Evaluation of China's Hubei Control Strategy for COVID-19 Epidemic: An Observational Study

Yu Liu

Sun Yat-Sen University School of Public Health

Fangfang Zheng

Guangdong Food and Drug Vocational College

Zhicheng Du

Sun Yat-Sen University School of Public Health

Jinghua Li

Sun Yat-Sen University School of Public Health

Jing Gu

Sun Yat-Sen University School of Public Health

Mei Jiang

the first affiliated hospital of Guangzhou Medical University

Daisuke Yoneoka

St Luke's International University: Sei Roka Kokusai Daigaku

Stuart Gilmour

St Luke's International University: Sei Roka Kokusai Daigaku

Yuantao Hao (✉ haoyt@mail.sysu.edu.cn)

Department of Medical Statistics and Epidemiology, School of Public Health, Sun Yat-sen University, Guangzhou 510080, China. <https://orcid.org/0000-0001-8024-5312>

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1 **Evaluation of China's Hubei Control Strategy for COVID-19**
2 **epidemic: An Observational Study**

3 Yu Liu¹, Fangfang Zheng², Zhicheng Du¹, Jinghua Li¹, Jing Gu¹, Mei Jiang³, Daisuke
4 Yoneoka⁴, Stuart Gilmour⁴ and Yuantao Hao^{1,*}

5 ¹Department of Medical Statistics and Epidemiology, School of Public Health, Sun Yat-
6 sen University, Guangzhou 510080, China.

7 ²School of Traditional Chinese Medicine Healthcare, Guangdong Food and Drug
8 Vocational College, Guangzhou 510520, China

9 ³National Clinical Research Center for Respiratory Disease, State Key Laboratory of
10 Respiratory Disease, Guangzhou Institute of Respiratory Health, the First Affiliated
11 Hospital of Guangzhou Medical University, Guangzhou 510120, China

12 ⁴Graduate School of Public Health, St. Luke's International University, Tokyo 104-
13 0045, Japan

14 *Correspondence: haoyt@mail.sysu.edu.cn

15

16 **Abstract**

17 **Background:** To fight against COVID-19, many policymakers are wavering on stricter
18 public health interventions. However, relying on these measures but different strategies,
19 both in and out of China’s Hubei province basically contained the epidemic in late
20 February 2020. This study aimed to assess the response process and estimate time-
21 varying effect of Hubei control strategy to provide insights for intervention design and
22 implementation.

23 **Methods:** We retrospectively compared the spread and control of COVID-19 between
24 China’s Hubei (excluding Wuhan) and non-Hubei areas using data that includes case
25 reports, human mobility, and public health interventions from 1 January to 29 February,
26 2020. The static and dynamic risk assessment models were developed to statistically
27 investigate the effect trends of Hubei control strategy on case growth after adjusting
28 importation risk and response timing with non-Hubei strategy as a contrast.

29 **Results:** The analysis detected much higher but differential importation risk in Hubei.
30 The response timing largely coincided with the importation risk in non-Hubei areas, but
31 Hubei areas showed an opposite pattern. A careful and comprehensive comparison
32 showed that Hubei control strategy implemented interventions characterized by
33 unprecedentedly strict and ‘monitored’ self-quarantine at home, while non-Hubei
34 strategy included physical distancing measures to reduce contact among individuals
35 within or between populations. In contrast with non-Hubei control strategy, Hubei
36 strategy showed a much higher, non-linear and gradually diminishing protective effect
37 with at least 3 times fewer cases.

Conclusions: A risk-based control strategy is crucial to design an effective response for COVID-19 control. Our study demonstrates that the stricter Hubei strategy can achieve much better control effectiveness. These findings highlight the health benefits of precise and differentiated strategies informed by constant monitoring of outbreak risk and policy impacts.

Keywords: COVID-19, Control strategy, Public health interventions, Time-varying effect

Background

The world is combating the ongoing COVID-19 pandemic, for which potential therapeutics and vaccines are still being investigated. Accordingly, great expectations are placed on non-pharmaceutical public health interventions to contain the epidemic [1, 2]. This has fueled interest in exploring their effectiveness in epidemic control. So far, the potential effects of anti-contagion policies were usually estimated and reported through process-based epidemiological simulations [3-8]. A limited number of control studies based on current and past epidemics focused on the static evaluation of individual or partial interventions [2, 9]. These approaches suffer from a few limitations. First, the information about how long policies should be maintained is obscure or unavailable. Second, the transmission risk in policy scenarios and the interactions between interventions in policy packages are neglected. Therefore, current studies cannot generate an efficient assessment of the time-varying effects of the interventions.

In response to the outbreak of COVID-19 in December 2019, a series of public health interventions has been employed by China's national, provincial, or municipal governments, effectively curbing the epidemic by the end of February. These interventions were triggered by launching the public health emergency response [10, 11]. Besides Wuhan, other cities in Hubei province were recognized as key areas of epidemic growth with city lockdown as milestones for COVID-19 control. Different control strategies were implemented inside and outside of Hubei. This concrete difference in policy interventions ultimately led to different levels of effectiveness. A careful and comprehensive comparison of these two control strategies may help to

identify whether or when these interventions should be deployed, consolidated, or relaxed. Such guidance would fill an urgent need in the governmental decision-making process, especially as COVID-19 is still running rampant and policymakers in many countries are wavering on stricter interventions.

Population movement from Wuhan during the 2020 Chinese New Year mass migration constituted an importation risk for the traveler's destinations [12-14]. In this study, we retrospectively compared the spread and control of COVID-19 in and out of Hubei using data on case reports, human mobility, and public health interventions during the period from 1 January to 29 February, 2020. We first characterized the association between the importation risk of COVID-19 and the policy-making process in each study prefecture. Then we documented the difference in control strategies and measures in and out of Hubei province across mainland China. Finally, we developed static and dynamic models to quantify the time-varying effects of Hubei and non-Hubei control strategies.

Methods

Data collection

To explore the role of importation risk on control strategy decisions across mainland China and ascertain their impacts, we collected case data, control measures, potentially related population and economic data, and travel data from 16 cities in Hubei province (excluding Wuhan) and 30 provinces outside Hubei, 46 prefectures in total, from the beginning of the COVID-19 epidemic to during its fundamental containment, that is, 1 January to 29 February 2020. The first three types of data were extracted from local

official websites. Travel data were retrieved through Baidu Qianxi platform, which derived from its Location-Based Services. Daily Baidu Mobility Indexes (dBMIs) of population outflow from Wuhan to each study prefecture were obtained.

To track all movements from Wuhan to each study prefecture before its closure on 23 January 2020 and measure their risks of COVID-19 importation, we calculated the total aggregate population outflow from Wuhan between 1 to 26 January 2020, that is, $x_{1i} = \sum_{t=1}^{26 \text{ Jan}} \text{dBMI}_{ti}$ for prefecture i . To represent their response timing in COVID-19 control, we collected the dates to launch the Level One response in non-Hubei areas (Additional file 2: Table S1) and the dates to shut down the cities in Hubei (Additional file 3: Table S2). S1 in Additional file 1 provides detailed information about data preparation.

Data analysis

To analyze the effect generated by the control strategy, we first introduced static models and then dynamic models, which were extended from Jia, *et al.* [12] The static models generate a cross-sectional analysis of the effect of control strategy on daily infections and the dynamic models investigate the time-varying effect. Only data after implementing COVID-19 control strategies were included for statistical modelling, that is, data after 26 January. Because our dynamic models were developed based on a sigmoidal growth pattern of cases, case data with abnormal fluctuations on the epidemic curves were first pre-processed. Cases that emerged in an abnormal spike due to the amendment of diagnosis criterion (especially for cities in Hubei) or intensive report of jail infections (happened in Shangdong and Zhejiang) were assumed to be infected

several days before and should have been diagnosed and reported earlier than their actual report date. A presumed ought-to-be-reported date was generated for each of them through random assignment. S2.1 in Additional file 1 provides a mathematical description for this process.

The static models, which origin from the gravity model [15], have been developed to depict the effect of population outflow from Wuhan on infections in other prefectures [12]. We extended it to statistically and cross-sectionally investigate the role of control strategies. The saturated static model has the following multiplicative exponential form:

$$y_i = c \cdot e^{\sum_k^3 \beta_k x_{ki}} e^{\lambda_1 \cdot I_{Hubei} + \lambda_2 \cdot D_{response} + \lambda_3 \cdot I_{Hubei} * D_{response}}$$

where y_i is the cumulative number of confirmed cases in prefecture i ; x_{1i} is the aggregate outflow from Wuhan between 1 to 26 January to prefecture i , as described above; x_{2i} is per capita GDP; x_{3i} is the population density; c and β_k are parameters to estimate. I_{Hubei} is an indicator function with $I_{Hubei} = 1$ for implementing Hubei strategy, otherwise $I_{Hubei} = 0$; $D_{response}$ is the response timing (23, 24, or 25 January); $I_{Hubei} * D_{response}$ denotes their interaction; λ_j s are the parameters.

A dynamic model under the Cox proportional hazards framework replaces the constant parameters in the static model with a time-varying hazard function $h_0(t)$ to model a sigmoidal growth of COVID-19 cases:

$$h(t|x_i) = h_0(t) e^{\sum_k^3 \beta_k x_{ki}} e^{\lambda_1 \cdot I_{Hubei} + \lambda_2 \cdot D_{response} + \lambda_3 \cdot I_{Hubei} * D_{response}}$$

where $h(t|x_i)$ is the hazard function describing cumulative number of confirmed cases at time t given other variables $x_i = \{x_{1i}, x_{2i}, x_{3i}\}$. Here, the logistic function with parameters α , γ and ω was utilized as the sigmoidal growth approximation [16, 17]:

$$h_0(t) = \frac{\alpha}{1+e^{-\gamma t+\omega}}$$

To further improve the model fitting, λ_j s are allowed to be time dependent, that is, $\lambda_j = \lambda_j(t)$. They are empirically determined by the results from the static models.

The R package `minpack.lm` [18] with a nonlinear least-squares Levenberg-Marquardt (LM) algorithm was used for model fitting and parameter estimation. Models were evaluated using the Bayesian Information Criterion (BIC) and R^2 . S2.2 and S2.3 in Additional file 1 provide detailed methodologies for this section.

After statistical modelling, the indices of control effectiveness were calculated by exploiting the integral of the differences between predicted and actual case number:

$$ICE_i = \sum_{t=26\text{ Jan}}^{29\text{ Feb}} [h(t|x_i) - \hat{h}(t|x_i)].$$

The normalized ICE_i s were used for final measurements of control effectiveness.

Results

Importation risk and response timing in each prefecture

In Wuhan, the 2020 Chinese New Year travel rush was interrupted by its lockdown on 23 January and the fluxes sharply declined to almost no movement since 27 January (Fig. 1a). The total aggregate amount of people who entered any study prefecture from Wuhan during this observation period (1-26 January) was used to measure their importation risk, which is shown on a heat map in Fig. 1b. More prefectures in Hubei are colored in dark red, indicating high risk of case importation. Comparison using the Wilcoxon Rank Sum test showed that the importation risk to other parts of Hubei is much higher than that to outside provinces with $P < 0.001$ (Additional file 6: Figure S1). Regional differences in risk, both in and out of Hubei, were also observed.

Since 23 January 2020, all the provinces across China successively launched or raised their major public health emergency response to Level One, the highest level (Fig. 1c). Following Wuhan's outbound traffic closure on 23 January, all other cities in Hubei subsequently announced their shutdown (Fig. 1c). The decline timelines on human mobility had a high consistency with the dates to execute the interventions (Additional file 7: Figure S2). Therefore, we used the date to launch the Level One response in non-Hubei provinces and the date to shut down the cities in Hubei excluding Wuhan to represent their respective response timing for COVID-19 control. Fig. 1d showed that the time to trigger COVID-19 control outside Hubei was generally consistent with the distribution of the local importation risk with $P < 0.001$ using Jonckheere-Terpstra test. But for cities in Hubei other than Wuhan, they were contrary to the importation risk with $P = 0.042$.

Control strategy in Hubei and non-Hubei regions

The major public health emergency response triggered an array of actions by provincial and/or local governments. The main policy instruments deployed included: 1) travel restrictions, 2) case finding and contact tracing, 3) isolation and management of infected individuals and exposed contacts, 4) social distancing, and 5) closed-off community management (Table 1). Despite many similar interventions implemented both in Hubei and non-Hubei areas, important differences remained in control strategies. The control strategy in Hubei required almost all people stay under 'monitored' self-quarantine at home. The concrete measures involved an unprecedentedly strict closure and traffic restrictions, the 'monitored' stay-at-home order, extreme social distancing

without any public or business activities, and complete closed-off community management. In contrast, other provinces allowed work resumption from 10 February after application and approval. All resumed enterprises were encouraged to work from home and businesses to telecommute. The limited enterprises approved to work on-site were required to take rigorous measures to prevent gatherings and cross-infection.

COVID-19 epidemic trend and association with control strategy

As of 29 February 2020, 30,702 cases of COVID-19 were confirmed in mainland China excluding Wuhan (Fig. 2a). Among of them, 17, 785 (58.9%) cases were reported in Hubei other than Wuhan and 12,917 (42.1%) outside Hubei. Most prefectures experienced a typical sigmoidal growth in cases, characterized by an accelerated increase in the beginning and a flat period after mid-February (Additional file 8: Figure S3). As expected, more serious epidemic and more rapid growth was observed in Hubei. Abnormal fluctuations were detected in Shandong, Zhejiang, and cities in Hubei, as described in Methods section.

Despite high association between case progress and importation risk (Fig. 2b), the daily total number of cases in Hubei area tended to split apart from those in provinces outside Hubei, which located under the overall fitted straight line (Fig. 2c), and the split pattern was kept over time (Additional file 9: Figure S4a and S4b). The infectious cases grouped by governments' response showed similar V-shape distribution to their importation risk (Fig. 2d and Additional file 9: Figure S4c and S4d), which indicates the potential effect of the interventions.

The static and dynamic models for quantifying the effect of control strategy

The preprocessing of case data with abnormally reported dates generated smooth epidemic curves (Additional file 10: Figure S5). In subsequent modelling, the cumulative Wuhan population inflow was always included because of its strong correlation with daily amount of infections. But each prefecture's GDP and population density were excluded as statistical tests provided no evidence of correlation ($P > 0.05$).

The static models including aggregate inflow population from Wuhan till 26 January and the control strategy as independent variables generated the consistently negative estimates of the coefficients on the Hubei strategy (Additional file 4: Table S3). This finding indicates that the implementation of the Hubei strategy was a continuous protective factor (all $P < 0.05$) in contrast with the non-Hubei strategy. Its protective effects declined over time and remained at a stable level in late February (Additional file 11: Figure S6a). It is noteworthy and significant that the R^2 increased more at the accelerated growth period of COVID-19 cases after introducing the control strategy (Additional file 11: Figure S6b), which implies it contributed more during the earlier dates of the epidemic. Subsequently, the response timing was added but no overall effect was found (all $P > 0.05$). However, when the interaction between the control strategy and response timing was added as well, the effect of response speed on the epidemic became statistically significant before early February ($P < 0.05$) and all had negative slope estimates (Additional file 4: Table S3). This suggests that the response timing in non-Hubei area may be a 'risk' factor during the earlier stage in the implementation of the control strategy.

The dynamic model using two variables of total population outflow from Wuhan (during 1 to 26 January) to each prefecture and the control strategy showed $R^2 = 0.910$ (Fig. 3a); and the inclusion of the response timing increased R^2 to 0.922 (Additional file 5: Table S4). According to the features of the coefficients from the static models, we also introduced a quadratic function of time t for the variable of control strategy, and a truncated function of time t with the cut-off T for the response timing. As expected, the BIC improved and R^2 further increased to 0.938 (Additional file 5: Table S4). The truncation date T was fixed on 10 February based on the BIC statistics.

Finally, the time-varying effect of the control strategy estimated by the dynamic model with time-dependent effects is shown in Fig. 3b. We used the non-Hubei strategy for COVID-19 control enacted on 23 January as a reference over time, and the response timing was unexpectedly showed to be a weak risk factor at about two weeks after its implementation. In contrast, the Hubei control strategy showed a very strong protective effect and the protective effect rapidly declined if the implementation was delayed. Precisely, the Hubei control strategy showed a 4 times greater protective effect than the non-Hubei strategy on 26 January if both were taken on 23 January. Despite a narrowing effect, the Hubei area achieved about 3 times fewer cases than non-Hubei areas in late February. The two-day delay of the Hubei strategy finally narrowed down the effect to 2 times fewer cases. The marginal analysis showed that the Hubei control strategy had the marginal effect curve equal to its effect trajectory enacted on 23 January (Fig. 3b). That is, in overall, the Hubei strategy for COVID-19 control would achieve 3 times fewer cases than the non-Hubei strategy.

Evaluation of control effectiveness

The differences in the growth trends between predicted and observed cases can be used to benchmark the control of COVID-19 for the prefectures (Additional file 12: Figure S7 and Additional file 13: Figure S8), providing an under-performing or over-performing order. We used the integral of the differences over time to create a total index for control effectiveness. After sorting these indexes, we can identify a list of under-performers and over-performers (Fig. 3c). Indeed, most prefectures in Hubei were prone to be over-performers because of their strong control measures. Prefectures like Zhejiang, Xiaogan and Suizhou were observed as under-performers.

Discussion

The COVID-19 epidemic broke out in December 2019. China employed almost all the available infectious disease control tools at an unprecedented scale [1] and successfully controlled the epidemic by the end of February 2020. Although importation risks were considered in policy making, risk-based differentiated need for COVID-19 control in and out of Hubei was inadequately assessed (Fig. 1). The whole of Hubei province was defined as a key area of the epidemic and a Hubei-specific strategy for COVID-19 control was executed, while other areas followed a non-Hubei control strategy.

The Hubei-specific control strategy consisted of a series of unprecedently strict stay-at-home measures. We compared all the main non-pharmaceutical interventions between the Hubei and non-Hubei strategy and found that all the Hubei measures different from non-Hubei ones served to strengthen citizens' adherence to self-quarantine at home directives (Table 1). In contrast, the control strategy executed

outside Hubei was typically a series of physical distancing measures which have been experimentally proven to be effective in delaying and reducing the height of the peak and median epidemic size [7, 19].

Besides the strong linear relationship between population movement from Wuhan and the number of infections documented as previous studies [20-22], the effect of applying different control strategies in and out of Hubei was revealed in this study. Despite the much higher importation risk in Hubei excluding Wuhan, the epidemic was under control one week after COVID-19 containment outside Hubei (Fig. 2a). Both the static or dynamic models showed that the Hubei strategy was a very strong protective factor in contrast with the non-Hubei strategy. This protective effect is time-varying, with the values higher in the earlier dates after being triggered, narrowing down gradually, and then staying at a stable level (Fig. 3b). By mid-February, the Hubei control strategy obtained 3 times fewer COVID-19 cases.

The government response is also of interest. Through the statistical modelling, a weak ‘protective’ effect was found for the later implementation of non-Hubei control strategy, and this protective effect disappeared about two weeks after implementing the measure (Fig. 3b). This result differs from a previous study [8] . This seemingly unreasonable result has a remarkable interpretation. The Level One response required suspected and confirmed cases to be isolated and reported immediately [6]. During the earliest phase of the epidemic, the virus was diffused and the response triggered aggressive case and contact identification. This earlier response means that more cases

were found earlier and isolated. Therefore, the accelerated response being a ‘risk’ factor is an artifact of improved tracing and disease detection.

Some limitations in our study have been recognized. First, we focused on province-level data outside Hubei but not city-level like Hubei area. It is known that the importation risk and daily amount of infections in most cities outside Hubei was incompatible with those in the Hubei area. These differences could confound the effect discovered for the Hubei control strategy. Second, random assignment for sharp discontinuities on cumulative case curves was used to smooth the data, but these corrections did not include other considerations of disease progression, such as the incubation period. Because the fluctuation presented in the early phase of the epidemic, and was at least partly driven by case definitions and health system processes, this assumption was necessary to simplify the assignment process.

Conclusions

A risk-based control strategy would improve the effective response for COVID-19 control. Our study shows that the stricter Hubei strategy can achieve much better control effectiveness. These findings highlight the health benefits of precise and differentiated strategies informed by constant monitoring of outbreak risk and policy impacts.

Abbreviations

COVID-19: Coronavirus disease 2019; dBMI: daily Baidu Mobility Index

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

YL and YH conceived and designed this study. FZ and MJ collected the data. YL and ZD developed the model and ran the analysis. JL, JG and DY advised on model development. YL and FZ drafted the manuscript. JL, JG and DY revised the manuscript and gave scientific comments. SG and YH provided critical revision for important intellectual content. All authors read and approved the final manuscript.

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Table 1. Comparison between Hubei and non-Hubei control strategy

Measures	Non-Hubei	Hubei
Travel restrictions		
Departure channels from the prefecture through water, land (i.e. road or train) and air transportation	No	Closed
Water, land or air passenger transport service within prefecture	No	Closed
Intra-prefecture public transport	Partially suspended	Closed
Strict traffic control within prefecture, including closure of intra-prefecture highway and shipping, physical isolation and roadblock setup	No	Yes
Case finding and contact tracing		
Community grid-based screening, e.g. screening and surveillance for people with recent Hubei/Wuhan travel history within the last 14 days	Yes	Yes
Daily health registration and report, e.g. the color-coded health scheme	Required	Required
Routine temperature checking at all places	Yes	Yes
Enhancement of monitoring and online reporting at fever clinics	Yes	Yes
Epidemiological investigation and tracing, e.g. contact follow-up and tracing, then medical observation and nucleic acid testing as needed	Yes	Yes
Isolation and management of infected individuals and exposed contacts		
Isolation and treatment for confirmed cases at dedicated hospitals	Yes	Yes
Quarantine and medical observation for suspected cases at dedicated hospitals	Yes	Yes
A 14-day mandatory quarantine at dedicated facilities for individuals who've recently had close contact with someone with COVID-19, and who might have been exposed to COVID-19	Yes	Yes
A 14-day monitored self-quarantine at home or dedicated facilities on individuals who have traveled to the	Yes	No

Measures	Non-Hubei	Hubei
epicenter (e.g. Wuhan or other Hubei area)		
Social distancing		
Extended Spring Festival Holiday	From 24 Jan to 9 Feb	From 24 Jan to 8 Mar
Public gatherings	Canceled or postponed	Canceled or postponed
The spring semester at school	Postponed	Postponed
Tourist spots and entertainment venues	Closed	Closed
Stay-at-home	Encouraged	Order
Work resumption	10 Feb after application and approval	9 Mar after application and approval
Work from home	Encouraged	Not applicable
Remote commerce	Encouraged	Not applicable
Strict procedures in essential public facilities (e.g. airports) and enclosed transport vehicles (e.g. planes)	Yes	Not applicable
Strict procedures in resumed enterprises	Yes	Not applicable
Government services provided online or through prior reservation	Yes	Not applicable
Strict health and quarantine measures at points of entry and exit	Yes	Not applicable
Closed-off community management		
Minimize entrance numbers	Yes	Yes
Set up checking points	Yes	Yes
Issue entry permits	Yes	Yes
Ban non-resident entry	Yes	Yes
Supervise face mask wearing	Yes	Yes
Enhance health monitoring	Yes	Yes
Register personnel and vehicles passing through	Yes	Yes
Shut down community shops	No	Yes
Execute unified distribution of goods (i.e. grocery delivery) by local community health workers	No	Yes

Figure titles and legends

Fig. 1. Geographical distribution of the risk of COVID-19 importation to each prefecture and their response timing. (a) Fluxes of population outflow from Wuhan, represented by dBMI, during period of 1 January to 29 February in 2019 and 2020. The vertical lines in grey and red represent the dates of Wuhan lockdown and Chinese Lunar New Year, respectively. dBMI: daily Baidu Mobility Index. (b) Spatial distribution of COVID-19 importation risk, measured by their aggregate population inflow from Wuhan until 26 January 2020. Provincial inflow from Wuhan was plotted at the upper left corner and municipal inflow in Hubei plotted at the lower right corner. The black area is Wuhan city. (c) Governments' response timing in each prefecture. The dates to raise provincial public health response to Level One for COVID-19 control were plotted using different colors (upper left). Similarly, time to execute city shutdown in Hubei was plotted (lower right). (d) The importation risk distribution grouped by governments' response. Samples with insufficient size at the response timing were excluded, such as Qinghai, Tibet and Xiangyang.

Fig. 2. COVID-19 progress and its association with importation risk and control strategy. (a) The epidemic curves of COVID-19 in Hubei and non-Hubei area by 29 February 2020. (b) Relationship over time between the number of confirmed cases (cumulative until 29 February 2020) and total population inflow (up to 26 January 2020) from Wuhan, both on a logarithm scale. (c) The relationship between the log-transformed total population outflow from Wuhan (up to 26 January 2020) and the log-transformed number of confirmed cases by prefectures on 29 January 2020. Circles are

419 prefectures in Hubei; rectangles are prefectures outside Hubei; and the point sizes are
420 proportional to the population density of the prefecture. The linear fitting is done for
421 overall (black), Hubei (red) and non-Hubei (cyan) data. (d) The distribution of
422 confirmed cases on 29 January 2020, grouped by governments' response including
423 response timing and response strategy on a logarithm scale. Samples with insufficient
424 size at the response timing were excluded, such as Qinghai, Tibet and Xiangyang.

425 **Fig. 3.** Estimation of time-varying effect of Hubei control strategy. (a) The fitted
426 performance of our dynamic model (see dynamic model I in Section S2.3 of Additional
427 file 1). (b) Change of estimated relative risk over time, comparing between Hubei
428 control strategy and non-Hubei control strategy (as reference). (c) Comparison of index
429 of control effectiveness between all study prefectures.

Supplementary information

Additional file 1: Text. Supplementary methods for data preparation and analysis.

Additional file 2: Table S1. Time to execute Level One public health emergency response.

Additional file 3: Table S2. Time to execute city shutdown in Hubei.

Additional file 4: Table S3. Results from the static models.

Additional file 5: Table S4. Parameter estimation for the dynamic models.

Additional file 6: Figure S1. Comparison of COVID-19 importation risk between Hubei and non-Hubei areas. The risk of COVID-19 importation to each prefecture is defined as their total population inflow from Wuhan until 26 January 2020.

Additional file 7: Figure S2. The response timeline of COVID-19 control on human mobility. (a) Provincial population outflow outside Hubei. The flow of each province was represented by the responding BMIs of their capital city. (b) Municipal population outflow in Hubei excluding Wuhan. (c and d) The decline timelines of the outflow BMIs were compared after they were scaled to the values on 22 January. Legends for provincial population flow outside Hubei (a and c) and municipal population flow in Hubei (b and d) are shared, and respectively displayed in (a) and (b). All the colors here followed the response timelines shown in Fig. 1c. BMI: Baidu Mobility Index.

Additional file 8: Figure S3. The epidemic curves of COVID-19 in each prefecture by 29 February 2020. Each circular bar on the polar coordinate system represents daily number of reported cases in the prefecture. The grey and red circular lines in bold indicate the dates of Wuhan lockdown and Chinese Lunar New Year. The polar

coordinates also show the number of prefectures with COVID-19 case report in parentheses. (a) Provincial epidemic curves outside Hubei. (b) Municipal epidemic curves in Hubei other than Wuhan.

Additional file 9: Figure S4. Associations between number of COVID-19 cases, importation risk and control strategy. (a-b) The relationship between the log-transformed total population outflow from Wuhan (up to 26 January 2020) and the log-transformed number of confirmed cases by prefectures on 9 February 2020 (a) and 19 February 2020 (b). Circles are prefectures in Hubei; rectangles are prefectures outside Hubei; and the point sizes are proportional to the population density of the prefecture. The linear fitting is done for overall (black), Hubei (red) and non-Hubei (cyan) data. (c-d) The distribution of confirmed cases on 9 February 2020 (c) and 19 February 2020 (d), grouped by governments' response including response timing and response strategy in a logarithm scale. Samples with insufficient size at the response timing were excluded, such as Qinghai, Tibet and Xiangyang.

Additional file 10: Figure S5. Change of the epidemic curves after re-assignment of report date for cases with abnormal fluctuations. They included Shandong and Zhejiang jail cases intensively reported on 20 February 2020 and clinically diagnosed cases in Hubei area due to the amendment of the diagnosis and treatment program of the COVID-19.

Additional file 11: Figure S6. Results generated by static models. (a) Change of relative risk over time, generated by the static model II. (b) Change of R2 over time, compared between static models.

475 **Additional file 12: Figure S7.** Predicted versus actual case growth in the prefecture
476 outside Hubei.

477 **Additional file 13: Figure S8.** Predicted versus actual case growth in the prefecture in
478 Hubei other than Wuhan.

479 **Additional file 14.** The original case data.

480 **Additional file 15.** The original travel data.

481 **Additional file 16.** The original population and economic data.

Figures

Figure 1

Geographical distribution of the risk of COVID-19 importation to each prefecture and their response timing. (a) Fluxes of population outflow from Wuhan, represented by dBIMs, during period of 1 January to 29 February in 2019 and 2020. The vertical lines in grey and red represent the dates of Wuhan lockdown and Chinese Lunar New Year, respectively. dBMI: daily Baidu Mobility Index. (b) Spatial distribution of COVID-19 importation risk, measured by their aggregate population inflow from Wuhan until 26 January 2020. Provincial inflow from Wuhan was plotted at the upper left corner and municipal inflow in Hubei plotted at the lower right corner. The black area is Wuhan city. (c) Governments' response timing in each prefecture. The dates to raise provincial public health response to Level One for COVID-19 control were plotted using different colors (upper left). Similarly, time to execute city shutdown in Hubei was plotted (lower right). (d) The importation risk distribution grouped by governments' response. Samples with insufficient size at the response timing were excluded, such as Qinghai, Tibet and Xiangyang. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

COVID-19 progress and its association with importation risk and control strategy. (a) The epidemic curves of COVID-19 in Hubei and non-Hubei area by 29 February 2020. (b) Relationship over time between the number of confirmed cases (cumulative until 29 February 2020) and total population inflow (up to 26 January 2020) from Wuhan, both on a logarithm scale. (c) The relationship between the log-transformed total population outflow from Wuhan (up to 26 January 2020) and the log-transformed number of confirmed cases by prefectures on 29 January 2020. Circles are prefectures in Hubei; rectangles are prefectures outside Hubei; and the point sizes are proportional to the population density of the prefecture. The linear fitting is done for overall (black), Hubei (red) and non-Hubei (cyan) data. (d) The distribution of confirmed cases on 29 January 2020, grouped by governments' response including response timing and response strategy on a logarithm scale. Samples with insufficient size at the response timing were excluded, such as Qinghai, Tibet and Xiangyang.

Figure 3

Estimation of time-varying effect of Hubei control strategy. (a) The fitted performance of our dynamic model (see dynamic model I in Section S2.3 of Additional file 1). (b) Change of estimated relative risk over time, comparing between Hubei control strategy and non-Hubei control strategy (as reference). (c) Comparison of index of control effectiveness between all study prefectures.

Supplementary Files

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