

Reproducibility of COVID-19 pre-prints in 2020*

Markers of open code or data not found in 81 per cent of pre-prints

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Abstract

We create a dataset of all the pre-prints published on arXiv, bioRxiv, and medRxiv between 28 January 2020 and 31 January 2021. We extract the text from these pre-prints and parse them looking for keyword markers signalling the availability of the data and code underpinning the pre-print. We are unable to find markers of either open data or open code for 81 per cent of the pre-prints on medRxiv in our sample, and X per cent of those on arXiv in our sample. Our paper demonstrates the need to have authors categorize the degree of openness of their pre-print as part of the pre-print submissions process, and more broadly, the need to better integrate open science training into a wide range of fields.

1 Introduction

Scientists use open repositories of papers to more quickly disseminate their research than is possible in traditional journals or conference proceedings. These repositories, such as arXiv, bioRxiv, medRxiv, and SocArXiv, are a critical component of scientific communication and many results build on the work published there. Thus it is important that the results that are published are credible. Pre-print repositories have drawn unprecedented attention in the context of the 2019 novel coronavirus (COVID-19) pandemic and the changes it has imposed on the scientific community (Else 2020). These repositories are not peer-reviewed, and, in general, anyone with appropriate academic credentials can submit a pre-print

Neither peer-review nor credentials are a panacea nor a guarantee of quality. And the gate-keeping and slow publication times of traditional journals mean pre-print repositories have an important role to play. But given the importance of these repositories, it is important that scientists impose on themselves various standards for their results. Following Weissgerber et al. (2021) we examine papers about COVID-19 published to arXiv, bioRxiv, medRxiv, and SocArXiv from January 2020, through to May 1, 2021. We search for markers of open science as indicators of reproducibility, specifically open data and open code.

We find that approximately 75 per cent of papers sampled from arXiv, 68 percent of papers sampled from bioRxiv, 80 per cent of papers sampled from medRxiv, and 84 per cent of papers sampled from socArXiv contain neither open data nor open code markers. Examining trends over time, we find that the proportion of pre-prints containing open data or code markers has fluctuated but shown no obvious increasing or decreasing trend throughout the pandemic. We also find that the presence of open data or open code markers has little influence on a pre-print's future publication, while the subset of sampled pre-prints that has been published contains an overall lower proportion of papers with these markers. Finally, we briefly examine the presence of open data and code markers in specific types of pre-prints, namely modelling, simulation, and machine learning research.

*Collins thanks CANSSI Ontario for financial support. Code and data are available at: <https://github.com/anniecollins/reproducibility>.

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The remainder of this paper is structured as follows: in Section 2 we discuss the process of constructing our dataset through retrieving pre-prints from the arXiv, bioRxiv, medRxiv, and socArXiv repositories and mining them for open data and open code markers. In Sections ?? and 3 we explore some key findings in this raw data and explore some logistic regression models that support these findings. Finally, in Section 4 we discuss the implications of these findings in the broader context of reproducibility and science during the COVID-19 pandemic, as well as next steps to expand on our findings and questions raised in the research process.

2 Data and Methodology

2.1 Overview

Our primary dataset consists of information extracted from the arXiv, bioRxiv, medRxiv, and SocArXiv pre-print repositories. We downloaded pre-prints that contained various keywords related to COVID-19 (a full list of these is available in Appendix A), and then identified the availability of open code and open data using the Open Data Detection in Publications (ODDPub) text mining algorithm (Riedel, Kip, and Bobrov 2020) in the `oddpub` package (Riedel 2019).

We constructed this dataset by first creating a local copy of each repository using the repository API. We identified papers related to the COVID-19 pandemic through several keyword searches to create our dataset of papers and associated metadata. This metadata varies by repository, but generally includes the following information: title, abstract, author(s), date posted, research field, DOI, version number, corresponding author, corresponding author’s institutional affiliation, and published DOI (if the pre-prints has since been published in a peer-reviewed journal). In the case of SocArXiv there are additionally fields that are self-reported by the submitting author about the availability of code and data.

We then checked these pre-prints for open data and code markers using the ODDPub algorithm. This required downloading each pre-print as a PDF and then converting the PDFs to text files. Some papers from SocArxiv were only available in .docx format and were downloaded as such and then converted to text format. We then conducted the open data and open code detection procedure. This involved searching for keywords and other markers of open data and open code such as references to GitHub repositories and similar. A full listing of these markers is included in Appendix B. This was conducted using the `open_data_search()` function from the `oddpub` package.

The result of this process is a dataset indicating the presence of open data or open code markers in each pre-print (with a logical vector for each marker, followed by the relevant open data or open code statements when applicable). Our final dataset was formed by joining this dataframe with the original sample dataframe, typically using the DOI or the unique filename, to form a dataset including all original, qualitative metadata for each pre-print alongside its open data and open code status and markers.

2.2 Summary statistics

The number of pre-prints posted per month increased dramatically in the first half of 2020 across all repositories, reaching its maximum sometime between April and June (depending on repository) and subsequently decreasing. The number of pre-prints posted monthly since August 2020 has remained reasonably steady, with the exception of medRxiv which experienced a spike up to nearly 1000 pre-prints posted in March 2021 (Figure 1). For context, COVID-19 was declared a pandemic by the World Health Organization (WHO) on March 11, 2020, at which point the number of cases globally had just surpassed 118,000 (primarily in east Asia) and the virus had been reported in 114 countries (World Health Organization 2020).

Broadly, we are unable to find markers of either open data or open code for around 68 percent of the sampled bioRxiv pre-prints, 80 per cent of the sampled medRxiv pre-prints, 76 per cent of the sampled arXiv pre-prints, and 84 per cent of all COVID-19 related socArXiv pre-prints. The distribution of the remaining

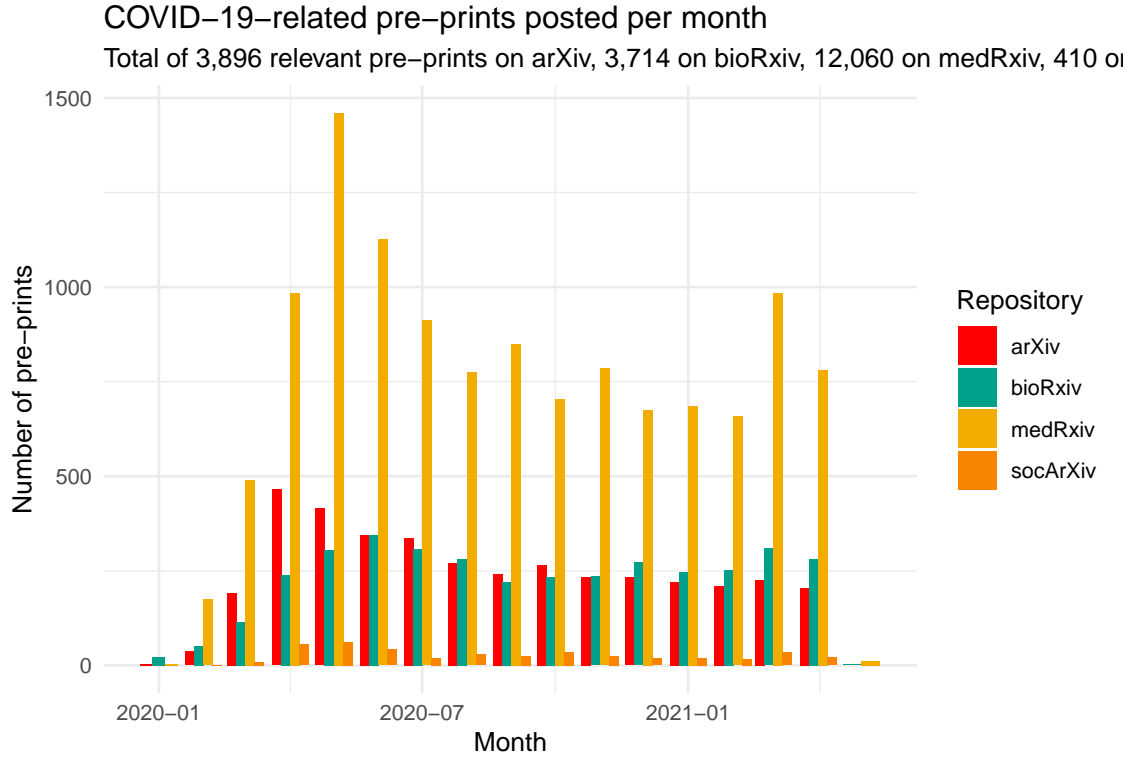


Figure 1: Number of pre-prints related to COVID-19

portion of pre-prints varies by repository (Table 1). Notably, 28 per cent of sampled pre-prints from bioRxiv contained open data markers, the highest of proportion of any repository. Similarly, 20 per cent of sampled arXiv pre-prints contained markers of open code, the highest of any of the repositories in question.

The distribution of total sampled pre-prints and sampled pre-prints with open data or code markers roughly follows that of COVID-19-related pre-prints posted in general (Figure 2). The proportion of pre-prints with open data or code has fluctuated over time but shows no consistent overall increase or decrease throughout the course of the pandemic, nor in conjunction with increases or decreases in the total number of pre-prints posted to any given repository (Figure 3). In our datasets, very few (if any) pre-prints were sampled for the month of January 2020. None of these pre-prints contained open data or open code markers, thus the 0 per cent rate of open data and code for this month across all repositories should be considered an outlier.

2.3 Publication status

Our metadata also contains an indication of whether or not a pre-print has been published in the form of a DOI linking to the corresponding published paper. The proportion of pre-prints that have been published varies by repository (Table 2). Notably, of all COVID-19-related pre-prints created during 2020 and 2021, approximately one third of those posted to bioRxiv and nearly 30 percent of those posted to medRxiv were eventually published in peer reviewed journals. This is high in comparison to the proportions from arXiv and socArXiv, which may be indication of a bias towards pre-print servers showcasing research from the biomedical and life sciences.

In Table 3 we disaggregate sampled pre-prints by whether there is an indication that it was published. We find that the proportion of pre-prints with open data or code markers among those that have been published is approximately the same as pre-prints that have not been published, differing by one percent only within the bioRxiv and arXiv samples, and three percent in the socArxiv sample (Table 3).

Table 1: Counts and proportions of open data and code markers in medRxiv sample

Open data markers	Open code markers	Count	Proportion of total
arXiv			
No	No	759	0.76
No	Yes	104	0.10
Yes	No	33	0.03
Yes	Yes	104	0.10
bioRxiv			
No	No	679	0.68
No	Yes	40	0.04
Yes	No	203	0.20
Yes	Yes	78	0.08
medRxiv			
No	No	1207	0.80
No	Yes	78	0.05
Yes	No	114	0.08
Yes	Yes	101	0.07
socArXiv			
No	No	342	0.83
No	Yes	14	0.03
Yes	No	37	0.09
Yes	Yes	17	0.04

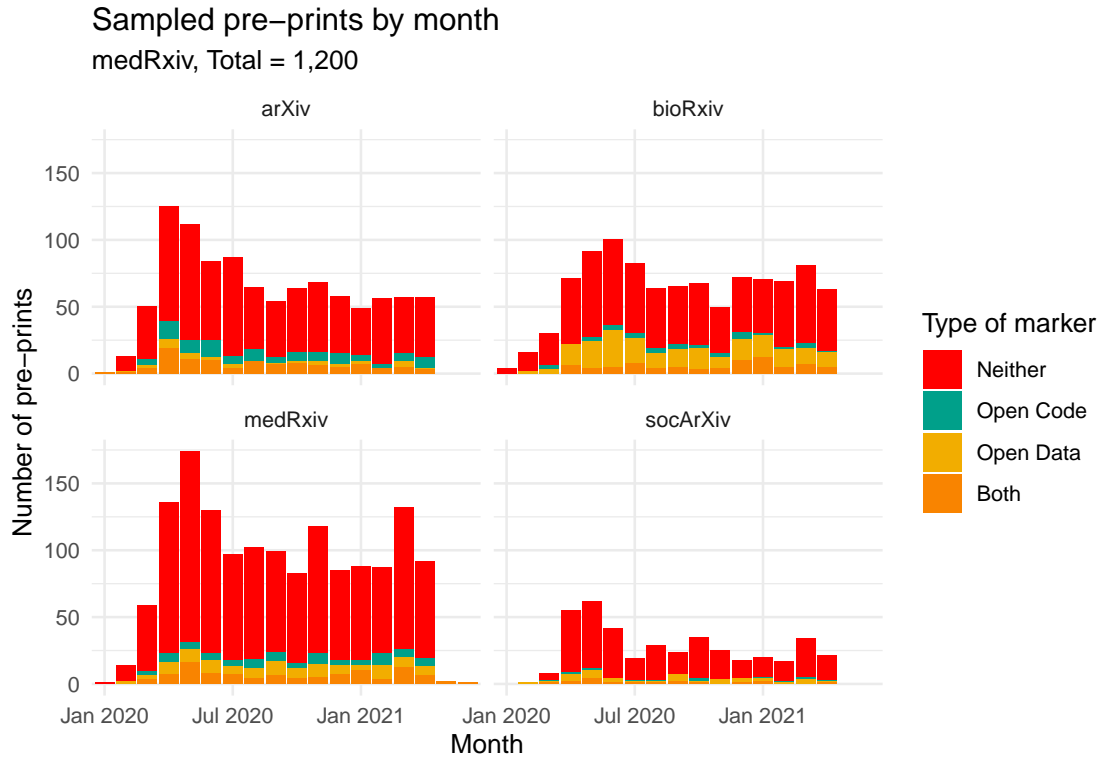


Figure 2: Number of pre-prints related to COVID-19 sampled from medRxiv, distinguished by presence of open data or code markers

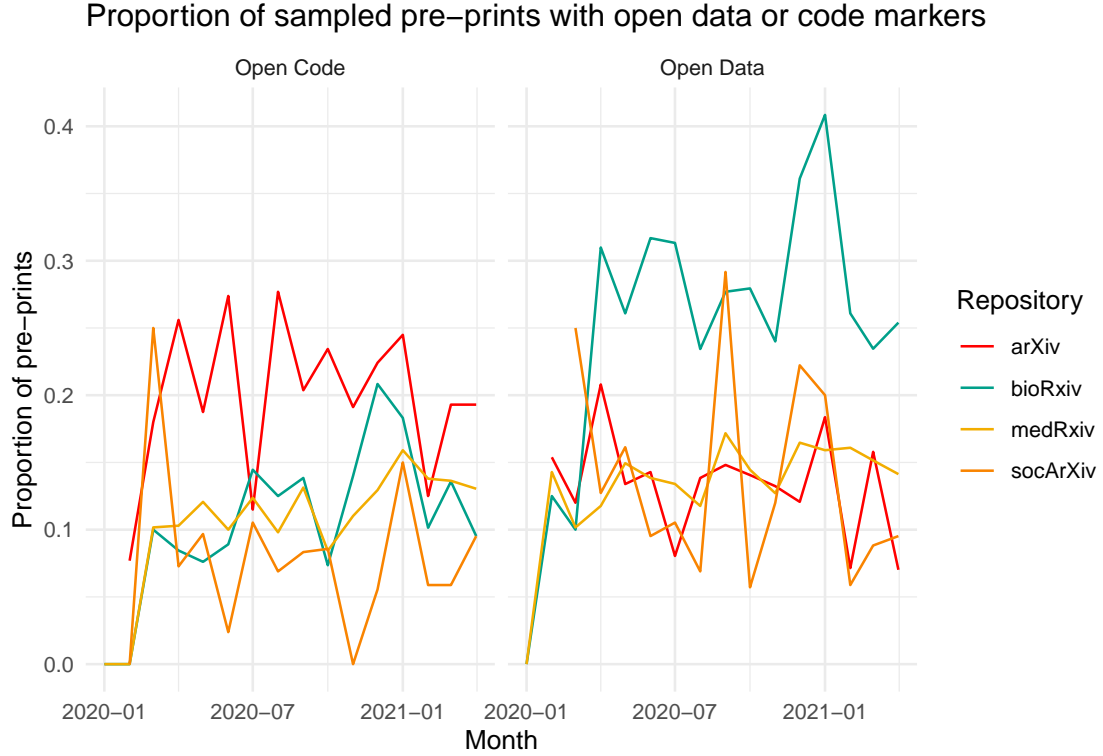


Figure 3: Proportion of pre-prints in sample with open data or open code markers by month

Table 2: Counts and proportion of published COVID-19 pre-prints in each repository

Repository	Published pre-prints	Proportion published
arXiv	663	0.17
bioRxiv	1230	0.33
medRxiv	3460	0.29
socArXiv	58	0.14

Table 3: Counts and proportions of open data markers by whether the pre-print was published

Published	Both	Neither	Open code	Open data	Proportion with neither
bioRxiv					
No	80	639	92	28	0.76
Yes	24	120	12	5	0.75
medRxiv					
No	56	451	23	135	0.68
Yes	22	228	17	68	0.68
arXiv					
No	70	871	59	81	0.81
Yes	31	336	19	33	0.80
socArXiv					
No	14	295	14	29	0.84
Yes	3	47	0	8	0.81

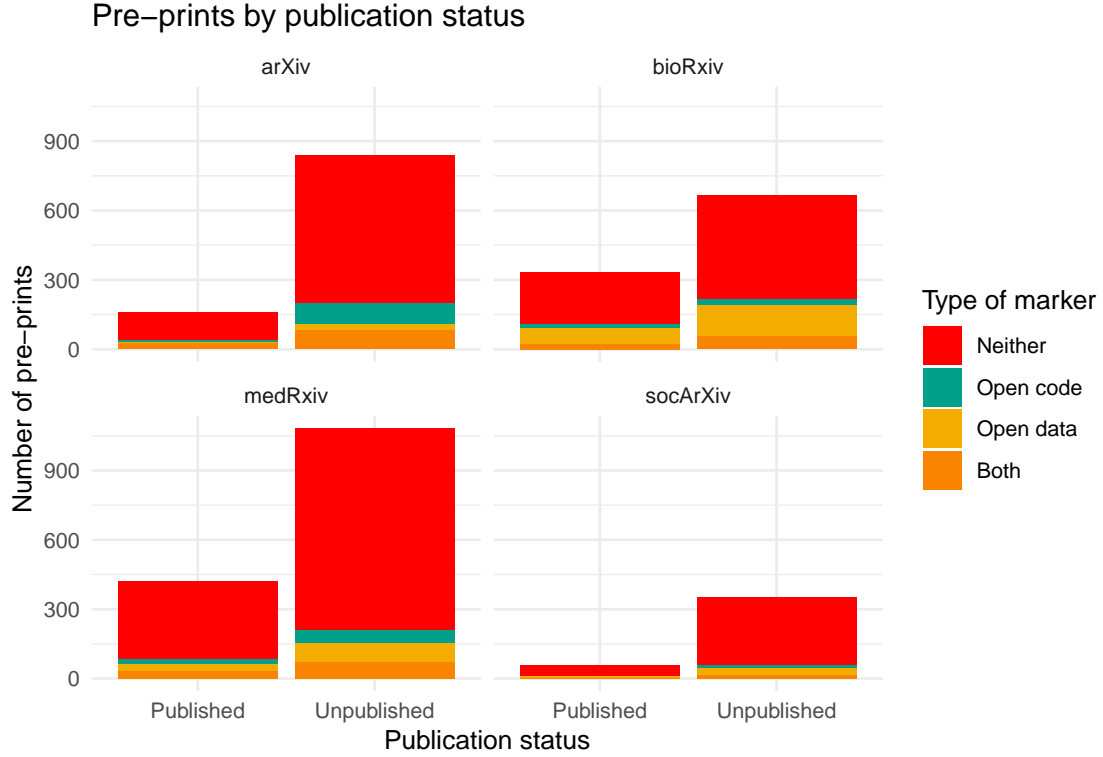


Figure 4: Number of pre-prints in sample with open data or open code markers by publication status

It is important to note that our dataset imperfectly characterizes publication. In particular, it likely does not have the publication details for some papers that were published. And even if it were a perfect record, there is a publication lag (estimated at an average of around 60 days) that may skew the results for the papers in the latter portion of our sample (Kwon 2020).

2.4 Pre-pandemic Pre-prints

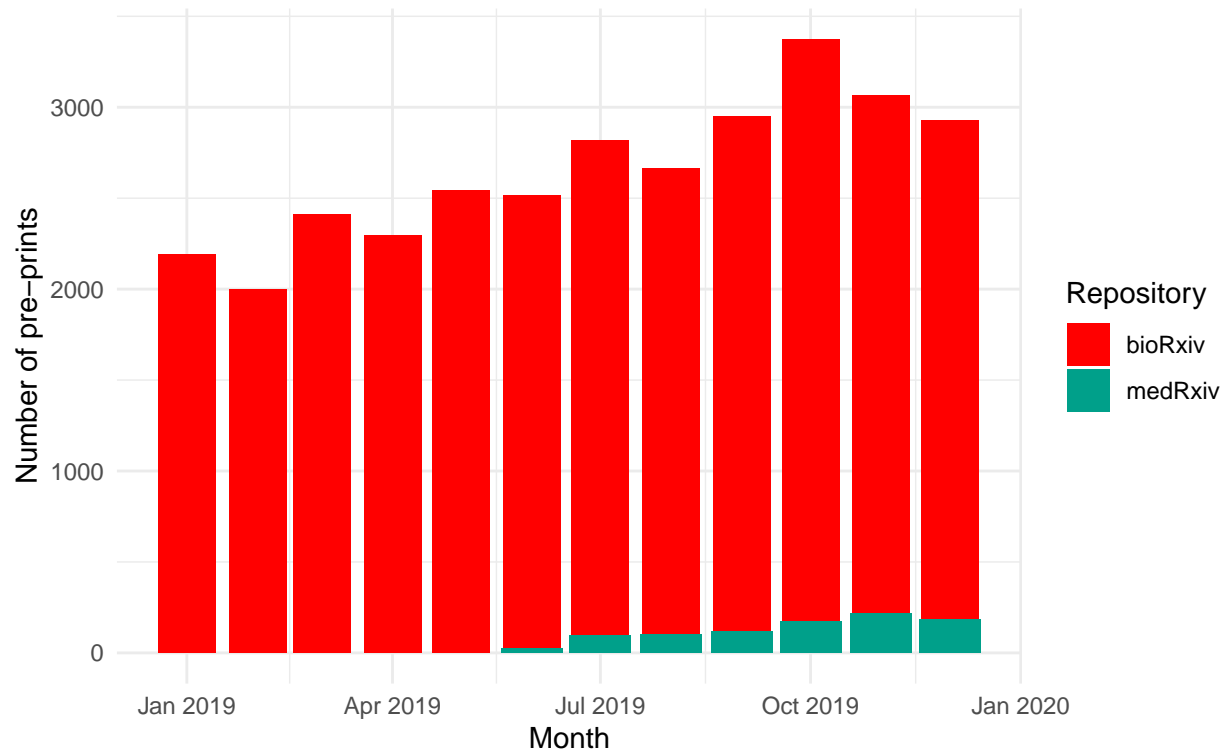
In order to examine the influence of the COVID-19 pandemic on open science practices in during the pandemic, we analyzed pre-prints posted between January and December 2019 from each of the four repositories using the same process as was done for the COVID-19-related pre-prints. Since medRxiv was founded in June 2019, all pre-prints unrelated to COVID-19 posted from the latter half of 2019 were analyzed (a total of 913). For bioRxiv, a random sample of 1,200 was taken from all non-COVID-19-related pre-prints posted in the relevant date range.

Table 4: Counts and proportions of open data and code markers in 2019 medRxiv and bioRxiv samples

Open data markers	Open code markers	Count	Proportion of total
bioRxiv			
No	No	752	0.63
No	Yes	98	0.08
Yes	No	234	0.20
Yes	Yes	116	0.10
medRxiv			
No	No	686	0.75
No	Yes	55	0.06
Yes	No	115	0.13
Yes	Yes	57	0.06

Pre-prints posted per month, 2019

Total of 31,752 pre-prints on bioRxiv, 913 on medRxiv



Between June and December 2019, the number of pre-prints posted to medRxiv monthly saw an overall increase which may be expected as the repository gained recognition and popularity in the medical research community. The number of papers posted monthly to bioRxiv also saw an overall increase throughout 2019. It is important to note here that due to its relative immaturity at the beginning of the COVID-19 pandemic, a significant portion of medRxiv's overall usage has been dedicated to COVID-19-related research. In total, 19,638 pre-prints have been posted to medRxiv since June 2019, 12,060 (approximately 61 per cent) of which relate to COVID-19.

Of the analyzed pre-prints from 2019, 63 percent of those posted to bioRxiv and 75 per cent of those posted to medRxiv showed no indication of open data or open code. Both of these proportions are approximately

Table 5: Counts and proportion of published COVID-19 pre-prints in each repository, 2019

Repository	Published pre-prints	Proportion published
bioRxiv	20445	0.64
medRxiv	555	0.61

Table 6: Counts and proportions of open data markers by whether the pre-print was published, 2019

Published	Both	Neither	Open code	Open data	Proportion with neither
bioRxiv					
No	38	264	34	87	0.62
Yes	78	488	64	147	0.63
medRxiv					
No	19	277	19	43	0.77
Yes	38	409	36	72	0.74

five per cent lower than the corresponding proportion of COVID-19-related pre-prints, meaning that the analyzed pre-prints from 2019 contained an overall higher prevalence of open data or code markers than pre-prints concerning COVID-19.

Examining publication rates for pre-pandemic papers, we observe that 64 per cent of pre-prints posted to bioRxiv and 61 per cent of pre-prints posted to medRxiv during 2019 were eventually peer reviewed and published (Table 5). These rates are approximately double those of the COVID-19-related pre-prints posted to servers during 2020 and 2021 (33 per cent and 31 per cent from bioRxiv and medRxiv respectively). When disaggregated by open data and code status, we find that published and unpublished pre-prints contain open data and code markers with similar prevalence (Table 6). This mimics the behaviour of published and unpublished COVID-19-related pre-prints.

3 Results

3.1 Summary of all papers, then differences by repository + reasons

Overall, approximately 76 percent of pre-prints analyzed across all four repositories (arXiv, bioRxiv, medRxiv, and socArXiv) contained no markers of open data or code. Of the repositories in question, bioRxiv had the lowest proportion of pre-prints with neither open data nor code markers at 68 per cent. BioRxiv also had the highest proportion of pre-prints with open data markers at 28 per cent.

3.2 Time and posting rate influence on open data/code

We find that time has little influence over the likelihood of a pre-print to have open data or code markers. In the context of the COVID-19 pandemic, this means that the prevalence of open data and code markers has not consistently increased nor decreased over the course of the pandemic, and also appears to be unimpacted by the monthly rate of pre-prints posted to medRxiv (which increased dramatically between January and May 2020 and has fluctuated since). On one hand, it is encouraging to note that open data and code does not appear to have suffered in times of high publication rates, namely April through July 2020. On the other hand, one might hope that more data has become openly available throughout the course of the pandemic, or that the rate of availability of open data or code has improved as the scientific community has recognized the importance of global collaboration in combating the pandemic, neither of which appear to be the case.

3.3 Publication - why is there little to no difference between published vs non published pre-prints? Publication bias? Insert chi-test results

The presence of open data or code markers does not appear to have significant influence over whether or not a pre-print posted to medRxiv has subsequently been published in a peer reviewed journal, however the proportion of published pre-prints with open data or code markers appears to be slightly lower than those that have not been published (15 per cent versus 20 per cent). This is not necessarily a significant result given the size of our sample and the potential inaccuracies in the medRxiv API's attempts to identify publication, however it does provide a potential area of further study.

3.4 Type of paper - leave for now?

The proportion of pre-prints with open data or code markers is significantly higher among pre-prints with keywords indicating machine learning-based research. This is a somewhat anticipated result, as machine learning tends to rely more heavily on computational and code-focused methodology, however the subset of sampled pre-prints with keywords relating to simulation is very small. On the other hand, the prevalence of pre-prints with open data or code markers only saw a slight increase in the subset of pre-prints with either modelling or simulation keywords. Since the pandemic has seen a rise in scientific and public focus on epidemiological modelling, it is likely that not all papers showing keywords for modelling actually propose their own models which would account for the minimal increase of open data and code markers in this context.

3.5 Pre-pandemic vs during pandemic - chi tests, publication

4 Discussion

- Add reference somewhere to that paper about the numbers: <https://link.springer.com/article/10.1007/s11192-020-03675-3>
- Add reference somewhere to that paper about keyword search and then analysis. Was it a Gary King one?

4.1 On the role of transparency and reproducibility

Transparency and reproducibility are hallmarks of quality scientific research. Open data and open code contribute greatly to both in allowing the scientific community to more easily verify the authenticity of purported scientific discovery and its supporting evidence, which is especially important in cases where scientific research may quickly and directly impact clinical practice or policy such as during the COVID-19 pandemic. Among a myriad of other impacts on biomedical research, COVID-19 has dramatically increased the popularity of pre-prints from both a production and consumption stand-point. The number of COVID-19 pre-prints posted to medRxiv increased dramatically in the early stages of the pandemic while non-COVID-19 pre-print rates remained consistent. The same trends were apparent in abstracts accessed by medRxiv users, where COVID-19 pre-print abstracts were viewed over 15 times the rate of non-COVID-19 pre-print abstracts (Fraser et al. 2021). For these reasons, it is more important now than ever to examine open science standards and reproducibility within pre-print repositories.

Open data is generally accepted to be beneficial to the scientific process, and to a paper's reproducibility potential, hence it is concerning that over 80 per cent of pre-prints in our sample contained no open data markers. This concern is slightly mitigated by recognition of challenges in working with biomedical data compared with data in other fields, notably privacy and ethics concerns when working with personal data (Floca 2014). The COVID-19 pandemic has seen an uptake in open science practices globally, as evidenced by the creation of open data repositories such as the dashboard maintained by the Center for Systems Science and

Engineering at Johns Hopkins University (Dong, Du, and Gardner 2020) or the large number of publishers who have removed paywalls from published COVID-19 research (Gill 2020). (MENTION/REFERENCE <https://wellcome.org/coronavirus-covid-19/open-data> ?) An important next step may compare open data and code availability in COVID-19 pre-prints with those from other topics posted to medRxiv to examine whether the pandemic has increased transparency from the previous norm.

Open code as an open science marker is much more context and field-dependent, as not all biomedical research papers will rely on computational methods for their analyses. However, in pre-prints where code comprises a large portion of the methodology or results, posting it openly to repositories like GitHub contributes greatly to a pre-print’s potential reproducibility. This gains importance as computational methods become increasingly popular in the rush to form predictions about emerging situations with limited data or laboratory research, which was the case for modelling studies in the early days of the COVID-19 pandemic (CITE). We also see growing concern over the quality and consequences of this sort of research, with bioRxiv no longer allowing purely computational work (Kwon 2020).

4.2 The role of of pre-print repositories

Many concerns have arisen from the unprecedented rate at which COVID-19 research has been posted and consumed via pre-print repositories, particularly in the early stages of the pandemic (Raynaud et al. 2020). Any rushed scientific research has potential to skip (or at least place less precedence on) quality open science practices, thus it may be reasonable to expect a decrease of open data or code markers in the pre-prints posted during times of increased overall posting to medRxiv. In our analysis, we found little relationship between time posted and likelihood of having open data or code markers with the proportion of papers containing these markers fluctuating greatly from month to month and no apparent decrease during periods of increased publication. This suggests that open science practices are more highly influenced by other factors, perhaps training, publication bias, or the nature of the paper itself. On the other hand, we do not see an overall long-term increase in either open data or open code markers throughout our year of analysis which we may expect in the context of the aforementioned open science movements the pandemic has fostered. Although not pre-print specific, Else (2020) found that overall research output has fluctuated between different fields and topics (namely modelling disease spread, public health, diagnostics and testing, mental health, and hospital mortality) throughout different stages of the pandemic which may account for some of the fluctuation and overall lack of linear trend over the course of the year.

To emphasize the ongoing need for open data and code in modelling a pandemic, we consider two high profile epidemiological models that emerged in early 2020. Modelling was conducted by Imperial College London (ICL) (Ferguson et al. 2020) and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington (Murray 2020), and both papers were initially posted to pre-print repositories. The ICL model went on to become the most cited pre-print as of December 2020 (Else 2020), and both had significant influence over policy and public health decisions worldwide (Adam 2020). An independent review of these two models by Jin et al. (2020) found that while code and data were openly available for both, only the ICL model was reproducible due to limited transparency on the underlying methodology of the IHME model. The open-source nature of these papers was fundamental to reproduction attempts and is a great example of the need for open data and code in reproducing COVID-19 research, particularly in evaluating pre-prints as they begin to influence public decision-making.

In the context of the above factors, it was disheartening in our analysis to find that the proportion of modelling- and simulation-related pre-prints with open data or code increased only marginally from that of the entire sample. One might hope that modelling papers should universally be subject to the same analysis as conducted by Jin et al. (2020) as for the examples above, which is made possible by the availability of relevant code and data. Although our analysis was not particularly robust, this shows a need for future investigation and potential overall improvement in open science standards for these types of pre-prints (of course subject to the data and code considerations already discussed). This need is again emphasized by the new-found speed at which pre-print articles may gain public, media, and political attention in the context of the pandemic.

4.3 The importance of open data and open code

Beyond pre-prints, COVID-19 has had great influence over publication and peer review processes as well, with expedited review timelines for COVID-19 papers at the expense of longer waits for other scientific research (Else 2020). Needless to say, it is important that open data and code standards be maintained in published work as well. Our findings in this regard were two-fold: that open data or code markers do not appear to directly influence a pre-print’s eventual publication, and that a lower proportion of published papers contain either open data or code markers than the general sample. Both of these raise concerns over publication bias, the potential that journals have favored novel yet less transparent or reproducible papers over those with null results but a high standard of open science practices. Concerns have already been raised through systemic reviews of COVID-19 publications (Raynaud et al. 2020), and oversights in data accessibility have led to high profile retractions of publications in the past, for example two papers from The Lancet and the New England Journal of Medicine that were withdrawn due to concerns over the private nature of their underlying dataset (Ledford and Noorden 2020).

In all fields of science, increasing access to data and code used for pre-printed or published research is a step in the direction of more transparent, reproducible, and reliable research. The ongoing COVID-19 pandemic has created a novel, constantly changing scientific culture that should be navigated with the utmost care so as to uphold standards of scientific practice for both the research community and the safety of the general public. Our analysis shows that there is much improvement to be made in the areas of open data and code availability within COVID-19 pre-print papers on medRxiv.

Demand for timely research / results in high frequency as epidemic is rapidly evolving. Preprints are more efficient at doing this because there is no time spent on peer review. However, they also allow lesser-known researchers to better disperse their research, because of the possibility that fast-tracked peer review may be biased towards established researchers. While there is a clear need for pre-prints, the point remains that they do not go through the peer review process. This question of quality and validity is particularly pertinent in the COVID-19 context because poorly validated results and false information may spread quickly, and have real effects. We are not saying that peer review implies that a paper is of a high-quality, we are instead saying that the provision of code and data alongside the preprint goes some way to allowing others to trust the findings of pre-prints even though they have not been peer-reviewed. One way this could be encouraged would be for pre-print repositories to have authors characterize the extent to which they have adopted open science practices as part of their submission. Although those papers that do not adopt these practices should not be rejected from pre-print repositories, greater clarity around this would be useful and might move the state-of-the-art forward.

4.4 Weaknesses and next steps

In this paper we consider only pre-prints from medRxiv, but this analysis can and should be extended to other pre-print repositories including bioRxiv and arXiv. The `medrxivr` package (McGuinness and Schmidt 2020) can be used with the bioRxiv API as well, and our code can be modified to conduct the same scraping and text mining procedure as was used for medRxiv data.

We also wish to expand our analysis to consider the geographic distribution of research and the potential influence of different practices and policies concerning open science as pre-prints vary by location. This is pertinent to our current paper as the epicenter of the virus spread (and thus of scientific output) has shifted throughout the pandemic which has implications for our time-based analysis.

An important weakness to note is the potential presence of false negatives in indicators of publication in our dataset. Abdill and Blekhman (2019) estimate that the false-negative rate may be as high as 37.5 per cent for data pulled from the bioRxiv API, meaning analysis of published papers may represent only a fraction of those that have actually been published. It is unclear to what extent this is the case for medRxiv or what bias may exist in the subset of pre-prints for which publication was detected, as it is likely that this process relies on title-based text matching (Abdill and Blekhman 2019). It is also likely that some of our more recent sampled pre-prints will be published in future which we could not account for at the time of our data collection.

We also recognize that this analysis relies heavily on text-based analysis which was not verified directly in most cases and may lead to higher levels of uncertainty. In future, we wish to take smaller sub-samples to validate factors like publication status or paper topic beyond simple keyword searches or API output.

A Keywords

Insert details on keyword search used to identify COVID-19 papers.

B Markers

Insert details on what markers the `oddpub::open_data_search()` uses. Include info here directly from package documentation (i.e. keywords/phrases used for text parsing)?

C Classification

Insert details on keyword search used for machine learning/modelling/simulation

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