

## ARTICLE OPEN



# Human mobility and infection from Covid-19 in the Osaka metropolitan area

Haruka Kato <sup>1</sup>✉ and Atsushi Takizawa <sup>1</sup>

Controlling human mobility is thought to be an effective measure to prevent the spread of the COVID-19 pandemic. This study aims to clarify the human mobility types that impacted the number of COVID-19 cases during the medium-term COVID-19 pandemic in the Osaka metropolitan area. The method used in this study was analysis of the statistical relationship between human mobility changes and the total number of COVID-19 cases after two weeks. In conclusion, the results indicate that it is essential to control the human mobility of groceries/pharmacies to between  $-5$  and  $5\%$  and that of parks to more than  $-20\%$ . The most significant finding for urban sustainability is that urban transit was not found to be a source of infection. Hence governments in cities around the world may be able to encourage communities to return to transit mobility, if they are able to follow the kind of hygiene processes conducted in Osaka.

*npj Urban Sustainability* (2022)2:20; <https://doi.org/10.1038/s42949-022-00066-w>

## INTRODUCTION

The COVID-19 pandemic was reported to positively impact urban sustainability in the short term<sup>1</sup>. However, the pandemic might not continue to impact urban sustainability positively even in the medium term. For example, several lockdowns caused changes in mobility, especially in public transportation, because of concerns about COVID-19 infection<sup>2</sup>. However, the modal shift from public transportations to cars will adversely effect on reduction of carbon dioxide emissions<sup>3</sup>. Controlling human mobility is thought to be an effective nonpharmaceutical intervention to prevent the spread of the COVID-19 pandemic worldwide, for example, in the United States, the EU, and China<sup>4–6</sup>. To control human mobility, states of emergency have been declared many times during the medium-term COVID-19 pandemic. For example, the Japanese government declared states of emergency several times in Osaka Prefecture<sup>7</sup>. During these emergency declaration periods, the Subcommittee on Novel Coronavirus Disease Control in Japan requested that residents reduce their human mobility by  $50\%$ <sup>8</sup>. During the first emergency declaration, this requirement reduced the home range in suburban cities of the Osaka metropolitan area by  $50\%$  due to residents changing their transportation methods to walking and cycling<sup>9–11</sup>. During the same first emergency declaration, a decrease in human mobility was also reported in Tokyo<sup>12</sup>. However, some studies have suggested that the effects of controlling human mobility differed in the early term and medium term<sup>13–15</sup>.

This study investigates the following research question: Where should we control human mobility to reduce the number of COVID-19 cases? The COVID-19 transmission was impacted by many factors such as population density, temperature, and vaccination rate<sup>16</sup>. However, it was found that human mobility affects COVID-19 transmission more strongly than other factors<sup>17</sup>. Besides, human mobility is a factor that governments' policies could intervene. Currently, the COVID-19 transmission is strongly influenced by the vaccination rate<sup>18</sup>. However, some people cannot be vaccinated because of religious or medical conditions. Besides, it is challenging to develop a vaccine immediately for any

new infectious disease in the future. Therefore, controlling human mobility is the most basic measure of a nonpharmaceutical intervention for the future infections. Those are reasons that this study needs to focus on human mobility.

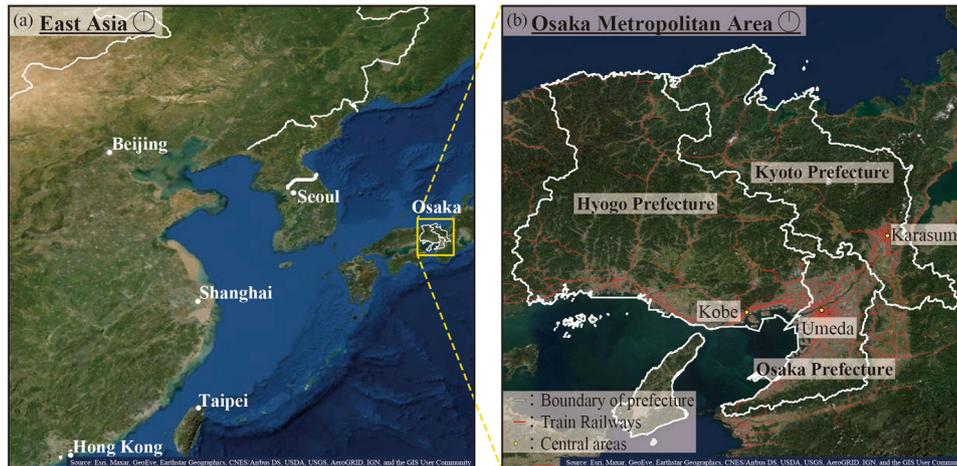
The effectiveness of controlling human mobility has been reported through the implementation of school and company closures<sup>9–11</sup>. In addition, in Japan, many prefectural governments requested that dining and drinking establishments close by 8:00 p.m. and refrain from serving alcohol<sup>7</sup>. However, to prevent the spread of the COVID-19 pandemic, it is necessary to consider restricting places that have not previously been considered. In addition, to maintain socioeconomic activities, it is essential to consider ending restrictions in places where infections are less likely to occur. Therefore, the type of human mobility contributes to how policymakers develop policies to control the spread of infection for urban sustainability.

This study aims to clarify the human mobility types that impacted the number of COVID-19 cases during the medium-term COVID-19 pandemic in the Osaka metropolitan area. The method used in this study was analysis of the statistical relationship between human mobility changes and the total number of COVID-19 cases after two weeks. The human mobility types are divided into six categories using Google Community Mobility Reports data: retail and recreation (retail/recreation), groceries and pharmacies (groceries/pharmacies), parks, transit stations, workplaces, and residential areas<sup>19</sup>. These human mobility types are analyzed based on the relative changes in the number of visitors to the six types of places. Random forest analysis is applied to determine this statistical relationship.

The Osaka metropolitan area from March 1, 2020, to September 30, 2021, was selected as a case study. During the medium term, the Osaka metropolitan area experienced five waves of increasing and decreasing numbers of COVID-19 cases. During this period, vaccination started for healthcare workers in February 2021 and for older people and adults in April 2021. As a result, the fourth state of emergency was lifted in the Osaka metropolitan area on September 30, 2021. In this study, the Osaka metropolitan area

<sup>1</sup>Department of Housing and Environmental Design, Graduate School of Human Life and Ecology, Osaka Metropolitan University, Osaka 5588585, Japan.

✉email: haruka-kato@omu.ac.jp



**Fig. 1** Map of the Osaka metropolitan area in Japan. In this study, the Osaka metropolitan area consisted of Osaka, Kyoto, and Hyogo Prefectures. In Fig. 1, (a) indicates the location of Osaka metropolitan area in the East Asia, and (b) indicates that of three prefectures in the Osaka metropolitan area. The Osaka metropolitan area has three central areas with multiple railways. The satellite map complies with copyright<sup>20</sup>.

consists of Osaka Prefecture, Kyoto Prefecture, and Hyogo Prefecture, as shown in Fig. 1. The satellite map in Fig. 1 complies with copyright<sup>20</sup>. Unlike other metropolitan areas, the Osaka metropolitan area has three central areas: Umeda in Osaka Prefecture, Karasuma in Kyoto Prefecture, and Kobe in Hyogo Prefecture. Because multiple railways and highways connect these areas, the number of infections tended to increase speedily. In the early term COVID-19 pandemic, it was found that city size correlated with COVID-19 cases<sup>21</sup>. Therefore, COVID-19 countermeasures were often discussed and collaboratively implemented by the governors of the three prefectures. For example, the three governors together requested that the Japanese national government declare a state of emergency. In addition, the emergency declaration periods have been the same for all three prefectures. Therefore, it is reasonable to analyze these three prefectures together as the Osaka metropolitan area.

Many studies on human mobility have used mobile phone data to predict the number of people infected with SARS-CoV-2. Restaurants, fitness centers, cafes, bars, and hotels have been found to be high-risk areas for infection<sup>22</sup>. In Japan, the human mobility of downtown nightlife was found to be higher risk than that of residences or workplaces<sup>23</sup>. In addition, prefectural governments have often considered COVID-19 countermeasures with reference to the human mobility of transit station<sup>24</sup>. For example, the Osaka Prefectural Government alerted people when the human mobility increased at the terminal stations<sup>24</sup>. Similar to this study, random forest analysis using Google Community Mobility Reports data indicated that the important mobility areas were retail/recreation, groceries/pharmacies, and transit stations in the case of the EU from March to April 2020<sup>25</sup>. In addition, in Germany from February to July 2020, the factors related to the number of cases were increasing human mobility of groceries/pharmacies and decreasing mobility of workplaces and retail/recreation<sup>26</sup>. Regarding individual human mobility, human mobility was reduced for workplaces and transport during the pandemic in Portugal<sup>27</sup>. The results indicated that workplace closure was nearly as effective as the stay-at-home order in the social distancing policy<sup>28</sup>. Japan had one of the greatest declines in human mobility worldwide<sup>29</sup>. In addition to mobility of workplaces, human mobility of parks has received attention. The number of urban park visitors increased worldwide during the pandemic<sup>30</sup>.

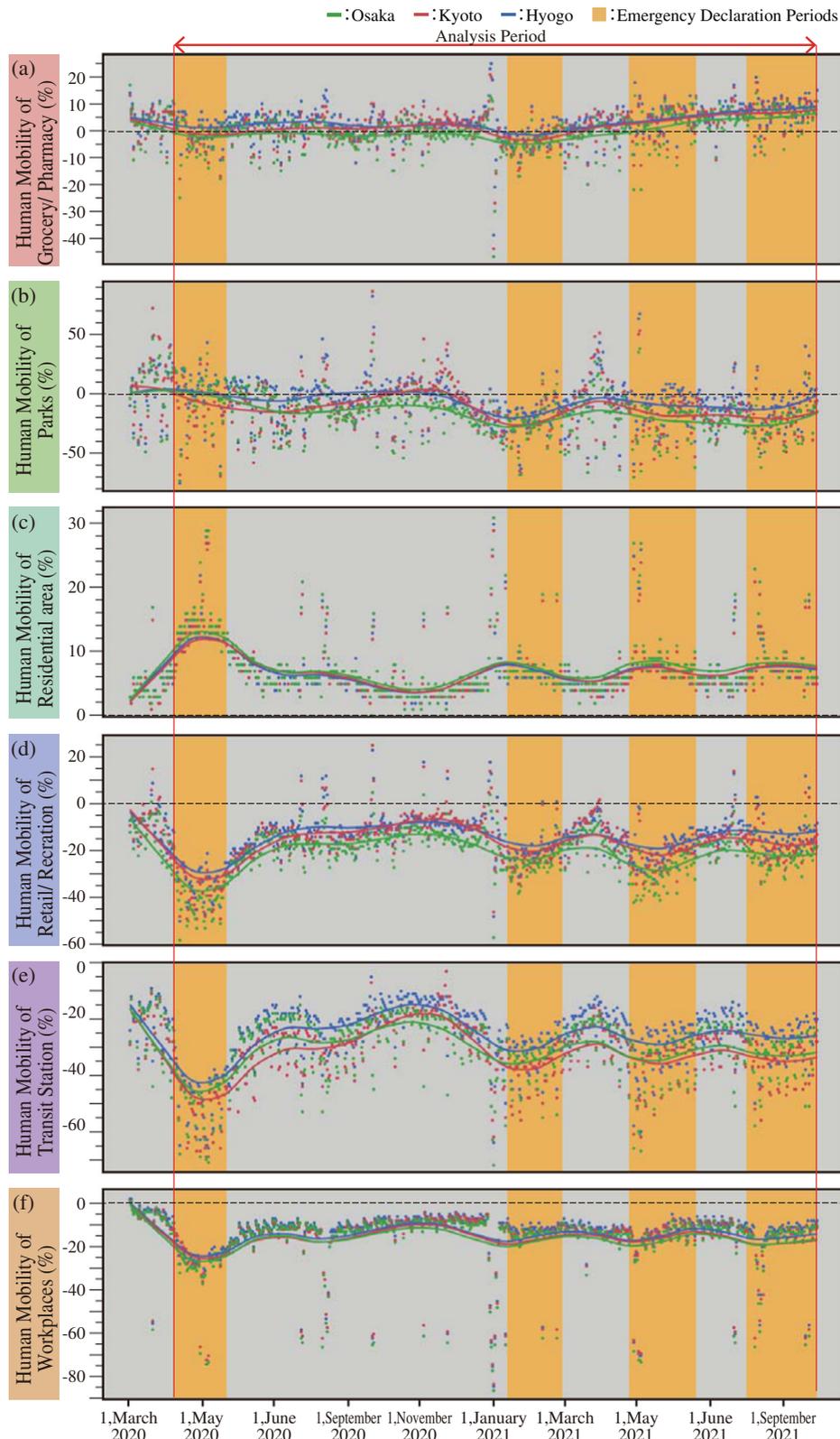
Based on previous studies, the novelty of this study is its clarification of human mobility types during the medium-term

COVID-19 pandemic. In Japan, the state of emergency was called a “soft lockdown” because the Japanese government did not restrict the activities of individuals<sup>31</sup>. For example, the Osaka Prefectural Government demanded that railroad companies conduct temperature checks at major terminal stations and move up the last train departure time<sup>32</sup>. Besides, based on the demand by the prefectural governments, railroad companies decided to remain the number of daytime train departures the same as before the pandemic, even if the number of passengers decreased significantly<sup>33</sup>. Some railroad companies in Osaka also provided incentives to those who took the train when the number of passengers was less<sup>34</sup>. Those hygiene processes reduced the density of human mobility at the transit station. Therefore, most citizens could go out at least occasionally, even under the state of emergency declaration. Therefore, there might be diversity in the relationship between human mobility types and the number of COVID-19 cases. The results will help policymakers plan effective human mobility control for urban sustainability. However, it is difficult to obtain highly accurate results for the medium-term COVID-19 pandemic<sup>13–15</sup>. That is because the number of COVID-19 cases and human mobility might have a nonlinear relationship due to some factors such as policy effects and new variants of SARS-CoV-2. Previous studies have analyzed the relationship between the number of COVID-19 cases and human mobility using machine learning methods such as the logistic growth model<sup>35</sup>, partial differential equation<sup>36</sup>, and neural network<sup>37</sup>. However, these machine learning methods might not necessarily provide highly accurate results for medium-term relationships, although they might produce highly accurate results for short-term relationships. That is because there is a risk of machine learning overtraining as there are multiple increasing and decreasing numbers of COVID-19 cases. Referring to the analysis of Delen et al.<sup>26</sup>, this study uses random forest analysis, providing more accurate results while avoiding overlearning compared to other machine learning methods.

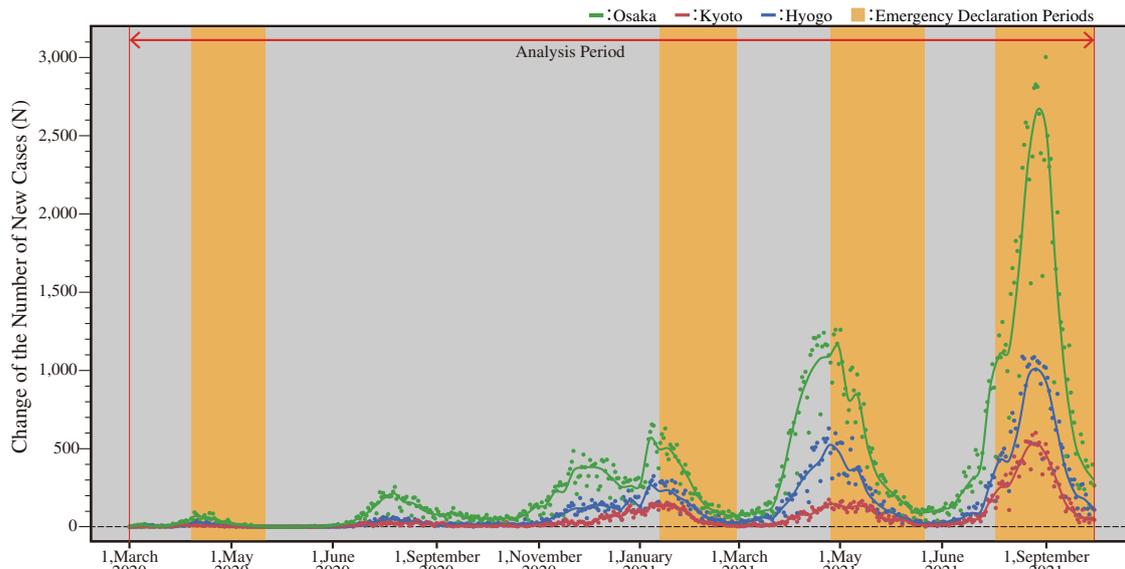
## RESULTS

### Changes in human mobility

Figure 2 shows daily changes in human mobility in the Osaka, Kyoto, and Hyogo Prefectures for the medium-term COVID-19 pandemic. Figure 2 shows the spline curve and the confidence interval. The smoothing parameter of the spline curve  $\lambda$  was set to 0.001. Additionally, Fig. 2 indicates the emergency declaration



**Fig. 2** Human mobility changes from March 2020 to September 2021. Human mobility types are retail/recreation (a), groceries/pharmacies (b), parks (c), transit stations (d), workplaces (e), and residential areas (f). Green points and line are the data of Osaka Prefecture, red points and line are the data of Kyoto Prefecture, and blue points and line are the data of Hyogo Prefecture.



**Fig. 3 Change in the number of COVID-19 cases.** Green points and line are the data of Osaka Prefecture, red points and line are the data of Kyoto Prefecture, and blue points and line are the data of Hyogo Prefecture.

period. The results show similar changes in the Osaka, Kyoto, and Hyogo Prefectures.

Figure 2 shows that human mobility varies according to the six types. After March 2020, all types of human mobility except human mobility of residential are decreased. This finding suggests that more people stayed at home, even without the stay-at-home order. When human mobility of residential are increased, other types of human mobility decreased. Due to the emergency declaration, human mobility decreased in transit stations and retail/recreation. In addition, the human mobility of workplaces declined sharply during holiday periods, such as summer vacations and the new year holiday. The human mobility of groceries/pharmacies remained at approximately 0%, although it changed slightly during the emergency declaration. The human mobility of parks increased during the first emergency declaration but then began to decrease.

### Change in the Number of COVID-19 Cases

Figure 3 shows the daily change in the number of people infected with SARS-CoV-2 in the Osaka, Kyoto, and Hyogo Prefectures. Figure 3 shows the spline curve and the confidence interval. The smoothing parameter of the spline curve  $\lambda$  was set to 0.001. Additionally, Fig. 3 indicates the emergency declaration period.

Figure 3 shows that the Osaka, Kyoto, and Hyogo Prefectures experienced five waves of increases and decreases in COVID-19 cases between February 2020 and December 2021. The first wave was from April to May 2020, the second from July to September 2020, the third from December 2020 to February 2021, the fourth from March to June 2021, and the fifth from July to September 2021. The number of infections gradually increased from the first to the fourth wave. States of emergency were declared during the first, third, fourth, and fifth waves. The declaration of a state of emergency effectively reduced the number of COVID-19 cases.

### Human mobility types that impact the number of COVID-19 cases

Table 1 and Fig. 4 show the human mobility types that impacted the total number of COVID-19 cases after two weeks in the Osaka, Kyoto, and Hyogo Prefectures. The statistical analysis was the random forest method. Table 1 shows the main effect and the

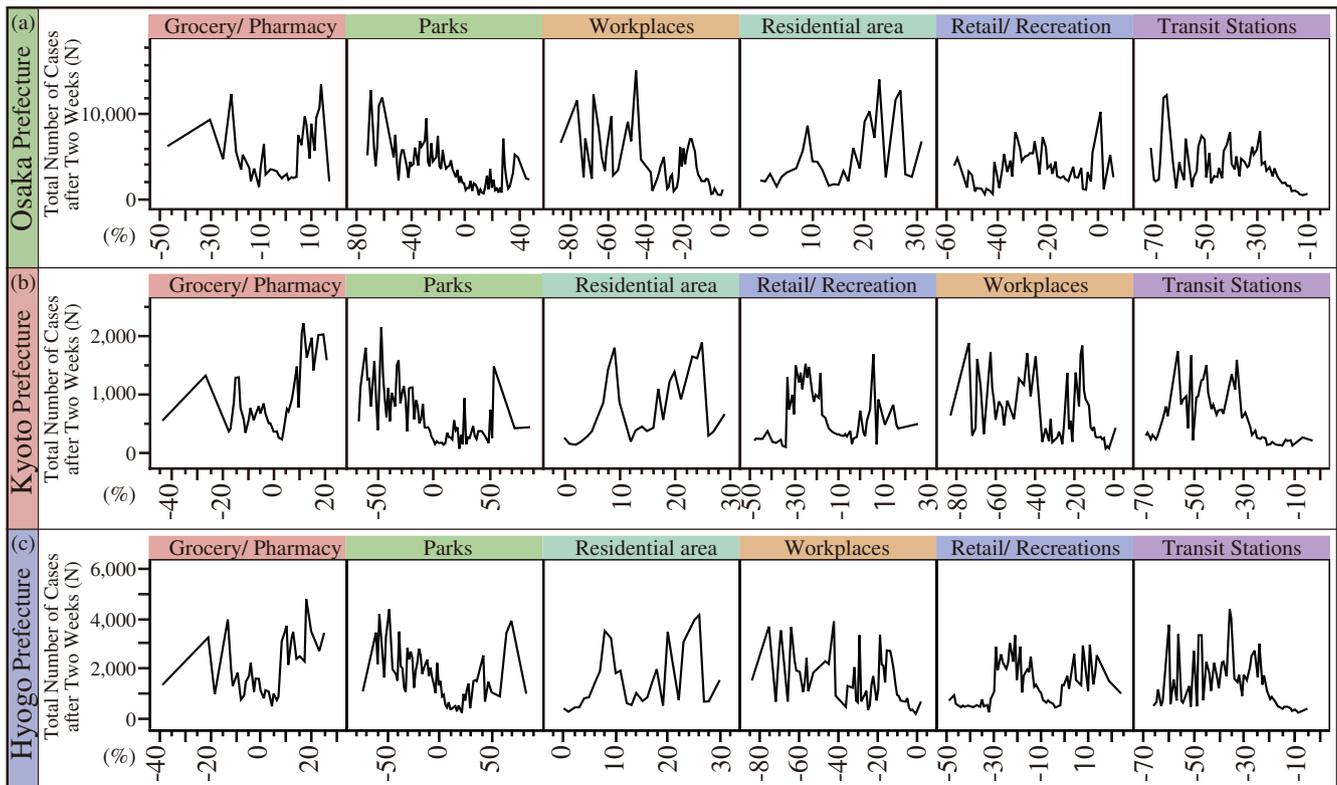
**Table 1.** Main effects and total effects by prefecture.

	Attributes	Main Effect	Total Effect	$R^2$
Osaka Prefecture	Groceries/pharmacies	0.246	0.437	0.777
	Parks	0.106	0.368	
	Workplaces	0.183	0.253	
	Residential areas	0.234	0.234	
	Retail/recreation	0.129	0.129	
	Transit stations	0.102	0.102	
Kyoto Prefecture	Groceries/pharmacies	0.185	0.418	0.821
	Parks	0.125	0.363	
	Residential areas	0.216	0.216	
	Retail/recreation	0.163	0.168	
	Workplaces	0.163	0.163	
	Transit stations	0.148	0.148	
Hyogo Prefecture	Groceries/Pharmacies	0.220	0.495	0.775
	Parks	0.097	0.303	
	Residential areas	0.237	0.245	
	Workplaces	0.165	0.165	
	Retail/Recreation	0.135	0.159	
	Transit stations	0.146	0.146	

In Table 1, each number is represented by a green-to-red graduation. Specifically, the red tab has higher numbers, and the green tab has lower numbers.

total effect for each prefecture. Figure 4 shows the variable importance in the Osaka, Kyoto, and Hyogo Prefectures. As shown in Table 1, the  $R^2$  scores of all models were over 0.7, indicating good accuracy. The results are discussed separately by prefecture.

In Osaka Prefecture, the  $R^2$  score was 0.777, which indicates that the model has good accuracy. The total effect was higher for human mobility in groceries/pharmacies (total effect = 0.437), parks (total effect = 0.368), workplaces (total effect = 0.253), and



**Fig. 4 Variable importance by prefecture.** The variable importance is assessed by the dependent resampled inputs, which are factor values constructed from observed combinations using a k-nearest neighbors approach. In Fig. 4, (a) indicates the variable importance of Osaka prefecture, (b) indicates that of Kyoto prefecture, and (c) indicates that of Hyogo prefecture.

residential areas (total effect = 0.234). The total number of COVID-19 cases after two weeks gradually decreased by decreasing the human mobility of groceries/pharmacies by approximately 5 to  $-5\%$ . In addition, the human mobility of parks increased from  $-20$  to  $20\%$ , which reduced the number of COVID-19 cases. It was also found that the total effect was lower for human mobility in transit stations (total effect = 0.102).

In Kyoto Prefecture, the  $R^2$  score was 0.821, which indicates that the model has high accuracy. The total effect was higher for human mobility in groceries/pharmacies (total effect = 0.418), parks (total effect = 0.363), and residential areas (total effect = 0.216). The total number of COVID-19 cases after two weeks gradually decreased by increasing the human mobility of groceries/pharmacies by approximately  $-5$  to  $5\%$ . In addition, the human mobility of parks increased from  $-20$  to  $50\%$ , which reduced the number of COVID-19 cases. It was also found that the total effect was lower for human mobility in transit stations (total effect = 0.148).

In Hyogo Prefecture, the  $R^2$  score was 0.775, which indicates that the model has good accuracy. The total effect was higher for human mobility in groceries/pharmacies (total effect = 0.495), parks (total effect = 0.303), and residential areas (total effect = 0.245). The total number of COVID-19 cases after two weeks gradually decreased by increasing the human mobility of groceries/pharmacies by approximately  $-5$  to  $5\%$ . In addition, the human mobility of parks increased from  $-50$  to  $10\%$ , which reduced the number of COVID-19 cases. It was also found that the total effect was lower for human mobility in transit stations (total effect = 0.146).

## DISCUSSION

In conclusion, the results of this analysis indicate that it is essential to control the human mobility of groceries/pharmacies to

between  $-5$  to  $5\%$  and the mobility of parks to more than  $-20\%$ . This finding is important because human mobility control would reduce the number of people infected with SARS-CoV-2. To control the human mobility of groceries/pharmacies, the government must actively encourage residents to shop online and diversify the time spent using grocery stores and pharmacies. The target value for reducing human mobility is between  $-5$  and  $5\%$ . That value means that human mobility of groceries/pharmacies needs to be controlled the same as before the pandemic. Figure 2 shows that human mobility of groceries/pharmacies is less affected by the pandemic. However, all generations go to groceries/pharmacies daily, compared to other human mobility. Besides, in groceries/pharmacies, we always have social contacts. Therefore, the human mobility of groceries/pharmacies effects strongly the number of COVID-19 cases, although that is less affected by the pandemic. We need to control the human mobility of groceries/pharmacies not to increase or decrease too much. In fact, during the Delta variant outbreak in the Osaka metropolitan area, there were many incidents of infection clusters in groceries and department stores. Previously, the Japanese government did not restrict the shopping necessary to maintain daily life, even during the emergency declaration period. This study suggests that controlling the human mobility of groceries/pharmacies can prevent the rapid increase in the total number of cases after two weeks in the emergency declaration period. The results differ from those of a previous study<sup>26</sup>. This finding is significant because this study clarified the necessity of reducing the human mobility of grocery stores and pharmacies. The difference from previous studies might be the change in the analysis method. Previous studies had difficulty obtaining highly accurate results of nonlinear relationships for the medium-term due to some factors such as policy effects and new variants of SARS-CoV-2. This study obtained novel findings by using random forests, which can clarify

nonlinear relationships with high accuracy while avoiding overlearning.

The human mobility of parks was also found to impact the number of infections. As previous studies have found<sup>25,26</sup>, increasing the human mobility of parks contributes to a decrease in the number of infections. This finding suggests that increasing the human mobility of parks decreases the number of infections. It means that parks could be actively used in the emergency declaration period instead of controlling human mobility in groceries/pharmacies.

The most significant finding for urban sustainability is that urban transit was not found to be a source of infection. The human mobility of transit stations has been used as a reference in policymaking<sup>24</sup>. Hence governments in cities around the world may be able to encourage communities to return to transit mobility if they can follow the kind of hygiene processes conducted in Osaka. Those hygiene processes are to maintain the number of daytime train departures even if the number of passengers decreases significantly<sup>33</sup>. Besides, effective hygiene processes are to provide incentives to those who take the train at times when the number of passengers is less. Those hygiene processes reduced the density of human mobility at the transit station<sup>34</sup>. The result suggest that governments could consider ending restrictions in transit stations where infections are less likely to occur. Increasing the number of people using public transportation would reduce air pollution such as carbon dioxide emissions.

This study also clarified that the government needs to consider the third most influential type of human mobility according to the characteristics of each prefecture. For example, the Osaka Prefecture government could reduce the number of infections by increasing the human mobility of workplaces to 0% by allowing people to go to work. The results suggest that it would be better for the government not to prevent people from going to work but rather to prevent them from shopping and other activities associated with work.

Currently, many people can be vaccinated against the disease in many countries. On the other hand, new variants of COVID-19 arise continuously. Therefore, it is unlikely that the pandemic will end, as the number of infections regularly increases and decreases. Human mobility control may continue to be the most effective method of a nonpharmaceutical intervention, even in the future. However, unlike in the early stages of the pandemic, it is not necessary to stop all human mobility through a lockdown. The results of this study indicate that the control of specific types of human mobility could have a greater effect according to the infection stage. For example, we could ask people to reduce their opportunities to go to groceries/pharmacies and inform people about the safety of going to parks and transit stations. This finding is important because it allows for the maintenance of social and economic activities even during pandemics for the post-COVID-19 pandemic.

However, the change might impact urban sustainability negatively during the medium-term COVID-19 pandemic. Air pollution was reduced by the human mobility limitation<sup>38</sup>. If governments simply reactivate human mobility, carbon dioxide emissions may increase due to car traffic<sup>39</sup>. Therefore, the government needs to conduct a mix of several policies, such as working from home, online shopping, and active use of public transportation. For example, designing walkable neighborhood is important for new-normal lifestyle using public transportations<sup>40</sup>. Improving walkability is expected to contribute to the health of residents<sup>41</sup>, ecological footprint<sup>42</sup>, and future population<sup>43</sup>. The mayor of Paris, Anne Hidalgo, proposed the realization of a 15-min city by 2024, in a move toward the design of walkable neighborhoods after the COVID-19 pandemic era, where people can live without using cars<sup>44</sup>. Those policies could contribute for

planners and policymakers to improving the urban sustainability for the post COVID-19 pandemic.

The limitation of this study was that it was able to analyze only six types of human mobility available on Google Community Mobility Reports. Therefore, we cannot deny the possibility that the control of human mobility proposed by this study might cause an increase in another type of human mobility and a gradual increase in the number of infections. For example, would it truly be effective to restrict mainly dining and drinking establishments? Besides, it is necessary to analyzed with the travel modes such as public transits, walking, and driving because this study clarified the urban transit was not found to be a source of infection. To address this limitation, future research should analyze more diverse types of human mobility and travel modes using GPS location history data. These GPS log data can be obtained at regular intervals from mobile phones with users' consent. For the analysis, it is essential to understand the infection status of users of GPS location history data. The data would allow for analysis of human mobility and infected samples to be matched. Currently, it is challenging to analyze such studies with big data due to privacy protection. However, we can clarify the relationship with the number of infections in more detail using such data in the future.

## METHODS

### Human mobility data

This study used Google Community Mobility Reports data to analyze human mobility. The data are available publicly to provide insights into what has changed in response to policies aimed at combating COVID-19<sup>19</sup>. The Google Community Mobility Reports chart movement trends by geography across six categories: retail/recreation, groceries/pharmacies, parks, transit stations, workplaces, and residential areas. Retail/recreation includes restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters. Groceries/pharmacies includes grocery stores, food warehouses, farmers markets, specialty food shops, drug stores, and pharmacies. Parks includes local parks, national parks, public beaches, marinas, dog parks, plazas, and public gardens. Transit stations includes public transport hubs, such as subway, bus, and train stations. The data show relative changes in visitors to the six types of places compared to the baseline days, which were the median value for the five weeks from January 3 to February 6, 2020<sup>45</sup>. Google published changes in visitors at six types of places in each prefecture, not each location. This study uses data from the Osaka, Kyoto, and Hyogo Prefectures in the Osaka metropolitan area.

This research protocol was approved by the Research Ethics Committee of the Graduate School of Life Science, Osaka City University (No. 21–58). In addition, all methods used in this study followed the "Guidelines for the Use of Device Location Data," which prohibit the use of GPS data for any purpose that involves identifying individual users to protect the privacy of users' GPS location history<sup>46</sup>. Informed consent was obtained from all subjects based on the privacy policy. However, the consent is not written paper because it is digital data. Additionally, the subjects can stop sending their human mobility data at any time by changing their mobile phones' settings.

### Number of COVID-19 cases data

This study analyzed the daily number of newly confirmed cases of SARS-CoV-2 in the Osaka, Kyoto, and Hyogo Prefectures in the Osaka metropolitan area. The data were obtained from public information on COVID-19 infections provided by the Japanese Ministry of Health, Labour and Welfare<sup>47</sup>. The published data include the number of new COVID-19 cases each day by prefecture. The data do not include any personally identifiable information.

### Statistical analysis

The random forest method was used to analyze the relationship between the total number of COVID-19 cases after two weeks and the human mobility data. The random forest analysis of this study is an unsupervised analysis. Random forest predicts a response value by averaging the predicted response values across many decision trees<sup>48</sup>. Each tree is grown

from a bootstrap sample of the training data. A bootstrap sample is a random sample of observations drawn with replacement. In addition, the predictors are sampled at each split in the decision tree<sup>49</sup>. Compared to machine learning, such as the logistic growth model, partial differential equation, and neural networks, random forests obtain highly accurate models with high  $R^2$  scores. That is because random forests tend to prevent the overlearning. For the statistical analysis, this study used JMP PRO 16.0.

The predictor variables are daily human mobility data of retail/recreation, groceries/pharmacies, parks, transit stations, workplaces, and residential areas. The response variable is the total number of COVID-19 cases after two weeks (fourteen days). The two-week lag is because SARS-CoV-2 takes approximately two weeks from infection to disease occurrence<sup>50</sup>. The effectiveness of Google mobility data was validated for 10-day forecasts of COVID-19 cases<sup>51</sup>. The number of trees in the forest is ten thousand for the random forest.

The scale of variables is both prefecture scale. Regarding the explanatory variables, this study analyzes the samples as Google users, with the population as the prefectural population. This is because 79.2% of the population in Japan uses Google<sup>52</sup>.

Based on the results of the random forest, this analysis focused on the  $R^2$  score, the main effect, the total effect, and the variable importance of the prediction profiler. The variable importance is assessed by the dependent resampled inputs, which are factor values constructed from observed combinations using a k-nearest neighbors approach. The assessed method is helpful if factors may be correlated with each other.

## DATA AVAILABILITY

The data presented in this study are available from Refs. <sup>19,47</sup>.

Received: 1 March 2022; Accepted: 15 July 2022;

Published online: 02 August 2022

## REFERENCES

- Le Quéré, C. et al. Temporary reduction in daily global CO<sub>2</sub> emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **10**, 647–653 (2020).
- Martínez, L. & Short, J. R. The Pandemic City: Urban Issues in the Time of COVID-19. *Sustainability* **13**, 3295 (2021).
- Zhang, R. & Zhang, J. Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. *Transp. Policy* **110**, 28–36 (2021).
- Li, Y. et al. The Impact of Policy Measures on Human Mobility, COVID-19 Cases, and Mortality in the US: A Spatiotemporal Perspective. *Int. J. Environ. Res. Public Health* **18**, 23 (2021).
- Hsiang, S. et al. The effect of large-scale anti-contagion policies on the COVID-19 pandemic. *Nature* **584**, 262–267 (2020).
- Vokó, Z. & Pitter, J. G. The effect of social distance measures on COVID-19 epidemics in Europe: an interrupted time series analysis. *GeroScience* **42**, 1075–1082 (2020).
- Japanese Cabinet. Secretariat (office for COVID-19 and other emerging infectious disease control). *Change Restrictions Lift of the State of Emergency*. <https://corona.go.jp/en/emergency/> (2021).
- Prime minister of Japan and His cabinet. [COVID-19] *Press Conference by the Prime Minister regarding the Novel Coronavirus*. [https://japan.kantei.go.jp/99\\_suga/statement/202108\\_00009.html](https://japan.kantei.go.jp/99_suga/statement/202108_00009.html) (2021).
- Kato, H., Takizawa, A. & Matsushita, D. Impact of COVID-19 pandemic on home range in a suburban city in the Osaka metropolitan area. *Sustain* **13**, 11 (2021).
- Kato, H. Development of a spatio-temporal analysis method to support the prevention of COVID-19 infection: Space-time kernel density estimation using GPS location history data in *Urban Informatics and Future Cities* (eds. Geertman, S., Pettit, C., Goodspeed, R. & Staffans, A) 51–67 (Springer. Nature 2021).
- Kato, H. & Matsushita, D. Changes in walkable streets during the COVID-19 pandemic in a suburban city in the Osaka metropolitan area. *Sustain* **13**, 20 (2021).
- Yabe, T. et al. Non-compulsory measures sufficiently reduced human mobility in Tokyo during the COVID-19 epidemic. *Sci. Rep.* **10**, 18053 (2020).
- Oh, J. et al. Mobility restrictions were associated with reductions in COVID-19 incidence early in the pandemic: evidence from a real-time evaluation in 34 countries. *Sci. Rep.* **11**, 13717 (2021).
- Wang, S. B. et al. Observing the silent world under COVID-19 with a comprehensive impact analysis based on human mobility. *Sci. Rep.* **11**, 14691 (2021).
- Nouvellet, P. et al. Reduction in mobility and COVID-19 transmission. *Nat. Commun.* **12**, 1090 (2021).
- Pluchino, A. et al. A novel methodology for epidemic risk assessment of COVID-19 outbreak. *Sci. Rep.* **11**, 5304 (2021).
- Carteni, A., Di Francesco, L. & Martino, M. How mobility habits influenced the spread of the COVID-19 pandemic: Results from the Italian case study. *Sci. Total Environ.* **741**, 140489 (2020).
- Haas, E. J. et al. Impact and effectiveness of mRNA BNT162b2 vaccine against SARS-CoV-2 infections and COVID-19 cases, hospitalisations, and deaths following a nationwide vaccination campaign in Israel: an observational study using national surveillance data. *Lancet* **397**, 1819–1829 (2021).
- Google. Google COVID-19 Community Mobility Reports. (2020).
- ArcGIS. ArcGIS REST Services Directory. [https://services.arcgis.com/ArcGIS/rest/services/World\\_Imagery/MapServer](https://services.arcgis.com/ArcGIS/rest/services/World_Imagery/MapServer) (2021).
- Stier, A. J., Berman, M. G. & Bettencourt, L. M. A. Early pandemic COVID-19 case growth rates increase with city size. *npj Urban Sustain* **1**, 31 (2021).
- Chang, S. et al. Mobility network models of COVID-19 explain inequities and inform reopening. *Nature* **589**, 82–87 (2021).
- Nagata, S. et al. Mobility Change and COVID-19 in Japan: Mobile Data Analysis of Locations of Infection. *J. Epidemiol.* **31**, 387–391 (2021).
- Osaka Prefecture. *The 67th Meeting of the Osaka Prefecture Task Force on COVID-19. (Reference) Changes in the number of people staying at stations [in Japanese]*. [https://www.pref.osaka.lg.jp/attach/38215/00417009/1-7\\_taizaizinkou0125.pdf](https://www.pref.osaka.lg.jp/attach/38215/00417009/1-7_taizaizinkou0125.pdf) (Accessed February 14 2022).
- Delen, D., Eryarsoy, E. & Davazdahemami, B. No place like home: Cross-national data analysis of the efficacy of social distancing during the COVID-19 pandemic. *JMIR Public Heal. Surveill* **6**, e19862 (2020).
- Steiger, E., Mussgnug, T. & Kroll, L. E. Causal graph analysis of COVID-19 observational data in German districts reveals effects of determining factors on reported case numbers. *PLoS One* **16**, e0237277 (2021).
- Tamagusko, T. & Ferreira, A. Data-driven approach to understand the mobility patterns of the portuguese population during the covid-19 pandemic. *Sustain* **12**, 9775 (2020).
- Woskie, L. R. et al. Early social distancing policies in Europe, changes in mobility & COVID-19 case trajectories: Insights from Spring 2020. *PLoS One* **16**, e0253071 (2021).
- Hakim, A. J. et al. Mitigation policies, community mobility, and COVID-19 case counts in Australia, Japan, Hong Kong, and Singapore. *Public Health* **194**, 238–244 (2021).
- Geng, D. H., Innes, J., Wu, W. L. & Wang, G. Y. Impacts of COVID-19 pandemic on urban park visitation: a global analysis. *J. For. Res.* **32**, 553–567 (2021).
- Japanese Law Translation. *Outline of the Act Partially Amending the Act on Special Measures against Novel Influenza, etc., and Other Relevant Acts*. [http://www.japaneselawtranslation.go.jp/common/data/outline/210621192151\\_905R207.pdf](http://www.japaneselawtranslation.go.jp/common/data/outline/210621192151_905R207.pdf) (Accessed July 1, 2021) (2021).
- Osaka Prefecture. *Requests based on the Emergency Measures: Request for Cooperation to public transportation (subway, bus, etc.)*. <https://www.pref.osaka.lg.jp/attach/40812/00404567/kinkyujitaisochi0802-0831.pdf> (Accessed April 6, 2022) (2021).
- Liaison Committee of Railroad Companies. *Guidelines for the control of novel coronavirus infections in railroad operations [in Japanese]*. <https://www.mlit.go.jp/tetudo/content/001448184.pdf> (Accessed April 6, 2022) (2021).
- West Japan Railway Company. *News Release: NEW WAY of RAILWAY ~Toward safety with a new normal life style of railway, [in Japanese]*. [https://www.westjr.co.jp/press/article/items/210218\\_00\\_newway.pdf](https://www.westjr.co.jp/press/article/items/210218_00_newway.pdf) (Accessed April 6, 2022) (2021).
- Gomez-Cravioto, D. A., Diaz-Ramos, R. E., Cantu-Ortiz, F. J. & Ceballos, H. G. Data Analysis and Forecasting of the COVID-19 Spread: A Comparison of Recurrent Neural Networks and Time Series Models. *Cognit. Comput.* (2021).
- Wang, H. Y. & Yamamoto, N. Using a partial differential equation with Google Mobility data to predict COVID-19 in Arizona. *Math. Biosci. Eng.* **17**, 4891–4904 (2020).
- García-Cremades, S. et al. Improving prediction of COVID-19 evolution by fusing epidemiological and mobility data. *Sci. Rep.* **11**, 15173 (2021).
- Badia, A. et al. A take-home message from COVID-19 on urban air pollution reduction through mobility limitations and teleworking. *npj Urban Sustain* **1**, 35 (2021).
- Axsen, J., Plötz, P. & Wolinetz, M. Crafting strong, integrated policy mixes for deep CO<sub>2</sub> mitigation in road transport. *Nat. Clim. Chang.* **10**, 809–818 (2020).
- Kato, H., Takizawa, A. & Matsushita, D. Impact of COVID-19 Pandemic on Home Range in a Suburban City in the Osaka Metropolitan Area. *Sustain* **13**, 8974 (2021).
- Cerin, E., Saelens, B. E., Sallis, J. F. & Frank, L. D. Neighborhood Environment Walkability Scale. *Med. Sci. Sport. Exerc.* **38**, 1682–1691 (2006).

42. Kato, H. Effect of Walkability on Urban Sustainability in the Osaka Metropolitan Fringe Area. *Sustain* **12**, 9248 (2020).
43. Kato, H. & Takizawa, A. Which Residential Clusters of Walkability Affect Future Population from the Perspective of Real Estate Prices in the Osaka Metropolitan Area? *Sustain* **13**, 13413 (2021).
44. World Economic Forum. *Paris Is Planning to Become a '15-minute City'*. Available online, <https://www.weforum.org/videos/paris-is-planning-to-become-a-15-minute-city-897c12513b> (2020).
45. Google. *Google COVID-19 Community. Mobility Reports Understand the data.* [https://support.google.com/covid19-mobility/answer/9825414?hl=en&ref\\_topic=9822927](https://support.google.com/covid19-mobility/answer/9825414?hl=en&ref_topic=9822927) (2020).
46. LBMA Japan. *Guidelines for the use of device location data [in Japanese]*. <https://www.lbmajapan.com/guideline> (2020).
47. MHLW (Ministry of Health, Labour and Welfare). *Visualizing the data: information on COVID-19 infections*, <https://covid19.mhlw.go.jp/extensions/public/en/index.html> (2021).
48. JMP Pro. *Predictive and Specialized Modeling: Bootstrap Forest: Overview of the Bootstrap Forest Platform*, <https://www.jmp.com/support/help/en/16.2/#page/jmp/overview-of-the-bootstrap-forest-platform.shtml#> (2021).
49. Hastie, T. J., Tibshirani, R. J. & Friedman, J. H. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*. 2nd ed. (Springer-Verlag, New York, 2009).
50. Li, Q. et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. *N. Engl. J. Med.* **382**, 1199–1207 (2020).
51. Ilin, C. et al. Public mobility data enables COVID-19 forecasting and management at local and global scales. *Sci. Rep.* **11**, 13531 (2021).
52. Statcounter GlobalStats. *Mobile Search Engine Market Share Japan (Jan–Dec 2021)*, <https://gs.statcounter.com/search-engine-market-share/mobile/japan/2021> (2021).

## ACKNOWLEDGEMENTS

This research was funded by JSPS KAKENHI (grant number 21K14318) and the Dai-ichi Life Foundation (Incentive Research).

## AUTHOR CONTRIBUTIONS

The H.K. was involved conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, validation, visualization, and writing (original draft preparation). The A.T. was involved validation and writing (review and editing). All authors have read and agreed to the published version of the manuscript.

## COMPETING INTERESTS

The authors declare no competing interests.

## INFORMED CONSENT

Informed consent was obtained from all subjects based on the privacy policy. Additionally, the subjects can stop sending their human mobility data at any time by changing their mobile phones' settings.

## INSTITUTIONAL REVIEW BOARD STATEMENT

The Research Ethics Committee of the Graduate School of Life Science, Osaka City University approved this research protocol (21-58).

## ADDITIONAL INFORMATION

**Correspondence** and requests for materials should be addressed to Haruka Kato.

**Reprints and permission information** is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2022