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Spatial variability in reproduction number and doubling time across two waves of the COVID-19 pandemic in South Korea, February to July, 2020

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Objectives: In South Korea, 13 745 cases of coronavirus disease (COVID–19) had been reported as of 19 July, 2020. To examine spatiotemporal changes in the transmission potential, we aimed to present regional estimates of the doubling time and reproduction number (\(R_t\)) for COVID–19 in the country.

Methods: Daily series of confirmed COVID–19 cases in the most affected regions were extracted from publicly available sources. We employed established mathematical and statistical methods to investigate the time-varying reproduction numbers and doubling time for COVID–19 in Korea.

Results: At the regional level, Seoul and Gyeonggi Province experienced the first peak of COVID–19 in early March, followed by a second wave in early June, with \(R_t\) exceeding 3.0 and mean doubling time ranging from 3.6 to 10.1 days. As of 19 July, 2020, Gyeongbuk Province and Daegu had yet to experience a second wave of the disease. During the first wave, mean \(R_t\) for these areas reached 3.5–4.4, and doubling time ranged from 2.8 to 4.6 days.

Conclusions: Our findings support the effectiveness of control measures against COVID–19 in Korea. However, the easing of restrictions that had been imposed by the government in May 2020 facilitated a second wave in the greater Seoul area.

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Introduction

Since the first COVID–19 cases were reported in Wuhan, Hubei Province, China in December 2019, more than 24.7 million cases of coronavirus disease (COVID–19), including more than 830 000 related deaths, had been reported worldwide (WHO) as of August 30, 2020. In South Korea, the novel coronavirus was first diagnosed in a 36-year-old Chinese woman who entered the country on January 20, 2020. South Korea has since experienced two heterogeneous waves of the disease, with a total of 13 745 cases, including 295 deaths, as of July 19, 2020 (KCDC, 2020a).

During the early phase of the COVID–19 outbreak in South Korea, public health authorities primarily conducted strict contact tracing and isolation of confirmed cases, as well as applying quarantine for those suspected of infection with the novel coronavirus (Covid–19 National Emergency Response Center E and Case Management Team KCDC, Prevention, 2020). As the number of COVID–19 cases continued to increase, Korean public health authorities set the alert to the highest level (Level 4) on February 23, and mandated the population to report any symptoms related to COVID–19 for further screening and testing. In addition, the country rapidly adopted a ‘test, trace, isolate, and treat’ strategy that has been deemed effective in eliminating localized outbreaks of the novel coronavirus (KCDC, 2020a). However, the total number of confirmed cases in South Korea spiked from 31 cases on February 18 to 433 on February 22. According to the Korea Centers for Disease Control and Prevention (KCDC), this sudden jump was mainly attributed to a super-spreader (the 31 st case) who had participated in a religious gathering of attendees of the Shincheonji Church of Jesus in Daegu (KCDC, 2020a). These superspreading events occurred in the Daegu and Gyeongbuk provincial regions, leading to more than 5210 secondary COVID–19 cases in Korea (KCDC, 2020a; Ryall, 2020). These events facilitated sustained transmission chains, with 38% of the cases in the country associated with the church cluster in Daegu (Kim et al., 2020).

On March 8, the KCDC announced that 79.4% of all cases had epidemiological links, while the remaining 20.6% cases were either...
sporadic cases or under investigation (KCDC, 2020a). Case clusters started to accumulate from churches in the Seoul capital area, and on March 17, 79 church attendees developed COVID-19 after a service at the River of Grace Community Church. In spite of social distancing orders put forward by the government, some churches continued to conduct services, which led to new clusters of infection. For instance, the Mannin Central Church in Seoul was involved in one of the clusters, with 41 infections linked to a gathering in early March; SaengMyeongSu Church in Gyeonggi Province was another cluster linked to 50 cases (Park, 2020).

As SARS-CoV-2 infection spread rapidly outside Korea, the number of imported cases started to increase, resulting in 476 imported cases out of 9661 total cases (4.9%) as of March 30. Consequently, as of 1 April, the KCDC implemented self-quarantine measures for travellers from Europe and the USA (KCDC, 2020a). In addition, incoming travellers with symptoms but negative test results for coronavirus, as well as asymptomatic short-term visitors, were ordered to follow a 2-week quarantine in the government facilities (KCDC, 2020a).

Such control measures undertaken by South Korea have been deemed successful in limiting the spread of the outbreak, without locking down entire cities (Normile, 2020). Therefore, after a sustained period of low incidence with fewer than 20 cases per day (April 16 to May 5), the government eased its strict nationwide social distancing guidelines on May 6, with a phased reopening of schools starting mid-May, 2020. However, a new cluster linked to nightclubs in Itaewon emerged in central Seoul in early May, resulting in a resurgence of cases that led to a second wave of COVID-19 in the greater areas of Seoul. As of May 29, the number of cases linked to this cluster had reached 266 (KCDC, 2020a). Accordingly, the Seoul city government ordered all clubs, bars, and other nightlife establishments in the city to close indefinitely (KCDC, 2020a). Simultaneously, another cluster emerged from an e-commerce warehouse in the Gyeonggi Province, resulting in 108 cases as of May 30.

In the last week of May, around 40–80 daily new cases of COVID-19 were being reported (KCDC, 2020a). Following this spike in the number of new COVID-19 infections — the first in nearly 2 months — public health authorities reimplemented strict lockdown measures in Seoul, along with school closures once more across the nation. In June, it was announced that the strict social distancing campaign would be extended indefinitely as a preventive measure in Seoul, Incheon, and Gyeonggi Province; however, phased reopening of schools was initiated on May 20. It was reported by the KCDC that a holiday weekend in early May triggered a new wave of infections focused in the greater Seoul area, the so-called second wave of COVID-19 in South Korea (2020). In Seoul, the average number of daily new cases reported from June 4 to June 17 was 43 (KCDC, 2020a). This was followed by sporadic clusters of infection across the country in July, most of them associated with religious facilities and door-to-door salespeople, especially in the densely populated Seoul region and adjacent areas. As a result, the government banned churches from organizing small gatherings other than regular worship services from July 10 (KCDC, 2020a). As of September 23, 23 216 cases of COVID-19 had been reported in South Korea, comprising 13.4% imported cases, 59.7% cases linked to local clusters, 14.5% unlinked local cases, and 12.4% cases under investigation (KCDC, 2020a).

To estimate the regional and temporal variability in the reproduction number for COVID-19 in South Korea, including the second wave concentrated in the greater Seoul areas, we analysed the spatiotemporal progression of the epidemic in the

Figure 1. Map showing the location of Seoul, Gyeonggi Province, Gyeongbuk Province, and Daegu.
country from mid-February to mid-July, 2020. Our focus was on estimating and interpreting the doubling time and effective reproduction number $R_t$, a metric that quantifies the time-dependent transmission potential of the disease, incorporating the effect of control measures, susceptible depletion, and behavioural changes. This key epidemiological parameter, $R_t$, represents the average number of secondary cases generated per case whenever conditions persist as they were at time $t$. Epidemic doubling times refer to the sequence of intervals at which the cumulative incidence doubles (Lee et al., 2020; Muniz-Rodriguez et al., 2020). Therefore, an increase in the doubling time implies a decline in disease transmission. In this report, we estimated the doubling time and the effective reproduction number in relation to two epidemic waves of the COVID-19 epidemic in South Korea by employing the time series of cases by date of symptom onset for the four most affected Korean regions: Seoul, Gyeonggi Province, Gyeongbuk Province, and Daegu. We also discuss the spatiotemporal variability in the reproduction number in terms of the public health policies that were put in place by the Korean government.

Methods

Data

Daily series of confirmed local COVID-19 cases in South Korea were collected from 20 January to 19 July; these were published by national and local public health authorities, including city or provincial departments of public health in South Korea (KCDC, 2020b). Our analysis focused on the regions with the highest caseloads, including Seoul, Gyeonggi Province, Gyeongbuk Province, and Daegu (Figure 1).

Imputing the date of onset

For a more accurate estimation of epidemic growth rates, an epidemic curve should be analyzed according to the date of symptom onset rather than the date of reporting, because reporting delays can fluctuate substantially over the course of an epidemic. Reporting delays distort the incidence pattern of epidemics, misrepresenting the outbreak trajectory, and thus possibly affecting the estimation of reproduction number (Tariq et al., 2019). A prior study suggested that obtaining knowledge about reporting parameters, such as delay patterns and structure, improves the estimating of reproduction numbers (Azmon et al., 2014). However, for the COVID-19 data in Korea, the date of symptom onset was only available for 732 cases reported in Gyeonggi Province, which yielded a mean of 4.5 days and standard deviation of 4.4 days for the distribution of delays from symptom onset to reporting of cases. Therefore, we utilized the empirical distribution of these 732 reporting delays from the onset of symptoms to reporting to impute the missing dates of onset for the remaining cases (Shim et al., 2020a). Specifically, we reconstructed 300 epidemic curves according to the date of symptom onset, from which we derived the mean incidence curve of local case incidence (Shim et al., 2020a; Tariq et al., 2019). For the calculation of $R_t$, the estimated mean incidence curve, based on the date of symptom onset, was used for the regions of interest (i.e., Seoul, Gyeonggi Province, Gyeongbuk Province, and Daegu) (Figure 2). Using the reconstructed mean incidence curve for local case incidence, we removed the first and last three data points to adjust for the reporting delays in our real-time analysis. We assumed that the first wave ended when the mean incidence became less than 0.2 individuals per day. Similarly, we assumed that the second wave began when the mean incidence of local cases became greater than 0.5 individuals per day. Slight variations to these thresholds did not affect our results.

Calculation of the doubling time

We analyzed the number of times COVID-19 cumulative incidence doubled and the evolution of the doubling times in the four most affected areas in Korea (i.e. Seoul, Gyeonggi Province,
Gyeongbuk Province, and Daegu) from January 20 to July 19. Using regional-level daily cumulative incidence data, we calculated the times at which cumulative incidence doubled, denoted by $t_{di}$. Specifically, we assume that:

$$2C(t_{di}) = C(t_{d_{i+1}})$$

where $t_{d0} = 0$, $C(t_{d_i}) = C_0$ ($i = 0, 1, 2, 3, \ldots, n_d$), and $C(t_{di})$ denotes the cumulative number of cases at time $t_{di}$ (Muniz-Rodriguez et al., 2020). Here, $n_d$ is defined as the total number of times cumulative incidence doubles. Specifically, the sequence of doubling times are described as $d_i = \Delta t_{di} = t_{di} - t_{di-1}$, where $j = 1, 2, 3, \ldots, n_d$. In addition, we used parametric bootstrapping with a Poisson error structure around the harmonic mean of doubling times to obtain the 95% confidence interval (Chowell et al., 2006a; Chowell et al., 2006b).

**Calculation of $R_t$**

We assume that $R_t$ can be estimated by the ratio of the number of new infections generated at time step $t$ ($i_t$) to the total infectiousness of infected individuals at time $t$, given by $\sum_{s=1}^{i_t} I_{t-s}w_s$ (Chong et al., 2018; Fraser, 2007a). Here, $w_s$ denotes the infectivity profile of the infected individual, which is dependent on the time since infection ($s$) but independent of calendar time ($t$) (He et al., 2020; Wallinga and Teunis, 2004). Specifically, $w_s$ is defined as a probability distribution describing the average infectiousness profile after infection. Individual biological factors such as pathogen shedding or symptom severity can affect the distribution $w_s$. For example, an individual would be most infectious at time $s$ when $w_s$ is the largest. Thus, $\sum_{s=1}^{i_t} I_{t-s}w_s$ indicates the sum of infection incidence up to time step $t-1$, weighted by the infectivity.

![Figure 3](image-url) The epidemic trajectory of COVID-19 in Seoul as of July 19, 2020. Upper panel: The epidemic curve shows the daily number of new cases by the imputed date of symptom onset. The dates of symptom onset for cases with missing data were imputed based on the empirical distribution of delay from the onset of symptoms to reporting. Lower panel: Real-time estimates of the time-varying reproduction number ($R_t$) in Seoul. The solid line indicates the daily estimated $R_t$, and the grey area indicates the 95% credible interval for $R_t$. The dotted line indicates the epidemic threshold of $R_t = 1$. 

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function \( w_\cdot \). Steady values of \( R_t \) above 1 indicate sustained disease transmission, whereas values less than 1 indicate that the number of new cases is expected to follow a declining trend.

The infectivity profile, \( w_\cdot \), can be approximated by the distribution of the generation time; however, times of infection are rarely observed, making it difficult to measure the distribution of the generation time (Fraser, 2007b). Therefore, the timing of symptom onset is often used to estimate the distribution of the serial interval (SI) instead, which is defined as the time interval between symptom onset in two successive cases in a chain of transmission (Cori et al., 2013). Specifically, the infectiousness of a patient is a function of the time since infection and is proportional to \( w_\cdot \) if we set the timing of infection in the primary case as the time zero of \( w_\cdot \) and assume that the generation interval equals the SI. The SI was assumed to follow a gamma distribution with a mean of 4.8 days and a standard deviation of 2.3 days (Nishiura et al., 2020). Analytical estimates of \( R_t \) were obtained within a Bayesian framework using the EpiEstim R package in R language, version 3.6.3 (R Foundation for Statistical Computing, Vienna, Austria) (Cori et al., 2013). \( R_t \) was estimated at 7-day intervals, and the median and 95% credible interval (CrI) were reported.

Results

City of Seoul

As of July 19, Seoul had reported a total of 1474 cases (10.7% of the total reported in South Korea), including 323 imported cases and 10 deaths, yielding an incidence rate estimated at 151 cases per million. In Seoul, the first peak based on the estimated dates of symptom onset occurred during the second week of March (March 8–14), with 18 new cases reported each day as the number of new cases linked to a Guro-gu call centre kept rising. Based on the estimated dates of symptom onset, the 7-day moving average of daily cases reached 19 cases on March 9 (Figure 3), whereas the highest value of \( R_t \) was estimated at \( R_t \sim 2.9 \) (95% CrI: 1.6–4.7) on February 19, which continued to stay above 1 until March 6 (Figure 3).

After its first peak in February, the number of daily new cases by date of symptom onset in Seoul gradually declined, dropping below five on April 1 and remaining under five new cases per day for about a month (Figure 3). However, in early May, despite a steady decline in imported cases, locally transmitted infections surged throughout the Seoul metropolitan area, with case clusters traced to clubs, churches, and sports facilities. Therefore, \( R_t \) increased, reaching 3.0 (95% CrI: 1.6–5.0) on May 4. During the first wave, the doubling time was estimated to be 7.5 (95% CI: 7.0–8.2) days in Seoul (Table 1).

The number of cases continued to increase thereafter, and in the first week of June, the average daily number of confirmed COVID-19 cases in the capital surpassed the previous high point recorded in the middle of March. The major clusters in Seoul were linked to nightlife (139 cases), the Guro-gu call centre (99 cases), Mannmin Central Church (41 cases), Richway (97 cases), and Yangcheon-gu table tennis club (41 cases), and Newly Planted Church in the Seoul Metropolitan Region (37 cases), as of June 18. On June 14, the average \( R_t \) in the capital dropped below 1 (95% CI: 0.8–1.2), implying that the spread of the virus had slowed down substantially in the city (Figure 3). During the second wave, the doubling time in Seoul decreased to 6.0 (95% CI: 5.4–6.7) days, indicating faster transmission compared with that during the first wave (Table 1). As of July 15, the \( R_t \) in Seoul was estimated at 0.9 (95% CI: 0.7–1.2), straddling the epidemic threshold of 1.0, and suggesting potential for further transmission of the virus.

Gyeonggi Province

Gyeonggi Province (literally meaning the ‘province surrounding Seoul’) is located in the western central region of Korea and is the most populous province in South Korea, with a population of 13.5 million people. In Gyeonggi Province, the daily number of new cases by date of symptom onset during the last weeks of February averaged 6.3 (Figure 4). Accordingly, the first peak of \( R_t \) occurred on February 22, reaching 8.9 (95% CrI: 4.8–14.2), with an estimated doubling time of 4.6 (95% CI: 4.2–5.5) days (Table 1). In the second week of March, South Korea recorded continuous drops in the number of daily new infections as large-scale testing of the followers of a religious sect in the south-eastern city of Daegu, the epicentre of COVID-19, was nearing its end; thereafter, the number of cases in Gyeonggi Province gradually decreased.

However, clusters of infections in Gyeonggi Province raised concerns about further community spread, with a resurgence of cases in the province occurring in late May and resulting in the highest peak in early June. From June 1–13, an average of 14 new cases were reported each day in Gyeonggi Province. The second peak of \( R_t \) in the region occurred on May 12, with an estimated \( R_t \) value of 4.8 (95% CrI: 3.0–7.0) and the doubling time estimated at 7.5 (95% CI: 5.4–8.6) days (Table 1). Following its second peak, \( R_t \) gradually decreased (Figure 4); however, a series of sporadic clusters continued to occur. Major clusters in Gyeonggi Province included Grace River Church (67), Coupang warehouse (67), Richway (59), Uijeongbu St Mary's Hospital (50), Guro-gu call centre/Bucheon SaengMyeongSu Church (50), door-to-door sales in the Seoul Metropolitan Region (32), and Yangcheongu sports facility (28). As of July 19, the number of local cases in Gyeonggi Province was 1027 (10.4% of the total reported cases in South Korea), including 29 deaths, with an \( R_t \) estimated at 0.8 (Figure 4). The incidence rate in the province was estimated at 108 per million.

Gyeongbuk Province

The first case in the Shincheonji cult cluster (the largest COVID-19 cluster in South Korea) appeared on February 18, resulting in sustained transmission chains, with 39% of the cases associated with the church cluster in Gyeongbuk Province. Consequently, the virus alert level was raised to ‘red’ (the highest level) on February 23, and the health authorities focused on halting the spread of the virus in Daegu and Gyeongbuk Provinces. Figure 5 shows that the peak of the epidemic occurred in the first week of March (with a reproduction number greater than 1 until March 9) (Figure 5). The doubling time in Gyeongbuk Province reached as low as 3.6 (96% CI: 3.5–4.0) days (Table 1). As of July 18, the number of cases in Gyeongbuk Province was 1393, including 54 deaths. Among these cases, 566 were related to the Shincheonji cluster. The incidence rate in Gyeongbuk Province was 523 per million, accounting for 10.2% of all confirmed cases in South Korea (KCDC, 2020a). The major clusters in Gyeongbuk Province were linked to Cheongdo Daenam Hospital (119 cases), Bonghwa Pureun Nursing Home (68 cases), Gyeongsan Seo Convalescent Hospital (66 cases),

| Region                  | Mean doubling time (95% CI) |
|-------------------------|----------------------------|
|                         | First wave                  | Second wave                 |
| Seoul                   | 7.5 (7.0–8.2)               | 6.0 (5.4–6.7)               |
| Gyeonggi Province        | 4.6 (4.2–5.5)               | 7.5 (5.4–8.6)               |
| Gyeongbuk Province       | 3.6 (3.5–4.0)               | 10.1 (4.6–14.5)             |
| Daegu                   | 2.8 (2.5–4.0)               | 10.0 (7.1–13.4)             |

Table 1: Regional variations in doubling times in days for COVID-19 cumulative incidence, and their 95% CI, from January 20 to July 19, 2020: Seoul, Gyeonggi Province, Gyeongbuk Province, and Daegu.
pilgrimage to Israel (41 cases), Yecheon-gun (40 cases), and Gumi Elim Church (11 cases).

City of Daegu

The epicentre of the South Korean COVID-19 outbreak has been identified in Daegu, a city of 2.5 million people, approximately 150 miles south-east of Seoul. The rapid spread of COVID-19 in Daegu was attributed to a superspreading event in a religious group called Shincheonji, resulting in an explosive outbreak of 4511 infections in the city of Daegu, resulting in a relatively short doubling time of 2.8 (95% CI: 2.5–4.0) days (Table 1 and Figure 6). Other major clusters in Daegu included the second Mi-Ju Hospital (196 cases), Hansarang Convalescent Hospital (124 cases), Daesil Convalescent Hospital (101 cases), and Fatima Hospital (39 cases). Daegu was the most severely affected area in South Korea, with 6932 cumulative cases as of July 19, accounting for 51.0% of all confirmed cases in Korea. According to our model, the number of new cases, based on the onset of symptoms, was estimated to be the highest on February 27, with the number gradually decreasing thereafter. Accordingly, the estimated Rt was above 2 until February 27 and dropped to below 1 on March 5, although recent sporadic infections have caused Rt to fluctuate around 1 (Figure 6).

Discussion

Estimates of the transmission potential of COVID-19 in Korea have displayed substantial spatiotemporal variation. Indeed, several factors influence the value of the reproduction number, including the transmissibility of an infectious agent, individual susceptibility, individual contact rates, and control measures (Anderson and May, 1991). Our results indicated that the effective reproduction number for COVID-19 declined to low levels after the first wave and straddled the epidemic threshold of 1.0 in March and
April, suggesting that social distancing measures had a significant effect on mitigating the spread of the novel coronavirus. Estimates of early national $R_t$ values for South Korea retrieved from other studies — 2.9 (95% CI: 2.0–3.9) in February (Ryu et al., 2020) and 2.6 (95% CI: 2.3–2.9) in March — are in good agreement with our $R_t$ estimates (Zhuang et al., 2020).

Our results suggest that South Korea has experienced two spatially heterogeneous waves of the novel coronavirus. At the regional level, Seoul and Gyeonggi Province have experienced two waves, whereas Daegu and Gyeongbuk Provinces are yet to experience a second wave. The highest epidemic peak occurred in Daegu and Gyeongbuk Province in late February and early March, with $R_t$ estimated at 4.4 (95% CI: 2.6–6.6) and 3.5 (95% CI: 0.9–7.3), respectively. During these epidemic peaks, the doubling times were estimated at 2.8 (95% CI: 2.5–4.0) days and 3.6 (95% CI: 3.5–4.0) days, respectively, which is similar to a prior estimate of doubling time of 3.8 (95% CI: 3.4–4.2) days (Lee et al., 2020). Gyeonggi Province and Seoul experienced their first wave in late February and early March, respectively. However, sporadic clusters of infections appeared in Seoul and near Gyeonggi Province, immediately after the government eased its strict nationwide social distancing guidelines on May 6. This resurgence of infections in Seoul and Gyeonggi Province (i.e. the province surrounding Seoul), after a sustained period with fewer than five cases per day in each region, led to a second epidemic wave with exponential growth dynamics. In Seoul, the mean doubling time decreased from 7.5 (95% CI: 7.0–8.2) days during the first wave to 6.0 (95% CI: 5.4–6.7) days during the second wave, indicating faster transmission during the case resurgences. Accordingly, our findings revealed sustained local transmission in Seoul and Gyeonggi Province, with the estimated reproduction number estimated to be above 1 until the end of May. In late May, the country implemented 2 weeks of strict social distancing measures, incorporating stringent virus prevention guidelines for the metropolitan area. These measures included the shutting down of public facilities, and regulating bars and karaoke rooms. In the second week of June, South Korea decided to indefinitely extend a period of strict social distancing measures, as nearly all locally transmitted cases were in the metropolitan area.

Although Korea has had a relatively low number of reported cases compared with other countries such as the USA and China, it is believed that South Korea is currently experiencing yet another resurgence of the virus (WHO). Originally, South Korean authorities predicted a resurgence of the virus in the fall or winter; however, this possible second wave started in and around Seoul, which, with 51.6 million inhabitants, accounts for about half of the entire population of the country. Secondary waves of the disease can result from multiple factors, including easing of travel restrictions and the resumption of social activities, especially in the high-population-density areas of Seoul and Gyeonggi Province.

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**Figure 5.** The epidemic trajectory of COVID-19 in Gyeongbuk Province, as of July 19, 2020. Upper panel: The epidemic curve shows the daily number of new cases by the imputed date of symptom onset. The dates of symptom onset for cases with missing data were imputed based on the empirical distribution of delay from the onset of symptoms to reporting. Lower panel: Real-time estimates of the time-varying reproduction number ($R_t$) in Gyeongbuk Province. The solid line indicates the daily estimated $R_t$ and the grey area indicates the 95% credible interval for $R_t$. The dotted line indicates the epidemic threshold of $R_t = 1$. 
Furthermore, a substantial proportion of COVID-19 cases are asymptomatic (Mizumoto et al., 2020); thus, they are not detected by surveillance systems, resulting in underestimation of the epidemic growth curve. It was also recently reported that individuals aged 20–39 years in South Korea drove the COVID-19 epidemic throughout society, with multiple rebounds, and an increase in infection among the elderly was significantly associated with an elevated transmission risk among young adults (Yu et al., 2020).

Our study shows some limitations, including the lack of dates of symptom onset for all cases, relying on a statistical reconstruction of the epidemic curve by dates of symptom onset from a previous study (Shim et al., 2020a). Overall, using the most up-to-date epidemiological data from South Korea, our study highlights the effectiveness of strong control interventions in South Korea, and emphasizes the need to maintain firm social distancing and contact tracing efforts to mitigate the risk of additional waves of the disease.

**Contributions**

ES retrieved, managed, and conceptualized the analysis of the data. ES, GC, and AT analyzed the data. ES and GC wrote the first draft of the paper. All authors contributed to the writing of the paper.

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