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Participatory development of a 3D telemedicine system during COVID: The future of remote consultations

Steven Lo[a,d,2,1,*], Spencer Fowers[b,1], Kwame Darko[c], Thiago Spina[b], Catriona Graham[d], Andrea Britto[b], Anna Rose[d], David Tittsworth[b], Aileen McIntyre[e], Chris O'Dowd[b], Roma Maguire[f], Wayne Chang[b], David Young[g], Amber Hoak[b], Robin Young[h], Mark Dunlop[f], Levi Ankrah[c], Martina Messow[h], Opoku Ampomah[c], Ben Cutler[b,2], 3DTM (3D Telemedicine) Collaborative research group, Roma Armstrong[e], Ruchi Lalwani[e], Ruairidh Davison[e], Sophie Bagnall[e], Whitney Hudson[b], Mike Shepperd[b], Jonny Johnson[b]

[a] *School of Medicine, Dentistry and Nursing, University of Glasgow, UK*
[b] *Microsoft Corporation, Redmond, WA, USA*
[c] *National Reconstructive Plastic Surgery and Burns Centre, Korle Bu Teaching Hospital, Accra, Ghana*
[d] *Canniesburn Regional Plastic Surgery Unit, Glasgow G4 0SF, UK*
[e] *West of Scotland NHS Innovation Hub, Queen Elizabeth University Hospital Campus, Govan Road, Glasgow G51 4TF, UK*
[f] *Computer and Information Sciences, Livingstone Tower, University of Strathclyde, Glasgow G1 1XH, UK*
[g] *Mathematics and Statistics, Livingstone Tower, University of Strathclyde, Glasgow G1 1XH, UK*
[h] *Robertson Centre for Biostatistics, University of Glasgow, Boyd Orr Building, G12 8QQ, UK*

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KEYWORDS
Telemedicine;

Abstract *Background:* The COVID pandemic brought the need for more realistic remote consultations into focus. 2D Telemedicine solutions fail to replicate the fluency or authentic-

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[2] Joint senior authors
[1] Joint first authors

* Corresponding author at: Canniesburn Regional Plastic Surgery Unit, Glasgow G4 0SF, UK.
E-mail address: Steven.lo@ggc.scot.nhs.uk (S. Lo).

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3 Dimensional;
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Realism

ity of in-person consultations. This research reports on an international collaboration on the participatory development and first validated clinical use of a novel, real-time 360-degree 3D Telemedicine system worldwide. The development of the system - leveraging Microsoft's Holoportation™ communication technology – commenced at the Canniesburn Plastic Surgery Unit, Glasgow, in March 2020.

Methods: The research followed the VR CORE guidelines on the development of digital health trials, placing patients at the heart of the development process. This consisted of three separate studies - a clinician feedback study (23 clinicians, Nov–Dec 2020), a patient feedback study (26 patients, Jul–Oct 2021), and a cohort study focusing on safety and reliability (40 patients, Oct 2021–Mar 2022). *"Lose, Keep, and Change"* feedback prompts were used to engage patients in the development process and guide incremental improvements.

Results: Participatory testing demonstrated improved patient metrics with 3D in comparison to 2D Telemedicine, including validated measures of satisfaction ($p<0.0001$), realism or 'presence' (Single Item Presence scale, $p<0.0001$), and quality (Telehealth Usability Questionnaire, $p = 0.0002$). The safety and clinical concordance (95%) of 3D Telemedicine with a face-to-face consultation were equivalent or exceeded estimates for 2D Telemedicine.

Conclusions: One of the ultimate goals of telemedicine is for the quality of remote consultations to get closer to the experience of face-to-face consultations. These data provide the first evidence that Holoportation™ communication technology brings 3D Telemedicine closer to this goal than a 2D equivalent.

Background

Real-time 3D Telemedicine has previously been proposed within a research setting only, with constraints on cost, complexity, bandwidth, and technology.[1,2] With the COVID pandemic, the use of remote consultation has increased exponentially and has brought the concept of a 3D consultation into focus.[3] Although there appears to be significant theoretical value in assessing surgical patients, as yet no validated clinical data exists on the benefits of such a system in comparison to standard 2D Telemedicine. Here, we detail the participatory development of a real-time 3D Telemedicine system, in conjunction with an international group of healthcare and industrial stakeholders. We also discuss the first real-world use of a 3D Telemedicine system with plastic surgery patients.

Increasing access to care in lower to middle income countries

Initial discussions regarding the development of a 3D Telemedicine system, leveraging Microsoft's Holoportation communication technology, commenced in December 2019 - between the Canniesburn Plastic Surgery Unit, Glasgow, UK; Korle Bu Teaching Hospital, Accra, Ghana; and Microsoft Corporation, Redmond, USA. This centered on the potential for increasing access to specialized reconstructive surgical care in Lower to Middle Income countries (LMIC). The research team visited the Ministry of Health, Ghana, in February 2020, to initiate an international collaboration on this project. Geospatial mapping set out the early vision, using census data and overland travel times to estimate increased access to reconstructive care.[4] With the global COVID pandemic enforcing the first UK lockdown in March 2020, the focus of the project rapidly pivoted to the potential delivery of remote care during COVID.

VR CORE guidelines on developing digital health technologies

The 3D Telemedicine system was co-developed with patients using international guidelines for digital or Virtual Reality (VR) clinical trials, as proposed by the Virtual Reality Clinical Outcomes Research Experts (VR CORE). These guidelines aim to improve methodological quality in digital health technology trials by dividing development into three phases (VR 1 to 3), akin to Clinical Trial Phases 1 to 3.[5] Participatory development is one of the key elements of these guidelines, focusing on the principles of human-centered design. The importance of this in digital trials has been previously underestimated, as *"lack of patient involvement, poor requirement definitions, and nonadaptation to user feedback are some of the common factors that explain failures of digital interventions"*.[5] The present study placed patients at the heart of the development process and reports on the participatory development (VR 1) and early clinical trial (VR 2) phases. The objectives of this research were to co-develop a patient-centered 3D Telemedicine system, compare validated outcome measures with a 2D system, assess alignment with an in-person consultation, and to ensure safety, reliability, and clinical concordance.

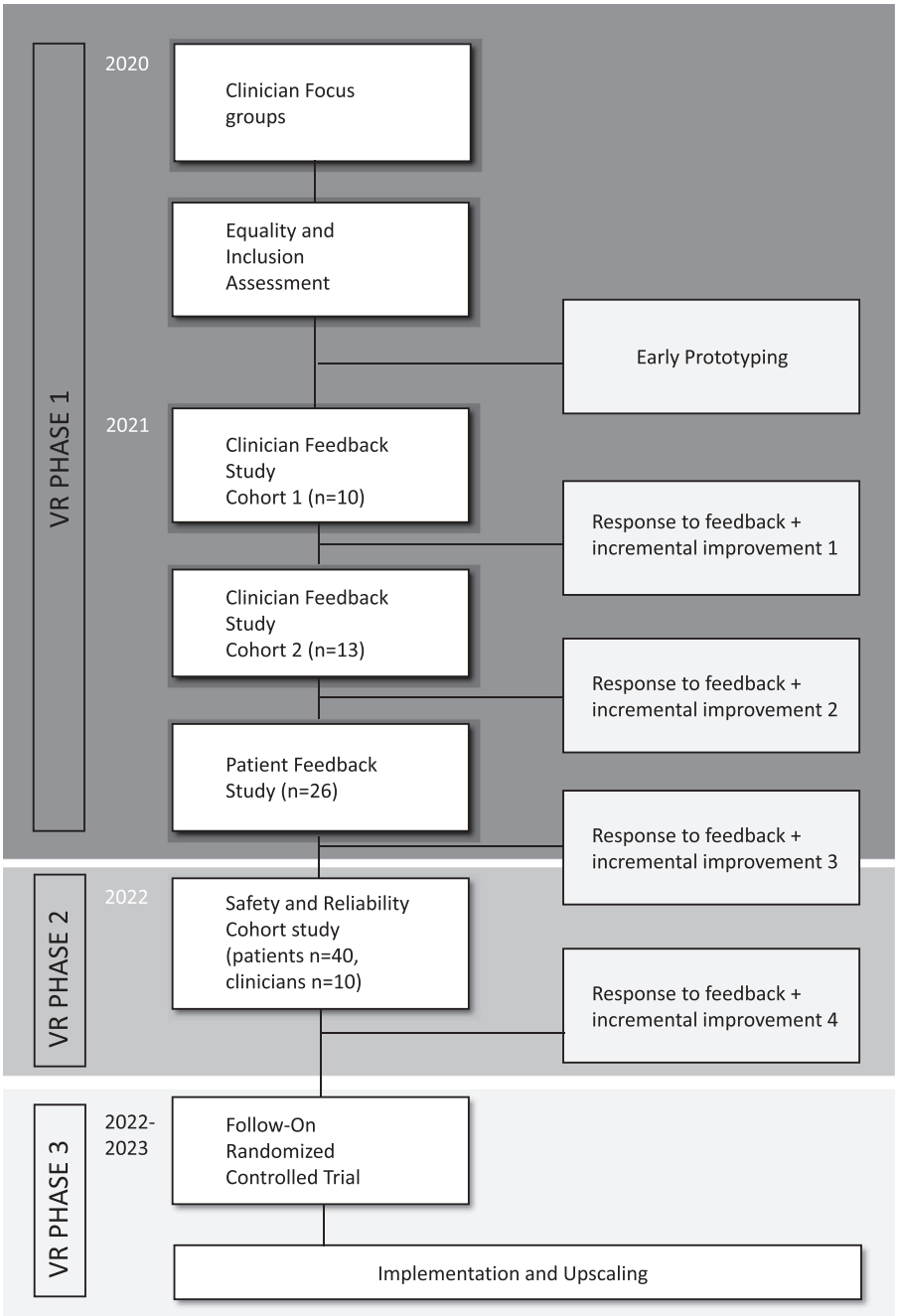
Methods and results

Ethics

NHS Greater Glasgow and Clyde (GGC) R and I granted approvals GN20HS181/ GN20HS300 for this research. NHS GGC governance meetings monitored the project biannually. Participants consented in writing. Patient data controlled by NHS GGC. STROBE guidelines were followed for reporting of cohort trials.

Approach and preliminary work

The research followed the VR CORE guidelines[5] and consisted of preliminary work including focus groups, stakeholder collaborations, equality assessments, and initial prototyping. Weekly collaboration meetings were held over a 2-year period in the UK, Ghana, and the USA, commencing in March 2020. To inform prototype development - a focus group was held with 23 clinicians from the Canniesburn Plastic Surgery Unit, Glasgow, UK, in June 2020 - exploring desired functions, identification of needs, potential benefits, risks, use during COVID, and implementation (Supplementary Table 1). An Equality Impact Assessment (EQIA)[6] focused on *"not leaving anybody behind in a digital world"*[7] and collected data on factors that may influence access or the use of novel technology, such as deprivation and educational level. This was followed by three separate studies: **a clinician feedback study** - providing feedback to incrementally improve and shape the 3D Telemedicine system prior to patient testing; **a patient feedback study** - to compare 3D and 2D Telemedicine systems; and a **cohort study** focusing on safety, reliability, and clinical concordance of 3D with face-to-face examination (Flowchart 1).



Flowchart 1

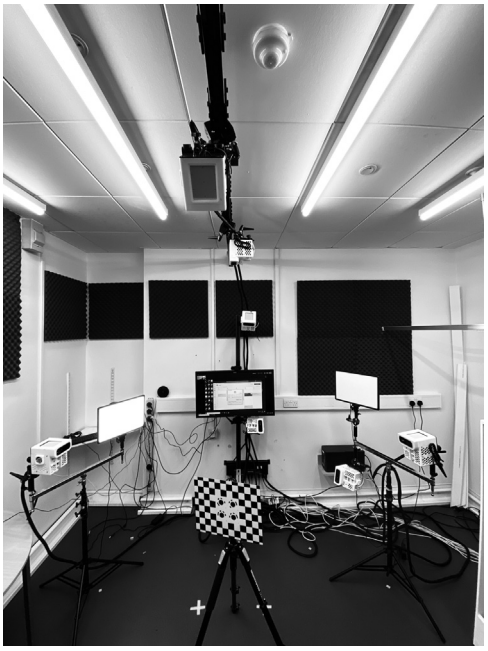


Figure 1 3D Rig Set up. Multiple Kinect cameras surround the patient within the clinic room. In the center is a chequerboard used to calibrate the system.

Prototyping and initial set up

The initial system set up took place in September 2020, when a research team from Microsoft Corporation, Redmond, USA, travelled to Glasgow, UK. The system, which was inspired by Microsoft's Holoportation™ research,[8] consisted of an array of 10 Azure Kinect cameras connected to a Fusion server that fuses each camera's depth output to create a 3D 360-degree model, and a Render server that covers the model in RGB video output. This was linked to a "viewer" room, where the patient could be viewed in 360-degrees on a computer screen over the existing hospital network (Figures 1-5, Supplementary Videos 1–3). The "viewer" room was set up in both the test site hospital (West Glasgow Ambulatory Care Hospital, WGACH) and remotely at the Canniesburn Plastic Surgery Unit. The WGACH viewer site was used in the present studies (full system features - Supplementary Table 1).

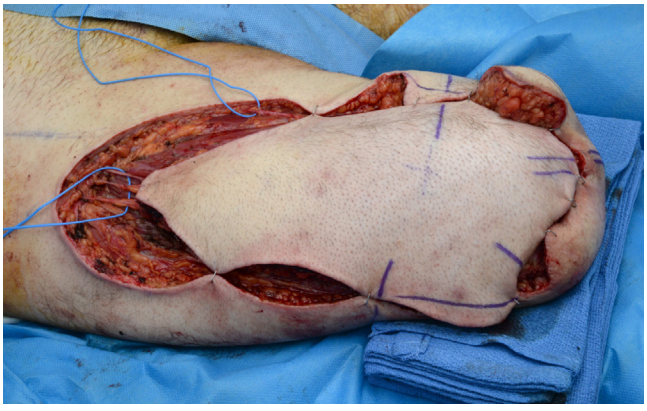


Figure 2 Sensate Anterolateral Thigh (ALT) Flap to Above Knee Amputation (AKA). This patient required resurfacing of an area of skin grafted post-traumatic residual limb that provided a poor interface with the prosthetic limb. A sensate ALT flap was used to resurface the residual limb.

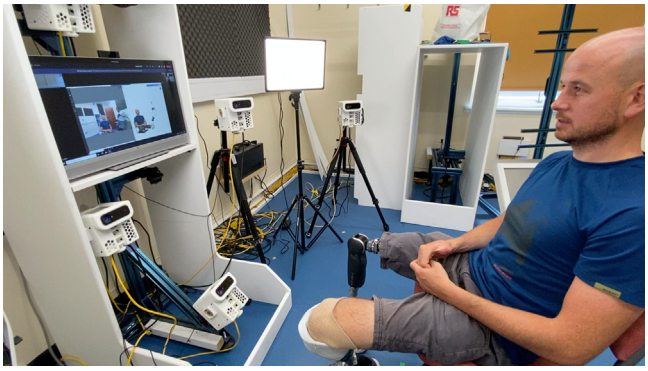


Figure 3 Patient in 3D Rig. The same patient with resurfaced AKA sitting in the 3D Telemedicine system. The screen allows him to view the same images as the clinician.

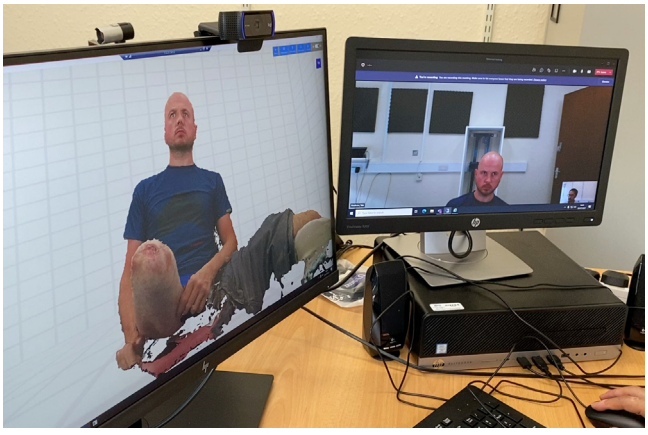


Figure 4 Clinician Viewer Room. The clinician can see the patient in 3D on the left screen. On the right is a standard Telemedicine video call. Note the difference in field of view and ability to position patient to see the right AKA.

VR PHASE 1: PARTICIPATORY CO-DEVELOPMENT

Patient and clinician participatory development

Patients and clinicians feedback was used to shape the development of the 3D Telemedicine system, assess the usability of the outcome instruments, and provide data for follow-on trials. Sample sizes were not required for the participatory development component of this study. Data analysis carried out by a blinded, independent statistical service using R version 3.4.1.[9]

Study 1: clinician feedback study: iterative improvements in 3D system

Clinician feedback testing focused on the optimization of the prototype system prior to patient testing. Full details

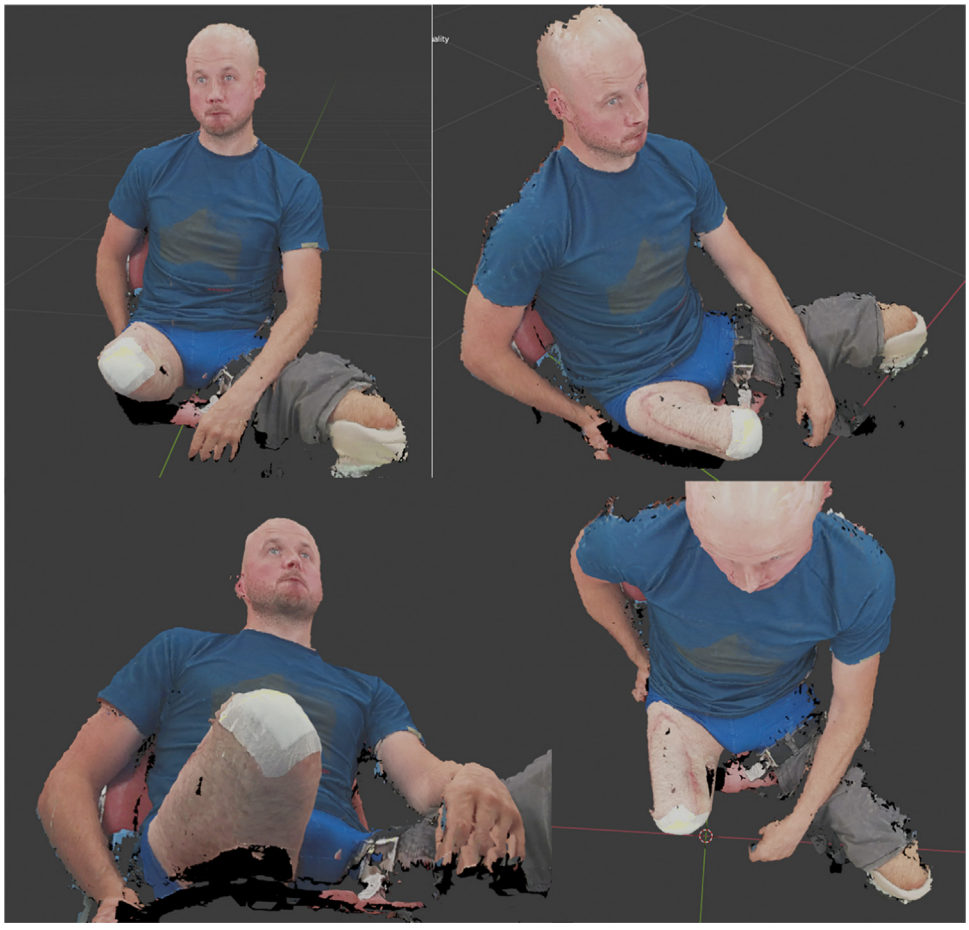


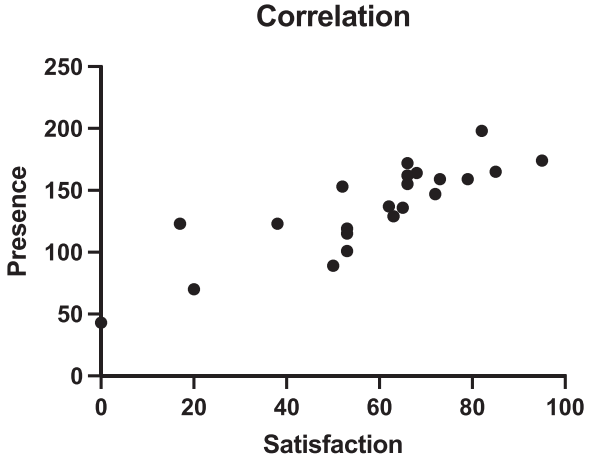
Figure 5 Multiple 3D Views. These images demonstrate the 3D camera output in real time.

are provided in Supplementary Appendix 1. In brief, 23 clinicians were assessed in two batches in November and December 2020 to provide incremental improvements in usability and to assess responsiveness to change between batches. Key findings included a strong correlation between the quality of consultation (satisfaction) and the realism or "presence" of the 3D system (Pearson $r = 0.8451$, $p<0.0001$, Graph 1). The 3D system was found to have a significantly higher realism or "presence" than the 2D system in batch 2. Improvements were instituted in response to clinician feedback, prior to patient testing (Supplementary Table 1).

Study 2: patient feedback study: 3D versus 2D telemedicine

Method

Patient feedback testing provided the first real-world data on patients' perceptions of the 3D Telemedicine system in comparison to 2D Telemedicine. A preliminary cohort of six patients was used to test the acceptability of the outcome instruments. Longer form scales such as the Presence Questionnaire with 29 items[10] were found to be too long and confusing for patients, and therefore short forms of "presence" testing were considered, with the final selection of the validated Single Item Presence scale.[11]



Graph 1 Correlation of Presence with Satisfaction. Clinician satisfaction correlation with Presence Questionnaire Score.

Participants

Twenty-six patients from the Canniesburn Plastic Surgery Unit clinic participated (July-Oct 2021) (Supplementary Table 2). Patients were seen in 3D and 2D Telemedicine by a single clinician, without randomization (11 patients 2D first

Table 1 Patient Feedback Study - 3D versus 2D Outcome Measures. Validated outcome measures included satisfaction, Mental Effort Rating Scale, Single Item Presence Scale, System Usability Scale, and Telehealth Usability Questionnaire. Nonvalidated outcome measures included patients' subjective views on the ability of clinician to make an accurate diagnosis, and ease of positioning their body part for examination.

	Category range	3D	2D	Mean difference	Significance
Satisfaction	0-100	88.23 (CI 85.21, 91.26)	51.35 (CI 43.09, 59.60)	36.88 (CI 28.73-45.04)	$p<0.0001$*
Mental Effort Rating Scale	1-9 (lower is better)	2.038 (CI 1.377, 2.699)	2.462 (CI 1.685, 3.238)	0.42 (CI −0.39-1.24)	$p = 0.2965$*
Single Item Presence Scale	0-100	80 (CI 74.9, 85.1)	52.58 (CI 44.15, 61.0)	27.42 (CI 17.24-37.61)	$p<0.0001$*
Telehealth Usability Questionnaire	0-100+	85.31 (CI 80.61, 89.93)	76.94 (CI 71.36, 82.52)	−8.35 (CI −12,24, −4.45)	$p = 0.0002$*
System Usability Scale (SUS)	0-100	87.02 (CI 81.69, 92.35)	N/A	N/A	N/A
Accuracy of diagnosis	1-5 (higher is better)	4.13 (CI 3.77, 4.50)	3.40 (CI 2.94, 3.86)	−0.73 (CI −1.20, −0.26)	$p = 0.0254$*
Ease of positioning body part	1-5	4.53 (CI 4.17, 4.90)	3.60 (CI 3.01, 4.19)	−0.93 (CI −1.49, −0.38)	$p = 0.0157$*

* dependent *t*-test.
+ Raw maximum score of 147 converted to a score out of 100
CI - 95% confidence intervals.

and 15 patients 3D first). Each consultation lasted 10 min, followed by the completion of questionnaires.

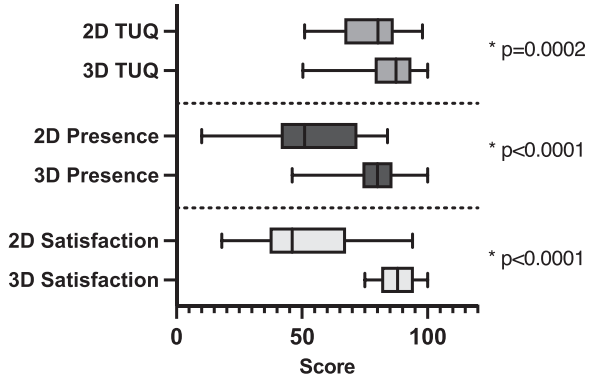
Outcome instruments

Single Item Presence scale asked the key question *"To which extent did you feel present in the virtual clinic, as if you were really there?"* to provide insights into how closely the 3D clinic aligns with an in-person consultation.[12] **Telehealth Usability Questionnaire (TUQ)** consists of 21 items covering subdomains of usefulness, ease of use, effectiveness, reliability, and satisfaction.[12] **Satisfaction** measured with 0-100 visual analogue scale.[13] **System Usability Scale (SUS)** measured usability with an industry standard scale that allows comparison across different technologies.[14] ***"Lose, Keep, and Change"*** feedback prompts were used to engage patients in the development process and guide incremental improvements.[15]

Results

3D versus 2D telemedicine validated outcome measures

3D was rated higher on satisfaction ($p<0.0001$), presence ($p<0.0001$), and quality (TUQ, $p=0.0002$) (Boxplot 1). The mental effort rating scale was equivalent ($P=0.2965$), scoring highly in both systems suggesting that the 3D system is not more complex to use than normal telemedicine systems. Patients' subjective views on the accuracy of diagnosis and the ease of positioning their body part for examination were also significantly higher (Table 1). All patients preferred 3D (for patient comments see Supplementary Table 3), and usability was rated highly (SUS 87.02).



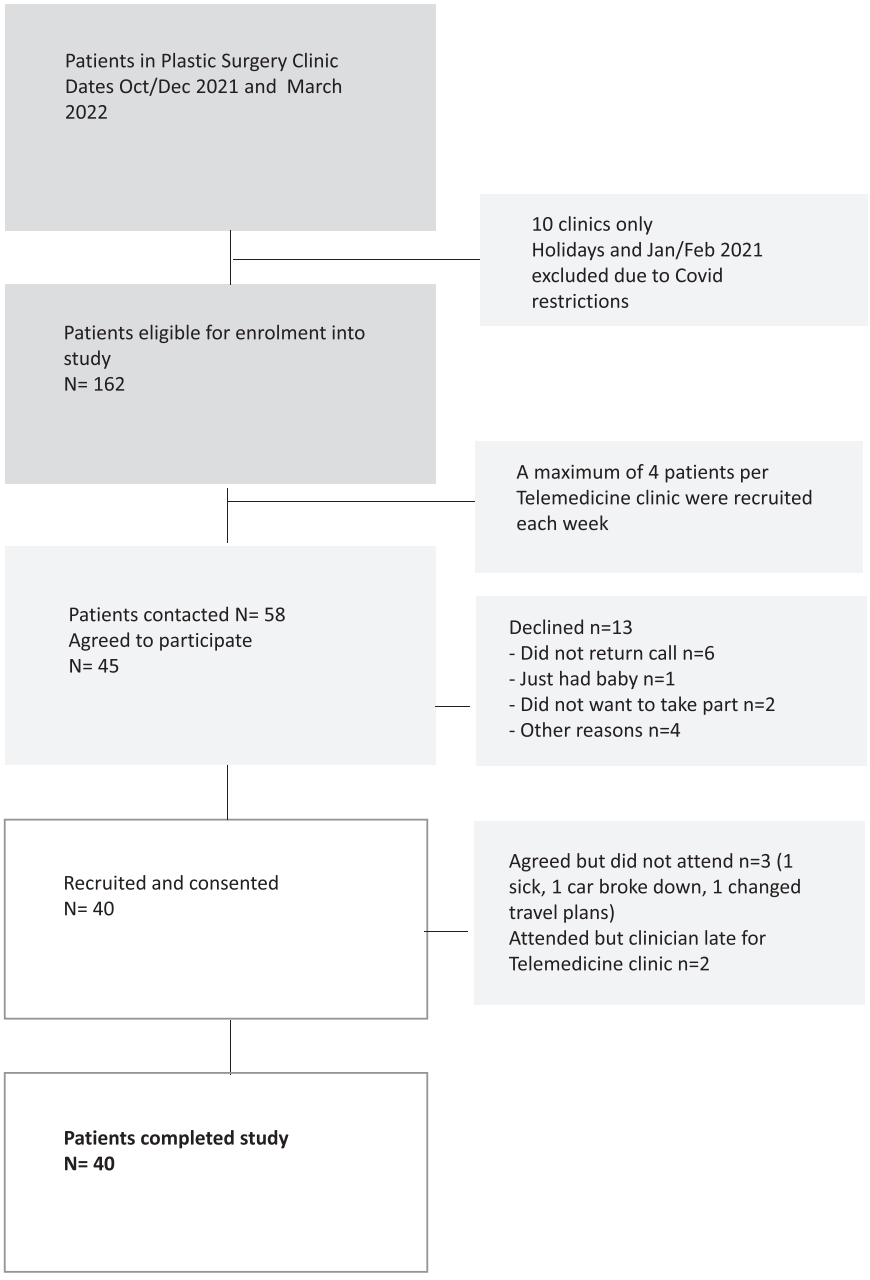
Boxplot 1 3D versus 2D patient outcome measures. Satisfaction, Presence (Single Item Presence Scale), and Quality (TUQ) all significantly higher for the 3D system. All scores converted to 0-100 scale.

Feedback process and subjective interview

"Lose, Change, and Keep" prompts noted limitations related predominantly to the quality of 3D spatial resolution in real-time (Supplementary Table 1). Subjective interview was overwhelmingly positive, with patients in particular finding that the 3D system allowed positioning their body part for examination much easier than with 2D (data not shown) (Supplementary Video 4).

Carry-over effects

Between-group comparisons of satisfaction, presence and TUQ were done using a general linear model, which included subject, group, and order factors (3D or 2D system first, to



Flowchart 2

determine any effect of carry-over). No effect of carry-over was noted for these outcome measures (data not shown).

VR PHASE 2: EARLY CLINICAL EFFICACY AND SAFETY

Study 3: cohort study: 3D telemedicine versus face-to-face

Method. The cohort study aimed to assess safety and reliability. A paired design was used with patients seen in 3D Telemedicine first, followed by face-to-face by the same clinician to allow the assessment of clinical concordance. Ten minutes were given per examination. Clinicians and patients both completed questionnaires for each consultation.

Sample size

The pilot study aimed to recruit 40 participants to allow adequate post-study power calculations. Primary and secondary outcomes are not designated pre-trial for pilot studies. Poststudy power calculations indicated that with a paired design, 16 patients would have been sufficient (using primary outcome with the University of North Norway UNN score as primary outcome; delta 0.4; SD 0.52; power 0.9)

Participants

A total of 40 patients and 10 clinicians (5 residents, 2 nurse specialists, 1 physiotherapist, and 2 consultants; mean age

Table 2 Cohort Study - 3D Telemedicine versus Face-to-Face UNN Score. The UNN score is subdivided into subdomains and co-operation, examination, treatment, informing patient, and overall.

	3D Telemedicine	Face-to-Face	Mean difference	Significance[+]
Patient co-operation[*]	1.05 (CI 0.98-1.12)	1.03 (CI 0.98-1.08)	−0.03 (CI −0.08, 0.03)	$P = 0.33$
Evaluate/examine patient[*]	1.80 (CI 1.55, 2.05)	1.03 (CI 0.97, 1.08)	−0.78 (CI −1.03, −0.52)	$P<0.0001$
Treat patient[*]	1.79 (CI 1.46,2.11)	1.11 (CI 0.99,1.23)	−0.68 (CI −1.00,−0.36)	$P = 0.0002$
Inform patient[*]	1.30 (CI 1.07,1.53)	1.18 (CI 1.03, 1.32)	−0.13 (CI −0.39, 0.14)	$P = 0.34$
Overall[*]	1.70 (CI 1.45, 1.95)	1.18 (CI 1.03, 1.32)	−0.58 (CI −0.85, −0.31)	$P = 0.0001$
Sum score	1.50 (CI 1.33-1.68)	1.10 (CI 1.03-1.16)	−0.40 (CI −0.57, −0.24)	<0.0001

[*] rated from 1 to 5, where 1=very good, 2= good, 3= neither good nor bad, 4=bad, and 5 = very bad.
[+] paired t-tests were used for analysis.

37.5; range 28-43; 7F, 3M) from the Canniesburn Plastic Surgery Unit participated (Oct 2021-Mar 2022, Flowchart 2). For inclusion criteria and patient demographics - see Supplementary Tables 4 & 5.

Outcome instruments

The UNN scale, which was validated for orthopaedic patients, is one of the only scales available to assess the quality of both telemedicine and face-to-face consultations.[16] **NASA TLX** is a measure of the workload or "task load" of an activity, assessing subdomains such as mental demand, physical demand, temporal demand, performance, effort, and frustration.[17]

Results

Operational and clinical safety

Operational safety issues occurred in 0%, technical issues 20%, reliability issues 7.5%, and image artefacts 12.5%. All issues were temporary and did not curtail the clinical consultation. The clinical concordance of 3D consultations with face-to-face management plan was 95%. Two cases of clinical discrepancy did not result in clinical safety concerns (Supplementary Table 6).

3D versus face-to-face validated outcome measures

The clinicians' UNN sum score was significantly higher for a face-to-face than for 3D consultation (Table 2). Nonetheless, the difference in sum score between 3D and face-to-face was only 0.4, with both consultation types approximating to scores between "good" and "very good". The minimal clinically important difference (MCID) has not yet been established for UNN score. The UNN authors suggested a difference of 0.3 as a noninferiority limit in their study, but this appears to be arbitrary and not based on clinical data. Patients rated the face-to-face higher on satisfaction than 3D, with mean scores 90.08 versus 83.58 (mean difference 6.50 [CI 2.40-10.60]; $p = 0.0027$; paired t-test).

Differences in clinician versus patient outcome measures for 3D system

Patients rated the 3D system higher on satisfaction than clinicians ($p<0.0001$). This may be related to differences in mental effort ($p = 0.0042$) and task load (NASA TLX, $p = 0.020$). Usability (SUS) and quality scores (TUQ) were equivalent (Table 3).

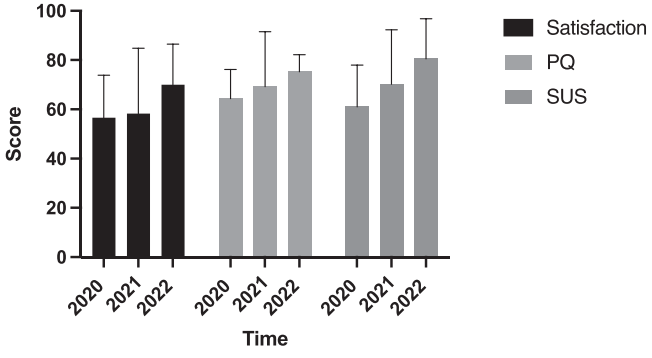
Ancillary analyses

Improvements over time

Clinician satisfaction, presence (PQ), and usability (SUS) significantly improved over the 2-year development process of these three studies (Graph 2).

Education and deprivation level

Deprivation scores - calculated using the Scotland Index of Multiple Deprivation[18] - and education level, did not signif-



Graph 2 Improvements in outcomes during the development process. Outcome measurements improved significantly during incremental feedback and development, for ratings of satisfaction, presence (PQ), and usability (SUS) over the development process. 2020 refers to scores from the Clinician Feedback Study Batch 1, 2021 refers to Clinician Feedback Study Batch 2, and 2022 refers to the Cohort study clinician scores. PQ is converted to a 100 point scale for this graph. 95% CI bars are shown. Comparison of 2020 with 2022 scores with unpaired t-test: Satisfaction ($p = 0.026$), PQ ($p = 0.021$), and SUS ($p = 0.017$).

Table 3 Cohort study – clinicians versus patient outcome measures of the 3D telemedicine system only.

	Category range	Clinicians ($n = 10$)	Patients ($n = 40$)	Mean difference	Significance
Satisfaction	0-100	70.08 (CI 64.84-75.31)	83.58 (CI 79.07-88.08)	13.50 (CI 7.67, 19.33)	$P<0.0001$ (paired t-test)
Mental Effort Rating Scale	1-9 (lower is better)	2.85 (CI 2.34-3.37)	1.86 (CI 1.37-2.28)	−1.025 (CI −1.71, −0.34)	$P = 0.0042$ (paired t-test)
NASA TLX Raw score	0-100[+] (lower is better)	19.08 (CI 14.22, 23.93)	12.20 (CI 8.40, 16.00)	−6.88 (CI −12.60, −1.16)	$p = 0.020$ (paired t-test)
System Usability Scale (SUS)	0-100	80.5 (CI 68.85-92.15)[*]	81.88 (CI 76.83-86.92)	1.38 (CI −9.91, −12.66)	$P = 0.8075$ (unpaired t-test)
Telehealth Usability Questionnaire (TUQ)	0-100[+]	84.95 (CI 78.58, 91.32)[*]	82.00 (CI 77.48, 86.52)	−2.95 (CI −12.43, 6.52)	$P = 0.5341$ (unpaired t-test)
Presence Questionnaire (PQ)	0-100[+]	75.32 (CI 70.38, 80.26)[*]	[**]	N/A	N/A

[*] completed only once at the end of study by each clinician, not per patient consultation ($n = 10$). Comparative statistical analysis is therefore unpaired.
[**] not included in patient questionnaires as overly long for inclusion.
[+] converted to a 0-100 scale.

icantly correlate with satisfaction, usability (SUS), quality (TUQ), or task load (NASA TLX) of the 3D system (Supplementary Table 7).

Harms

No harms occurred during 3D Telemedicine consultations.

Discussion

3D telemedicine: the future of remote consultations

This is the first study to examine and demonstrate the potential benefits of 3D Telemedicine in comparison to a 2D equivalent. Previous research has either existed in a research setting only or has not proven any validated benefits of 3D Telemedicine over existing telemedicine technology.[19] Therefore, until now, the advantages of 3D Telemedicine have been purely speculative. This is also the first clinical system to employ Microsoft's Holoportation™ communication technology, which creates a true 360° 3D system that fuses multiple depth cameras, with previous research only employing single depth cameras, which do not permit a true 360° coverage.[19,20]

Placing patients at the heart of the development process

Development of the 3D system has focused on medical communication from the ground-up and has not been adapted from business or other user groups. The VR CORE Guidelines, akin to the Model for the Assessment of Telemedicine Guidelines, place participatory design at the heart of the development process.[21] Clinician and patient feedback testing allowed for the co-development of a system that was fit to context and user group. This incremental, methodical approach directly translated to improved outcome measures, as can be seen by improvements in clinician satisfaction from 56.6% to 70.1% and usability (SUS) from 61 (grade D) to 80.5 (grade A) over the development cycle (Graph 2). It is hoped that in using a patient-centered development approach, this system will be both relevant and embraced by patients in future clinical practice.

3D telemedicine increases the realism and satisfaction of the remote consultation

Patient feedback testing suggested a strong user preference (100% preferred 3D), satisfaction ($p<0.0001$), and closer alignment with an "in-person" consultation for the 3D Telemedicine system in comparison to 2D. The Single Item Presence scale asking the question *"To which extent did you feel present in the virtual clinic, as if you were really there?"* strongly favored the 3D system ($p = 0.001$). The Telehealth Usability Questionnaire, an overall measure of the quality of telemedicine, favored the 3D system ($p = 0.0002$). Subjective interviews were very positive, with patients in particular finding positioning their body part for examination much easier with the 3D system.

The importance of "Presence" or realism in remote clinical consultations

Critically, this study points toward real-time 3D Telemedicine bringing the remote consultation experience closer than ever toward a face-to-face consultation.

This is one of the fundamental goals of telemedicine. Although patients still prefer a face-to-face consultation (higher UNN score/ satisfaction), 3D Telemedicine was rated significantly higher in terms of satisfaction and realism than 2D Telemedicine (Table 1). These study data also highlight the importance of 'presence' or realism of a Telemedicine system. Firstly, 'presence' correlates strongly with satisfaction of the clinical consultation (Graph 1). Secondly, data from other groups suggest that 'presence' correlates with improved human performance. The more immersive experience provided by 3D Telemedicine may therefore increase the fluency and execution of the consultation,[22] and patient satisfaction is seen as a key driver in healthcare systems.[23] Together, these provide impetus and rationale to continue research into more immersive forms of Telemedicine.

Clinical relevance of real-time 3D consultations in plastic surgery

Although testing indicated improved key metrics in patient satisfaction and presence or realism, these are relatively abstract terms that are difficult to translate into direct clinical benefits for patients. These potential benefits are numerous - for example, examining patients with flap reconstructions on the side or back of the body, conducting remote physiotherapy without requiring the patient to reposition multiple times, the ability to examine multiple joints from different angles, ease of positioning the patient with limited mobility who is unable to move for the camera, and avoiding having an intermediary to move a camera around the patient. Furthermore, the ability to draw the 3D patient model allows the clinician to more accurately explain an operation on the actual patient's body, and in doing so provides a more 'personalized medicine' approach. Together, these advantages allow the clinician to conduct a higher fidelity, more fluent consultation than with a 2D system.

Safety and clinical concordance

Clinical concordance of the 3D system with in-person consultations (95% in this study) is equivalent or exceeds previous estimates for other surgical Telemedicine consultations. These include 92% surgeons estimating that their telemedicine decisions are as good as face-to-face[24] and 8.9% of orthopaedic telemedicine patients requiring additional face-to-face consultations (compared to 2.5% in this study).[16] These data came from nonpaired studies, which are considerably less accurate in measuring concordance than the paired design used in the present study, due to the heterogeneous nature of medical conditions.

Leave nobody behind in a digital world

The 3D system aimed to not *"leave anybody behind in a digital world,"* and therefore the interface was made as simple as possible for patients. Technological equality and inclusion of the system were demonstrated by high usability of the system irrespective of patient deprivation or education levels (Supplementary Table 7).

Outcome measurement instruments

Given that the key goal of any Telemedicine system is to bring the remote consultation as close as possible to the experience of a face-to-face consultation, "presence" was deemed to be one of the primary research outcomes. Many scales measuring "presence" in digital environments were found to be too lengthy and confusing by patients.[10,25] Questionnaires that work with clinicians or university students will not necessarily translate adequately to patients, with 27% of the UK population having the lowest level of literacy.[26] The Single Item Presence question *"To which extent did you feel present in the virtual clinic, as if you were really there?"* was clear, simple, and resonated strongly with patients.[11] This will therefore form the primary outcome for the follow-on RCT. The Telehealth Usability Questionnaire (TUQ) is a newer, validated questionnaire measuring subdomains of usefulness, ease of use, effectiveness, reliability, and satisfaction, giving a metric of the overall quality of the telemedicine system.[12] Although it contains questions on generic topics that do not differentiate between technical systems, such as *"Telehealth saves me travelling"*, it is clear to understand and provides a number of important metrics, and thus it will therefore be used as a secondary outcome in the follow-on trial.

Limitations, bias, and generalization

Inherent limitations of these data include a lack of randomization and blinding. The use of validated, generic outcome scales minimizes information bias and allows generalization of these data to other trials employing the same instruments.

Future directions

A follow-on VR Phase 3 Randomized trial will provide definitive evidence of clinical benefits. Concurrently, a test bed has been set up in Ghana to explore increasing access to reconstructive surgical care in LMIC. Health economics, health frameworks, and organizational change will be incorporated in future analyses. Further technical changes will focus on improving clinician satisfaction by reducing mental effort and task load (supplementary Appendix 2). This may be aided by improving spatial processing of a 3D object through increased resolution, higher frame rate, reduced lag time, and the use of more intuitive, natural interfaces such as the HoloLens.[27]

Summary

This research details the participatory development of a 3D Telemedicine system, with the first validated comparative clinical use in patients worldwide. One of the ultimate goals of telemedicine is for the quality of remote consultations to

get closer to the experience of face-to-face consultations. Together, the data presented here point toward significant potential in bringing the remote consultation closer to this goal, which is of particular relevance to specialities with a strong 3D focus such as plastic Surgery. In summary:

1) **3D Telemedicine increases the realism of the remote clinical consultation** and is closer in experience to a face-to-face consultation than a 2D consultation.
2) **"Presence" or realism correlates with satisfaction with the consultation.** This is a strong driver to invest in technologies that increase the fidelity of telemedicine consultations.
3) **3D Telemedicine appears to significantly increase patient satisfaction** in comparison to a standard 2D consultation.
4) **Safety and clinical concordance are acceptable for 3D Telemedicine -** equivalent or exceeding estimates for 2D Telemedicine.

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Terminology

Presence, immersion, and realism. "Presence" is an experiential, subjective, and psychological quality in virtual environments associated with the feelings of "being there". **"Immersion"** is associated with objective; technical aspects of virtual systems that help the user feel a sense of presence. **"Realism"** can be considered as a dimension of "presence", with stronger realism leading to increased presence. For the purpose of this paper, which is aimed at a clinical audience, these terms are used interchangeably.

Conflict of interest

The authors have no disclosures.

Patient consents

Patient consents were obtained for the publication of identifiable photographs and videos

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Supplementary materials

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