RESEARCH

The effects of pre-response before COVID-19 outbreak on strategic decision making

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Abstract

Background: In the case of COVID-19, many countries have introduced their own policies for prevention. In Sweden, herd immunity policy was implemented and it was difficult to reduce the number of fatalities. In South Korea, the number of fatalities was not high because the public had earlier received a risk warning from the government and followed the policy well. In order to prevent the spread of infectious diseases, the government's policy is important, but it is also important for people to agree and follow the policy. As such, an individual's behavior such as preventive measures and pre-responses may be linked to the prevention of the spread of COVID-19.

Methods: To evaluate the effect of strategy selection between individuals and groups when pre-response action, we incorporate a compartmental epidemic model into a game-theoretical framework and use this to fit the cumulative confirmed data of Sweden (Feb. 27 - Mar. 12) and South Korea (Feb. 4 - Mar. 3).

Results: The transmission rate (β) is estimated from the fitted model, and the reproduction numbers (R_0) of two countries, Sweden and South Korea are estimated by 6.93 and 3.71, respectively. The probability of infection (φ_p) of Sweden is about 12% higher than that of South Korea. As the probability of attack that an epidemic occurs (θ) increases, the individual's equilibrium gradually increased than group optimum.

Conclusions: When comparing the prevention policies of Sweden and South Korea, it was confirmed that pre-response can be an appropriate preventive strategy against the transmission of infection. The selection of a strategy between individuals and groups can lead to the collapse of altruism that tends to select an action strategy for personal benefit, as the probability of the epidemic attack increases.

Keywords: evolutionary game theory; strategic decision making; COVID-19; pre-response

Introduction

People in the local community neglect preventive measures until the infectious disease, including COVID-19, actually outbreak in the area [1]. However, several people (e.g., involve those who experience with infectious diseases) have prepared preventive measures to prevent infection [2, 3, 4]. Since the recent outbreak of COVID-19, many countries are protecting people from viruses through preventive measures. In Sweden among many countries, the herd immunity policy had implemented with support from the public as a strategy that opens up much of society [5]. Although the policy also supported by scientists and governments, it was difficult to reduce the number of fatalities. On the other hand, South Korea had notified coronavirus risk early warnings to the public, so that many people acted to prevent themselves (e.g., wearing masks, self-isolation) [6]. As a result, the number of fatalities was not high, and it was positively evaluated by plenty of countries about the preventive policy.

People do not act in a rational way when purchasing the daily necessities or protective equipment, including masks, disinfectants, and toilet paper if the outbreak of infectious disease occurs [7]. Also, global health crises such as COVID-19 require large-scale behavioral changes, but serious psychological burdens and pressures on individuals may not be capable of rational behavior [8]. Certainly, some people behave selfishly, and people who are particularly vulnerable may suffer more. However, cooperation and orderly behavior are common across the categories of emergencies and disasters, and people often show remarkable altruism [9].

Shi Zhao *et al.* [10] concluded that the imitating social learning process that individual-level behavioral change has the potential to significantly reduce COVID-19 incidence in terms of size and timing at the city-level. T. Cruwys *et al.* [11] presented three recommendations for

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recognizing how important the change in collective behavior to new epidemics and how to improve this response by using group processes. B. Pejo and G. Biczok [12] expressed the effect of individual incentives on decisions made with respect to wearing masks and social distancing through game theory, and the social balance and cost of implementing the government's epidemic response mechanism are discussed.

As such, an individual's behavior, such as preventive measures and pre-responses to COVID-19, may play an important role in preventing the spread of infectious diseases. Thus, when decisions are made by individuals, local governments, and countries, they may also be linked to infectious diseases such as COVID-19, so that we can consider a mathematical model that includes the dynamics and perspectives of evolutionary behavior to cope with COVID-19. In other words, we are faced with the choice question of whether to act for the common or for personal benefit. Thus, the game theory can be used to analyze the situation in which an individual has to make a decision in a group environment and the situation in which each individual's decision affects the cost of others in the group. Depending on people's selective behavioral strategies for government policy, the effectiveness of preventing infectious diseases may also vary.

In this study, by integrating the game theory and an epidemic model, we evaluate the effect of strategy selection between individuals and groups by pre-response action strategies when COVID-19 emerges in the local community. The framework of the game theory evaluates the impact of strategy selection by establishing a situation that compares payoffs between individuals and groups [13, 14]. We estimate the transmission rate and probability of infection from the proposed model based on the cumulative confirmed data of Sweden and South Korea from the early event time until the government's preventive policy. Using the fitted model, the transmission rate and the reproduction numbers in Sweden and South Korea are evaluated, and we identify the differences in strategy choice between individuals and groups on prevention strategies for COVID-19.

Materials and Methods

Description of game

All individuals have same information and use this information in the same way to be rational. This is a population game (homogeneous population) where players are individuals (susceptible) with two strategies, and they will end up one of the strategies prior to COVID-19 outbreak: those who pre-response take action strategy and those who take non-action. An individual can decide between pre-response action strategy (from here, briefly 'action strategy') and non-action strategy.

We denote the proportion of the population who have preacted before COVID-19 outbreak as p, and use r_a and r_{na} to denote the perceived cost of the risk of utility loss for adopting the action strategy and non-action strategy, respectively. Assume that the action strategy cannot be completely prevented from infection but can be prevented sufficiently, and the condition hold $r_a < r_{na}$. Hence, the payoff E_a to an individual choosing the action strategy is

$$E_a = -r_a,$$

whereas the payoff E_{na} to an individual choosing the non-action strategy is

$$E_{na} = -r_{na}\theta\varphi_p,$$

where θ represents the probability of attack risk when an epidemic occurs, φ_p represents the probability of infection about those who adopt the non-action strategy being infected after COVID-19 outbreak.

A mixed strategy is specified by the probability P that an individual will choose to action strategy and the probability $1-P$ that an individual will choose to non-action strategy. Then, the payoff function to an individual playing a mixed strategy is

$$\begin{aligned} E(P,p) &= PE_a + (1-P)E_{na} \\ &= -Pr_a - (1-P)r_{na}\theta\varphi_p. \end{aligned}$$

Since r_a and r_{na} changes only the size of the dynamic as a constant, those can be rescaled, and define the relative risk of action compared with infection is $r = \frac{r_a}{r_{na}}$ (*i.e.* $r_a < r_{na} \Leftrightarrow \frac{r_a}{r_{na}} < 1$, and for $r < 1$, it means that there is a relationship between non-action and infection). Then, we have the payoff to an individual playing a mixed strategy (action with probability P) in a population in which the proportion of preaction level is p is given by

$$E(P,p) = -Pr - (1-P)\theta\varphi_p.$$

p_{ind} is the quantity to expect rational behavior as maximizing the probability that people will not become infected. We define as an individual equilibrium, p_{ind}, and show the existence and convergence of the *Nash* equilibrium in the appendix. This equilibrium solution is values determined to maximize the payoff for their strategy, and since this is a population game, the payoff is determined to depend on the strategy frequencies of the entire population.

From the point of view of public health authorities (*i.e.* group interest), the (scaled) cost of all susceptible (game players) is formulated to achieve a preventive policy that minimizes mortality. We have, then,

$$C(p) = pr + (1-p)\theta\varphi_p,$$

Table 1 Parameters description of the payoff function in game.

Paramters	Description	Range	Reference
p	the rate of people who acted to protect from the COVID-19	[0.001 , 0.2]	assumed
α	the initial attack rate proportion of susceptible population is infected	$[10^{-8}, 10^{-6}]$	[13, 14]
θ	the probability of attack that an epidemic occurs	[0.001, 0.05]	[14]
r	the relative risk	$[10^{-5}, 10^{-2}]$	[13]

where r is recaled and $p \in [0,1]$. And all parameters are the same as the description in Table 1. With a summary of Table 1, data on mask sales in South Korea have been available since February 28, and by March 3, the total sales volume is 23,150,000. During this period, South Korea was prior to the implementation of the 5-day rotation system for purchasing masks, and the mask was sold out every day. Therefore, if an average of two masks were purchased per person, we can assume that about 20% of people acted for prevention. (20% of South Korea's entire population is 10,253,837.)

We define as a group optimum, p_{gr}, that the minimum mortality cost can be calculated. The minimum value of $C(p)$ on [0,1] can be obtained from either the local minimum of (0,1) or the endpoint $C(0) = \theta\varphi_0$ and $C(1) = r$. The government's control goal is to minimize the overall cost of all of the susceptibles.

Formulation of epidemiological model

Both the individual equilibrium p_{ind} and the group optimum p_{gr} is specified from the infection probability φ_p. The φ_p depends on the modified SIR model for infectious disease dynamics in which the compartment reflects the status of infection and the incidence of new cases is proportional to the product of the density of susceptible and infectious individuals. The compartments is composed as susceptible (S), infectious (confirmed) (I), removed (discharged or recovered) (R) and susceptible who preacted from COVID-19 (S_a), respectively. We assume that people who act occur at a rate proportional to the prevalence of COVID-19. If people respond to media reports on COVID-19 prevalence, as the prevalence rate increases, the public will be more aware of the risk of infection and act to prevent it. However, other cases can be also considered enough. Especially, S'_a is expressed as νI as an example of the following [15]. Thus, our modified model is

$$\begin{aligned} S' &= -\beta(S + wS_a)I - S'_a, \\ I' &= \beta(S + wS_a)I - \gamma I, \\ R' &= \gamma I, \\ S'_a &\geq 0, \end{aligned} \tag{1}$$

where S'_a could take an observed quantity indicated situations of COVID-19. w is probability of becoming infected among susceptibles who have preacted. To estimate the transmission rate β, cumulative confirmed data by the initial onset of COVID-19 from each country were used, and γ is the mean duration of discharged. All parameter values and descriptions are shown in Table 2.

Susceptibles conduct to prevent COVID-19 in accordance with the government's official announcement or the dependence on the circumstances around susceptibles. Such behavior was not perfectly protected against COVID-19 but it was possible to prevent the spread of the COVID-19 sufficiently, and this situation might be demonstrated through South Korea [18]. Therefore, we assume that p is the proportion of susceptibles who have preacted prior to an outbreak, and $1-p$ is the proportion of susceptibles. When the outbreak begins, all susceptibles become infected at a rate of α. Thus, the initial proportion of infected individuals is $(1-p)\alpha$. The remaining initials are: $S(0) = (1-p)(1-\alpha)$, $R(0) = 0$ and $S_a(0) = p$.

Probability of infection

Suppose that we can consider the probability of infection in the situation until before the government official announcement. Then τ is indicated that time, and we can figure out the probability of infection from that time. For a given the system (1) we can find the probability of infection for COVID-19:

$$\varphi_p = \frac{\beta(S(\tau) + wS_a(\tau))I(\tau)}{\beta(S(\tau) + wS_a(\tau))I(\tau) + S'_a(\tau)}.$$

The probability of infection can be obtained from the results of the simulation in the system (1). This probability represents various scenarios depending on the incidence of action strategy selection.

Results

For Sweden, we obtained $\beta = 0.472$ by estimating transmission rates from the time after COVID-19 occurred until the government's quarantine policy was implemented, and γ for COVID-19 was referred to as an estimated value. From that, the basic production number, R_0, could be obtained as 6.93.

In Figure 1, the red circle represents the actual data, and the solid line, dashed line and dotted line according to the change of p indicate the number of infected for the system (1). Comparing the number of cumulative confirmed cases

Table 2 Parameters description of epidemic model.

Paramters	Description	Range	Reference
β	trasmission rate	estimated	–
γ	mean duration of discharged	[5, 14.7]	[16, 17]
ν	the quantity of exit in the compartment of the people who acted	[0, N^a]	[15]
w	probability of becoming infected among susceptibles that have acted	[0, 1]	assumed

[a] N is the number of people who act for prevention per day in each country

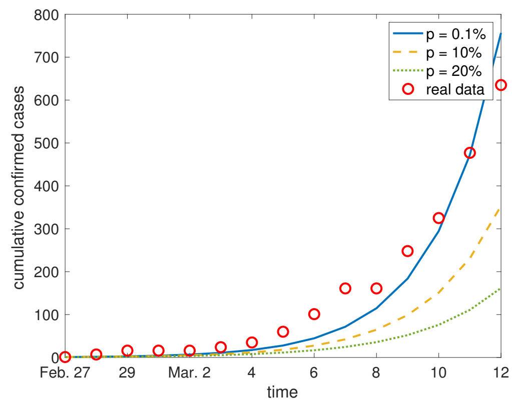

Figure 1 Comparison of Sweden's actual cumulative confirmed data according to the rate of people who preacted (p), from February 27 to March 12 (on March 12, public meetings with more than 500 participants from across Sweden are prohibited, outdoor activities are also prohibited (Government offices of Sweden)).

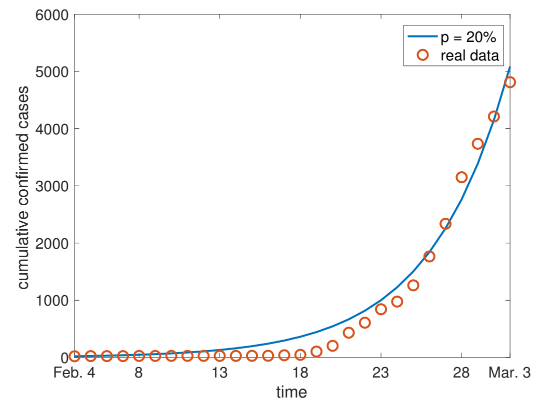

Figure 2 Fitting model where use actual cumulative confirmed data from February 4 (abolition of contact detail classification, self-isolation reinforcement, released from isolated) to March 3, and noted that drive-through operating instructions starting on the 4th.

between $p = 0.001$ and $p = 0.2$ on March 12, the number of cumulative confirmed cases is delayed and reduced by about 65%. Sweden was estimated to $\beta = 0.472$ and $R_0 = 6.93$, and the probability of infection φ_p in Sweden during this period was 0.82 and 0.78 when $p = 0.001$ and $p = 0.2$, respectively, and there is about a 12% difference compared to the probability of infection in South Korea that φ_p is 0.66 when $p = 0.2$.

Figure 2 shows the results of fitting the actual cumulative confirmed data from South Korea. The period establishes from the time when the government announced a plan to block the spread of community to the time before drive-through sorting stations were made in all parts of the country. For $p = 0.2$, South Korea was a higher rate of self-prevention than Sweden in an earlier stage, and it was estimated that $\beta = 0.253$, and $R_0 = 3.71$. Also, the probability of infection φ_p was 0.66. When compared to Sweden, it can be seen that the rate of people who pre-acted (p) before the government makes a preventive policy affects the value of the transmission rate β and R_0.

In Table 3, the probability of infection (φ_p) and the number of cumulative confirmed cases are shown according to the rate of people who pre-acted in Sweden (Feb. 27 - Mar. 12) and South Korea (Feb. 4 - Mar. 3), respectively. The bold type is the best fit to the model for each country and is a baseline that can explain the situation well.

Figure 3 indicates the difference between p_{gr} and p_{ind} to assess people's behavior changes from government policies. The effect of strategic selection between individuals and groups is evaluated by the symbol of Δp, where if Δp is positive, then the population will act for group interest. Otherwise, the population will act for individual benefit. And people show different types of strategic choices depending on the value of θ. Figure 3(a) shows that people tend to choose the strategy for the benefit of the individual when the p is small, regardless of the relative risk (r), but mostly choose the strategy for groups. Figure 3(c), where the value of θ has increased, tends to choose strategies more for personal gain. Figure 3(b) is between Figure 3(a) and Figure 3(c). In particular, it can be seen that the relationship between p and r is a linear correlation, and there is an effect between relative risk and action strategy on COVID-19.

Disscussion

This study was to evaluate the effect of pre-response behavior on COVID-19 infection transmission based on the cumulative confirmed cases in two contries; Sweden (Feb. 27 - Mar. 12) and South Korea (Feb. 4 - Mar. 3). To do this,

Table 3 Probability of infection and the number of cumulative confirmed cases for each country according to the rate of pre-response.

Country		**Sweden**			**South Korea**	
the rate of people who pre-acted (p)	**0.1%**	10%	20%	0.1%	10%	**20%**
Probability of infection (φ_p)	**0.825**	0.809	0.79	0.716	0.694	**0.669**
Cumulative confirmed cases	**756.34**	353.26	161.77	27277.13	11592.98	**4824.15**

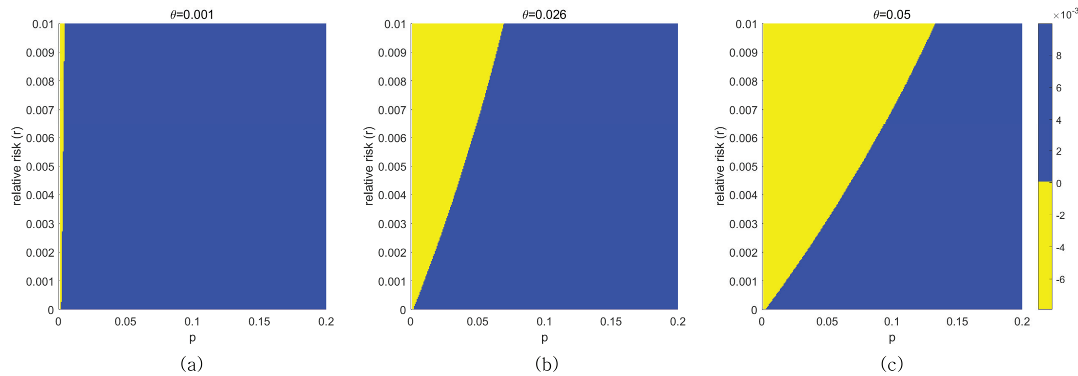

Figure 3 Δp $(= p_{gr} - p_{ind})$ is expressed according to the variation of the rate of people who preacted (p) and the relative risk (r) when θ varies. A positive value of Δp represents a strategy choice for group benefit, otherwise it represents a strategy choice for personal benefit.

we used the model incorporating the game theory and an epidemic model and investigated how people choose strategies from the perspective of individuals and groups. In Sweden, β was 0.472 by fitting the model in the period from the first confirmed to the government banning meeting activities, and R_0 was 6.93. In South Korea, where many people acted in advance for prevention, β and R_0 was 0.253 and 3.71, respectively. Considering that South Korea has a lower transmission rate and R_0 than that of Sweden, it is regarded that pre-response behavior when COVID-19 occurs is an appropriate preventive strategy for transmission of infection.

In addition, the probability of infection (φ_p) could be obtained by an epidemic model through payoffs of action strategy and non-action strategy. The probability of infection in Sweden and South Korea was 0.78 and 0.66, respectively, so that the probability of infection for South Korea was low as well. And Δp was examined to compare the effect of strategy selection between individuals and groups. When an epidemic outbreak is less likely to occur, most people choose action strategies for groups regardless of the relative risk. In the opposite case, the higher the relative risk, the more it tends to choose action strategies for the benefit of the individual.

What is important here is to take a pre-response action strategy. As we can see from the comparison of prevention policies of Sweden and South Korea, pre-response can be an appropriate preventive measure against the transmission of infection. In particular, it was confirmed that action strategies for groups can be an effective way to prevent the spread of infection in local communities, as well as national or government as the probability of the epidemic attack increases. Finally, we may suggest that our research does not give the correct solution to what actions people should take or what mechanisms or policies should be introduced to make the entire system more efficient in the first outbreak of infectious disease. Therefore, we will solve the problem of this view in further work.

Conclusions

In Sweden, we obtained that the transmission rate was 0.472, the basic reproduction number was 6.93, and the probability of infection was 0.825. In South Korea, we obtained that the transmission rate was 0.253, the basic reproduction number was 3.71, and the probability of infection was 0.669. We examined the tendency to act for the benefit of individuals as the probability of attack that an epidemic occurs increases. We emphasized the importance of pre-response action strategy for everyone to prevent the spread of COVID-19.

Supplementary information

Additional file 1 – proof of individual equilibrium

The file describes the proof of existence of Nash equilibrium and convergent stability about individual equilibrium.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials
All data and materials used in this work were publicly available.

Competing interests
The authors declare that they have no competing interests.

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Author's contributions
IHJ designed and conceived the studies. DWK and JHJ collected the data and drew a conclusion. All the members discussed the results and wrote the manuscript.

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