covered the death rates of individuals aged 0 to 110 years, categorized into 5-year intervals.

To conduct a survival analysis [69], we first estimated the instantaneous hazard function of mortality $q(x)$, which is known to increase exponentially by age following the Gompertz function $q(x) = \alpha e^{\beta x}$ [70]. The parameters of this function were calculated with exponential regressions from the mortality rates.

Next, we proceeded to compute the cumulative hazard function $Q_x(t)$ by integrating the instantaneous hazard function over the age interval x to the time of death t. Subsequently, the survival function $s_x(t)$ was established as a probability measure, specifically the exponential of the negative $Q_x(t)$ as follows [69]:

$$Q_x(t) := \int_x^{x+t} q(s)ds \qquad\qquad s_x(t) := e^{-Q_x(t)}$$

Finally, we calculate the life expectancy function at every age x as the inverse of the fatality function $1 - s_x(t)$ with respect to time. The domain of this life expectancy function is the probability of dying and provides an estimate of the remaining lifespan for an individual at age x. Given that life expectancy serves as a proxy for the mean duration of life, and adopting the assumption of a normal distribution for the probability of mortality from any cause, we evaluated this function at the median value of 0.5. This approach produces a function that depends solely on age x.

Results

The impact of lockdowns and other Non-Pharmaceutical Interventions (NPIs) on COVID-19 transmission

Using the baseline parameter values estimated from the available data as described in the Model calibration section, we have obtained a good agreement between the *SHARD* model output (1) and empirical data on hospitalization and death from Spain, Italy, the Basque Country, and Tuscany. Figure 2 shows the trends of disease transmission during the dates when those measures were implemented as shown in Table 2.

Upon reviewing decrees and announcements from official government websites [39, 71, 74], we observe that the increase and decrease of the estimated values of the transmission rate (β) generally reflect the declaration and the lifting of lockdowns and other NPIs in Spain, Italy, (Fig. 3), the Basque Country, and Tuscany (Fig. 4). The estimated death rates (μ) among the hospitalized cases (see section 1 of Additional File) allowed for good agreement between model output and data. Nonetheless, these results likely demonstrate the underreporting of deaths, especially at the regional level.

Spain

The model's estimations indicate that the peak of COVID-19 transmission in Spain occurred from late February to early March 2020 ($\beta = 0.21$), before the implementation of the lockdown (Fig. 3a). A steep decline in transmission started immediately after the declaration of the 1st state of alarm on March 11, 2020, prompting the whole population to stay at home except for emergencies, purchasing food or medicines, and work. An additional work-from-home order for non-essential jobs would then be declared on March 29, 2020.

With the gradual relaxation of restrictions at the end of April 2020, allowing increased mobility and a phased reopening of businesses, COVID-19 transmission rates began to rise again ($\beta = 0.04$). The associated rise in

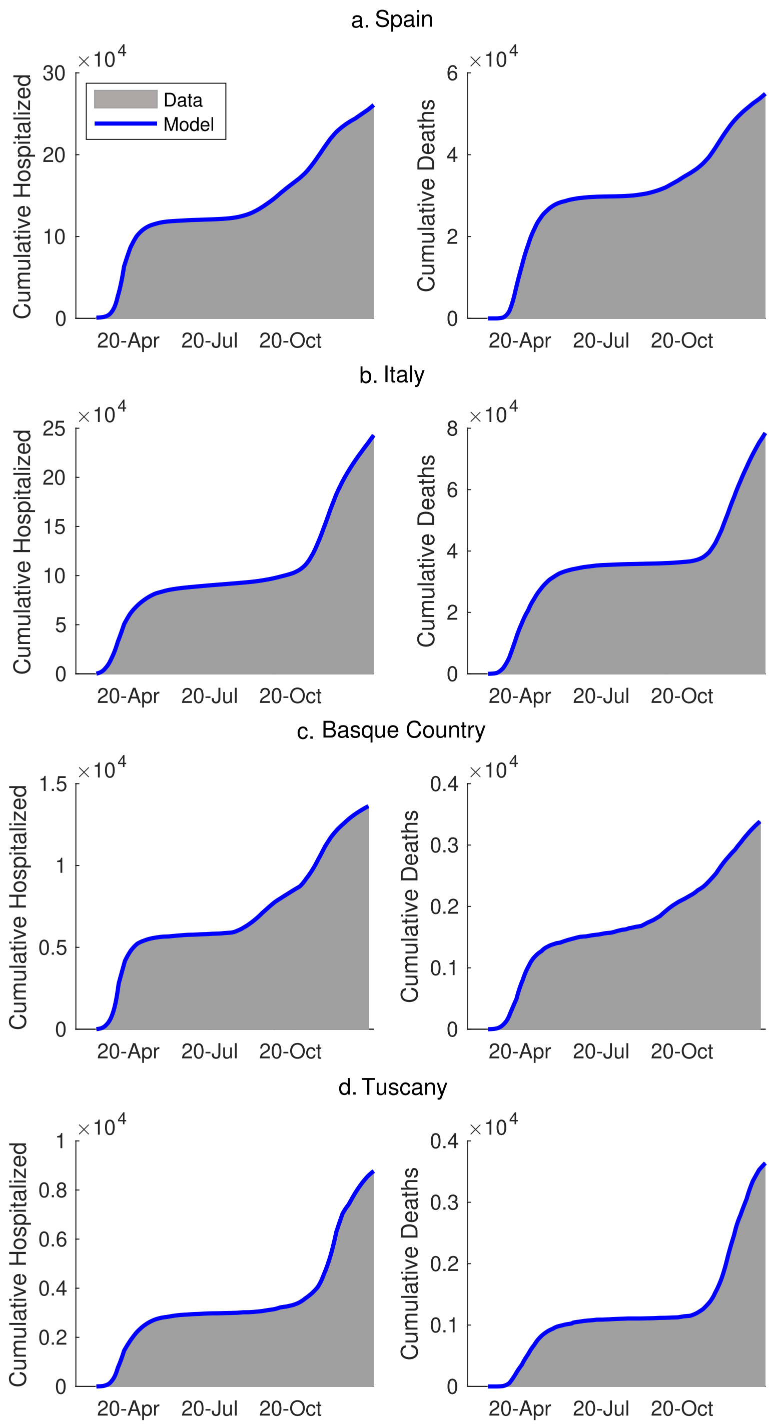

Fig. 2 After calibration, solutions of the *SHARD* model (blue) agree with the data (gray) on the COVID-19 cumulative hospitalizations (left column) and cumulative deaths (right column) in Spain, Italy, the Basque Country and Tuscany in 2020

COVID-19 transmission persisted even after the state of alarm was lifted on June 21, 2020, signaling the reopening of national borders and the establishment of a "new normal." It was only by the end of July 2020 that transmission rates began to decrease ($\beta = 0.13$). Throughout the period from July to September 2020, Spain did not introduce any further nationwide mandates. However, various autonomous communities within the country implemented their own localized Non-Pharmaceutical Interventions (NPIs) at regional or municipal levels [75–78].

Table 2 Dates and events of lockdown and other NPIs implemented in Spain, Italy, the Basque Country and Tuscany in 2020 to control COVID-19

	Timeline of NPIs for Spain [71]
Date	**Event**
14-Mar-20	1st state of alarm (stay-at-home order, national borders closed, schools closed)
29-Mar-20	Work from home order for non-essential jobs
28-Apr-20	De-escalation of restrictions
13-May-20	Resumption of non-essential jobs
21-Jun-20	End of 1st state of alarm
Jul-20 to Sep-20	Interventions at the regional government level
25-Oct-20	2nd state of alarm (curfew, limited gatherings, regional border control)
	Timeline of NPIs for Italy [72, 73]
Date	**Event**
31-Jan-20	State of emergency declared
23-Feb-20	Regional lockdowns
4-Mar-20	Schools and universities closed
9-Mar-20	Partial lockdown extended to the whole of Italy
22-Mar-20	Complete national lockdown
4-May-20	National lockdown eased (reopening of some businesses)
18-May-20	Reopening of bars, shops, and some social activities
4-Jun-20	Unrestricted inter-regional movement resumed
15-Jun-20	Recreational activities resumed
13-Oct-20	New set of restrictions (mask-wearing, limitations on gatherings, social distancing)
14-Oct-20	Further restrictions on movement
6-Nov-20	Regional lockdown by risk
	Timeline of NPIs for Basque Country [71, 74]
Date	**Event**
14-Mar-20	1st state of alarm (stay-at-home order, national borders closed, schools closed)
29-Mar-20	Work from home order for non-essential jobs
28-Apr-20	De-escalation of restrictions
11-May-20	Mobility allowed within the municipality of residence
13-May-20	Resumption of non-essential jobs
25-May-20	Mobility allowed within the historical territory of residence
8-Jun-20	Mobility allowed within the Basque Country
21-Jun-20	End of 1st state of alarm
25-Oct-20	2nd state of alarm (curfew, limited gatherings, regional border control)
11-Dec-20	Mobility allowed within the historical territory of residence
	Timeline of NPIs for Tuscany [72, 73]
Date	**Event**
9-Mar-20	Partial lockdown
22-Mar-20	Complete lockdown
4-May-20	National lockdown eased (reopening of some businesses)
18-May-20	Reopening of bars, shops, and some social activities
4-Jun-20	Unrestricted inter-regional movement resumed
15-Jun-20	Recreational activities resumed
13-Oct-20	New set of restrictions (mask-wearing, limitations on gatherings, social distancing)
11-Nov-20	Placed under orange risk
15-Nov-20	Placed under red risk
4-Dec-20	Placed under orange risk

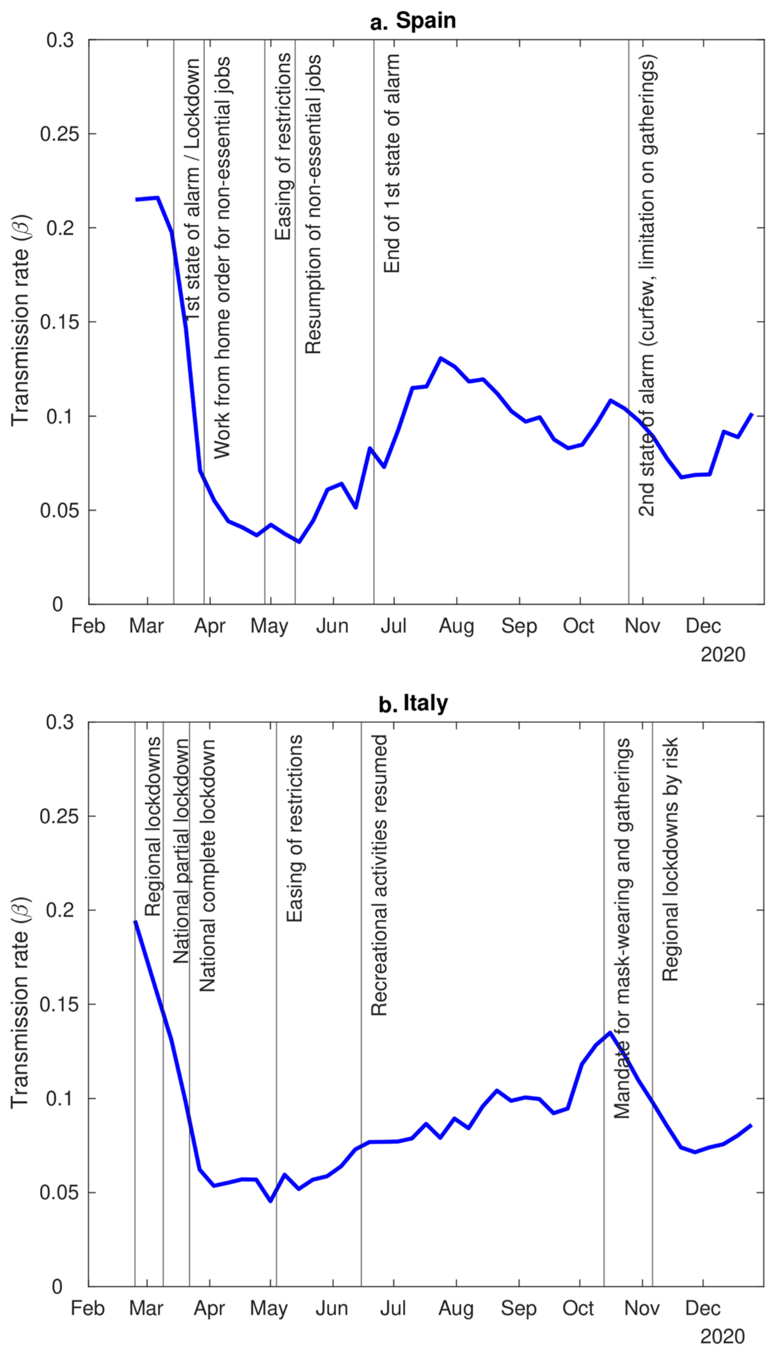

Fig. 3 Estimated COVID-19 transmission rate in Spain (top) and Italy (bottom) in 2020 after model calibration. Vertical lines denote the start and easing of the NPIs listed in Table 2 for each country. Reductions in transmission rate can be observed in both countries after the implementation of the key NPIs

A third wave of COVID-19 started in October 2020 has triggered the declaration of the second state of alarm in Spain. Despite sharing the same name, this second state of alarm was characterized by a milder set of interventions compared to the initial one [44]. Nevertheless, our model's estimations reveal a rapid reduction in COVID-19 transmission rates shortly after the initiation of the second state of alarm (transitioning from $\beta = 0.11$ to $\beta = 0.07$). However, this decline was followed by an increase in transmission, starting in the second week of December 2020 and persisting until the year's end ($\beta = 0.10$).

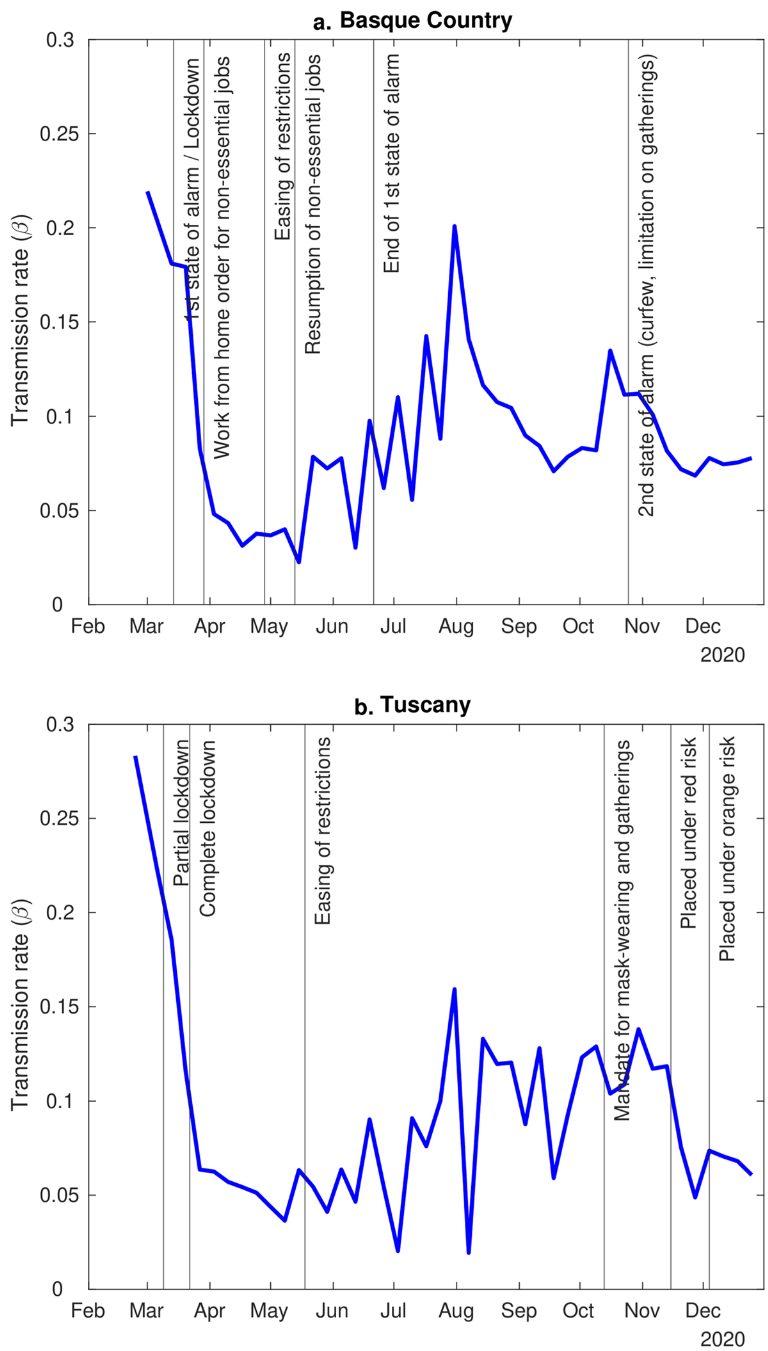

Fig. 4 Estimated COVID-19 transmission rate in the Basque Country (top) and Tuscany (bottom) in 2020 after model calibration. Vertical lines denote the start and easing of the NPIs listed in Table 2 for each region. Not shown in the graph: Tuscany was also placed under orange risk on November 11, 2020. Reductions in transmission rate can be observed in both regions after the implementation of key NPIs

Italy

Our model indicates that the COVID-19 interventions implemented in Italy in 2020 had a substantial impact (see Fig. 3b). The peak transmission rate in Italy was recorded in February 2020 ($\beta = 0.19$). However, unlike Spain, Italy experienced a rapid decline in transmission after the introduction of several interventions.

In detail, regional lockdowns were put in place in late February, resulting in a reduced transmission rate ($\beta = 0.16$). A partial national lockdown was enforced on March 9, further reducing the transmission rate ($\beta = 0.13$). A complete national lockdown was implemented on March 22, leading to a significant decrease in transmission ($\beta = 0.09$). COVID-19 transmission in Italy reached its lowest levels from April to early May, with a transmission rate of $\beta = 0.05$. However, transmission rebounded as restrictions were eased on May 4, and recreational activities resumed on June 15 ($\beta = 0.07$). This gradual increase in transmission continued until late September ($\beta = 0.09$).

A spike in COVID-19 transmission occurred from late September to the second week of October, with a rate of $\beta = 0.14$. Subsequently, the Italian government mandated mask-wearing and imposed limitations on gatherings. Transmission sharply declined, further aided by the implementation of regional lockdowns based on risk levels on November 6 ($\beta = 0.10$). The second set of NPIs coincided with the mitigation of transmission in Italy until the end of November ($\beta = 0.07$). By December, transmission began to slowly increase again, reaching a rate of $\beta = 0.08$ by the end of the year.

Basque Country

In the Basque Country region, the links between NPIs and COVID-19 transmission rates followed a pattern similar to Spain, as both regions generally implemented a similar schedule of interventions (see Fig. 4a).

The highest transmission rate in the Basque Country was recorded during the first week of March ($\beta = 0.22$). This was mitigated to low levels by April and the beginning of May (ranging between $\beta = 0.02$ and $\beta = 0.04$) following the implementation of the first state of alarm. A slight increase in transmission was observed by the end of May ($\beta = 0.07$) as the Basque government eased mobility restrictions, starting with allowing movement within municipalities on May 11 and gradually permitting movement within the entire region on June 8 [45].

From July to August, there was an upward trajectory in COVID-19 transmission following the end of the state of alarm. Similar to Spain as a whole, this second wave peaked in August ($\beta = 0.20$) without the introduction of additional interventions. Transmission then declined until October when an incipient third wave emerged. The third wave of COVID-19 in the Basque Country immediately peaked ($\beta = 0.13$) and started to decline as the second state of alarm was declared in Spain on October 25 ($\beta = 0.11$). By the end of 2020, COVID-19 transmission in the Basque Country had stabilized at a constant and relatively low level ($\beta = 0.08$).

Tuscany

Similar to Italy, the Tuscany region (as shown in Fig. 4b) experienced its highest COVID-19 transmission rate at the onset of the outbreak at the end of February ($\beta = 0.28$). Subsequently, transmission underwent two distinct phases of decline. The first decline in transmission occurred from February to late March ($\beta = 0.06$), primarily attributed to the partial lockdown imposed on March 9. The second decline in transmission took place as Italy implemented a complete lockdown, which lasted until early May ($\beta = 0.03$).

Following the relaxation of restrictions on May 18, transmission in Tuscany exhibited significant fluctuations, overall displaying an increasing trend until early October ($\beta = 0.12$). Transmission slightly decreased ($\beta = 0.10$) following a mask mandate by the Italian government on October 13, only to exhibit a slight rebound thereafter. By November 11 ($\beta = 0.12$), the region was classified under an orange risk category (medium risk). One week later, it was elevated to red risk (high risk), leading to a decline in transmission until the end of November ($\beta = 0.04$). By December 2020, the Tuscany region was re-classified under orange risk, and transmission remained at relatively lower levels until the end of the year.

Overall impact of NPIs on transmission

Our findings highlight the clear relationship between the Non-Pharmaceutical Interventions (NPIs) implemented and the transmission of COVID-19 in Spain, Italy, the Basque Country, and Tuscany during 2020, underscoring the effectiveness of these measures.

In all four regions examined, the most substantial reduction in transmission occurred following the initiation of the lockdown in March 2020 (Figs. 3 and 4). Specifically, our model estimates a transmission reduction of 74% in Spain, 66% in Italy, 78% in the Basque Country, and 72% in Tuscany during the implementation of the initial major NPIs from the first week of March to the first week of April (as illustrated in Fig. 5). Despite differences in methodologies, our estimates align with the findings in [24], which also analyzed the impact of NPIs in March 2020 across Spain, Italy, and other European countries.

As restrictions gradually eased in May 2020, we observed an increase in transmissions across all regions. Notably, the increase in transmission after the lifting of the lockdown was more pronounced in Spain and the Basque Country, leading to second waves of infections peaking in July and August 2020, respectively.

In response to the rising transmission rates by the end of October 2020, policymakers in Spain, Italy, the Basque Country, and Tuscany implemented a second set of NPIs. From the fourth week of October to the fourth week of November, our model indicates a corresponding decline in transmission of 34% for Spain, 42% in Italy, 39% in the

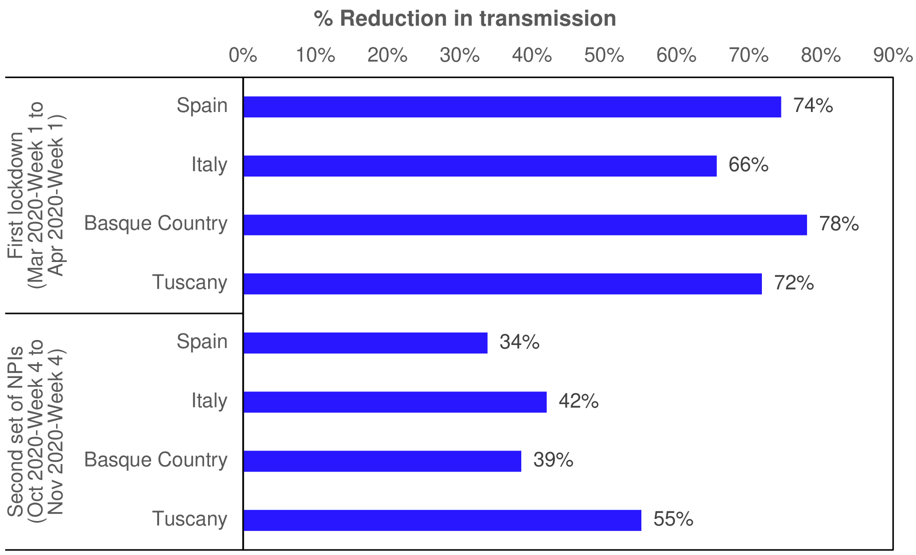

Fig. 5 Reductions in transmission rate (β) were larger after the first lockdown in March 2020, compared to when the second set of NPIs was implemented in October 2020 for Spain, Italy, the Basque Country and Tuscany

Basque Country, and 55% in Tuscany. It is important to note that these percentages should not be used to directly compare the effectiveness of each government's NPIs, especially for the Basque Country and Tuscany, where estimated transmission fluctuated significantly.

The instantaneous reproduction number

We considered daily laboratory-confirmed SARS-CoV-2 cases during 2020 to compute the instantaneous reproduction number R_t using the approach proposed in [63]. One important input to compute R_t via data-driven methods is the generation time. Based on viral load dynamics and duration of infectiousness for SARS-CoV-2 [79], we choose an $Erlang(3, 8/3)$ as a distribution of the generation time. So the expected value is at day 8, the maximum infectivity is 5.5 days, and the infectiousness decreases to zero after 20 days.

The estimation of R_t together with daily confirmed cases during 2020 in Spain, Italy, the Basque Country, and Tuscany are presented in Figs. 6a, b, 7a and b, respectively. To account for reporting delays and other incidence data anomalies, a 7-day moving average of cases is also presented. Vertical lines are shown at approximate peak times which by the definition of R_t should correspond with times when R_t is equal to the threshold value 1. Observe that although the instantaneous reproduction number can present fluctuations in its value, as long as $R_t > 1$, the incidence presents an increase in cases.

In Spain, the COVID-19 incidence data presents three epidemic waves with estimated peaks in early April, late September, and early November (Fig. 6a). Observe that the R_t value is very close to 1 near these dates. In the pre-lockdown phase of the pandemic, before the first peak, the value of R_t was always greater than one which agrees with the increasing trend in daily cases. From the end of March until mid-June, when mobility restrictions were imposed, the R_t value shows a clear decreasing trend. By late June, the state of alarm expired and the second wave started to take shape in July, so R_t was above one during this period. Madrid was the epicenter of the pandemic with cases rising non-stop so the peak was not reached until the end of September when the Madrid government imposed mobility restrictions for 14 days [80]. When the restrictions ended, the cases started to rise again leading to the third peak. On October 25, the Spanish government decreed a state of alarm again to deal with the wave of infections, and a third peak was reached soon after. The cases started to decrease after early November with an R_t below 1.

Similar to Spain, three COVID-19 waves were observed in the Basque Country in 2020 with approximate peak dates on April 3, September 2, and November 16 (Fig. 7a). After the lifting of the first state of alarm in June 2020, small-sized outbreaks appeared in different parts of the Basque Country, contributing to the second wave of COVID-19 in the region. In response to the third wave of infections, the second state of alarm was decreed in October, which was then followed by the decrease of R_t to values less than 1.

In the Italian context, we observed two waves in 2020 (Fig. 6b). By March, Italy was the most affected country in terms of confirmed cases within the European Union with an R_t way above 1. On March 22, a complete national lockdown was declared and the R_t value decreased

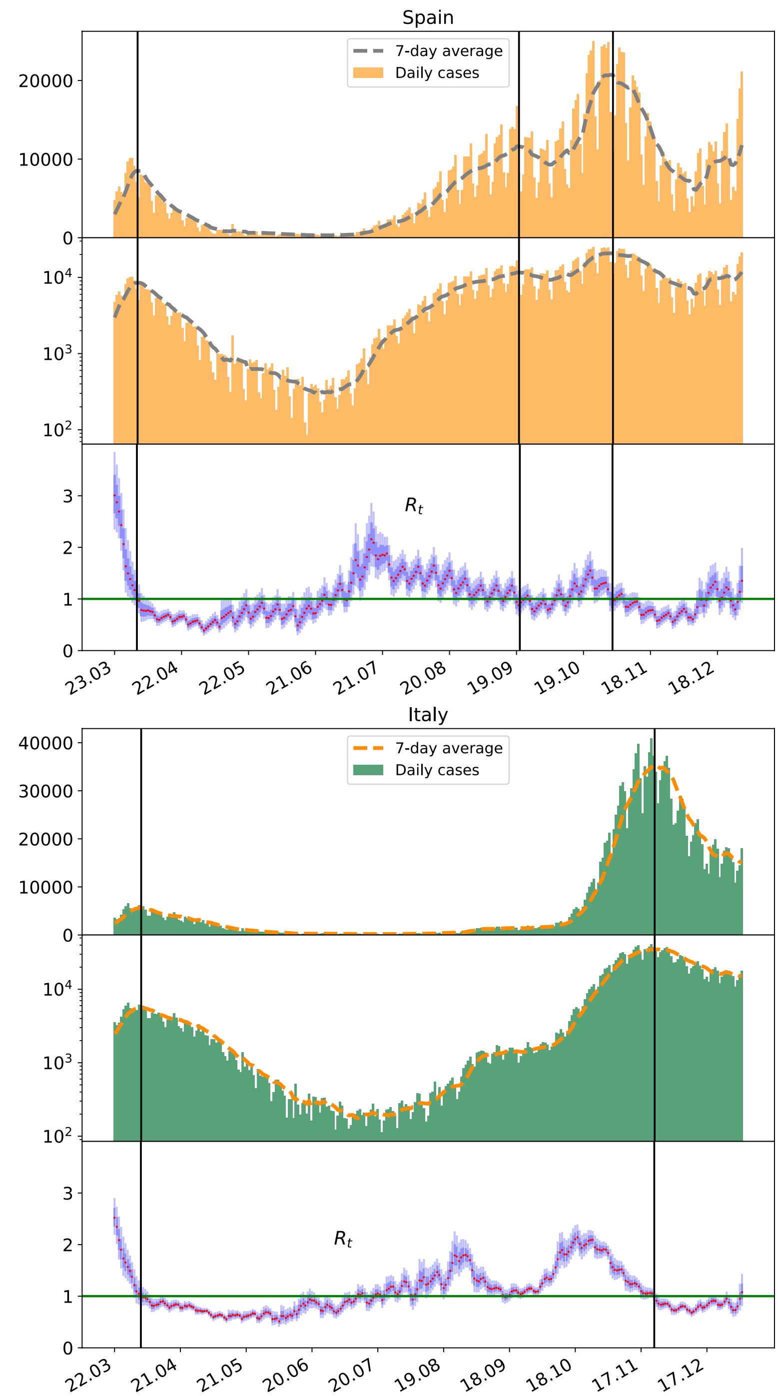

Fig. 6 In each subfigure, the first row shows confirmed SARS-CoV-2 cases from March to late December 2020. The dashed line represents a 7-day moving average. The second row shows the number of confirmed cases on a logarithmic scale. The third row shows the instantaneous reproduction number R_t. The red dots represent the median estimate for R_t. The dark and light blue shaded areas represent 50% and 90% quantiles for R_t, respectively. The green solid line indicates the threshold value 1 on the reproduction number and the vertical black lines indicate peak times

quickly afterwards. On June 4, the mobility restrictions were relaxed and R_t started to slowly increase during July and August. Nevertheless, the number of active cases was relatively low. From September to October, the Italian R_t was always above 1 leading to the second epidemic wave. Hence, in the middle of October, the Italian government reintroduced mobility restrictions to limit the spread of SARS-CoV-2. Subsequently, the instantaneous

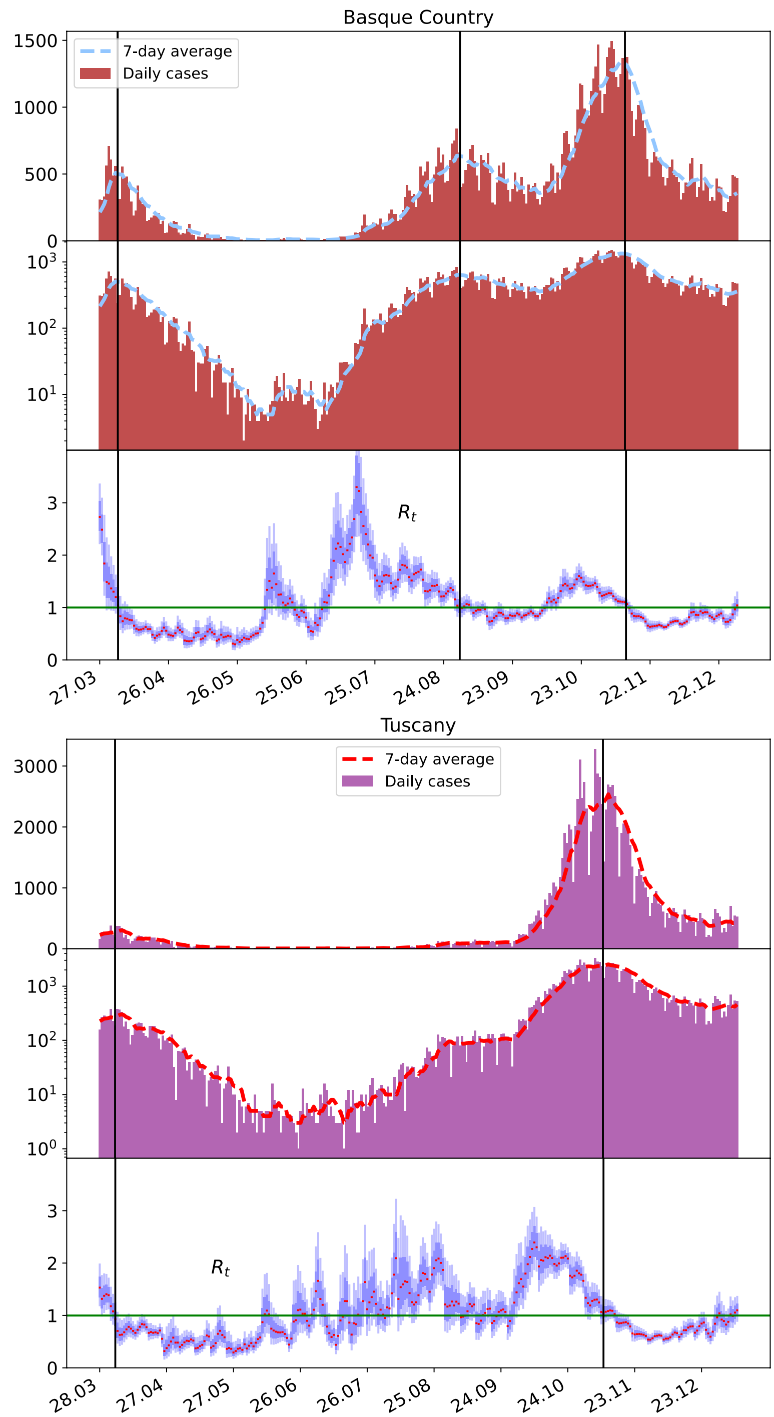

Fig. 7 In each subfigure, the first row shows confirmed SARS-CoV-2 cases from March to late December 2020. The dashed line represents a 7-day moving average. The second row shows the number of confirmed cases on a logarithmic scale. The third row shows the instantaneous reproduction number R_t. The red dots represent the median estimate for R_t. The dark and light blue shaded areas represent 50% and 90% quantiles for R_t, respectively. The green solid line indicates the threshold value 1 on the reproduction number and the vertical black lines indicate peak times

reproduction number decreased reaching the threshold value of 1 around November 20, the approximate peak date of the second wave. The instantaneous reproduction number in the Tuscany region (Fig. 7b) presents similar trends as the rest of Italy, with two waves that peaked just a few days earlier than the national average.

Life expectancy losses

Our findings indicate a reduction in life expectancy in Spain (1.51 years, 3.93%), Italy (1.27 years, 3.62%), the Basque Country (0.77 years, 2.53%), and Tuscany (0.66 years, 2.13%) from 2019 to 2020. This suggests a greater impact of COVID-19 at the national than the regional level. These estimates align well with other studies [46, 47]. Furthermore, our baseline life expectancy values for 2019 (as depicted in Fig. 8) are consistent with official sources such as the National Institute of Statistics (INE) [68] and the Italian National Institute of Statistics (ISTAT) [14]. These sources also confirm that women tend to have longer life expectancies than men and that life expectancy at birth is higher for women.

In all examined regions, men experienced a more significant relative reduction in life expectancy compared to women. When comparing Spain and Italy (as illustrated in Fig. 9), it is evident that Spanish women had the largest absolute decline in life expectancy, with a loss of 1.62 years from 2019 to 2020, surpassing all other groups. This decrease was particularly pronounced in younger Spanish women. Interestingly, the gender difference in life expectancy reduction is more prominent in Italy than in Spain. Italian men experienced the same level of reduction as the Spanish population (4.28%), while Italian women had a comparatively smaller reduction in life expectancy (3.55%).

Regarding age, the findings consistently indicate that the older the population, the greater the reduction in life expectancy, irrespective of the region or gender. A closer examination reveals that for individuals in Spain under the age of 75, women experienced a slightly higher decrease (3.93%) compared to men (3.77%). Conversely, Spanish men aged 75 and older saw more significant declines (11.34%) than women (11.27%).

In the comparison between the Basque Country and Tuscany regions (Fig. 9), men's life expectancy decreased by an average of 0.82 and 0.63 years, respectively. Meanwhile, Basque and Tuscan women experienced reductions of 0.73 and 0.63 years, respectively. Additionally, our results reveal that, in relative terms, men in both regions experienced more substantial reductions in life expectancy (2.54% in the Basque Country and 2.25% in Tuscany) compared to women (2.10% in the Basque Country and 2.20% in Tuscany).

When comparing the four regions, we notice that relative life expectancy losses tend to increase with age. However, there is an interesting observation in the Basque Country, where we see a plateau in the loss of life expectancy for individuals older than 70 years. This phenomenon might be attributed to various factors, including demographic composition, healthcare infrastructure, and the specific impact of COVID-19 in these regions. The smaller population size in the Basque Country can result in more significant fluctuations in data, potentially leading to variations in observed trends. It is important to note that further research and analysis would be needed to provide a comprehensive explanation for these observations.

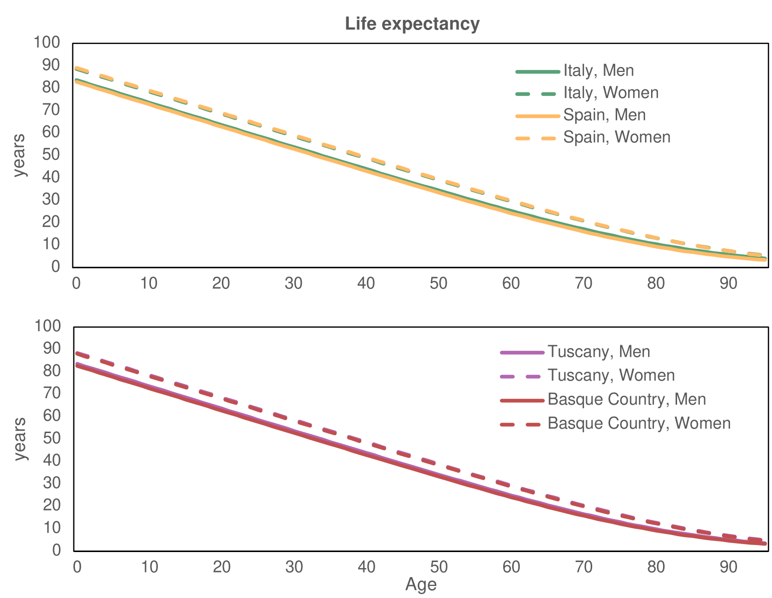

Fig. 8 Life expectancy in Spain, Italy, the Basque Country, and Tuscany in 2019 by sex and age. The comparison between sexes reveals higher life expectancy for women (dashed lines) than men (solid lines) across all age groups in all settings

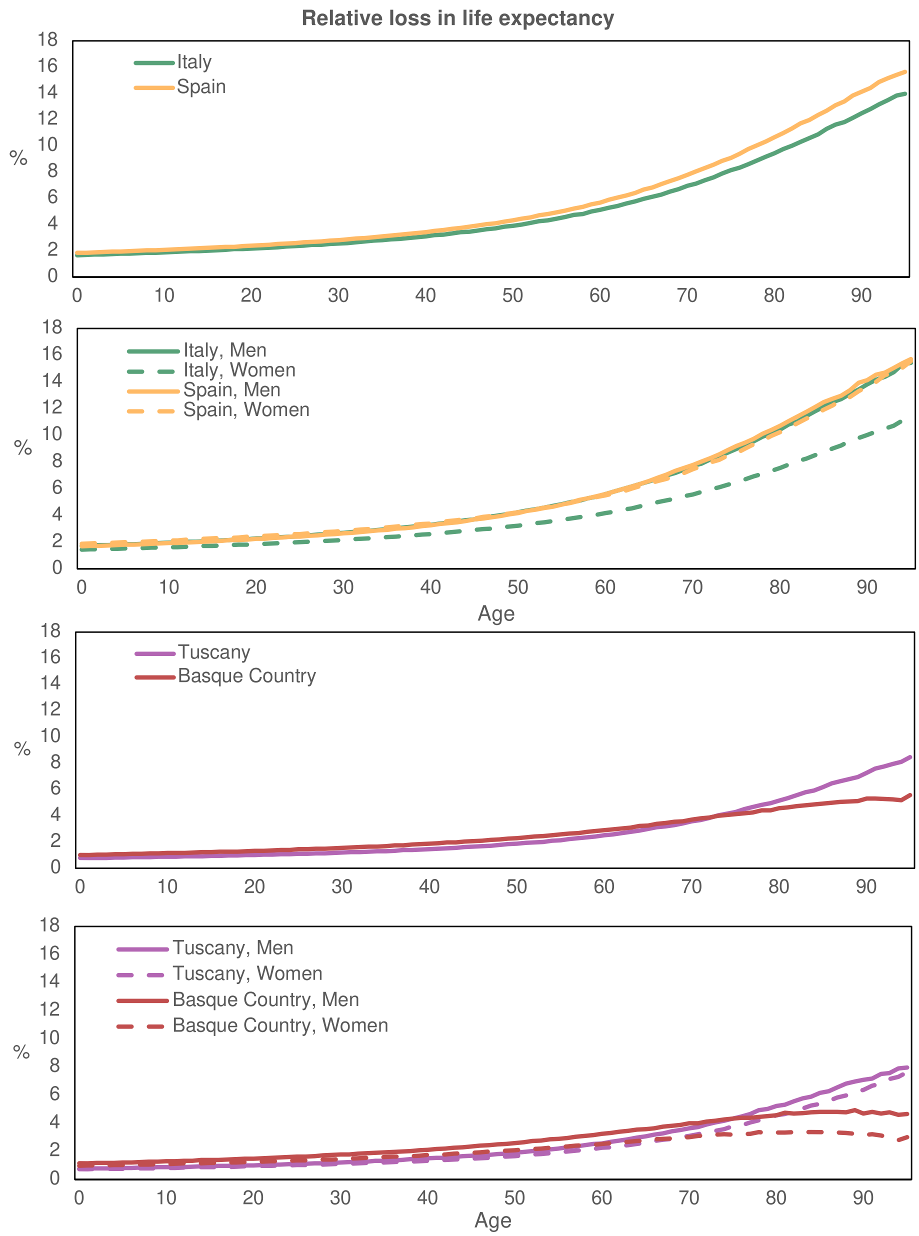

Fig. 9 Life expectancy loss in 2020 in percentage points with respect to 2019 at different ages. The top plot illustrates the differences between Spain and Italy, while the bottom plot compares the impact on men (solid lines) and women (dashed lines)

Life expectancy by comorbidity in the Basque Country

The Basque Modeling Task Force (BMTF) project in collaboration with the Osakidetza Basque Health Service enabled the possibility to extend the analysis of life expectancy in the Basque Country. Having access to the complete healthcare information (clinical and administrative datasets) about the entire population of the Basque Country in an anonymized format, allowed us to calculate the comorbidity level of every individual and to classify it into four categories [50]. The difficulties in obtaining similar data for the rest of Spain or Italy prevented us from making the analogous study in these regions.

This adjustment took into account the Charlson Comorbidity Index (CCI), ranging from high comorbidity to no comorbidities at all. With the comorbidity level distribution among the population and following a similar approach employed in cardiovascular risk models [81], we transformed the comorbidity index into a hazard ratio [82], normalizing it according to the distribution of comorbidity levels in the general population. The risk factor associated with comorbidity was incorporated as a multiplicative factor in the instantaneous hazard function.

In the Basque Country, individuals with higher comorbidity levels experienced more substantial reductions in life expectancy compared to those with fewer or no comorbidities, spanning all age groups (see Fig. 10). Notably, these reductions became more pronounced with increasing age. For instance, among 25-year-olds, individuals with a high comorbidity level saw a 2.4% reduction in their life expectancy, while those without comorbidities experienced only a 1.3% reduction. Conversely, among 60-year-olds, individuals with a high comorbidity level experienced a 5.4% reduction in life expectancy, whereas those with no comorbidities had a 2.5% reduction.

Discussion

The impact of NPIs during the first year of the COVID-19 pandemic in Spain and Italy has been evaluated by many studies, mainly by measuring the changes in R_t during the dates when NPIs were declared [24, 27, 83, 84]. Overall, more focus has been given to assessing the first round of NPIs in March 2020 [25, 33, 52, 85–87], than the second set of NPIs enacted in October 2020 [88, 89].

In this paper, we proposed an alternative to evaluating the impact of the lockdowns and NPIs in Spain, Italy, the Basque Country, and Tuscany to control COVID-19 transmission. We revealed the relationship between the reductions in transmission rate and the NPIs by calibrating an epidemiological model to hospitalization and death data. We also validated our approach by showing that the estimated transmission rate mirrors the instantaneous reproduction number (R_t), even though the former was estimated using hospitalization and death data while the latter was estimated using incidence data. We further computed the changes in life expectancy from 2019 to 2020, paying close attention to variations by age, sex, and the presence of comorbidities.

Our results demonstrated dramatic reductions in transmission rate when the NPIs were declared in Spain, Italy, the Basque Country, and Tuscany. Importantly, our results highlight the greater impact of the first set of NPIs, including the national lockdowns, in March 2020 (66% to 78% reduction in transmission) than the second set of NPIs in October 2020 (34% to 55% reduction in transmission). These findings affirm the key role of lockdowns and NPIs in curbing COVID-19 transmissions in 2020. Despite economic costs [90], these lockdowns and NPIs facilitated significant disease mitigation, affording governments time until vaccinations became available in 2021.

Our methodology of estimating the transmission rate also provides an alternative to using instantaneous reproduction numbers to gauge the impact of lockdowns and NPIs. While our model necessitates determining more parameter values, it allows for encapsulating more data through the process of model calibration.

Our findings also highlight that the life expectancy in all four settings decreased after the pandemic across all ages and sexes, consistent with studies of life expectancy

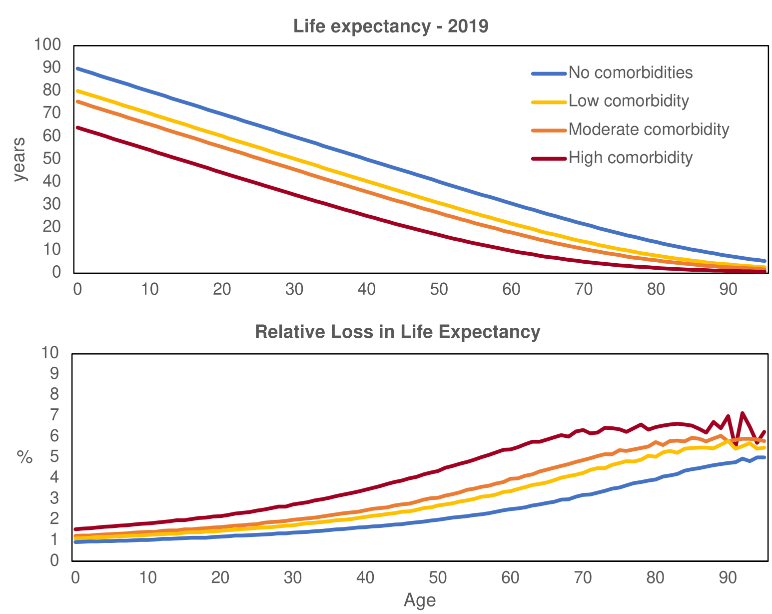

Fig. 10 Life expectancy by age and comorbidity level in 2019 in the Basque Country (top) and the relative decline in life expectancy from 2019 to 2020 (bottom)

in other countries heavily affected by the pandemic [7, 46, 47]. Relative losses in life expectancy were higher for men and the elderly. In the Basque Country, reductions in life expectancy were more significant among people with comorbidities than those with less or no comorbidities. These findings uphold the decision to prioritize vaccination for those with comorbidities and the elderly for vaccinations and NPIs against COVID-19 [33].

Our results rest on several assumptions and limitations of our model. Primarily, the choice of a fixed relative infectiousness value for mild and asymptomatic cases (ϕ), which also directly affects the model output for the number of infected individuals who are not in the hospital ($A(t)$), may have hindered the realism of our model, as it would be likely affected by the changes in the mobility of the population. Nevertheless, when looking at the cumulative number of infected individuals, our model outputs (see section 2 of Additional File) are aligned with estimates of seroprevalence in Spain [24, 91, 92], Italy [93], the Basque Country [91], and Tuscany [93, 94]. Further research could focus on refining the model to incorporate relevant dynamics (such as mobility, compliance to NPIs, vaccination, waning immunity, and the emergence of COVID-19 variants) to answer questions relating to the effectiveness of health policies.

Conclusion

In conclusion, our work contributes to understanding the effects of NPIs on COVID-19 by estimating a time-varying transmission rate over multiple waves. Our analysis of the two sets of NPIs in Spain, Italy, the Basque Country, and Tuscany highlights the much larger impact of the first set of NPIs compared to the second. Moreover, we showed that our approach is robust to the estimation of the instantaneous reproductive number and results on seroprevalence. Lastly, our results confirm the heterogeneous impact of COVID-19 on the population's life expectancy, underlining the importance of designing interventions that prioritize the elderly and those with comorbidities.

Abbreviations

COVID-19	Coronavirus disease 19
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
NPIs	Non-pharmaceutical interventions
WHO	World Health Organization
CNE	Centro Nacional de Epidemiología
ISS	Istituto Superiore di Sanità
R_t	Instantaneous reproduction number
CCI	Charlson comorbidity index

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22239-9.

Supplementary Material 1. The additional PDF file includes details on parameter estimation for the death rate, the estimated prevalence of SARS-CoV-2 in each region, and the pseudocode for model calibration.

Authors' contributions

CDSE, CC, RBA, NS, and MA conceptualized the study. JM, JBV, and OI curated the data. CDSE, CC, AB, RBA, and FS contributed to the analysis and preparation of the figures. CDSE, CC, RBA, FS, NS, and MA contributed to the preparation and editing of the draft. All authors read and approved the final manuscript.

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Data availability

The COVID-19 data on incidence, hospitalizations, and deaths are publicly available in Centro Nacional de Epidemiologia (CNE) (https://cnecovid.isciii.es/covid19/#documentaci%C3%B3n-y-datos) [13] for Spain, and the Istituto Superiore di Sanità (ISS) (https://covid19.infn.it/iss/#) [62] for Italy and Tuscany. The COVID-19 data used for the Basque Country were provided by the Basque Health Service (Osakidetza). Our data agreement with Osakidetza clearly stipulates that the data used in this study cannot be shared publicly. Aggregates of the data are publicly available in https://opendata.euskadi.eus/catalogo/-/evolucion-del-coronavirus-covid-19-en-euskadi/ [49]. The data for life expectancy computations are publicly available from Instituto Nacional de Estadística (INE) (https://www.ine.es/jaxiT3/Tabla.htm?t=37664&L=0) [68] for Spain, Istituto Nazionale di Statistica (ISTAT) (https://demo.istat.it/tvm2016/index.php?lingua=eng) [14] for Italy and Tuscany, and EUSTAT (https://www.eustat.eus/estadisticas/tema_28/opt_0/tipo_1/ti_defunciones/temas.html) [61] for the Basque Country.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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