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Commentary

A response to the comment to "A.J. Collings, K. Brown, Reconstruction and physical fit analysis of fragmented skeletal remains using 3D imaging and printing"

Dear Editor and Commentary Authors,

Thank you for your extensive commentary on our article. We are pleased you took such interest in it and took the time to construct a thorough response. As you say this is an area of particular relevance and importance currently as the development of 3D technology progresses. Being early-career researchers working in collaboration with our local police force and scientific services, we value all comments and are always open to further ideas and connections to progress applied forensic research. We would be more than happy to work with you going forward, it is clear we have a lot to learn from each other.

Your commentary does give us the opportunity to better explain the context of our current work. We appreciate that as your centre integrates this work daily into casework you are perhaps at a more advanced stage than us within the UK, specifically England and Wales. Currently, there are only a few examples (although numbers are increasing which is fantastic to see) of police-academic collaborations (for example the University of Portsmouth Forensic Innovation Centre [1] which is at the time of study completion where we were both based), which facilitate targeted, impactful research, driving the inclusion of new methods into the criminal justice process, including forensic investigations. However, integration of new technology into the criminal justice system in England and Wales is slow. Contrary to daily caseloads, only a small handful of our cases implement this kind of technology yet and very few make it to court. Complexities with funding, workload, capacity, capability, accreditation, and connections, all raised in the House of Lords Enquiry (in particular, notes 113, 173, and 187) [2], make it unusual for investigators to call upon new technology, especially of course those that they have a limited awareness of. This includes an understanding of arising imaging and printing modalities, which is not common knowledge across forensic researchers and practitioners alike.

With that in mind, it is perhaps not surprising you disagree with our current study design; we certainly appreciate where it seems so obvious to not require analysis for you, the landscape in which we are operating is quite different. Nonetheless, is it not the point of scientific progress to make incremental steps forward and test assumptions that appear obvious at first pass?

As you are absolutely correct in highlighting, there is a wide range of structured light scanning (SLS) devices available, which vary considerably in terms of their quality and price-point. There is such a wide range that, for us, it would be impractical to compare across the whole spectrum. Furthermore, given the speed of technological advancement and rate at which new models are being released, such comparisons rapidly become out-of-date. The most sensible approach for us, at this time, was to test an existing affordable benchtop SLS scanner and 3D printer already available to us within our institution, and therefore by extension, the police constabulary with which we are partnered.

By comparing the EinScan Pro available with the μCT machine available through our engineering department, we appreciate we were not comparing like-for-like. However, it was not our intention nor our aim to find out which of the different technologies was better suited for surface visualisation, this is a misrepresentation of our work. Our aim was to assess whether low-cost SLS is *good enough* for visualisation and whether enough resolution was maintained during fused filament deposition (FFD) printing to enable us to perform a physical fit and presentation in court to juries, for example (as indicated in paras. 2 and 7 of the Introduction). Exploring this possibility opens up a new avenue for investigators to realistically consider for casework. In time this could result in purchases of their own equipment and cost-effective in-house training with support from the University, but we certainly are not there just yet.

Thank you for providing some extra data demonstrating the GOM scanner. We would be really interested to know where that model sits on the price-point scale compared with the EinScan Pro. It is really interesting (and exciting!) to hear that it could be considered to compete with the results of μCT, perhaps the comparison between that SLS model and μCT would be of value? We would certainly be happy to collaborate with you further on a full and robust study to that effect, demonstrating the differences between the models and their performance in comparison with μCT (although we note the caveats we raise earlier about specific model comparisons).

A comment was raised around the order of scanning the fragments. Whilst we appreciate this may not be the optimal order, we were limited by time and access constraints to the μCT, which is likely reflective of casework in England and Wales. We do not tend to operate out of designated forensic imaging facilities, instead we often operate within teaching and research active universities. The spray we used is an extremely fine powder suspension designed to locate microfractures in structures. Given that after spraying and cleaning the fragments themselves fit together, as did the 3D printed replicas of the μCT models, indicates to us that the spray did not have a significant influence on the parameters of the study. Of course, it may have been ideal to have tested μCT both with and without spraying, but please be assured if we had any doubt that the spray had impacted our conclusions, we would not have published this work. We agree testing the grade and influence of various sprays could be a really valuable area for further research, given reflective forensic evidence types such as blades, and again we would be more than happy to collaborate with you on that.

We also agree with the comments around the scale bars, small but important errors, thank you for catching them. They were unfortunately missed by both authors, the reviewers, and editors, and we will publish a correction to these: **Fig. 1. Black scale bar in A is equal to 8 mm; Figs. 2 and 3, the white scale bar is equal to 17 mm.** For clarification, these measurements are for the burned bone fragments as shown

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in the figures. The approximate size of the unburned bone fragments given in the first paragraph of the Methods section is correct (2–3 cm in height) and stated as being cut to this size, before burning. We believe these errors have no significant impact on the value of the study and would like to reassure you that we are very mindful of the impact of heat on dry human bone as that was, in fact, the nature of the previously unrelated study from which these fragments originated.

In answer to your question 'did the authors really study only some fragments of one single bone?' As stated in our Methods, yes. We used 'two adjoining fragments from each of the three sections' of an archaeological human femur. We therefore had six fragments in total, which all technically originated from the same long bone, but had been sectioned before burning. Those sections were not all directly adjacent to one another in the shaft. As such, for the purposes of the study, it would not have mattered if the three pairs had originated from the same long bone or different long bones. Further, we came to our conclusion precisely *because* we knew that one of the fragments being tested was a legitimate fit. It was vital to our methodology that we knew they fitted together in the first place. If we had not known, then there would have been no way of verifying whether the 3D printed fragments failed to fit because of the loss in resolution through printing or because they simply did not originate from the same section of bone - an important part of validation. Furthermore, in order for us to assess the quality of the fit produced by the 3D printed fragments it was crucial that we knew what the authentic fit of the original bone fragments felt like in the first place, we are sure you can agree.

While our sample size was small, in our opinion there was a scientific, logical, and measured approach to whether physcial fit analysis (PFA) was viable or not. Since we did have multiple bone fragments, six as mentioned, we stand by our conclusions and believe there may have been possible misunderstanding in the interpretation of our methodology. We entirely agree, however, that the next step in progressing this work is to complete a validation study with a wider range of differentially (traumatic and non-traumatic) fractured bones employing blinded testing protocols. We should note, we are limited in our access to human skeletal material for destructive research and, again, would be very interested in working together with you on such a study.

We absolutely appreciate the limitations, but we cannot agree that our study is obsolete. Of course, we welcome constructive criticism and would be excited to see further research that tests and scrutinises our conclusions. That being said, we stand by our current data and their value. We tested whether fragments known to originate from the same bone would still fit together, to the standard where physical fit could be confirmed, after scanning them with a μCT and SLS and subsequently 3D printing them with an FFD printer. For μCT we verified it worked, for SLS we also verified it worked just not to the same standard, but good enough for visual demonstration. We therefore cautioned, that when using such techniques, it is important to consider the end goal and whether that is *visualisation/demonstration* of fit or *physical fit confirmation*. As you rightly point out, the next step is blind-testing validation of this work to reduce the effects of observer bias.

We further do not believe we generalise all SLS at all, the quote referred to uses the phrase 'while the SLS scanner certainly demonstrated potential'. We have chosen our language carefully here in order to avoid generalisation, please note the use of **'the** SLS scanner' as opposed to 'SLS scanning' or 'SLS scanners'. As such, to add 'used in this study' is superfluous as the sentence already specifies we are referring to **THE** SLS scanner (i.e. the one used in the study).

Again, you are absolutely correct to raise the issue of printing high resolution fragments with a lower resolution printer. Printing using a lower resolution than the models were scanned at results in a net loss of resolution, we are conscious of that effect. As previously explained, however, this comes down to the technology available. We were using a low-cost and accessible printing device to reflect the current reality of conducting such work in our institution. We would also like to note that by verifying physical fit is possible using a comparatively low-end model, then by virtue we are implying that these results can be achieved using a higher resolution printer as well.

We should clarify that this work was not related to, or conducted in response to, a real case scenario. This study was borne out of the author's knowledge of forensic anthropology, virtual anatomy, and discussion with our police partners on common issues they face. It was then conducted, as stated in the Methods, using 'fragmented bone samples' originating from 'a dry, archaeological human femur donated to the University of Portsmouth teaching collection' which had been sectioned and burned in a 'previous and unrelated study'. Our motivation for our research is to raise awareness and assess the feasibility of such techniques so that we can progress toward validation and increased effective implementation of these methods in UK casework.

Finally, we really appreciate the opportunity to discuss our work further. We hope that with some further context it can be appreciated that we are not yet in the position to apply high-end techniques at every stage of the process and that currently the reality for applied 3D imaging and printing forensic research in England and Wales is about what is realistically most accessible as opposed to the absolute best. As we stated initially, and throughout our response to your commentary on our paper, we welcome open dialogue and exchange of ideas and believe the most effective way to progress applied forensic research nationally and internationally is through collaboration. We look forward to working with you in the future.

Regards,

Dr Amber J Collings FRAI and Dr Katherine Brown MCSFS

References

[1] Forensic Innovation Centre|University of Portsmouth, 2013. https://www.port.ac.uk/research/research-centres-and-groups/forensic-innovation-centre (Accessed 20 March 2021).

[2] House of Lords – Science and Technology Select Committee, Forensic science and the criminal justice system: a blueprint for change, 2019. https://publications.parliament.uk/pa/ld201719/ldselect/ldsctech/333/33302.htm (Accessed 22 March 2021).