Journal of Biomedical Informatics 90 (2019) 103102

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Computer mediated reality technologies: A conceptual framework and survey of the state of the art in healthcare intervention systems

Zear Ibrahim, Arthur G. Money*

Department of Computer Science, Brunel University London, Uxbridge, London UB8 3PH, United Kingdom

ARTICLE INFO

Keywords:
Computer mediated reality technology
Virtual reality
Augmented reality
Health care
Falls prevention

ABSTRACT

Introduction: The trend of an ageing and growing world population, particularly in developed countries, is expected to continue for decades to come causing an increase in demand for healthcare resources and services. Consequently, demand is growing faster than rises in funding. The UK government, in partnership with the European Commission's Vision for 2020, propose a paradigm shift towards the delivery of more patient-centred self-care interventions, facilitated by novel ubiquitous computer mediated reality technology applications, as a key strategy to overcome the scarcity of health resources gap. If this vision is to become a reality, it is crucial that state of the art research focuses efforts on the development of applications that support the delivery of patient-centred self-care interventions.

Objectives: This study presents a conceptual framework, a system impact assessment taxonomy and systematic literature review of the state of the art in Computer Mediated Reality Technologies (CMRT) research. The intended function of the CMRT applications are considered systematically, with a view to establish the extent to which existing research focuses on delivering digitised, patient-centred healthcare applications, the care contexts in which these are delivered, and the specific CMRTs that are used to deliver such applications.

Methods: A conceptual framework of the state of the art is derived via a systematic concept-centric incremental thematic analysis protocol. The survey considers systems that have been presented within the literature between 2010 and 2017. Primarily, the literature is considered in the context of the type of patient-practitioner relationship that the respective applications support, i.e. Traditional, Collaborative, or Patient-centred care, and the phase of healthcare intervention that is supported i.e. Primary-care, Secondary-Care and Tertiary-care. Inclusion criteria focuses on systematic CMRT implementations and analysis considers a range of clinical contexts (type), settings (location) and system specification concepts consisting of Augmented, Virtual and Mixed Reality technology in conjunction with 3D-Modelling. As a measure of the value added by respective CMRT systems, an impact assessment is carried out according to the National Service Framework Research Quality metric, and via a bespoke overall System Value score metric.

Results & conclusion: Several research challenges emerge as a result of surveying the research literature, which include: a large quantity of research effort being focused on invasive surgical procedures through CMRT from a paternalistic Traditional patient-practitioner perspective; lack of research effort in the CMRT healthcare domain that develop ubiquitous systems which specifically target the older population within the home setting; little to no consideration of ecological validity and design architecture for user or interface interaction of systems; current CMRT systems are lacking deployment on ubiquitous mobile platforms; protecting and informing patients when using sensory/camera based CMRT from the privacy of their home through self-assessment means. In terms of impact, Traditional CMRT systems achieve the highest score for Research Quality, and Patient-Centred Systems achieve the highest scores for System Value. In response to these challenges, recommendations and future research directions are proposed to overcome each respective challenge.

1. Introduction

It is now widely accepted that the world population is ageing, particularly in developed countries, where birth rates are declining whilst life expectancy continues to increase [1]. This is having a significant impact on social care and health provision needs. The Office for

* Corresponding author at: Brunel University London, Department of Computer Science, Uxbridge, London UB8 3PH, United Kingdom.
E-mail address: arthur.money@brunel.ac.uk (A.G. Money).

https://doi.org/10.1016/j.jbi.2019.103102
Received 12 June 2018; Received in revised form 30 October 2018; Accepted 29 December 2018
Available online 12 January 2019

National Statistics estimates that since 2006 there are in excess of 1.7 million additional people aged 65 and over in England alone [2,3]. Therefore, the growing ageing population is putting a significant strain on public health resources [4]. For example in the UK, the NHS's total revenue expenditure continues to increase significantly beyond proposed budget increases [5]. According the National Audit Office [6] and The Health Foundation [7], the scarcity of healthcare resources are a result of three burning factors: (1) a growing ageing population (2) a shortfall in skilled clinical staff (3) an increased prevalence of long-term chronic conditions largely due to increased life expectancy. Developing new and innovative Information and Communication Technology (ICT) applications to assist in the delivery of healthcare is seen as one of the key enabling strategies that has the potential to overcome the scarcity of resources issue, whilst also improving the quality and effectiveness of the care that is delivered [8]. Moreover, it is increasingly accepted that good quality care is synonymous with the provision patient-centred care [9–12]. Hence, there has been a strategic shift away from the traditional paternalistic models of healthcare delivery, where the patient is a passive recipient, towards a more patient-centred model that empowers the patient be responsible for elements of their own care, take on the role of the "expert patient," and be involved in the decisions that are made about their own care [13,14]. However, the shift towards patient-centred self-care delivery can only be realised if appropriate, innovative, and enabling ICT applications are developed to assist the patient to deliver such care more effectively and efficiently. Furthermore, innovative ICTs promise to overcome numerous other operational efficiency issues such as the ever increasing volume of transactions within the system, the ongoing need to integrate new scientific evidence into practice, and the limitations of existing paper-based information management systems that are currently used in practice [15]. In line with this need to shift towards more technology-based patient-centred models of care delivery, the UK government has introduced several initiatives, such as the 'Five year forward Plan' for the NHS [16], 'Going paperless by 2018' [17] and in collaboration with the European Commissions (EUC) vision for 2020, which are supporting the 'Personalized Digital Health-care' agenda [18].

The area of Computer Mediated Reality Technologies (CMRT), an umbrella term for Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR) and 3D-modelling (3DM), has received significant research interest in recent years particularly within the area of developing technology-based solutions for healthcare [19,20]. CMRT, sometimes also referred to as mobile-health (mHealth) or mobile-sensing (mSensing) is on the EUC's priority list of research and funding with a view to tackling the scarcity of healthcare resources issue [21]. CMRT's are commonly installed and deployed on ubiquitous platforms such as desktop machines, smart-phones and other portable devices. Through the usage of these platforms, CMRT is essentially the overlaying of computer graphics onto the real world. This adds information and enhances the perception of reality using primarily visual and audio stimulation. There are numerous existing examples of CMRT research applied to a wide range of healthcare sectors which include, but are not limited to; medical training, healthcare education, clinical assessment, diagnosis and mental health [22–27]. A number of systematic reviews have been carried around the area CMRT for health domain, which include the application of CMRTs to: behavioural health [27], medical training [23], neurosurgery [28], stroke rehabilitation [29], ageing in place [30], and mental health interventions [31]. Although numerous CMRT systematic reviews have been presented in the literature to date, such reviews tend to focus mainly on specific sub-domains of a much broader context of technology-based interventions. To the best of our knowledge, there is no existing research which surveys, categorises, and assesses the impact across the full healthcare-based CMRT landscape, the types of existing technology-based CMRT systems, their key collaboration functions, the technologies they exploit, and the specific types of clinical application they support. Furthermore, there is little existing research which, as a result of taking this holistic view, identifies the

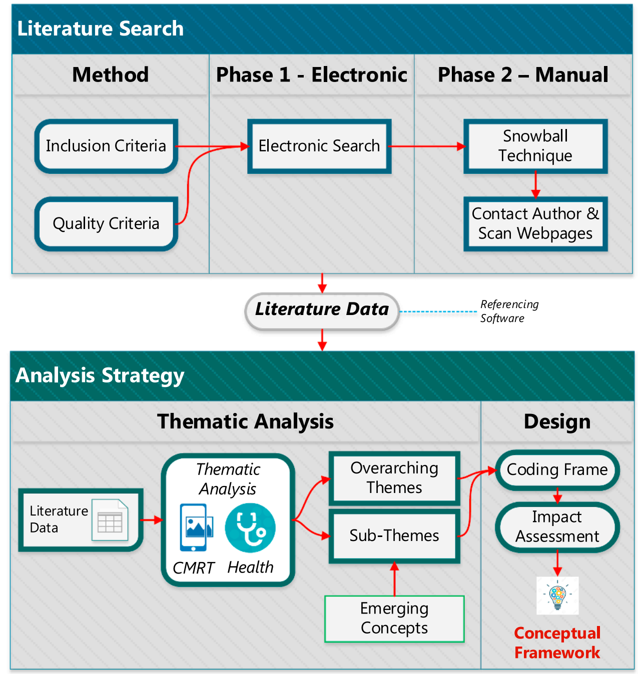

Fig. 1. Literature search strategy [32,33] and the analysis strategy [34] at a high level.

areas of clinical practice which appear to be well catered for and identifies areas which require more attention. In light of the need to better understand the state of the art CMRT technology for the healthcare landscape, this paper provides a comprehensive review, a conceptual framework and impact assessment of healthcare-based CMRT applications, which was developed as a result of carrying out a survey of the range of CMRT applications presented in the literature.

Accordingly, Section 2 outlines the Research Methods used to conduct the literature survey. Subsequently, Section 3 presents the Conceptual Framework for Healthcare CMRTs and its component parts. Section 3 presents the results of the literature survey gathered in-line with the defined classifications. Finally, Section 4 surmises the outcomes of the literature survey and identifies existing gaps and future research challenges that face CMRT health research.

2. Research methods

This section presents the research methods employed to carry out the systematic literature survey and develop the subsequent conceptual framework [32]. An overview of the high-level literature selection and associated analysis protocol are presented in Fig. 1. Section 2.1. Provides a detailed *Literature Search Strategy* and Section 2.2 provides the *Data analysis strategy* employed to develop the resulting *Conceptual Framework* for Healthcare CMRTs presented in Section 3.

2.1. Literature search strategy

The *Literature Search Strategy* defined the literature that was included in the final sample. In combination with Kofod's guidelines on systematic literature reviews [32], a secondary strategy also known as a 'tollgate approach' was adopted [33]. The overall strategy comprises of a method with two types of criteria that need to be satisfied for a study to be included in the final sample. The Inclusion (*IQ*) and Quality Criteria (*QC*) contain a set of rules whereby literature is systematically filtered. Furthermore, the developed criterion are then applied to two further phases of the literature search; *Phase 1*- which is an *Phase 1 –* Electronic Search using numerous online digital libraries and *Phase – 2*

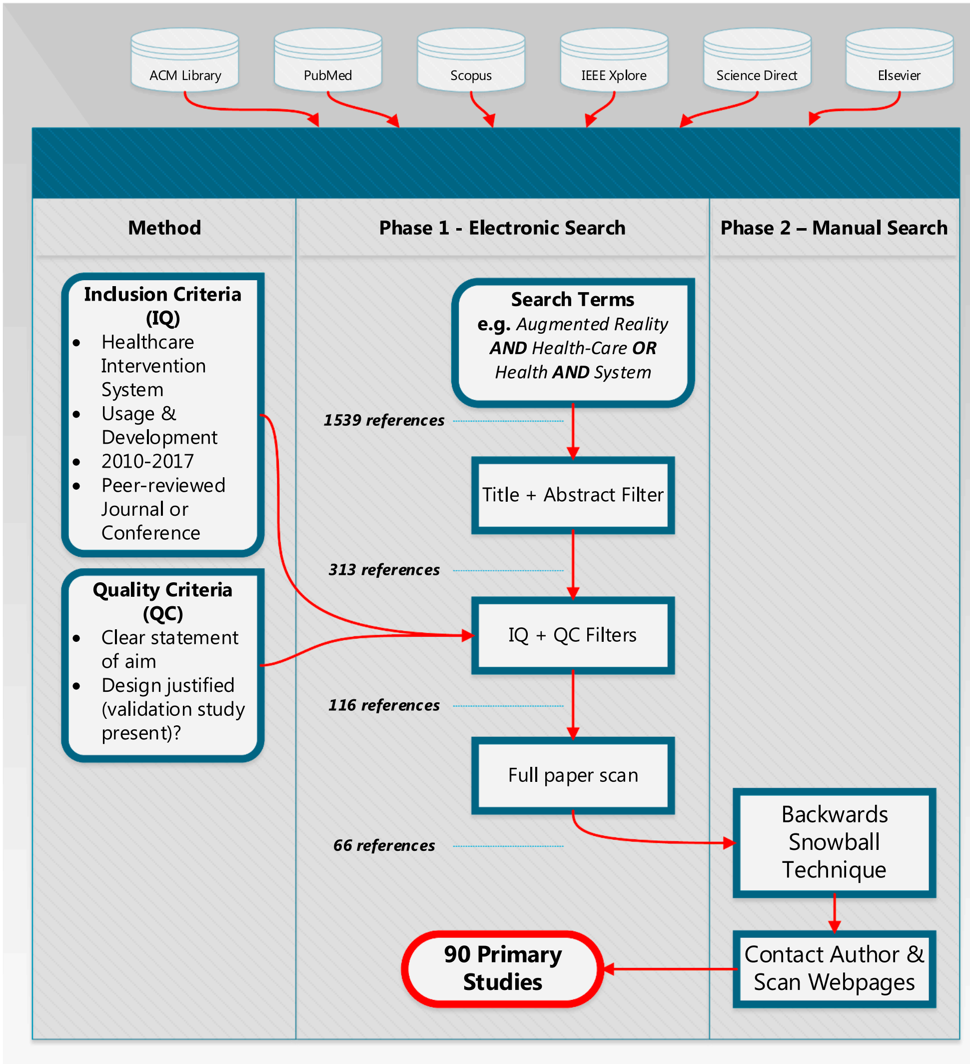

Fig. 2. Detailed literature search strategy adapted from [33] employing quality and search filters.

applying *Phase 2* – Manual Search strategies to gather further literature not available through electronic search patterns. Fig. 2 presents a detailed view of the high-level *Literature Search Strategy* employed.

2.1.1. Method

According to Kofod-petersen [32], the selection of primary studies is done through the deployment of an *IC* and *QC* filter. During this process, the author removes literature from electronic and manual search results that are not thematically relevant to the research area. The established *IC* and *QC* are defined in Table 1. The title, abstract and results of papers included through the *IC* and *QC* are manually scanned according to the pre-set criterion.

Table 1
Inclusion and quality criteria (IC & CQ) adapted from structured literature review in computer science disciplines [32].

Criteria Identification	Criteria
IC 1	The study is presenting a Healthcare Intervention system using CMRT
IC 2	The study describes the usage & development of the system
IC 3	The study is presented between 2010 and 2017
IC 4	The study is peer-reviewed either through a Journal or Conference
QC 1	Is there a clear statement of the aim of the research?
QC 2	Are system or algorithmic design decision justified?

2.1.2. Phase 1 – electronic search

In Phase 1, an electronic search was conducted using five online literature databases these were: *ACM digital library, PubMed, Scopus, IEEE Xplore and ScienceDirect which* have a substantial focus on Computer Science and algorithmic systems deployed across a multitude of research communities including but not limited to healthcare. Initially, a number of survey papers were sourced which provided candidate search terms and keywords to gain knowledge on the research domain [22–24,27,35,36]. Secondly, the search strings were formed by grouping key terms. Each group contains terms that are either synonyms, different forms of the same word, or terms that have

Table 2
Key word synonym groupings.

	Group 1	Group 2	Group 3	Group 4
Term 1	Mediated Reality	Health-Care	System	Intervention
Term 2	Augmented Reality	Health-Delivery	Software	Provision
Term 3	Mixed Reality	Care	Technology	Delivery
Term 4	Virtual Reality	Health		

similar or related semantic meaning within the domain. Table 2 exemplifies this approach.

The four resulting groups identified, can be then be deployed to retrieve different sets of the relevant literature. The primary goal is to find the literature that is the intersection of the sets. Implementing this search strategy can be achieved by applying the AND (∧) and OR (∨) operators. The OR operator can used within the groups and the AND operator between the groups. Using the Keywords identified in Table 2, the following search string exemplifies a single example search:

$$\begin{aligned}&([\text{GROUP 1, TERM 1}] \wedge [\text{GROUP 2, TERM 1}]\\&\quad \vee [\text{GROUP 2, TERM 3}] \wedge [\text{GROUP 3, TERM 1}])\\&= \text{"Mediated Reality } \textbf{AND} \text{ Health}\\&\quad - \text{Care } \textbf{OR} \text{ Health } \textbf{AND} \text{ System"}\end{aligned}$$

2.1.3. Phase 2 – manual search

Once the exhaustive electronic search criterion have been satisfied, the relevant references are stored within a reference management application. Phase 2, employs a backward snowball-technique [37], where the stored literature's reference lists are scanned for potential literature missed in *Phase 1*. Additionally, in exceptional circumstances where an item of literature is not accessible via electronic gateway subscriptions, the relevant authors are contacted in attempts to gain access to the full paper. This forward and backward search approach results in a comprehensive representation of the current research community's efforts in the chosen area.

2.2. Data analysis strategy

The Conceptual Framework was derived as result of surveying and analysing the literature dataset of representative literature formulated in Section 2.1. Thematic analysis was performed to review and categorise the dataset. Thematic analysis is a qualitative analysis method for searching, analysing and representing the *overarching themes* and *sub-themes* that emerge from textual datasets [34]. A *Concept-Centric* approach was taken when applying the thematic analysis technique [38], with a view to developing an overarching narrative-based conceptual representation of the state of the art of CMRT health research. Analysis of the literature dataset, was both inductive, as the development of the themes were data driven, and deductive, beginning with pre-defined (*a priori*) themes that are theory driven and linked to the analytical interest of researcher(s) [39]. The first stage involved deductive coding according to the mode of healthcare delivery CMRT applications support. As specified by the World Health Organisation [40–42], there are three key healthcare delivery stages: Primary-Care; Secondary-Care; or Tertiary-Care interventions. Analysis considered each CMRT application within the sample, and identified which of the three delivery stages are targeted by each respective application. Furthermore, Ventola's [26,43] taxonomy of clinical context for mobile health applications provided eight pre-defined codes that represent the clinical context in which each respective CMRT systems are deployed. Subsequently, the dataset was examined iteratively, and incremental inductive concept-centric thematic analysis was carried out with the goal of modelling emergent themes that represent the interconnected structure and relationships that emerged from the literature. This process involved several stages of splicing, linking, deleting and re-assigning themes and sub-themes. To further develop themes and sub-themes, a consensus pool of themes and sub-themes (*coding frame*) containing the penultimate dataset was reviewed alongside existing literature reviews before a final conceptual representation was arrived at.

3. Conceptual framework for healthcare CMRTs

A detailed description of the conceptual framework is presented in this section. Fig. 3 presents the Conceptual Framework of Healthcare CMRT.

3.1. Patient-practitioner interaction paradigm & delivery stage

The Conceptual Framework of Healthcare Computer Mediated Reality Technologies presented in this section provides a concept-centric representation of the state of the art in CMRT applications for healthcare. There are a wide range of CMRT systems presented in the literature, which aim to assist in the delivery of healthcare interventions according to three *Patient-Practitioner Interaction Paradigms (PPIP)*: (1) *Traditional CMRT Systems* support healthcare interventions that typically occur within the hospital setting and support the practitioner in their traditional role as the expert; (2) *Collaborative CMRT Systems* support health interventions that are delivered either within the hospital or home setting, and support collaboration between patient and practitioner as joint experts; (3) *Patient-Centred CMRT Systems* enable the service user to be the primary expert (but permit some practitioner-based input occasionally) and enable delivery of self-care interventions outside of the clinic/hospital settings.

CMRTs can aim to support health interventions at numerous *Delivery Stages*. These are informed by the health intervention delivery stages as defined by the World Health Organisation [40–42]. CMRTs that focus on the *Primary* care stage provide support for the first point of contact with the patient and aims to provide diagnosis of disease, to prevent further complications, and to promote preventative health awareness and proactively encourage healthy behaviour in the population. CMRTs for *Secondary* care stage interventions provide support for interventions that have already progressed through the primary stage and have been referred to the secondary stage by a primary care professional. Typically, these are consultant-led services that focus on treatment and health promotion to prevent re-occurrence of the condition/injury. The *Tertiary* care stage delivers highly specialised treatment. Usually patients at this level of care are facing issues that cannot be cured and hence careful management of chronic and complex conditions is prioritised along with maximising patient function, quality of life and life expectancy. Some examples of tertiary stage interventions include neurosurgery, cardiac surgery and cancer management.

3.2. Clinical context & clinical setting

The clinical context that CMRTs are developed for may be categorised using the taxonomy of clinical context for mobile health applications [26,43]. Table 3 presents the eight clinical contexts used to categorise CMRTs in this survey, and provides their respective definitions and example areas of application.

Interventions delivered by CMRTs may be deployed across three treatment settings: *Home* typically incorporates treatment settings that include the patient home but also incorporates treatment settings that the patient spends time in, outside of the traditional clinical settings. *Clinic* relates to all clinical settings that exclude the hospital setting such as GP surgeries, nursing homes, health centres, and community treatment clinics. The *Hospital* setting relates specifically to treatment that is delivered within a general hospital setting.

3.3. System Specification

In terms of the *System Specification,* i.e. the types of mediated technology deployed by respective CMRT systems, the type of software and hardware used, and the types of user interaction supported, numerous themes and sub-themes emerged from the analysis. Table 4 presents the emergent *System Specification* categories used in this survey.

Mediated Technology defines the type of technology employed as part of the system being reviewed. The grouping comprises of *Augmented Reality (AR)*, *Virtual Reality (VR)*, *Mixed Reality (MR)* and *3-Dimensional*

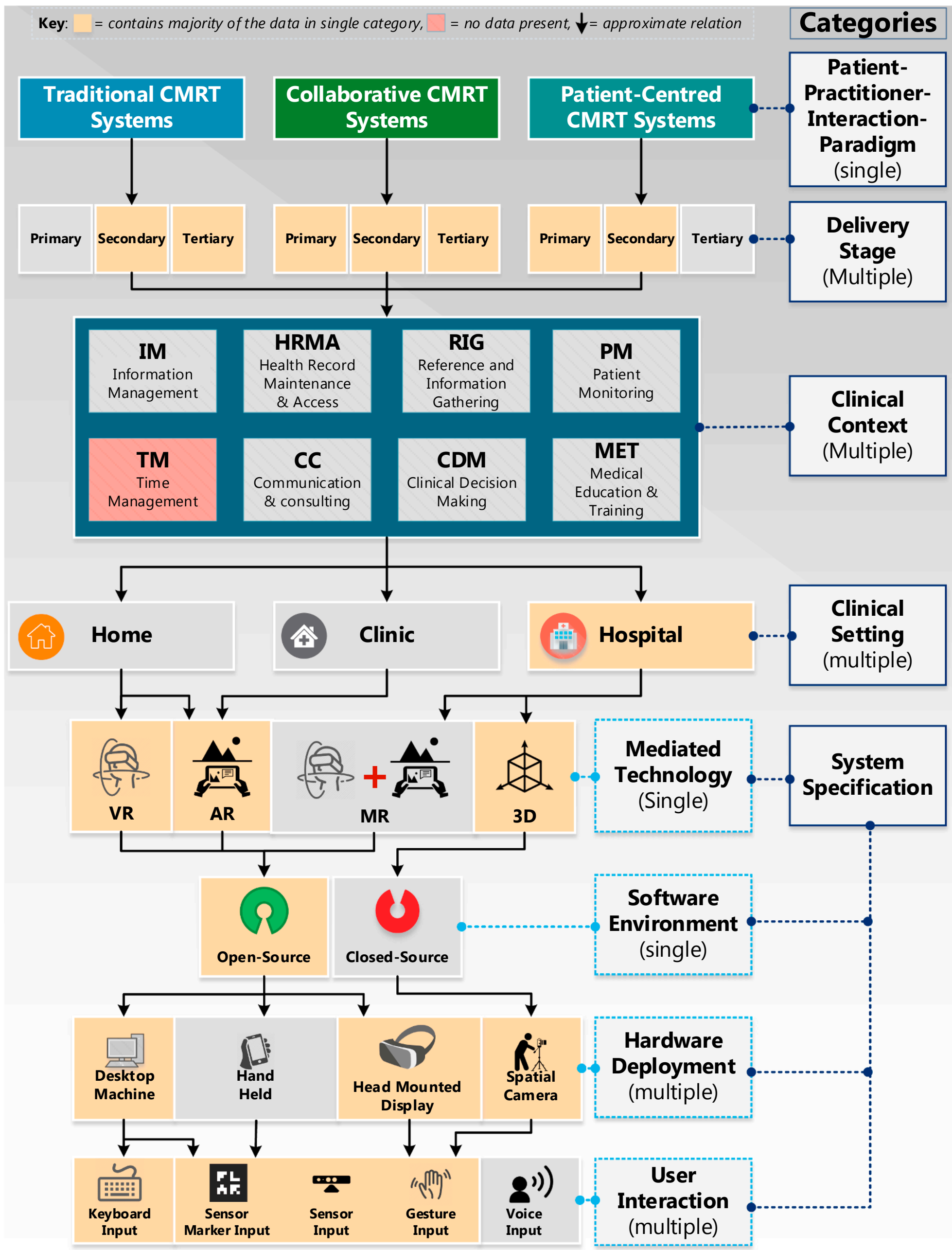

Fig. 3. Conceptual framework for healthcare computer mediated reality technologies.

Modelling (3DM). The *Software Deployment* states whether the software deployed as part of the *Mediated Technology* system is *Open-Sourced* (OS), defining if it is community driven and the source code can be accessed easily, or *Closed-Sourced* (CS) where the software is deployed as an Application Programming interface (API) or Software Development Kit (SKD). The source code behind *CS* software cannot be

Table 3
Clinical context acronyms & definitions [26,43].

Acronym		Context	Examples
1	IM	Information Management	Take Photographs, Dictate Notes
2	TM	Time Management	Schedule Appointments, Record Call Schedule
3	HRMA	Health Record Maintenance and Access	Access e-Health/Medical Records, Access Images and Scans
4	CC	Communication and Consulting	Voice/Video Call, Multimedia Messaging
5	RIG	Reference and Information Gathering	Medical Textbook/Journals/Literature, Drug Reference
6	CDM	Clinical Decision Making	Decision Support system, Treatment Guidelines, Disease Diagnosis, Medical Exams and Interpretation
7	PM	Patient Monitoring	Collect Clinical Data, Monitor Health/Location/Safety
8	MET	Medical Education and Training	E-Learning/Teaching, Surgical Simulation, Continuing Medical Education, Skill assessment tests

Table 4
System specification acronyms & definitions.

Category	Acronym	Definition
Mediated Technology	AR	Augmented Reality
	VR	Virtual Reality
	MR	Mixed Reality
	3DM	3-Dimensional Modelling
Software Deployment	OS	Open-Sourced
	CS	Closed-Sourced (Proprietary)
Hardware Deployment	DM	Desktop Machine
	HH	Hand-Held/Mobile Device
	HMD	Head-Mounted-Display
	SC	Spatial Camera
User Interaction	KI	Keyboard Input
	SMI	Sensor-Mark Input
	SI	Sensor-Input
	VI	Voice-Input
	GI	Gesture Input

edited and is hidden from developers. Furthermore, *Hardware Deployment* focuses on categorising the systems hardware usage and has four variables; *Desktop-Machine (DM)*, *Hand-Held (HH)* device, *Head-Mounted-Display (HMD)* and *Spatial Camera (SC)*. The devices which are categorised are necessary pieces of equipment dependant on the CMRTs used. Finally, *User Interaction* defines the interaction a patient or healthcare practitioner would have with the necessary pieces of equipment. The types of input are defined as: *Keyboard Input (KI)*, *Sensor-Mark-Input (SMI)*, *Sensor-Input (SI), Voice-Input (VI) and Gesture-Input (GI)*. The *SMI* and *SI* variables, specifically define whether the system requires a marker to be used for registration of depth or visual data, as this is a key factor identifying the over usability and efficiency and invasiveness of the CMRT systems at the time of care provision.

3.4. Impact assessment

In addition to the conceptual representation, the CMRT applications have been individually assessed based on the studies' *Research Quality* (Empirical Value) in accordance with the National Service Framework (NSF) Quality Assessment Criteria [44]. Furthermore, the *System Value* is assessed according to the extent to which the proposed system delivers the more desirable factors of the outlined in the Patient-Practitioner Interaction Paradigm (as described in Section 3.1) i.e. to deliver more patient-centred, preventative, feasibly deployable, and widely adoptable CMRTs. The specific rationale and scoring criteria used for this value score is outlined in detail later in this section.

3.4.1. Research quality

In line with the NSF presented by the American Heart Association (AHA) [45], each research paper included in the sample has been awarded a rating based on three categorisations: Design, Quality and Applicability which reflects the empirical value of each study. The categories require a level of evidence supporting the markers of good practice which have been outlined in the tables below. *Research Quality* has been assessed using five questions with a possible score on each question of 0, 1 or 2 – giving a maximum score of 10, as indicated in Table 5. In accordance with the NSF scoring criteria, high quality research studies are those which score at least 7/10. Medium quality studies score 4–6/10. Poor quality studies score 3/10 or less.

Table 5
Quality assessment.

Each quality item is scored as follows: Yes = 2, In part = 1, No = 0 Score		Score
1	Are the research question/aims and design clearly stated?	
2	Is the research design appropriate for the aims and objectives of the research?	
3	Are the methods clearly described?	
4	Is the data adequate to support the authors' interpretations/ conclusions?	
5	Are the results generalizable?	
	Total	**/10**

3.4.2. System value

In line with the need to overcome the ever increasing scarcity of resources gap, it is imperative that new systems focus on the enablement of a shift towards more patient-centred self-care interventions via the novel development and use of state of the art CMRT technologies. Indeed, it is recognised that we are in the midst of a shift towards the delivery of more personalised health system, in which patients should be provided with gradual opportunities of become stakeholders and intellectual partners in patient-centred treatments and outcomes [46]. In recognition of this, a bespoke *System Value* score has been calculated for the literature sample included in this study. In essence, the bespoke System Value score attributes higher scores to CMRTs that aim to deliver patient-centred, primary preventative, widely and feasibly deployable, that are widely applicable across a range of clinical contexts. Table 6 presents the System Value assessment taxonomy employed to score the studies included in the literature sample and details of the associated rationale for the scoring carried out.

CMRT systems therefore are categorised using three distinct levels of System Value: Low value systems are those with scores of 10/30 or less, Medium value systems score 11–20/30, High value systems score 21/30 or higher.

3.5. Traditional health – care CMRT systems

Table 7 presents systems that have been identified as delivering care using a *Traditional* approach between patient and practitioner as described by in Section 3.1. Subsequently**,** the data presented in Table 7 is described according to the Conceptual Framework for Healthcare CMRTs which is formally presented in Section 3.

3.5.1. Delivery stage

Analysis of the literature dataset reveals that there are no Traditional Healthcare CMRT systems that focus solely on the delivery of *Primary* care interventions. All systems that deliver Primary care interventions additionally deliver either *Secondary* and/or *Tertiary* interventions [47,48,50,59,77]. For example [47] deliver Parkinson's dance therapy, displaying preventative dance techniques for the general older adult population, hence subscribing to *Primary* prevention practices, but simultaneously delivering *Tertiary* interventions when used by patients who have already presented with Parkinson's. The studies presented in [48,50,59] deliver *Primary*, *Secondary* and *Tertiary* interventions in the domains of Anaesthesia Simulations [59], Vein Imaging [48] and Wound Measurement [50]. An example of how such systems are applied across all three categories are exemplified via the wound measurement system [50] which adapts 3D wound models and captures metric measurements using a *Hand-Held (HH)* iPad tablet and Structure Scanner. The measurements such as length, width, depth, perimeter, area and volume can employed by nurses at the *Primary* prevention stage and apply appropriate dressing to prevent future damage or incorrect healing. Additionally, the same metrics can be used for more specialised treatment such as growth-factor therapy at *Secondary* or invasive surgery planning at *Tertiary* stage.

Systems that focus exclusively on *Secondary* care interventions are more frequently presented in the literature [56,63,65,68,76,79,84,85]. These systems are implemented in a variety of medical contexts such as; human anthropometric measurements [76,79,84], clinical malignant breast examinations [85] and pathology examinations [63]. Body shape evaluation in adolescent scoliosis is an example of these systems, which develops a validated simulation tool that allows clinicians to illustrate the potential result of the surgery to patients in comparison to other non-invasive techniques [56]. Numerous studies deliver both *Secondary*

Table 6
System value assessment scoring taxonomy.

Conceptual Category	Sub – Category	Rationale		Score
Delivery Stage	*Primary*	Would be better than Secondary (more preventative).		3
	Secondary	Would be better than Tertiary (more preventative).		2
	Tertiary	Least preventative.		1
Clinical Context	*Eight clinical contexts*	The more clinical contexts, the more desirable. One point for each context.		8
Clinical Setting	*Home*	Lowest level of integration/interoperability requirements.		3
	Clinic	Mixed integration.		2
	Hospital	Requires tethering to hospital systems, more integration and intraoperative development needed.		1
System Specification	*Four Mediated Technologies*	Equally valuable technologies, hence one point for each technology deployed.		4
	Software Environment	Open Source is of more value than Closed Source due to ease of deployment and cost benefit of implementation in accordance with current systems.	OS CS	1 0
	Hardware Deployment	The higher the number of hardware types the less desirable due interoperability and integration complexity)		4 - n
	User Interaction	Sensor and natural gesture capture/input are most desirable as they offer natural, rich, and unobtrusive data input opportunities. Keyboard and sensor marker input are less desirable, obtrusive and less naturalistic forms of data input.	Sensor, Gesture, Voice Keyboard, Sensor Mark	1 0
Total Max				**/30**

and *Tertiary* interventions [52,57,61,64,69,71,78,80,81,87–89]. Needle placement appears to be a prominent area of focus for such systems, specifically exploiting the visualisation capabilities of CMRTs. For example, [57,64,69,91] use the visualisation aspect for needle placement and haptic feedback and propose a variety of training systems to promote health whilst also delivering highly specialised treatment. An example of how needle placement systems deliver at *Secondary* and *Tertiary* levels can be seen in [64], which delivers *Secondary* care by virtualising partially segmented patients and mimicking haptic interaction with the virtual patient during palpation, ultrasound probing and needle insertion, whilst at the *Tertiary* level, focusing on cholangiography which requires needle insertion of the bile ducts, which would form part of surgical treatment. Dental surgery systems are another prominent theme for *Secondary* and *Tertiary* care CMRTs. For example, [80] delivers *Secondary* care using high speed and accurate 3D Dental iOS Scanning system to create bespoke dental abutments, and *Tertiary* care through the same system for scanning the oral cavity and providing potential planning for surgical intervention if need be. Other examples of *Secondary* and *Tertiary* clinical applications include; X-Ray imaging, biopsy training, anaesthesia simulation, facial measurements, spinal scoliosis analysis, bone cutting procedures, haptic palpitations, and orthopaedics respectively [52,61,71,78,81,87,88,92].

The systems presented in [49,53–55,58,60,62,66,67,70,72–75,82,83,90] focus on delivering *Tertiary* care exclusively in different forms such as surgical procedures or training methods for surgical procedures. The re-occurring theme of dental treatment is also evident within pure *Tertiary* care for visualisation purposes of guided bracket placement in orthodontic correction [only 1 available 71]. For example, [83] delivers *Tertiary* based care using image tracking of teeth using CT images of the jaw. The image tracking is fundamental aspect in orthodontic correction due to the time consuming process and potential of not being corrected fully. Liver and MRI guided surgery follows quite complex interventions and the usage of bespoke systems for training purposes, [67,74] display unique surgical systems through a combination of different technologies where Mediated Reality forms a small part. The *Tertiary* aspect proposed by [74] aims to delivery an improvement to the current MRI Guided Needle surgery by using 3D images modelled from animated autostereoscopic images and integral videography (IV).

3.5.2. Clinical context

In terms of *Clinical Context,* Clinical Decision Making *(CDM)*, Patient Monitoring *(PM)* and Medical Education/Training *(MET)* are the areas that the majority of systems focus on. Numerous systems focus exclusively on these three contexts [48,57–59,69,78,82,89]. The bone cutting procedure presented in [78] is one example that demonstrates a mixture of contexts such as Treatment Guidelines *(CDM)* and Surgical Simulation for cutting *(MET)*, and collecting clinical data for evaluation purposes *(PM)*. A smaller number of systems portray all three *Clinical Context* with one or two additional clinical focuses [50,52,55,62,70,75,77,80]. For example, Wu [50] proposes a *Hand-Held* mobile system for wound measurement, structure sensor technology deployed on a tablet device enables the practitioner to collect chronic wound dimensions. The application takes 3D photographs (models) and provides wound measurements using structure scanning technology *(IM)*. The 3D scans can be stored and retrieved *(HRMA)* which has the potential to enable clinical decisions at a later stage and identification of different types of wounds *(CDM)*. The clinical data collected through the scanned 3D models can be analysed through external software (PM) and can also serve an educational tool for wound care nurses *(MET)*.

Whilst systems delivering application within the CDM, PM, and MET contexts are able to deliver specialised treatment and also serve as platform that delivers training, a number of systems aim at achieving similar results but do not collect clinical data for patient monitoring *(PM)* purposes [49,61,64,67,71,74,85,87,88]. Simulated needle placement/insertion is a prominent area of focus for such systems [61,64]. The data collected by these systems relates to the trainee's performance whilst carrying out a simulated procedure and not on data sourced directly from the patient. Furthermore, the systems presented by [67,71,74] remain within the *CDM* and *MET* domain but include a focus on Information Management *(IM)* context or accessing previously scanned images *(HRMA)*. Illustrative visualisations presented by [67] for pre-planned models in liver surgery contains features such as; dictating notes while in surgery through the developed system alongside surgical simulation and treatment guidelines. Information sharing between practitioner and patient is also achieved by [71] via 3D photographs that enable the evaluation of the success of reconstructive facial surgery.

Systems that focus on *PM* with one or two additional settings are presented in [47,51,56,65,66,68,76,79,81]. For example [47] targets patients with Parkinson's using dance therapy classes combined with Google Glass technology. *PM* and *MET* are crucial factors in this system as the health, safety and therapy education form part of the proposed intervention. Another example is [56], who delivers a Body Shape Analysis system for Idiopathic Scoliosis. It involves taking photographs using 3D imaging *(IM)*, retrieval of captured images *(HRMA)* and collecting clinical data over a period of time forms part of the evaluation of the patient's health *(PM)*. *PM* and/or *CDM* have also been presented through anthropometry measurements [51,56,65,68,71,76,79], with exception of [66] who delivers objective gait analysis *(CDM)* for

Table 7
Traditional computer mediated reality technology systems.

System	Delivery Stage			Clinical Context								Clinical Setting			System Specification				Impact	
	Primary	Secondary	Tertiary	IM	TM	HRMA	CC	RIG	CDM	PM	MET	Home	Clinic	Hospital	Mediated Tech.	Software Deploy.	Hardware Deploy.	User Interaction	Res. Quality (/10)	Sys. Value (/30)
Abbasi et al. [47]	X		X							X	X	X	X		AR	OS	HMD	SI,GI	7	18
Ai et al. [48]	X	X	X						X	X	X		X	X	AR	OS	SC	SI	7	18
Andersen et al. [49]			X	X			X		X		X			X	AR	CS	HH	SI,GI	6	12
Anghel et al. [50]	X	X	X	X		X			X	X	X	X	X	X	3DM	OS	HH	SI,GI	7	24
Arenas et al. [51]		X		X					X	X			X		3DM	OS	HH	SI	5	13
Blum et al. [52]		X	X	X					X	X	X		X	X	AR	CS	HMD	KI,GI	4	15
Borgmann et al. [53]			X	X		X	X	X		X	X			X	AR	OS	HMD	SI	7	14
Bourdel et al. [54]			X			X			X					X	AR	CS	SC	SI	6	9
Chen et al. [55]			X			X			X	X	X			X	AR	OS	DM,HMD	KI	8	10
Cheriet et al. [56]		X		X		X				X			X		3DM	CS	DM,SC	KI,SI	8	11
Coles et al. [57]		X	X						X	X	X		X	X	AR	OS	SC	SI,GI	6	16
Dehbandi et al. [58]			X						X	X	X		X		3DM	OS	DM,SC	SI	6	11
Deserno et al. [59]	X	X	X						X	X	X		X		VR	OS	DM	KI	8	16
Dickey et al. [60]			X								X			X	AR	OS	HMD	SI,VI	6	10
Dong Ni et al. [61]		X	X						X		X		X	X	VR	CS	DM	KI,GI	6	13
Fan et al. [62]			X			X			X	X	X			X	3DM	OS	HH	SI	7	12
Farahani et al. [63]		X				X			X				X		VR	OS	DM,HMD	KI	8	10
Fortmeier et al. [64]		X	X						X		X		X	X	VR	OS	DM	KI,GI	7	14
Galantucci et al. [65]		X							X	X			X		3DM	CS	DM,SC	KI,SI	7	10
Gholami et al. [66]			X						X	X			X		3DM	OS	DM	KI,SI	6	11
Hansen et al. [67]			X	X					X		X		X	X	AR	CS	DM,SC	GI	7	11
Hsu et al. [68]		X		X						X			X		3DM	CS	SC	SI	8	11
Kanithi et al. [69]		X	X						X	X	X		X	X	AR	CS	SC	KI,SMI	7	13
Khanal et al. [70]			X				X		X	X	X		X	X	VR	OS	DM	KI,GI	7	14
Kovacs et al. [71]		X	X	X					X		X		X		3DM	CS	DM,SC	KI,SI	7	12
Kramers et al. [72]			X			X			X					X	AR	CS	HMD	SMI	5	8
Li et al. [73]			X			X			X					X	AR	OS	DM,SC	SMI	4	8
Liao et al. [74]			X	X					X		X			X	AR	CS	SC	SMI	7	9
Lin et al. [75]			X			X			X	X	X		X	X	VR	OS	DM	KI,GI	9	14
Liu et al. [76]		X							X	X			X		3DM	CS	DM,SC	SMI	7	9
Mithun et al. [77]	X	X		X					X	X	X		X	X	AR	CS	DM	KI	7	16
Nakao et al. [78]		X	X						X	X	X		X	X	AR	OS	SC	SI	4	15
Ng et al. [79]		X							X	X			X		3DM	CS	DM,SC	SI	6	10
Park et al. [80]		X	X	X			X		X	X	X		X		3DM	CS	DM,SC	KI,SI	5	14
Paul et al. [81]		X	X						X	X			X		3DM	CS	DM,SC	KI,SI	6	11
Qi et al. [82]			X						X	X	X		X	X	VR	OS	DM	KI,GI	8	13
Reichl et al. [83]			X					X	X				X		AR	CS	DM	KI	7	9
Schloesser et al. [84]		X						X	X				X		3DM	CS	DM,SC	KI,SI	5	10
Solanki et al. [85]		X							X		X		X		AR	CS	DM	KI,GI	6	11
Theopold et al. [86]			X			X			X				X	X	3DM	CS	DM	VI,KI	7	11
Ullrich et al. [87]		X	X						X		X		X	X	VR	OS	DM	KI,GI	8	14
Vankipuram et al. [88]		X	X						X		X		X	X	VR	OS	DM	KI,GI	8	14
Wang et al. [89]		X	X						X	X	X		X		AR	CS	DM,SC	KI,SMI	7	11
Yudkowsky et al. [90]			X			X			X					X	MR	CS	DM,SC	KI,SI	5	8
Overall Mean																			**6.6**	**12.3**

Acronym description: **AR** = Augmented Reality, **VR** = Virtual Reality, **MR** = Mixed Reality, **3DM** = 3D Modelling; **OS/CS** = Open/Closed Source; **DM** = Desktop Machine, **SC** = Spatial Camera, **HMD** = Head Mounted Display, **HH** = Hand Held; **KI** = Keyboard Input, **SI/SMI** = Sensor/Sensor Mark Input, **GI** = Gesture Input, **VI** = Voice Input; **Poor quality study** 3/10, **Medium quality Study** 4–6/10, **High quality study** 7/10; **Low value system** 10/30 or less, **Medium value system** 11–20/30, **High value system** 21/30 or more.

objective multiple sclerosis assessment (PM). Nonetheless, derivable body volume and metrics are gathered to estimate body composition, human energy requirements in morphology and diagnose malnutrition in resource-poor clinical settings *(PM).* Additionally, product manufacturing and physical ergonomic solutions are evaluated in order to improve comfort, health, safety, and productivity (*CDM*) [76,79].

Systems that purely focus on MET are few in number [60]. The Google glass technology employed by [60] has been deployed as a urologic training tool and contains steps for prosthesis placement.

A number of systems focus on delivering pre-operative or pre-captured scans for surgical intervention *(HRMA)* and surgical navigation aids or systems *(CDM)* [54,63,72,73,86,90]. Some of the surgery subdomains covered by these systems include laparoscopic myomectomy, pathology examination, neurosurgical guidance, and endoscopic sinus surgery. For example, [72] delivers a mobile platform that utilizes augmented reality and image-based tracking in order to add preoperative contextual *(HRMA)* information to neurosurgical procedures *(CDM)*, specifically providing augmented spatial information whilst carrying out surgical procedures.

3.5.3. Clinical setting

None of the CMRTs presented in the sample focus solely on the *Home* setting. Two Traditional CMRTs however, do cater for the *Home* alongside Clinic and/or Hospital settings [47,50]. The Parkinson's therapy system [47] using Google Glass technology that is intended to be used either in the *Home* or the *Clinic*. Furthermore, the wound measurement system deployed using a hand-held tablet device presented in [50] is intended for use in all three settings, i.e. *Home*, *Clinic*, or *Hospital*.

A much larger proportion of systems are designed for deployment in the *Clinic* or *Hospital*, with approximately half of the systems presented in the literature sample conforming to this category [48,52,57,61,64,67,69,75,77,78,82,86–88,91]. From these systems; a prominent theme for both needle placement and biopsy training systems is on needle handle and control, albeit for altered contexts such as training, patient comfort and treatment which requires *Clinic* or *Hospital* based training and delivery settings [57,61,69].

The remaining systems focus solely on either the *Clinic or the Hospital* setting. Systems focused purely on the *Clinic* do not require full surgical or operating theatre settings to be deployed [51,56,58,59,63,65,66,68,76,79–81,83–85,89]. For example, areas such as body shape analysis [56], facial analysis [65,71] and dental care [80,83,89] do not require hospitalisation of the patients and can be performed in the local clinic. This is also the case for the spine analysis [81] and anaesthesia simulation [59] examples in the sample. The systems deployed within pure *Hospital* settings are all developed for supporting surgical procedures [49,53,54,60,72,73,89,90]. Despite the training nature of the tools developed, they require full surgical theatre settings and hence require the hospital setting for deployment.

3.5.4. System specification

3.5.4.1. Mediated technology. Approximately half of the *Traditional* systems presented in the literature sample make use of *AR* technologies to overlay additional information onto the current reality through either a wearable or fixed computer aided interface [47–49,52–55,57,60,67,69,72–74,77,78,83,85,89]. The full range of *Mediated Technology* is deployed across the *Traditional* systems landscape and for a variety of care settings and often for the *CDM*, *PM* and *MET* clinical contexts. For example, AR tends to be associated with *CDM*, *HRMA*, and *MET*. As an example, [52] use AR to visualise pre- or intra-operative images onto the patients anatomy with a view to making decisions going forward (CDM, PM, MET). Whereas, [47] uses AR to portray Parkinson's therapy exercises onto the environment rather than a patients anatomy (PM, MET). With regards to systems that utilise *VR* technologies, simulation of medical procedures tends to be the typical function (MET) of such technologies [59,61,63,64,70,75,82,87,88]. For example simulation and modelling for training for specialist procedures is an emerging area, specifically needle practices to avoid patient harm by inexperienced practitioners [61,64,75,82]. Within regards to VR where we have different types of care such as orthopaedic surgery [88] and a simulated environment for training purposes is required which can provide realistic haptic feedback, which yet again influences the type of mediated technology deployed.

Many of the *3DM* systems tend to be delivering systems that support *IM, CDM, PM* clinical contexts [50,51,56,58,65,66,68,71,76,79–81,84,86]. For instance, modelling the outcome of a specific treatment such as facial measurement for potential surgery [65,71] requires the usage of capturing and manipulating *3DMs* (*IM*). Likewise, capturing the current state of a patients dental health (*IM, PM*) [80], or analysing spinal scoliosis (CDM, PM) [81] again which is linked to the usage of mediated reality technology type. One system delivers care in the *Traditional* care stage via *MR* for ventriculostomy, a neurosurgical procedure [90]. The therapeutic cerebrospinal fluid drainage is simulated with a library of virtual brains (VR) on neurosurgery residents' performance in simulated and live surgical Ventriculostomies. With the usage computed tomographic scans of actual patients, a library of 15 virtual brains was developed and a head and hand-tracked AR and haptic simulator formed part of the final system for intervention training.

3.5.4.2. Software deployment. The majority of the systems be deployed used bespoke *Closed-Source* (*CS)* software [49,52,54,56,61,65,67–69,71,72,74,76,77,79–81,83–86,89,90]. For example, [72] has deployed an AR based system using the Vuforia Software SKD which is closed system and is open community based modifications to the code. Another example is [76] who uses 3D modelling for human body anthropometric measurements. The system is deployed using Computer Aided Design (CAD) to process 3D measurements and displays modelled body shapes, which again is a closed system.

The remaining half of the data propose *OS* based systems [47,48,50,51,53,55,57–60,62,63,66,70,75,78,82,87,88]. Examples of *OS* based systems are presented in [47,60] who use the Google Glass SDK for training procedures and uses *OS* Application Programming Interfaces *(API)* which can be modified by the community. However, these modifications must remain in-line with Google's development guidelines. Another example is shown by [63] who employs the Oculus Rift's open sourced software for pathology examinations through an *HMD*.

3.5.4.3. Hardware deployment. The *Traditional* systems tend to utilise three of the four hardware deployment categories (*DM*, *HMD*, *SC*) fairly frequently, however, pure HH hardware deployments tend to be less frequently used, with only four examples of such deployments being presented within the sample. For example, a wound care system using HH is presented in [50], and HH based brachytherapy mould casting is presented in [51], and a medical tele-monitoring intervention using HH in the form of a hand held surface scanner is presented in [49]*,* and a mobile spatial information acquisition system and autostereoscopic display for surgeons to observe surgical target intuitively [62]. The usage of pure *HMD* systems is more frequent [47,52,53,60,72,93]. Whilst [47] uses *HMD's* to visualise physical exercises onto a patient's plane, [52] uses different types of HMD's to augment medical images onto a patient's anatomy. Systems that deploy CMRT and the associated algorithms using only *DM* deployment, are even more frequent [59,61,64,66,70,75,77,82,83,85–88]. Out of these systems, a considerable number deploy *DM's* as a method of interaction between the captured data and the clinician or trainee. For example [87] uses a desktop interface as interaction between system and trainee for educational Haptic palpitations purposes in a virtual environment. Similarly, [59] propose a simulation tool for Anaesthesia procedures. There are also a set of systems that purely deploy SC's attached to

Table 8
Collaborative computer mediated reality technology systems.

	Delivery Stage			Clinical Context								Clinical Setting			System Specification				Impact	
Systems	Primary	Secondary	Tertiary	IM	TM	HRMA	CC	RIG	CDM	PM	MET	Home	Clinic	Hospital	Mediated Tech.	Software Deploy.	Hardware Deploy.	User Interaction	Res. Quality (/10)	Sys. Value (/30)
Abushakra et al. [94]		X								X	X	X			VR	CS	HMD	GI,VI	6	13
Aung et al. [95]		X								X	X		X	X	AR	CS	DM,SC	KI,SMI,GI	5	11
Banerjee et al. [106]	X								X	X		X	X		3DM	CS	DM,SC	GI,SMI	6	14
Bernabei et al. [103]	X	X	X				X		X	X	X	X	X	X	3DM	OS	SC	SI	3	22
Bian et al. [107]	X								X	X		X	X		3DM	OS	DM,SC	GI,SMI	6	15
Bianco et al. [108]	X					X			X			X			AR	CS	HH	SI	6	13
Bifulco et al. [109]	X	X							X	X	X	X	X	X	AR	CS	HMD	KI,SMI,VI	7	19
Brinkman et al. [96]		X							X	X			X		VR	CS	DM,HMD	KI	6	9
Chinthammit et al. [110]	X	X					X		X		X	X	X		AR	CS	HMD	SI	7	18
Gorini et al. [97]		X							X	X		X	X		VR	CS	HMD	SI	7	14
Herrero et al. [104]		X	X						X	X		X	X		VR	CS	DM,SC	KI	4	13
Hurter et al. [111]	X								X	X		X	X		MR	OS	HMD	SI	3	16
Jeffs et al. [98]		X							X	X		X	X		VR	CS	SC	SI	3	14
Kakadiaris et al. [105]	X	X	X	X				X	X	X	X	X	X	X	AR	OS	HH	SI	4	23
Maani et al. [112]		X	X						X	X			X		VR	CS	DM,HMD	GI	4	11
Malinvaud et al. [99]		X							X	X		X	X		VR	CS	DM,HMD	GI	6	13
Money et al. [100]		X							X		X	X			VR	OS	DM	KI	9	12
Ponce et al. [101]		X		X			X			X		X			AR	OS	HH	SI	4	14
Raghav et al. [113]	X								X	X		X	X		VR	OS	DM,HMD	KI,SI,GI	9	16
Stone et al. [114]	X						X		X	X		X			3DM	OS	DM,SC	GI	7	14
Dijkstra et al. [115]	X								X	X		X	X		VR	CS	DM,HMD	KI	6	13
Tashjian et al. [116]	X								X	X				X	VR	OS	DM,HMD	KI	6	10
Vankipuram et al. [117]	X	X					X		X		X		X		VR	CS	DM	KI	7	14
Wang (F) et al. [118]	X						X		X	X		X			3DM	CS	DM,SC	GI	7	13
Wang et al. [119]		X				X			X				X		3DM	CS	DM	KI,SI	5	11
Weiß et al. [102]	X	X	X						X		X		X		AR	CS	HH	SMI	5	14
Wiederhold et al. [120]		X							X	X		X	X		VR	CS	HMD	KI	5	13
Wrzesien et al. [121]	X								X	X		X	X		AR	CS	DM,HMD	KI,SI	5	14
Yu et al. [122]	X								X	X		X			3DM	CS	DM,SC	SI	6	12
Overall Mean																			**5.7**	**14.1**

Acronym description: **AR** = Augmented Reality, **VR** = Virtual Reality, **MR** = Mixed Reality, **3DM** = 3D Modelling; **OS/CS** = Open/Closed Source; **DM** = Desktop Machine, **SC** = Spatial Camera, **HMD** = Head Mounted Display, **HH** = Hand Held; **KI** = Keyboard Input, **SI/SMI** = Sensor/Sensor Mark Input, **GI** = Gesture Input, **VI** = Voice Input; **Poor quality study** 3/10, **Medium quality Study** 4–6/10**, High quality study** 7/10**; Low value system** 10/30 or less, **Medium value system** 11–20/30, **High value systems** 21/30 or more.

medical instruments [48,54,57,68,69,74,78]. Laparoscopic surgery and imaging is one area that targets to minimise usage of multiple devices that could obstruct the procedure. For example, [78] focusses on augmenting Bone Cutting procedures using endoscopic images.

Many studies in the sample utilise multiple hardware deployment technologies as part of the proposed system. For example, a sizeable set of systems use *DM's* alongside additional *SC* devices [56,58,65,67,71,73,76,79–81,84,89,90]. For instance, [56,81] comparably require spatial devices to measure external bodily features and process them using dedicated or bespoke machines. One system, [63], explores VR Pathology Examination using a *HMD* to immerse the pathologist in an virtual environment where images can be visualised. A *DM* was also employed to provide a platform for storing said images which can be viewed virtually through the HMD.

3.5.4.4. User interaction. A substantial proportion of *Traditional* systems are *KI* systems deployed along with one other additional *User Interaction* method [52,55,56,59,61,63–66,69–71,75,80,81,83,84,86–90]. From these system, the *GI* is a common additional User Interaction method of interaction due to often being deployed for 'hands-on' clinical procedures [52,61,64,70,82,87,88]. For example; the needle placement [64], haptic palpation [87] and orthopaedic procedures [88] require practical training aspects and trainee's must experience the sensation of inserting needles into complex and dangerous areas of the body. Moreover, [56,65,71,80,81,84,90] proposed an additional *SI* category. For example, [56] requires marker-less visual input for body shape analysis opposed to [69,89] who propose *SMI* for visual marker based registration to deliver care.

A large number of systems propose system interaction solely through *SI* [48,51,53,54,58,62,68,78,79] or combined with one an additional category [47,49,50,57,60]. For example, systems that deploy interventions purely using sensor based input are non-invasive and reoccurring areas of research often focus on anthropometrics [50,56,68,71,76,79,84] such as wound measurement or hand surface estimation. From these systems, [68] employs a comparable 3D surface scanner to model/estimate hand and palm surface areas in contrast with pre-captured MRI Scans, the visual data inputted is environmental and does not employ any markers or other tools to capture 3D measurements. Systems that display usage of markers are less frequently presented in the sample *(SM)* [72–74,76]. For example, [73] receives visual input for endoscopic navigation from sensor markers and preoperative images which allows surgeons to stereoscopically observe the subsurface and surrounding anatomical structures of the surgical field, providing more detailed and intuitive information for safer surgeries.

3.5.5. Impact assessment

Principally, the CMRT systems and the associated studies proposed in Table 7 resulted in a mean score of 6.6/10 in terms of *research quality*. This indicates the quality of studies presented are located towards the high end of medium quality research exhibiting efforts close to higher efforts [45]. Furthermore, the Traditional CMRT systems sample contains no poor quality studies. A total of 18 out of 44 studies (40.9%) are classified as medium quality studies. The remaining 26 out of 44 studies (59.1%) are classified as high quality studies. Conversely, the *system value* assessment resulted in a mean score of 12.3/30 indicating the presented that on average, Traditional CMRT systems deliver the low-medium system value. A total of 13 out of 44 systems (29.5%) fit into the low value category. The bulk of the systems, comprising of 30 (68.2%) are located in the medium value category. There is only 1 system scoring 24/30 that fits into the high valued description. It is interesting to note, that this system, proposes a *Hand-Held* mobile system for chronic wound measurement and manages to remain within the clinical expertise of the practitioner, whilst delivering educational and decisional directions to the patient [50]. The system is applicable in the *Home,* the *Clinic* or *Hospital* and delivers a significant step towards transitioning current paternalistic, practitioner centred care models to delivering clinically evidenced and guided instructions directly to the patient whilst maintaining the expertise's view.

Overall, the majority of studies deliver reputable quality empirical results with appropriate generalizability and repeatability measures. Additionally, there has been suitable usage of novel techniques with large effort in tethered based hospital systems. However, form a system value perspective, Traditional CMRT systems, by their very nature, tend to focus on perpetuating more paternalistic models of care which in turn is reflected in the comparatively poor performance in terms of system value, the proposed rationale of which values systems that are more patient-centred, and preventative in nature.

3.6. Collaborative CMRT health – care systems

Table 8 presents systems that have been identified as delivering care using a collaborative approach between patient and practitioner as described in Section 3.1.

3.6.1. Delivery stage

The most common care stage focused on by *Collaborative* systems is *Secondary* care [89,94–101]. For example, [94] delivers pure *Secondary* intervention through therapeutic breathing exercises and control techniques to assist in regulating breathing conditions such as lung cancer. Another interesting area of research is the *Secondary* specialist treatment for tinnitus [99]. The usage of 3D and *VR* environments through immersion in auditory and visual scenes has been compared to the current Cognitive Behaviour Therapy with varying results.

There are few systems that deliver all three models of care [98,102,103]. The proposed system by [102] approaches the decision making process for prostate cancer from a collaborative stance through augmenting potential solutions and 3D printing models of the patients' prostates. The augmentation combined with printing the current the model prostates can be employed for *Primary* prevention methods such as visualising healthy prostates and exploring signs of this when to visit the clinician. *Secondary* care is delivered through similar visualisation techniques which can be employed to discuss potential surgical intervention and associated factors. *Tertiary* care can be delivered through surgical planning procedures using augmented and printed models of the patient's prostate.

Systems that deliver *Secondary* and *Tertiary* care stages are less common [104,105]. One example is in the area of fibromyalgia, which causes the patient to feel pain all over the body. One study, [104], uses *VR* software to induce positive emotions through *Secondary* Specialist and *Tertiary* care. The pain reduction or phobia treatment has also been receiving interest from a purely *Primary* preventative perspective amongst other medical contexts [106–108,111,113–118,121,122]. For example, exposure therapy for dental phobia treatment [113] is being investigated also using Virtual Reality software and proposes to reduce or prevent the phobia from triggering in the first place.

Other systems focus on the *Primary* and *Secondary* care delivery phases [109,110,117]. For example, [110] delivers *Primary* care through guiding patients through motor skill exercises to avoid musculoskeletal complications, whilst also delivering *Secondary* care to assist those with rehabilitation following surgery, stroke, or a musculoskeletal injury. Furthermore, training for ECG tests through augmented telemedicine using *Primary* and *Secondary* models is also becoming an area of interest [109]. Due to the flexibility of long distance training for specialists, augmenting telemedicine using HMD's and marker registration, untrained people can receive preventative methods for detecting unusual heart activity, and potentially more advanced specialist care.

3.6.2. Clinical context

The *Collaborative* systems included in the sample tend to deliver applications within the *CDM* and *PM* contexts

[96–99,104,106,107,111–113,115,116,120–122]. From these systems, [112] for example aims to reduce pain through the usage of VR and could form part of the wound care treatment guidelines *(CDM)* by submerging patients in the proposed "Snow World". Moreover, the system also collects data and evaluates a patient pain level before and after the treatment *(PM)*.

The *CDM* and/or *PM* aspects are also seen with additional *Clinical Contexts* being *CC, RIG and MET* [100,102,103,105,108–110,114,117,119]. The ECG test training [109] for example ensures treatment guidelines for correct ECG procedures are followed through the telemedicine aspect (*CDM),* whilst simultaneously providing a training facility *(MET)* through a form of voice/video calling (CC). Lastly, data is also collected on performance and teaches the monitoring of health status *(PM)*. Another example being [110], where the exercises delivered as part of prevention or rehabilitation phases follow specific treatment guidelines to ensure correct mobility and comfort is achieved *(CDM)*, the "Ghostman" system delivers these exercises through long distance communication using *HMD* displays and cameras to augment the therapists instructions in real time *(CC)*. Finally, the teaching component of rehabilitation is delivered through simple motor skills exercises which can be performed solely by the user *(MET)*. The teaching of these skills requires time and expertise of a therapist. The availability and cost of these demands are leading to the use of a tele-rehabilitation model to reach a wider population of potential clients.

Systems that deliver purely for *PM* and *MET* are few in numbers [94,95]. For example, [94] delivers the *PM* aspect through a Mobile VR based applications that monitors the patients respiratory system and lung capacity through the microphone which accordingly visualises animations to support breathing techniques. Consequently, the *PM* aspect is delivered through the same visual animations which are based upon the user's respiratory system and provides visual ques to assist efficient breathing.

3.6.3. Clinical setting

Many of the *Collaborative* systems can be deployed in multiple *Clinical Settings* [95,97–99,103–107,109–111,113,115,120,121]. However, systems that can be delivered purely within one clinical setting are less common. For example, a small number of systems are designed purely for the *Home* setting [94,100,101,108,114,118,122]. An example of a system developed solely for the *Home* setting is [108], which delivers a *Primary* system for fall prevention which can empower older adults in the decision making process for home modifications and provide a potentially prolonged life expectancy and avoid falls. Systems that are deployed purely within the *Clinic* setting usually have a requirement for specialist equipment [96,102,112,117,119]. The usage of "robot like VR goggles" for example is used to perform wound debridement which would require a specialist wound care clinic as hospitals do not usually store such equipment due to the lower frequency of patients requiring such treatment [112]. The AR shoulder rehabilitation system presented in [95] is deployed at the *Clinic* and *Hospital* setting due to the patients' health and progression being monitored through the proposed "RehabBio" system which uses EEG, EMG and ECG to capture muscle, heart and breathing activity. These devices cannot typically be deployed within the *Home* due to the specialist equipment required.

Numerous systems [97,99,104,106,107,110,111,113,115,120,121,123] have the potential to be deployed at *Home* or in the *Clinic* setting. From these systems, [99,104] can comparably be installed equally well within the home or clinic and delivers pain reduction therapy and occur in a safe and more comfortable environment from a patient's perspective. Deployment across all settings; *Home*, the *Clinic,* and *Hospital* settings are least common, however, there are a small number of systems that do [103,105,109]. The development of an automatic marker free registration mobile device for augmenting pre-scanned anatomical data onto the human torso has multiple potential usages [105]. The application known as "iRay" can be utilised at *Home* for anatomy education, at the *Clinic* and, *Hospital* for intervention and surgical planning. Due to the nature of pain management interventions required in hospitalised patients, using the Samsung Oculus rift VR setup [116], the system can only feasibly be deployed in a *hospital* setting.

3.6.4. System specification

3.6.4.1. Mediated technology. The full range of mediated technologies is deployed across *Collaborative* systems with significant efforts invested into fully immersive therapeutic *VR* monitoring systems focused particularly on *CDM*, *PM* and *MET* clinical contexts. For example, *VR* has been noticeable within the majority of the systems [94,96–100,104,112,113,115–117,120] and tend to focus on *CDM* and *PM* clinical contexts. An example system for inducing positive emotions in fibromyalgia [104] targets patients that have taken on the strategy to avoid activity in an attempt to reduce pain. Immersing the patient into a virtual environment (*PM*) and commencing significant daily activities (*CDM*) could enable chronic patients to experience a more fulfilling life.

A number of systems employ *AR* technologies [95,101,102,105,108–110,121] which evolve around the empowering the user through medical education (*MET*). The treatment decisions (*CDM*) for prostate cancer patients uses AR to visualise healthy and unhealthy prostates alongside 3D printed versions in an attempt to educate the patient and pre-empt cancerous prostates (*MET*) [102].

The use of *3DM* has also been presented in a reduced set of systems with additional clinical contexts focused in *HRMA* and *CC* [103,106,107,118,119,122]. For example, [103] investigated indoor navigations using a 3D range camera for the visually impaired. A blind or visually impaired patient would be able to stereophonically (CC) hear where a clear path is from room to room as objects were detected with the range camera. Additionally, [119] presents an intuitive nose surgery planning and simulation system, using 3D laser scan image and lateral X-ray image (*HRMA*), to provide high quality prediction of the postoperative appearance, and design of the patient specific prosthesis model automatically.

3.6.4.2. Software deployment. The deployment of software within the Collaborative system paradigm tend to focus on the delivery of Closed-Source *(CS)* systems [94–99,102–104,106,109,110,112,115,117–122]. For example, [96] proposes a VR tool to train and monitor patient dialogue's using a virtual avatar to expose patient to various social situations with a view to reducing social phobia. The development of the avatar and the remaining system functionality is packaged within the Delft Remote Virtual Reality Therapy platform (DRVET) which is a closed system. Another example is the "Ghostman" system [110] which proposes a visual augmentation system designed to allow a physical therapist and patient to inhabit each other's viewpoint in an augmented real-world environment. This allows the therapist to deliver instruction remotely and observe performance of a motor skill through the patient's point of view for rehabilitation following surgery, stroke, or a musculoskeletal injury. The HMD used in "Ghostman" system uses the 'Vuzix' SDK which can be accessed publicly, but its source cannot be edited.

The remaining systems are deployed using Open-Sourced *(OS)* software [100,101,105,107,111,113,114,116]. The usage of the Oculus Development Kit (SDK) has been evident throughout some of these systems, for example [113,116] both deployed to their system using the *OS* based *HMD*. The usage of the Oculus system for pain therapy and dental phobia is well suited to this type of intervention, due to the full immersion of the patient which can be achieved and acts as a distraction which evidently can be useful for these types of intervention.

3.6.4.3. Hardware deployment. A large proportion of *Collaborative* systems deploy *DM's* and *HMD's* as the key *Hardware Deployment* platform [96,99,112,113,115,116,121]. The dental phobia treatment using an immersive *VR* environment, more commonly termed as Virtual Reality Exposure Therapy (VRET), utilises a *DM* and *HMD* to re-create dental practices [113]. Similarly, the remaining studies in this group have developed immersive environments to treat a numerous chronic issues which require a constant connection between *HMD* and *DM*. Whilst popular methods of employing *VR* technologies are usually deployed with a combination of *DM's* and *HMD's*, there are occurrences of using projector or spatial based camera's *(SC)* instead of *HMD* to portray the VR environment [95,104]. The induction of positive emotions for fibromyalgia are performed using group therapy methods as it is recommended for chronic pain sufferers, and the usage of a projector-based approach solves the challenge of delivering immersive *VR* environments to multiple patients simultaneously. There are also instances of sole *HMD* usage without the need for a *DM* or *SC* [94,97,109–111,120]. For example, [111] employs a HoloLens system detect vital signs through spatial averages of the luminance (L) and chrominance (U, V) pixel intensities.

Sole usage of mobile devices is not uncommon (*HH*) [101,102,105,108]. For example, [102] has capitalised on the *HH* augmentation system advances and proposes to educate patients on prostate cancer care and potential solutions through an iPad and structure Sensing technologies. Similarly, sole usage of spatial camera's *(SC)* is not uncommon [98,103]. For example, [103] presents a *3DM* system for healthcare mobility aids through a 3D range camera which is positioned spatially *(SC)*. Objects are augmented and modelled thus allowing a wheelchair dependant blind or visually impaired patient to direct their path stereophonically. Sole usage of *DM* for again is not unusual [100,117,119]. The proposed *VR* simulation platform is designed to provide a cost-effective alternative to co-located team training. Advanced cardiac life support (ACLS) is a protocol that provides guidance on the clinical interventions that need to be provided during cardiac arrests and respiratory failures. The user interacts with the system mainly using a desktop machine with a keyboard. ACLS interaction is provided through a bespoke haptic joystick attached to the *DM*.

3.6.4.4. User interaction. Development of pure sensor based (SI) and marker based (SMI) input to assist in care procedures is growing in popularity in research communities and is increasingly being combined with Mediated Technologies [95,97,98,101–103,105–111,119,121]. These systems at the core, all have a form of visual input whether through a standard or bespoke sensor camera. From these systems, the delivery of care using pure sensory input (SI) is noteworthy [97,98,101,103,105,108,110,111]. For example, the HoloLens system proposed by [111] has been used detect vital signs through calculating spatial averages of the camera's video signal. Contrarily, [101] uses a bidirectional video feed, using standard and commercially available cameras at the site of the provider and the patient. Moreover, from these systems it is also evident that pure marker based *(SMI)* is infrequent [102] and is usually combined with *KI* and *VI* or *GI* [95,106,107,109,113]. For example, the ECG augmented system employs Telemedicine to direct untrained people in the correct practices to perform ECG diagnosis and can control the system with Voice commands [109].

However, the usage of a keyboard with a desktop is an aspect that remains an essential for of interaction for certain training and treatment procedures. The following systems take input either solely through KI or in combination with sensor based input (SMI,SI) and GI [95,96,104,106,107,109,113,115–117,119–121,123]. An example of a system that has marker based registrations (SMI) at its core of interaction is [95]. The usage of KI is employed through the *DM* where the practitioner can monitor and provide further input values. The user has to wear markers on the finger tips and other body parts to provide monitoring facilities for the bespoke app *(SMI)*. Finally, the user performs the *AR* induced exercises through gestures (movement) and is monitoring accordingly (*GI*). The remaining systems all require a form of computer/keyboard based input either solely in addition to sensory data.

There is only one system that uses Voice based input *(VI)* combined with *GI* [94]. The system presents a VR based therapy to assist individuals, especially lung cancer patients or those with breathing disorders to regulate their breath through real-time analysis of respiration movements using a smartphone. The Mobile VR based applications monitors the patient's respiratory system and lung capacity through the microphone and visualises animations to support breathing techniques.

3.6.5. Impact assessment

Predominantly, Collaborative CMRT systems presented in Table 8 scored a mean score of 5.7/10 in terms of *research quality,* i.e. representing, on average, medium quality systems. Indeed this is reflected in that the majority, 18/29 (62.1%) of the sample fall within the medium quality research category. A total of 8/29 (27.6%) studies achieved a high quality research score with the remaining 3/29 (10.3%) being considered of low quality research. On the contrary, the mean *system value* resulted in 14.1/30, placing it in again in the medium valued systems category. More specifically, a total of 25/29 (86.2%) of systems are placed in the medium value grouping with the remaining 4/29 (13.8%) systems equally split across the low and high categories respectively. It is worthy to note that there are a number of systems that are located on the cusp the high value category [103,105,109,110]. These systems, tend to achieve higher scores due to the unobtrusive nature of the solutions via the use of pure sensing *(SI)* [103] technologies and marker *(SMI)* based therapies through AR and VR technologies [109] delivering ECG training for untrained candidates. Both examples provide patients with opportunities of becoming stakeholders in their treatment and final outcomes.

Generally, a larger focus on the development and investigation in virtualisation software for therapeutic treatment with acceptable repeatability measures is evident within this sub-sample of the literature. There is eccentric effort on utilising novel technologies, however evidence can also be found in the smaller absolute number of Collaborative CMRT systems, compared for example with Traditional CMRT systems, suggesting the research community's current focus tends to be still focusing on more paternalistic technology-based solutions for care.

3.7. Patient-centred CMRT health – care systems

Table 9 presents systems that have been identified as delivering care using a Patient-Centred approach**.** Subsequently**,** as part of the presentation, the data is described according to the defined Conceptual Framework in Section 3.

3.7.1. Delivery stage

Systems that attempt to deliver *Primary, Secondary*, and *Tertiary* of care are few in numbers [124,125,136,138,140]. The anatomy education area has received noteworthy interest from a *Patient-Centred* perspective and is featured in [124,138,140]. For example, [124] develop a system that uses Computerised Tomography (CT) scans and augments them onto the patient's body through a depth camera to track the pose of a user standing in front of a large display. The *Primary* care element of the system relates to the capability to educate through self-learning and ultimately being able to prevent further complications in a range of bodily areas. Further *Secondary care* treatment focuses on educating the patient with existing bodily complexities. Finally, the *Tertiary* care aspect focusses on surgical bodily adjustments which emphasise researching potential solutions or apprehend existing procedures.

Systems that focus on single care *Delivery Stage* cover the majority of the these systems [127–129,131–135,137,139]. *Tertiary* based systems [133,135,137] include indoor navigation using a mobile device and beacon technology for wheelchair users is one example [133]. Such systems aim to increase or maintain current mobility in patients with chronic mobility issues. Moreover, [137] provides specialist surgical care through a brain anatomy education system. This *Tertiary* based system involves the patient being able to interact with the brain model

Table 9
Patient-centred computer mediated reality technology systems.

System	Delivery Stage			Clinical Context								Clinical Setting			System Specification				Impact	
	Primary	Secondary	Tertiary	IM	TM	HRMA	CC	RIG	CDM	PM	MET	Home	Clinic	Hospital	Mediated Tech.	Software Deploy.	Hardware Deploy.	User Interaction	Res. Quality (/10)	Sys. Value (/30)
Blum et al. [124]	X	X	X			X					X	X	X		AR	CS	SC	SI,GI	3	19
Brennan et al. [125]	X	X	X						X	X	X	X			3DM	OS	DM,HMD,SC	SI	7	16
Cardona Reyes et al. [126]		X	X						X	X	X	X	X		VR	OS	DM,SC	SI,GI	8	17
Choi et al. [127]		X							X		X	X			VR	CS	HH	SI,GI	7	13
Chong et al. [128]	X					X			X	X	X	X			3DM	CS	HH	SI	8	14
Domhardt et al. [129]	X			X			X			X	X	X			AR	CS	HH	SMI,GI	4	15
Hervás et al. [130]		X	X					X	X	X	X	X	X	X	AR	OS	HH	SI,GI	6	20
Noll et al. [131]		X							X		X	X			AR	CS	HH	SMI	1	11
Ofli et al. [132]	X								X	X	X	X			AR	OS	DM,SC	SI,GI	7	15
Oliveira et al. [133]			X						X	X		X	X	X	AR	OS	HH	SMI,VI,GI	6	16
Ortiz et al. [134]	X								X		X	X			VR	CS	DM,HMD	SI,GI	4	13
Saez et al. [135]			X						X	X		X	X	X	3D	OS	HH	SI	7	15
Sigam et al. [136]	X	X	X	X					X	X		X	X		3D	CS	HH	SI	7	19
Soeiro et al. [137]			X			X			X		X	X	X	X	MR	CS	HH	SMI,GI	4	15
Yeom et al. [138]	X	X	X					X			X	X	X		AR	CS	SC	SI,GI	4	19
Zhao et al. [139]	X								X		X	X			AR	OS	DM,SC	SI,GI	6	14
Zilverschoon et al. [140]	X	X	X					X	X		X	X	X	X	3D	OS	DM	KI	7	20
Overall Mean																			**5.6**	**15.9**

Acronym description: **AR** = Augmented Reality, **VR** = Virtual Reality, **MR** = Mixed Reality, **3DM** = 3D Modelling; **OS/CS** = Open/Closed Source; **DM** = Desktop Machine, **SC** = Spatial Camera, **HMD** = Head Mounted Display, **HH** = Hand Held; **KI** = Keyboard Input, **SI/SMI** = Sensor/Sensor Mark Input, **GI** = Gesture Input, **VI** = Voice Input; **Poor quality study** 3/10, **Medium quality study** 4–6/10, **High quality study** 7/10; **Low value system** 10/30 or less, **Medium value system** 11–20/30, **High value systems** 21/30 or more.

and allows the doctor and patient to perceive and perform a more accurate stimulation of brain conditions. The *secondary* based systems [127,130,131] are similarly few in numbers. For example, [127] delivers a *Secondary* based intervention for stroke rehabilitation. The VR mobile game-based upper extremity delivers a program for patients who have experienced stroke through training and instruction-based exercises. Likewise, [131] delivers *Secondary* care through a mobile AR based blended learning environment for skin dermatology called “mArble”. The system uses AR to interactively overlay the desired findings on the user’s skin. The systems in the last segment of the single care *Delivery Stages* [128,129,132,134,139] focus on *Primary* care interventions. For example, [129] delivers *Primary* intervention through a mobile AR monitoring system. The systems assists with monitoring food intake and associated carbohydrates which in turn allows for insulin-dependent diabetic to estimate the amount of insulin necessary to account for a given meal using the derived carbohydrate-count. Conversely, [134] delivers *Primary* care through a hand motion-based virtual reality-based ‘exergame’. The system which is designed for occupational health purposes and allows the user to perform simple exercises using a cost-effective non-invasive motion capture device to help overcome and prevent some of the musculoskeletal problems associated with the over-use of keyboards and mobile devices.

3.7.2. Clinical context

The majority of *Patient-Centred Systems* focus on providing educational context interventions (MET) associated with treatment guidelines (CDM) and a few deviations into different contexts [124,127–129,131,134,137–140]. For example, [134] provides a system where the VR ‘exergame’ provides a set of treatment guidelines (*CDM*) for hand-motion exercises to prevent or reduce musculoskeletal complexities. Simultaneously while the treatment guidelines are delivered to the patient, the exercises can be utilised away from the application and become regular activities to perform during the day-to-day routine. Similarly, [139] provides a system where individuals are assisted to maintain, enhance and recover hand skills using AR and bare-hand tracking through an exercise induced system. The AR based exercise system allows patients to interact with the system and are given a set of exercises which follow general treatment guidelines (*CDM*) for the enhancement of finger functions. Concurrently, the therapeutic healthcare exercises taught, can be performed away from the proposed system and aim to improve the range of motion of fingers over a period of time (*MET*). The systems that include small deviations from the pure educational context cover roughly half of the *Patient-Centred Systems* [124,129,137,138]. For example, [124] delivers an AR anatomy education system that accesses previous CT *(HRMA)* scans and augments them onto the users body whilst simultaneously providing educational aspects *(MET)*. Similarly, [138] also delivers an AR anatomy education based application but uses haptic feedback as a tool to learn anatomy. The usage of 3D models generated from medical textbook (RIG) which can be interacted with using the haptic feedback hardware provides equitable access to more engaging experiences.

Besides the training based interventions, there are also systems that focus on CDM and PM [133,135,136]. For example, [136] delivers a wound surface areas measurement system using 3D structure sensing technology that focusses on improving the reliability and accuracy of surface measurements. Ultimately this would enable estimation of the Healing Rate of wounds (*PM*) and facilitate Decision Making process to identify correct Treatment Guidelines (*CDM*) according to the type of wound. Despite the focus in the same clinical contexts, [133] the area of care differs. The AR indoor navigation system provided using a mobile device and beacon markers allows wheel chair users to decide on the most efficient route (*CDM*) to navigate safely (*PM*) around various indoor locations.

The disparity in treatment is also evident within systems that deliver to theme of CDM, PM and MET and are present in small numbers [125,126,130,132]. For instance, [130] contextual information in cognitive impairment guidance through AR and map topology widely varies in care in comparison to [132] who delivers an interactive AR exercise guidance ‘coach’ for older adults. The cognitive impairment guidance systems supplies spatial orientation and support to cognitively impaired people in their daily activities *(CMD)*. The system monitors the patient in relation to points of interest and well-known places *(PM)* in which user-friendly augmented reality contextual guidance routes to a destination are provided *(CDM)*. The user based context rather than the conventional street names and quantitative distances provides an easy to learn and demonstrates previous instructions *(MET). Comparatively, the Kinect Based AR exercise Coaching system uses IR sensors to monitor patient progress throughout the session (PM) and provides clinical context and guidance to newer exercises (MET) in accordance with their progress (CMD).*

3.7.3. Clinical setting

A large proportion of the *Patient-Centred Systems* subscribe to deployments within a pure *Home* based setting [125,127–129,131,132,134,139]. For example, [139] delivers a low-cost and multi-modal residential-based AR-assisted therapeutic healthcare exercise system to enhance the finger dexterity which is deployed on a regular desktop computer using web camera’s. Similarly, [134] delivers a hand motion-based VR based ‘exergame’ for occupational health purposes. The system allows the user to perform simple exercises using a cost-effective non-invasive motion capture device to help overcome and prevent some of the musculoskeletal problems associated with the over-use of keyboards and mobile devices.

A few systems subscribe to a *Home* and *Clinic* based setting [124,126,136,138]. The Anatomy Education Magic Mirror system can easily be adapted for home use through the usage of a standard LED TV [124]. There are also systems that can be implemented in all settings [130,133,135,137,140]. For example, the indoor navigation system could install it’s markers in a variety of locations and enable efficient wheelchair navigation within a hospital environment or smaller clinic [133]. Similarly, the brain anatomy education systems allows both the doctor and patient to interact with the brain model. This type of care could potentially be delivered in all settings due to the simplicity of the mobile system [137].

3.7.4. System specification

3.7.4.1. Mediated technology. The type of *Mediated Technology* employed *Patient-Centred Systems* quite varied, although there is a predisposition towards MET. For example, the usage of AR has mainly focused on anatomy education (MET) by augmenting body parts onto the patient [124,138], but there are also systems for indoor navigational purposes that use AR to scan beacon’s (markers) and deliver direct instruction to patients (PM) [133]. The remaining AR systems [129–133,139] are again diverse in nature, for example [139] augments and portrays different objects into the patients hands and aims to aid (MET) in therapeutic healthcare exercises for finger movement. *MR* has also been receiving attention through mainly a mobile based approach [137]. For example, the mixing of both AR and VR within a single system to visualise brain data (*HRMA*) could provide a more in depth and detailed explanation (*MET*) of medical procedures and operative decisions (*CDM*). The AR mode produces a virtual representation of the brain superimposed over the patient’s head enabling the doctor to visualize in real time a three-dimensional virtual model of the brain over the patient’s head, aligned with the real position of the patient’s brain. The VR mode allows for hands-on interaction with the model enabling the patient to grasp the concept of potential solutions.

The usage of *3DM* to scan and measure surfaces has also been a prominent area for development [125,128,135,136,140]. Even though the modelling aspect in some cases might not be featured, facilitating surface measurements through 3D camera capabilities has proven to be a valuable route for investigation [136]. Lastly the usage of VR is also limited in the data set [126,127,134]. For example in [127], a mobile game-based upper limb dysfunction VR program is presented for patients who have experienced stroke. The exercises are presented in Virtual form and allow the patient to follow at their own pace (*MET*).

3.7.4.2. Software deployment. The majority of these systems [124,127–129,131,134,136–138] deploy software using *CS* technologies. For example [124,138] use the Microsoft Kinect Platform which hides behind a closed development environment, similarly [134] uses the 'LeapMotion' SDK and [137] uses the Metaio SDK which conform to the same closed environment disadvantages. The remaining systems focus on deploying software using OS applications [125,126,130,132,135,139,140]. The Usage of the Android Development Platform, AR Library, and Blender has for instance been featured in [133] and provides plenty of room for collaboration with open development communities. Additional novel OS technologies lie in the Faro IR scanning API [125], Leap Motion [126] and Kinect platform [132].

3.7.4.3. Hardware deployment. Compared with *Collaborative* and *Traditional Systems*, *Patient-Centred Systems* tend to deploy a larger proportion of applications on *HH* devices [127–131,133,135–137]. The mobile technologies attempt to simplify the relationship between patient and practitioner whilst simultaneously allowing the patient to comprehend medical knowledge using a common everyday device. Wheelchair indoor navigation provides an elegant system which uses a common smartphone to scan beacon locations and assist with navigating, such a system can be employed solely by the user [133]. On the contrary, comprehending brain anatomy with the assistance of practitioner and the visualisation aspect through an ubiquitous device has also proven medical value [137]. Surprisingly, systems that present physical therapeutic exercises [125,126,132,134,139,140] all make use of a *DM* associated with either a *HMD* or *SC* to detect movement. Lastly usage of pure SC is also present [124,138]. Both systems deploy an Xbox Kinect camera which can be used for gesture and depth perception. Perhaps surprisingly both systems are focused in the same medical area of augmenting anatomy education.

3.7.4.4. User interaction. The combination of SI and GI has been prominent within *Patient-Centred Systems* [124,126,127,130,132, 134,138,139]. The usage of pre-captured models or images augmented in real time is an approach not uncommonly taken [124,138]. For example, the augmentation of anatomy using pre-captured CT scans allows for precise visualisation of otherwise difficult to present structures. The system allows the user to interact with the model using gestures (*GI*) through a Microsoft Kinect scanner (*SI*) where the users fingertips are positioned within the frame [124]. There are also systems that do not make use of pre-captured models and scan the environment in real time using purely *SI* with a smart phone camera [125,128,135,136]. The pure visual input without markers is an effective method for scanning and developing treatment plans in Wound Care and has proven its usability.

Scanning the environment, patient, or other solid objects using *SMI* is also becoming a feasible solution for medical complexities [129,131,133,137]. The simplicity of smart phones camera allows for easy registration of placed markers to augment and portray useful information onto the plane of vision. For instance, [137] places markers on the patients head which allows for a virtual representation of the brain superimposed over the patient's head. Lastly, there is only one system that utilises a keyboard (*KI*) to provide a 3D Anatomy Visualisation educational tool for residents delivering exceptional bone quality structure and dissection capability particulars [140].

3.7.5. Impact assessment

The Patient-Centred CMRT systems presented in Table 9 achieved a mean score of 5.6/10 in terms of *research quality*. These system types, therefore on average, deliver studies of medium research quality. It is worthy to note that the absolute number of studies presented here are fewer than in other system type samples, and hence generalisations may therefore be significantly skewed as a result of the small sample size. Despite the lower total number of studies, a comparatively high proportion of the research 8/17 (47.1%) delivers high quality research studies. Furthermore, 7/17 (41.2%) studies were scored as medium quality research. The last 2/17 (11.8%) are defined as low research quality. The *system value* presents a mean of 15.9/30 which are categorised as medium value systems. This is the highest scoring average of all three system category types. Perhaps surprisingly, all 17/17 (100%) systems are contained within the medium research quality indicator. It is also interesting to note, that with the exception of one [131], no studies fall into the lower end of the medium quality category. It would therefore appear that there is greater consistency in terms of the system value of applications presented as Patient-Centred CMRT systems, quite feasibly as a result of these system types having an inherent focus on delivering patient-centred solutions. This is perhaps most closely aligned with the scoring rationale for *System Value*, which credits systems that focus on delivering patient-centred, preventative, patient enabling solutions.

4. Challenges and future research recommendations

This study presents the state of the art in Computer Mediated Reality Technologies (CMRT) for healthcare delivery. The emerging CMRT concepts and systems presented have been categorised in-line with a concept-centric thematic analysis of the representative literature sample. As conceptualised in the proposed framework, the three overarching *PIPPs* (*Traditional*, *Collaborative*, *Patient-centred*) that emerged from the literature sample form the basis of the overarching analysis, discussion and impact assessment taxonomy presented.

When considering the broader view of the typical function that systems fulfil according to the three overarching *PPIPs*; *Traditional* systems account for more than half of the whole literature sample [47–90]. The care delivered by *Traditional* systems tends to focus on augmenting (AR) and visualising (3DM) an improved treatment strategy or training methodology for use by specialist practitioners. As a result, a significant proportion of the proposed systems deliver instruments which exclusively focus on specialist *Secondary* care [51,56,63,65,68,76,79,84,85] and *Tertiary* care levels [53–55,58,60,62,66,67,70,72–75,82,83,141]. Consequently, systems are mainly designed for deployment within hospital or clinical settings for *CDM*, *PM* and *MET* purposes. Example clinical application areas that are dominant in this sub-set include: human anthropometric measurements; composite bone perforation; orthodontic bracket placement; and MRI guided needle surgery. The remaining studies focus on delivering *collaborative* systems [94–122], whilst the minority of systems focus on delivery of *patient-centred* interventions [124–140].

Collaborative systems tend to focus on providing therapeutic treatment by virtually immersing (VR) the patient in a pre-designed environment [94,96–99,104,112,113,115–117,120] that are often used for to stimulation of social anxieties and dental phobias. Additionally, management of fibromyalgia and burn wounds are areas of clinical application that have been targeted by *Collaborative* systems and have shown potential for enabling patients with chronic conditions to experience a more fulfilling life. Interestingly, compared to the *Traditional* systems, the *Collaborative* systems mainly position themselves at the *Primary* care levels [68,106–108,111,113–116,118,121] and *Secondary* care levels [94–101,119,120]. Comparatively, the *Clinical Context* of *Collaborative* systems tend to be oriented towards *CDM* and *PM* contexts [96–99,104,106,107,111–116,118,120–122] and show systems mainly deployed within the *Home* and *Clinic* settings. There is and observed decrease in *Collaborative* systems delivering within the *MET* context compared with *Traditional* systems, which could be attributed the key opportunities of CMRTs being seen as delivering most value in enabling patient-practitioner collaboration in practice as opposed to within training settings.

With regards to *Patient-Centred* systems, all systems deliver treatment purely from the patient's perspective [124,127,129,131, 133,134,136–139]. The provision of care delivered by *Patient-Centred* systems tends to focus on equipping the patient with ubiquitous tools to support, instruct and visualise personalised health information relating to normal bodily function [124,131,134,137,139] such as anatomy or dermatologic education. Furthermore, the small number of *Patient-Centred* systems makes it challenging to suggest trends within this subset of systems particularly with reference to the *Delivery Stage* other than to observe that *Primary*, *Secondary*, and *Tertiary* care examples have all been presented in the literature. However, when comparing the *Clinical Setting* catered for by *Patient-Centred* systems compared with *Traditional* and to a lesser extent *Collaborative*, it seems that *Patient-Centred* systems tend to focus more on the delivery of applications for the *Home* setting and less on the *Hospital* and *Clinic* settings.

When considering all studies presented across Tables 5–7, there appears to be a shift in focus of the *Clinical Setting* which is related to the respective PPIP in question. *Traditional* systems tend to focus on delivering applications for *Hospital* and *Clinic* settings; *Collaborative* systems tend to focus more on the *Clinic* setting, and to some extent, the *Home* setting; and *Patient-Centred* systems tend to cater for the *Home,* and to some extent, the Clinic setting. Additionally, when considering the type of intervention that specific PPIP systems support, currently, *Traditional* systems tend to support more invasive type surgery interventions, whereas *Collaborative* systems tend to deliver a more balanced mix of both invasive surgery interventions and instructive therapy interventions, with *Patient-Centred* systems tending to support non-invasive interventions and more instructive therapies. There also appears to be a relationship between the *Delivery Stage* and the chosen PPIP. *Traditional* systems, which are support to more paternalistic forms patient-practitioner relationships, tend to focus on delivering *Secondary* and/or *Tertiary* care delivery i.e. with the clinician being at the 'helm' and steering the *Clinical Decision Making* (CDM). The systems in the *Traditional* data set seem to conform to this observation with no systems purely delivering *Primary* care interventions. With regards to *Collaborative* systems, a larger proportion of these systems shift towards the delivery of *Primary* care interventions. *Patient-Centred* systems present a more diverse range of care delivery, but, despite the smaller data set there seems to be a decrease in pure *Tertiary* care interventions. Interestingly, there did not appear to be any discernible relationship between PPIP and the chosen *Mediated Technology* type employed as part of the proposed systems. In addition, there did not appear to be any particularly dominant relationship between *Mediated Technology* type and the chosen *Software Deployment* i.e. *Open Source* or *Closed Source* (OS/CS) platforms.

From a *Hardware Deployment* perspective, PPIP appears to be profoundly related to the *Clinical Setting*. Systems deployed at the *Traditional* level strongly rely on intermediary *Hospital* or *Clinic* based systems such as MRI and CT photographs to visualise, overlay and augment treatment procedures using *HMD's*, *DM's* and SC's. At the *Collaborative* level this phenomenon marginally diminishes whilst the *Patient-Centred* systems display very little usage of *HMD's* and *DM's*. Instead, there is a greater focus on *HH* devices.

Furthermore, there appears to be little coherent direction towards CMRT systems that are particularly aimed at the ageing population, and particularly with development focused within the patient-centred paradigm [100,108]. The home modification software presented by Money et al. [100], concluded that there is potential to improve the patient-practitioner relationship via collaborative use of CMRTs in multi-agency teams, hence empowering the patient within the decision making process.

When considering the relationship between the three PPIP categories (Traditional, Collaborative, Patient-Centered) and the *research quality* and *system value* metric, Traditional CMRT scored 6.6/10 (high-medium) and performed the best for *research quality* and conversely performed the worst in terms of *system value* with 12.3/30 (low-medium). Collaborative systems performed on average basis overall for both metrics, however on single *research quality* basis performed the worst with 5.7/10 (low-medium) and 14.1/30 (low-medium) for *system value*. Patient-Centred systems scored 6/10 (high-medium) for *research quality*. The most striking observation is that Patient-Centred systems performed the best in terms of *system value* with 15.9/30 (medium). Interestingly, a possible anecdotal trend that emerges from these results is that *research quality* and *system value* may be, to some extent, inversely related to one another. This certainly seems to be the case for Traditional CMRT systems, perhaps as a result of the more traditional/ well established research methodologies and repeatability measures that are evident within the comparatively saturated field of Traditional CMRT systems (indicated by the larger number of Traditional CMRT systems overall). Conversely, the comparative lack of research volume focusing on developing less paternalistic system types (i.e. Collaborative and Patient-Centred CMRT systems) may manifest itself in these studies adopting more ad-hoc study designs in terms of the experimental setup, design, delivery and subsequent evaluation of studies.

Furthermore, there are no systems located in the extreme high end of the taxonomy (25+). Despite the limited data, it can be extrapolated with caution that this might be due to the difficulty associated with establishing ecological validity in conjunction with the novel technologies used in many of the higher scoring studies. The research in these areas is still in its infancy but has shown promising results and indicating that there is a need for more research effort in the collaborative and patient-centred system domains.

One final observation relating to the literature in general; despite the positive focus on *HH* devices*,* increased research aiming to identify appropriate instrumentation and methodologies in delivering unobtrusive CMRT sensing technologies in the home, there remains a gap in the research efforts presented to date, i.e. to consider the privacy concerns and the diffusion of the ubiquitous CMRT within the home setting. Indeed, it is recognised that we are in the midst of a shift towards the delivery of more personalised, home-based health systems, in which the upcoming generation of older adults will undoubtedly become increasingly equipped, and enabled with opportunities to become stakeholders and intellectual partners in patient-centred treatments and outcomes [46]. However, as Harper et al. [142] highlights, attitudes towards what is considered 'private' greatly varies between people with respect to the environment, content and task at hand. Hence, it can conceptually be argued that the developer at this point cannot and should not actively decide on which visual aspects to block or process. Intricacies in terms of independent daily living, and the introduction of *OS* technology, raises several questions in relation to privacy perception. (1) When, what and how information gets recorded and stored? (2) Who is the data overseer and who can request access to this information? (3) What happens to the data once it's processed and stored? Belloti and Sellen [143] have presented a framework that surrounds the previous questions and concludes with an example in practice. Whilst this framework delivered on some of the foundational queries surrounding privacy, it does not cater for today's emerging *OS* systems and the patterns of ubiquitous device usage and the cascading effect this has on social norms, values and what is deemed appropriate material for decision making in relation to current organizational policies. Rough yet significant ground work has been disseminated by Caine et al. [144] which concluded that older adults are often willing to compromise certain levels of privacy with sensing devices in order to gain support in remaining independent. In order to benefit from the use of video-based monitoring (including being able to identify each individual in a multi-person environment, and label events with accuracy, for example being able to accurately distinguish between a fall and someone getting on their knees to pick something up) while minimizing potential privacy intrusion, requires novel proof of concept-design in relation to algorithmic techniques and associated *OS* implementations. Park et al. [145] presents an initial concept design for silhouette extraction using multiple cameras, a wearable RFID reader and supplementary RFID tags that are attached to various objects including furniture, appliances, and utensils around the home. Whilst this technique delivers multi-scale and multi-view synchronised data, markers often deliver interoperability design issues and integration overhead. Therefore, novel hardware-less algorithmic techniques and integrating this with the due diligence of clinicians and developers alike, remains an un-ventured field which requires further research and development effort [146].

In light of these results, the findings indicate that relatively little research effort has been invested into developing *Patient-Centred* systems that embracing the need to move away from paternalistic models of healthcare towards supporting more patient-centred models of care with a view to overcoming the scarcity of resources issue that is primarily presenting itself as a consequence of an ageing population. Therefore, there remain significant opportunities for further research to be carried out in the area of CMRT systems that deliver patient-centred tools and interventions particularly for an older population. As a direct consequence of carrying out this state of the art survey of existing CMRT systems, numerous challenges and associated recommendations have emerged which should be addressed by CMRT healthcare research domain.

Challenge and Recommendation 1: *There is a disproportionate number of current Traditional healthcare CMRT systems that have a narrow focus on development of fixed position Traditional systems for training/educating clinical staff in invasive surgical procedures.* These systems are typically tethered to existing hospital and clinic-based legacy systems, hence are non-portable and perpetuate the existing focus on traditional and more paternalistic models of healthcare delivery. Although *Traditional* CMRT research has shown significant and successful progression, and valuable usage of CMRT systems, in line with government policies and initiatives, there is a real need to focus a greater proportion of research effort into exploring how CMRTs can be exploited to facilitate less paternalistic patient-centred models of care. For instance, there are no examples of CMRT education/training systems for invasive surgery that focus on educating the patient in any way or facilitating more collaborative interactions between patient-practitioner before, during, or after surgery. Therefore, there is a need to invest more research effort into developing, deploying and evaluating Traditional CMRT that focus on the patient and facilitate improved collaboration between patient and practitioner.

Challenge and Recommendation 2: *There is lack of research effort in the CMRT healthcare domain that develop ubiquitous systems which specifically target development of patient-centred systems for the older population through camera enabled sensory input.* Only one study [108] focuses in this area and has delivered valuable outputs, but apart from this example such studies are absent from the existing research literature. The example of [108] presents an AR tool that allows occupational therapists to walk-through and asynchronously envision modifications (place objects) in collaboration with older adults, facilitating a two-way discussion according to the goals of older clients. Hamm et al. [147] who carried out a systematic survey of health intervention technologies, concluded that even from a wider range of technologies, extrinsic risks and personalising the home to aid mobility and reduce fall risks by self-assessment have yet to be fully explored. Therefore, there is a *need to i*nvest, develop and analyse CMRT using synchronous camera-enabled scanning methods for real-time and on-capture assessment for delivery of care of older adults through visual sensory input. Some promising avenues via which this may be achieved lie within the image processing and edge detection research domain through recently commercialised mobile depth-sensor enabled platforms [148–150]. It is worthy to note that the present study is significantly different from Hamm et al. [147], who focused specifically on falls prevention technologies and the full range of technologies that are deployed within the falls prevention space, whereas the present study focuses on all areas of health care delivery, but on CMRT systems specifically.

Challenge and Recommendation 3: *A large number of CMRT systems give little of no consideration to the design and functionality of the proposed systems from a user-centred-design perspective.* Existing studies tend to focus on the algorithmic techniques or patient experimental analysis that form the principal focus alongside alleviating patient morbidities. In the present age of technology deployment, and the development and use of open-sourced intraoperative systems, usability of healthcare systems is a fundamental feature that significantly impacts on the adoption and use of systems, particularly those that are to be used by patients. Therefore existing systems developed using novel and open-sourced Software Developments Kit's (SDK) must invest more effort into developing engaging mechanisms and interaction platforms that consider user needs and interaction needs.

Challenge and Recommendation 4: *Current CMRT systems are lacking deployment on ubiquitous mobile platforms*. A total of 17 systems out of the available 90 have deployed *HH* CMRT devices, nine of these are delivered at the Patient-Centred level. The remaining *HH* systems deliver therapeutic treatment or educational tools in collaboration with a practitioner or require the patient to be present either in the *Clinic* or *Hospital* settings. Although these systems enable patients to collaboratively or self-assess their functional abilities and cognitive function, there is little consideration given to assessing the environment in which the patients function. Furthermore, the vast majority of Traditional and Collaborative systems do not aim to deploy solutions on ubiquitous and mobile technology platforms but rather tend to opt for static, tethered hardware platforms for system deployment. Therefore, the ecological validity of the proposed systems become questionable when considering the real-life usage scenarios of such proposed systems. One method of overcoming this challenge is to encourage evaluation of proposed systems in the context of coherent validation studies and clinical interventions to better establish the feasibility, efficiency and effectiveness of the proposed healthcare CMRT system for the given deployment scenario. Such solutions can provide abundant room for further progress in determining the most efficient methods of discovering appropriate and valid system development requirements than can be realistically adopted in practice and thus become part of practical care and treatment interventions.

Challenge and Recommendation 5: *Protecting and informing patients when using sensory/camera based CMRT from the privacy of their home through self-assessment means.* The privacy domain of the CMRT remains an aspect that has to be cautiously navigated due to current legal policy of storing, collecting and processing patient data. The 'Go paperless scheme' has some aspects that are being met such as transparency of medical data being collected [17], however access to medical scan data post-assessment and/or treatment of the patient remains at the discretion of the clinician. With the development and deployment of ubiquitous sensor/camera based CMRT systems within the home, the challenge of informing the user and avoiding their privacy being breached only perpetuates the difficulty associated with adhering to security policies. Therefore, there is a need to investigate algorithmic CMRT solutions that could provide patients with transparency and/or reasonably access to the nature of personal data collected. Reassuring opportunities for evaluating privacy matters from a technological standpoint have risen in the AR facial recognition domain [148]. The collaborative effort of community driven code on platforms such as Github [151], provide the research community with valuable opportunities such as dynamically distorting images based on patient presence in the camera's view. Such methods show promise in allowing the patient to be better informed about their privacy in a timely manner before it is breached without their consent, but further empirical research is needed to ensure patients and their data is kept secure.

5. Conclusions

This study presents a conceptual framework of the Computer

Mediated Reality Technology (CMRT) systems employed within the context of three patient-practitioner interaction paradigms (PPIPs). The conceptual framework was derived from, and used, to survey a range of computer-mediated systems that have been proposed within the literature between 2010 and 2017. A thematic analysis was performed in order to review and categorise the identified systems [34]. In conjunction with the thematic analysis, an author-centric [38] approach was used to ascertain and present relevant existing and theory for classification of healthcare based CMRT, and develop a logical approach to grouping and presenting the systems key concepts that have emerged from the analysis.

Healthcare CMRT systems are found to belong to one of three PPIP categories; *Traditional* (practitioner in their traditional role as the expert), *Collaborative* (collaboration between patient and practitioner as joint experts) and *Patient*-Centred (service user to be the primary expert). Via this relationship, systems were then categorised in accordance with the nature of care delivered; *Primary* (diagnosis/preventative), *Secondary* (specialist/treatment) and *Tertiary* (invasive/highly specialised). Subsequently, the system's *Clinical Context* (type) [Information Management, Time Management, Health Record Maintenance and Access, Communication and Consulting, Reference and Information Gathering, Clinical Decision Making, Patient Monitoring, Medical Education and Training] and *Clinical Setting* (location) [*Hospital*, *Clinic* and *Home*] were categorised. Lastly, the *System Specification* produced four sub-categories which consist of prominent CMRT concepts: *Mediated Technology* (Augmented, Virtual, Mixed Reality and 3D-Modelling), *Software Deployment* (Open/Closed-Source), *Hardware Deployment* (Desktop Machine, Hand-Held, Head-Mounted-Display and Spatial Camera) and *User Interaction* (Keyboard Input, Sensor-Mark Input, Sensor-Input, Voice-Input and Gesture Input).

As a function of the proposed framework, there is an abundance of traditional patient-practitioner CMRT research which focuses on augmenting and improving treatment strategies for invasive surgical procedures and has shown significant and successful progression. However, there is lack of research effort that focusses on investigating non-invasive patient-centred systems through ubiquitous mobile platforms. This is partly due to the nature of the traditional interaction between patient and practitioner where tertiary care and post-surgical care is prioritized. Consequently, little effort has been spent on targeting the older population through synchronous ubiquitous CMRTs, despite the recommended governmental strategies of reducing restricted resources caused by the increase in cost of care and the ageing population.

Furthermore, from a technological perspective, the delivery of CMRTs has mainly been focused within *Hospital* or *Clinic* settings for patient monitoring, education of clinicians and decision making by clinicians. This may be due to the interoperability requirements of legacy hospital systems and proposed CMRT solutions that seek to their predefined function and to deliver specialised paternalistic secondary and tertiary treatment. Accordingly, this seems to have further perpetuated the lack of investigation into the delivery of home-based healthcare services and the enablement of older patients to engage in self-care and management practice.

As the delivery of health care continues to shift towards the delivery of more personalised, home-based health systems, there is also a shift in focus towards *HH* devices and increased deployment of unobtrusive CMRT sensing technologies in the home. Consequently, a gap has emerged that fails to consider the privacy concerns and the diffusion of the ubiquitous CMRT within the home setting. Rudimentary studies have started unravelling obtrusive multi-scale and multi-view synchronized data capture for in-home assessment of privacy, yet development of novel hardware-less algorithmic techniques and the inclusion of clinical practices and *open-sourced* development remains uncharted territory which warrants further attention.

To address and overcome the challenges faced by CMRT implementation and to adhere to the endorsed governmental strategies, this study has proposed a range of challenges to better enable and catalyse the much-needed departure from paternalistic models of care to towards more enabling patient-centred approaches that empower patients to deliver personalised self-care as expert patients. Future CMRT systems in healthcare would benefit from expending more effort into focusing development, deployment and evaluation of mobile synchronous CMRT for patient-centred non-invasive preventative healthcare procedures. To this end, the education of the older population in aspects such as fall prevention and home adaptations; mobility exergames; anatomy education and wound/dermatology care provide major opportunities for self-assessment in the absence of clinicians in the home. Moreover, exploring opportunities for the development of accurate, efficient and reliable techniques and CMRT healthcare systems that help to educate and empower patients, increase patient involvement whilst improving the ecological validity of said applications in practice, may better enable the shift of current paternalistic models of care. Likewise, the delivery of CMRT systems specifically, would also benefit from exploring novel open-sourced and community driven solutions to improve mapping between environmental and clinical patient data practices of privacy, assessment and analysis.

Conflict of interest

The authors declared that there is no conflict of interest.

References

[1] Office for National Statistics, English Life Tables No. 17 – Office for National Statistics, 2015. Available: < https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/lifeexpectancies/bulletins/englishlifetablesno17/2015-09-01 > (accessed: 14-May-2018).

[2] AgeUK, Briefing: Health and Care of Older People in England 2017, 2017.

[3] Office for National Statistics, Disability-Free Life Expectancy (DFLE) and Life Expectancy (LE): At Age 65 by Region, Office for National Statistics, England, 2016.

[4] B. Alexander, E. O'Mahony, Performance of the NHS Provider Sector: 2016, 2016.

[5] T. Lloyd, Funding Overview: Historical Trends in the UK Historical Trends in the UK, 2015.

[6] National Audit Office, Managing the supply of NHS clinical staff in England, 2016. Available: < https://www.nao.org.uk/report/managing-the-supply-of-nhs-clinical-staff-in-england/ > (accessed: 07-Jul-2017).

[7] S. Lafond, A. Charlesworth, A. Roberts, A Perfect Storm: An Impossible Climate for NHS Providers' Finances? An Analysis of NHS Finances and Factors Associated with Financial Performance, 2016.

[8] Department of Health, Equity and Excellence: Liberating the NHS (White Paper), London, 2010.

[9] The Evidence Centre for National Voices, Supporting Shared Decision-Making, 2014. Available: < https://www.nationalvoices.org.uk/publications/our-publications/supporting-shared-decision-making > (accessed: 16-Feb-2017).

[10] National Voices, Supporting Self-Management, 2014. Available: < https://www.nationalvoices.org.uk/publications/our-publications/supporting-self-management > (accessed: 16-Feb-2017).

[11] T. Kelsey, W. Cavendish, Personalised health and care 2020: using data and technology to transform outcomes for patients and citizens. a framework for action, Natl. Inf. Board (November) (2014) 1–66.

[12] C. Foot et al., People in Control of Their Own Health and Care: The State of Involvement, 2014.

[13] A. Darzi, High Quality Care for All, NHS Next Stage Review Final Report Department of Health, 2008.

[14] Department of Health, Liberating the NHS: 'No decision about me, without me' Government response to the consultation, London, 2012.

[15] A. Liddell, S. Adshead, E. Burgess, Technology in the NHS Transforming the Patient ' S Experience of Care, King's Fund, 2008, pp. 1–61.

[16] NHS, Quality Commission Care, Health Education England, Health England Monitor Public, Development Authority Trust, Five Year Forward View, 2014.

[17] J. Hunt, Department of Health, NHS Challenged to go Paperless by 2018, NHS Efficiency, 2013. Available: < https://www.gov.uk/government/news/jeremy-hunt-challenges-nhs-to-go-paperless-by-2018–2 > (accessed: 20-Feb-2017).

[18] European Commission, EN Horizon 2020, Health Demographic Change and Well-Being, European Union, 2016.

[19] E.J. Topol, Transforming medicine via digital innovation, Sci. Transl. Med. 2 (16) (2010) pp. 16cm4.

[20] E.J. Topol, S.R. Steinhubl, A. Torkamani, Digital medical tools and sensors, J. Am. Med. Assoc. 313 (4) (2015) 353–354.

[21] Research Councils UK, Areas of Research - Research Councils UK, 2014. Available: < https://www.epsrc.ac.uk/about/plans/deliveryplan/prosperityoutcomes/health/ > (accessed: 18-Feb-2017).

[22] E. Zhu, A. Lilienthal, L.A. Shluzas, I. Masiello, N. Zary, Design of mobile augmented reality in health care education: a theory-driven framework, JMIR Med. Educ. 1 (2) (2015) 1–18.

[23] E.Z. Barsom, M. Graafland, M.P. Schijven, Systematic review on the effectiveness

of augmented reality applications in medical training, Surg. Endosc. Other Interv. Tech. 30 (10) (2016) 4174–4183.
[24] U.V. Albrecht, C. Noll, U. Von Jan, Explore and experience: mobile augmented reality for medical training, Stud. Health Technol. Inform. 192 (1–2) (2013) 382–386.
[25] B.M.C. Silva, J.J.P.C. Rodrigues, I. de la Torre Diez, M. Lopez-Coronado, K. Saleem, Mobile-health: a review of current state in 2015, J. Biomed. Inform. 56 (2015) 265–272.
[26] S. Karthikeyan, T. Yk, N. Bindra, Medhi, Smartphone' – a user-friendly device to deliver affordable healthcare – a practical paradigm, J. Heal. Med. Inform. 7 (2016).
[27] G. Riva, R.M. Banos, C. Botella, F. Mantovani, A. Gaggioli, Transforming experience: the potential of augmented reality and virtual reality for enhancing personal and clinical change, Front. Psych. 7 (SEP) (2016).
[28] A. Meola, F. Cutolo, M. Carbone, F. Cagnazzo, M. Ferrari, V. Ferrari, Augmented reality in neurosurgery: a systematic review, Neurosurg. Rev. 40 (4) (Oct. 2017) 537–548.
[29] K.R. Lohse, C.G.E. Hilderman, K.L. Cheung, S. Tatla, H.F.M. Van der Loos, Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy, PLoS One 9 (3) (2014) e93318.
[30] K.J. Miller, B.S. Adair, A.J. Pearce, C.M. Said, E. Ozanne, M.M. Morris, Effectiveness and feasibility of virtual reality and gaming system use at home by older adults for enabling physical activity to improve health-related domains: a systematic review, Age Age. 43 (2) (2014) 188–195.
[31] L.R. Valmaggia, L. Latif, M.J. Kempton, M. Rus-Calafell, Virtual reality in the psychological treatment for mental health problems: an systematic review of recent evidence, Psych. Res. 236 (Feb.) (2016) 189–195.
[32] A. Kofod-Petersen, How to do a Structured Literature Review in computer science, Doc. released as a Guid. to Perform. a Struct. Lit. Rev. NTNU. Retrieved December, 2014, pp. 1–7.
[33] W. Afzal, R. Torkar, R. Feldt, A Systematic Review of Search-Based Testing for Non-Functional System Properties, 2009.
[34] D. Marks, L. Yardley, Research Methods for Clinical and Health Psychology, SAGE Publications, Ltd, 1 Oliver's Yard, 55 City Road, London England EC1Y 1SP United Kingdom, 2004.
[35] D.W. Krevelen, Augmented Reality: Technologies, Applications, and Limitations, Research Gate, 2007. Available: < https://www.researchgate.net/profile/Rick_Van_Krevelen2/publication/292150312_Augmented_Reality_Technologies_Applications_and_Limitations/links/56ab2b4108aed5a01359c113.pdf > (accessed: 15-Feb-2017).
[36] D.W. Krevelen, R. Poelman, A survey of augmented reality technologies, applications and limitations, Int. J. Virt. Real. 9 (2) (2010) 1–20.
[37] S. Jalali, C. Wohlin, Systematic literature studies: database searches vs. backward snowballing, ESEM' 12 Proceedings of the ACM-IEEE International Symposium on Empirical Software Engineering and Measurement, 2012, pp. 29–38.
[38] J. Webster, R.T. Watson, Analyzing the past to prepare for the future: writing a literature review, MIS Q. 26 (2) (2002).
[39] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2) (2006) 77–101.
[40] WHO, Terminology-A Glossary of Technical Terms on the Economics and Finance of Health Services, 1998.
[41] T.C. Beard, S. Redmond, Declaration of ALMA-ATA, Lancet 313 (8109) (1979) 217–218.
[42] R.S. Mans, W.M.P. van der Aalst, R.J.B. Vanwersch, Healthcare Processes, Springer International Publishing, Cham, 2015.
[43] C.L. Ventola, Mobile devices and apps for health care professionals: uses and benefits, P T 39 (5) (2014) 356–364.
[44] N. Agrawal, The national service framework for long term conditions, BMJ 330 (7503) (2005) 1280–1281.
[45] American Heart Association, 2005 American Heart Association (AHA) guidelines for Cardiopulmonary Resuscitation (CPR) and Emergency Cardiovascular Care (ECC) of pediatric and neonatal patients: pediatric basic life support, Pediatrics 117 (5) (2006) e989–e1004.
[46] V.L. Patel, J.F. Arocha, J.S. Ancker, Cognitive informatics and behavior change in the health care domain, Health Informatics, first ed., Springer International Publishing, Switzerland, 2017, pp. 3–11.
[47] J. Abbasi, Augmented reality takes Parkinson disease dance therapy out of the classroom, JAMA 317 (4) (2017) 346.
[48] D. Ai, et al., Augmented reality based real-time subcutaneous vein imaging system, Biomed. Opt. Exp. 7 (7) (2016) 2565.
[49] D. Andersen, et al., Medical telementoring using an augmented reality transparent display, Surgery (United States) 159 (6) (2016) 1646–1653.
[50] E.L. Anghel, et al., The reliability of a novel mobile 3-dimensional wound measurement device, Wounds a Compend. Clin. Res. Pract. 28 (11) (2016) 379–386.
[51] M. Arenas, et al., Individualized 3D scanning and printing for non-melanoma skin cancer brachytherapy: a financial study for its integration into clinical workflow, J. Contemp. Brachyther. 9 (3) (2017) 270–276.
[52] T. Blum, R. Stauder, E. Euler, N. Navab, Superman-like X-ray vision: towards brain-computer interfaces for medical augmented reality, 2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2012, pp. 271–272.
[53] H. Borgmann, et al., Feasibility and safety of augmented reality-assisted urological surgery using smartglass, World J. Urol. 35 (2017) 967–972.
[54] N. Bourdel, et al., Use of augmented reality in laparoscopic gynecology to visualize myomas, Fertil. Steril. 107 (3) (2017) 737–739.
[55] X. Chen, et al., Development of a surgical navigation system based on augmented reality using an optical see-through head-mounted display, J. Biomed. Inform. 55 (Jun.) (2015) 124–131.
[56] F. Cheriet, L. Song, P. Debanné, O. Dionne, H. Labelle, 3D digitizing device applied in evaluation and simulation of postoperative trunk surface shape in adolescent idiopathic scoliosis, International Conference on 3D Body Scanning Technologies, (2010).
[57] T.R. Coles, N.W. John, D. Gould, D.G. Caldwell, Integrating haptics with augmented reality in a femoral palpation and needle insertion training simulation, IEEE Trans. Hapt. 4 (3) (2011) 199–209.
[58] B. Dehbandi, et al., Using data from the microsoft kinect 2 to quantify upper limb behavior: a feasibility study, IEEE J. Biomed. Heal. Inform. 21 (5) (2017) 1386–1392.
[59] T.M. Deserno, J.E.E. De Oliveira, O. Grottke, Regional Anaesthesia Simulator and Assistant (RASimAs): medical image processing supporting anaesthesiologists in training and performance of local blocks, Proceedings – IEEE Symposium on Computer-Based Medical Systems, 2015, pp. 348–351.
[60] R.M. Dickey, N. Srikishen, L.I. Lipshultz, P.E. Spiess, R.E. Carrion, T.S. Hakky, Augmented reality assisted surgery: a urologic training tool, Asian J. Androl. (May 2015) (2015) 732–734.
[61] Dong Ni, et al., A virtual reality simulator for ultrasound-guided biopsy training, IEEE Comput. Graph. Appl. 31 (2) (2011) 36–48.
[62] Z. Fan, Y. Weng, G. Chen, H. Liao, 3D interactive surgical visualization system using mobile spatial information acquisition and autostereoscopic display, J. Biomed. Inform. 71 (Jul. 2017) 154–164.
[63] N. Farahani, et al., Exploring virtual reality technology and the Oculus Rift for the examination of digital pathology slides, J. Pathol. Inform. 7 (1) (2016) 22.
[64] D. Fortmeier, A. Mastmeyer, J. Schroder, H. Handels, A virtual reality system for PTCD simulation using direct visuo-haptic rendering of partially segmented image data, IEEE J. Biomed. Heal. Inform. 20 (1) (2016) 355–366.
[65] L.M. Galantucci, F. Lavecchia, G. Percoco Politecnico di Bari, 3D face measurement and scanning using digital close range photogrammetry: evaluation of different solutions and experimental approaches, International Conference on 3D Body Scanning Technologies, (2010).
[66] F. Gholami, D.A. Trojan, J. Kovecses, W.M. Haddad, B. Gholami, A microsoft kinect-based point-of-care gait assessment framework for multiple sclerosis patients, IEEE J. Biomed. Heal. Inform. 21 (5) (2017) 1376–1385.
[67] C. Hansen, et al., Illustrative visualization of 3D planning models for augmented reality in liver surgery, Int. J. CARS 5 (2010) 133–141.
[68] Y.W. Hsu, C.Y. Yu, Hand surface area estimation formula using 3d anthropometry, J. Occup. Environ. Hyg. 7 (11) (Sep. 2010) 633–639.
[69] P.K. Kanithi, J. Chatterjee, D. Sheet, Immersive augmented reality system for assisting needle positioning during ultrasound guided intervention, Proceedings of the Tenth Indian Conference on Computer Vision, Graphics and Image Processing – ICVGIP '16, 2016, pp. 1–8.
[70] P. Khanal, et al., Collaborative virtual reality based advanced cardiac life support training simulator using virtual reality principles, J. Biomed. Inform. 51 (Oct.) (2014) 49–59.
[71] L. Kovacs, F. Armbrecht, S. Raith, A. Volf, N.A. Papadopulos, M. Eder, Three-dimensional surface imaging -an objective approach of quality assurance in facial plastic, reconstructive and aesthetic surgery? International Conference on 3D Body Scanning Technologies, (2010).
[72] M. Kramers, R. Armstrong, S.M. Bakhshmand, A. Fenster, S. De Ribaupierre, R. Eagleson, A mobile augmented reality application for image guidance of neurosurgical interventions, Am. J. Biomed. Eng. 3 (6) (2013) 169–174.
[73] L. Li, et al., A novel augmented reality navigation system for endoscopic sinus and skull base surgery: a feasibility study, PLoS One 11 (1) (Jan. 2016) e0146996.
[74] H. Liao, T. Inomata, I. Sakuma, T. Dohi, 3-D augmented reality for MRI-guided surgery using integral videography autostereoscopic image overlay, IEEE Trans. Biomed. Eng. 57 (6) (2010) 1476–1486.
[75] Y. Lin, X. Wang, F. Wu, X. Chen, C. Wang, G. Shen, Development and validation of a surgical training simulator with haptic feedback for learning bone-sawing skill, J. Biomed. Inform. 48 (Apr.) (2014) 122–129.
[76] X. Liu, J. Niu, L. Ran, T. Liu, Estimation of human body volume (BV) from anthropometric measurements based on three-dimensional (3D) scan technique, Aesth. Plast. Surg. 41 (4) (2017) 971–978.
[77] P. Mithun, N.R. Raajan, Neural network based augmented reality for detection of brain tumor, Int. J. Eng. Technol. 5 (2) (2013) 1688–1692.
[78] M. Nakao, S. Endo, S. Nakao, M. Yoshida, T. Matsuda, Augmented endoscopic images overlaying shape changes in bone cutting procedures, PLoS One 11 (9) (2016).
[79] B.K. Ng, B.J. Hinton, B. Fan, A.M. Kanaya, J.A. Shepherd, Clinical anthropometrics and body composition from 3D whole-body surface scans, Eur. J. Clin. Nutr. 70 (11) (2016) 1265–1270.
[80] H.S. Park, C. Shah, Development of high speed and high accuracy 3D dental intra oral scanner, Proc. Eng. 100 (January) (2015) 1174–1181.
[81] L. Paul, H. Tober, G. Hegewald, Innovative 3D Spine Form Analysis and Parametrization of Scoliosis, Lordosis, Kyphosis and Malposition with TERGOSKOP, 2010.
[82] D. Qi, K. Panneerselvam, W. Ahn, V. Arikatla, A. Enquobahrie, S. De, Virtual interactive suturing for the Fundamentals of Laparoscopic Surgery (FLS), J. Biomed. Inform. 75 (Nov.) (2017) 48–62.
[83] T. Reichl, N. Navab, Image-based tracking of the teeth, MICCAI'12 Proc. 15th Int. Conf. Med. Image Comput. Comput. Interv. - vol. Part II, 2012, pp. 601–608.
[84] R.L. Schloesser, M. Lauff, H. Buxmann, K. Veit, D. Fischer, A. Allendorf, Three-dimensional body scanning: a new method to estimate body surface area in neonates, Neonatology 100 (3) (2011) 260–264.

[85] M. Solanki, V. Raja, Haptic based augmented reality simulator for training clinical breast examination, 2010 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES), 2010, pp. 265–269.
[86] J. Theopold, K. Weihs, C. Feja, B. Marquaß, C. Josten, P. Hepp, Detection of articular perforations of the proximal humerus fracture using a mobile 3D image intensifier – a cadaver study, BMC Med. Imag. 17 (1) (2017) 47.
[87] S. Ullrich, T. Kuhlen, Haptic palpation for medical simulation in virtual environments, IEEE Trans. Vis. Comput. Graph. 18 (4) (2012) 617–625.
[88] M. Vankipuram, K. Kahol, A. McLaren, S. Panchanathan, A virtual reality simulator for orthopedic basic skills: a design and validation study, J. Biomed. Inform. 43 (5) (2010) 661–668.
[89] J. Wang, et al., Augmented reality navigation with automatic marker-free image registration using 3-D image overlay for dental surgery, IEEE Trans. Biomed. Eng. 61 (4) (2014) pp.
[90] R. Yudkowsky, et al., Practice on an augmented reality/haptic simulator and library of virtual brains improves residents' ability to perform a ventriculostomy, Simul. Healthc. J. Soc. Simul. Healthc. 8 (1) (2013) 25–31.
[91] D. Magee, Y. Zhu, R. Ratnalingam, P. Gardner, D. Kessel, An augmented reality simulator for ultrasound guided needle placement training, Med. Biol. Eng. Comput. 45 (10) (2007) 957–967.
[92] O. Grottke, et al., Virtual reality-based simulator for training in regional anaesthesia, Br. J. Anaesth. 103 (4) (2009) 594–600.
[93] J.L. Mosso, et al., Virtual reality on mobile phones to reduce anxiety in outpatient surgery vol. 142, IOS Press, 2009.
[94] A. Abushakra, M. Faezipour, Augmenting breath regulation using a mobile driven virtual reality therapy framework, IEEE J. Biomed. Heal. Inform. 18 (3) (2014) 746–752.
[95] Y.M. Aung, A. Al Jumaily, Augmented reality-based RehaBio system for shoulder rehabilitation, Int. J. Mechatr. Autom. 4 (1) (2014) 52.
[96] W.-P. Brinkman et al., A virtual reality dialogue system for the treatment of social phobia, CHI '12 Ext. Abstr. Hum. Factors Comput. Syst., 2012, pp. 1099–1102.
[97] A. Gorini, F. Pallavicini, D. Algeri, C. Repetto, A. Gaggioli, G. Riva, Virtual reality in the treatment of generalized anxiety disorders, Stud. Heal. Technol. Inform. 154 (2010) 39–43.
[98] D. Jeffs, et al., Effect of virtual reality on adolescent pain during burn wound care, J. Burn Care Res. 35 (5) (2014) 395–408.
[99] D. Malinvaud, et al., Auditory and visual 3D virtual reality therapy as a new treatment for chronic subjective tinnitus: results of a randomized controlled trial, Hear. Res. 333 (2016) 127–135.
[100] A.G. Money, A. McIntyre, A. Atwal, G. Spiliotopoulou, T. Elliman, T. French, Bringing the home into the hospital: assisting the pre-discharge home visit process using 3D home visualization software, in: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 6768 LNCS, no. PART 4, 2011, pp. 416–426.
[101] B.A. Ponce, et al., Telemedicine with mobile devices and augmented reality for early postoperative care, 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2016, pp. 4411–4414.
[102] S. Weiß et al., Mobile Augmented Reality and 3D Printing to Involve Patients in Treatment Decisions for Prostate Cancer, 2016, pp. 1–6.
[103] D. Bernabei, F. Ganovelli, M. Di Benedetto, M. Dellepiane, R. Scopigno, A low-cost time-critical obstacle avoidance system for the visually impaired, in: Int. Conf. Indoor Position. Indoor Navig., no. September, 2011, pp. 21–23.
[104] R. Herrero, A. García-Palacios, D. Castilla, G. Molinari, C. Botella, Virtual reality for the induction of positive emotions in the treatment of fibromyalgia: a pilot study over acceptability, satisfaction, and the effect of virtual reality on mood, Cyberpsychol. Behav. Soc. Netw. 17 (6) (2014) 379–384.
[105] I.A. Kakadiaris, M.M. Islam, T. Xie, C. Nikou, A.B. Lumsden, IRay: Mobile AR Using Structure Sensor, in: Adjun. Proc. 2016 IEEE Int. Symp. Mix. Augment. Reality, ISMAR-Adjunct 2016, Sep. 2017, pp. 127–128.
[106] T. Banerjee, M. Skubic, J.M. Keller, C. Abbott, Sit-to-stand measurement for in-home monitoring using voxel analysis, IEEE J. Biomed. Heal. Inform. 18 (4) (2014) 1502–1509.
[107] Z.P. Bian, J. Hou, L.P. Chau, N. Magnenat-Thalmann, Fall detection based on body part tracking using a depth camera, IEEE J. Biomed. Heal. Inform. 19 (2) (2015) 430–439.
[108] M. Lo Bianco, S. Pedell, G. Renda, Augmented reality and home modifications : a tool to empower older adults in fall prevention, Proceedings of the 28th Australian Conference on Computer-Human Interaction, 2016, pp. 1–10.
[109] P. Bifulco, F. Narducci, R. Vertucci, P. Ambruosi, M. Cesarelli, M. Romano, Telemedicine supported by Augmented Reality: an interactive guide for untrained people in performing an ECG test, Biomed. Eng. Online 13 (1) (2014) 153.
[110] W. Chinthammit, et al., Ghostman: Augmented reality application for Telerehabilitation and remote instruction of a novel motor skill, Biomed. Res. Int. 2014 (Apr.) (2014) 646347.
[111] C. Hurter, D. McDuff, Cardiolens, in: ACM SIGGRAPH 2017 Emerging Technologies on - SIGGRAPH '17, 2017, pp. 1–2.
[112] C.V. Maani, et al., Virtual reality pain control during burn wound debridement of combat-related burn injuries using robot-like arm mounted VR goggles, J. Trauma 71 (1 Suppl.) (2011) S125–S130.
[113] K. Raghav, A.J. Van Wijk, F. Abdullah, M.N. Islam, M. Bernatchez, A. De Jongh, Efficacy of virtual reality exposure therapy for treatment of dental phobia: a randomized control trial, BMC Oral Heal. 16 (1) (2016) 25.
[114] E.E. Stone, M. Skubic, Fall detection in homes of older adults using the microsoft kinect, IEEE J. Biomed. Heal. Inform. 19 (1) (2015) 290–301.
[115] K. Tanja-Dijkstra, et al., Improving dental experiences by using virtual reality distraction: a simulation study, PLoS One 9 (3) (2014) e91276.
[116] V.C. Tashjian, et al., Virtual Reality for management of pain in hospitalized patients: results of a controlled trial, JMIR Ment. Heal. 4 (1) (2017) e9.
[117] A. Vankipuram, et al., Design and development of a virtual reality simulator for advanced cardiac life support training, IEEE J. Biomed. Heal. Inform. 18 (4) (2014) 1478–1484.
[118] F. Wang, E. Stone, M. Skubic, J.M. Keller, C. Abbott, M. Rantz, Toward a passive low-cost in-home gait assessment system for older adults, IEEE J. Biomed. Heal. Inform. 17 (2) (2013) 346–355.
[119] J. xiao Wang, et al., Real time 3D simulation for nose surgery and automatic individual prosthesis design, Comput. Meth. Progr. Biomed. 104 (3) (2011) 472–479.
[120] B.K. Wiederhold, K. Gao, L. Kong, M.D. Wiederhold, Mobile devices as adjunctive pain management tools, Cyberpsychol. Behav. Soc. Netw. 17 (6) (2014) 385–389.
[121] M. Wrzesien, J.-M. Burkhardt, M. Alcañiz Raya, C. Botella, Mixing psychology and HCI in evaluation of augmented reality mental health technology, Proceedings of the 2011 annual conference extended abstracts on Human factors in computing systems – CHI EA '11, 2011, p. 2119.
[122] M. Yu, Y. Yu, A. Rhuma, S.M.R. Naqvi, L. Wang, J.A. Chambers, An online one class support vector machine-based person-specific fall detection system for monitoring an elderly individual in a room environment, IEEE J. Biomed. Heal. Inform. 17 (6) (2013) 1002–1014.
[123] G. Riva, M. Bacchetta, M. Baruffi, E. Molinari, Virtual reality-based multidimensional therapy for the treatment of body image disturbances in obesity: a controlled study, Cyberpsychol. Behav. 4 (4) (2001) 511–526.
[124] T. Blum, V. Kleeberger, C. Bichlmeier, N. Navab, Mirracle: An augmented reality magic mirror system for anatomy education, in: Proceedings – IEEE Virtual Reality, 2012, pp. 115–116.
[125] P.F. Brennan, K. Ponto, G. Casper, R. Tredinnick, M. Broecker, Virtualizing living and working spaces: proof of concept for a biomedical space-replication methodology, J. Biomed. Inform. 57 (Oct.) (2015) 53–61.
[126] H. Cardona Reyes, J. Muñoz Arteaga, Multidisciplinary production of interactive environments to support occupational therapies, J. Biomed. Inform. 63 (Oct.) (2016) 90–99.
[127] Y.H. Choi, J. Ku, H. Lim, Y.H. Kim, N.J. Paik, Mobile game-based virtual reality rehabilitation program for upper limb dysfunction after ischemic stroke, Restor. Neurol. Neurosci. 34 (3) (2016) 455–463.
[128] J.W. Chong, N. Esa, D.D. McManus, K.H. Chon, Arrhythmia discrimination using a smart phone, IEEE J. Biomed. Heal. Inform. 19 (3) (2015) 815–824.
[129] M. Domhardt, et al., Training of carbohydrate estimation for people with diabetes using mobile augmented reality, J. Diab. Sci. Technol. 9 (3) (2015) 516–524.
[130] R. Hervás, J. Bravo, J. Fontecha, An assistive navigation system based on augmented reality and context awareness for people with mild cognitive impairments, IEEE J. Biomed. Heal. Inform. 18 (1) (2014) 368–374.
[131] C. Noll, B. Häussermann, U. von Jan, U. Raap, U.-V. Albrecht, Demo: mobile augmented reality in medical education: an application for dermatology, in: Proc. 2014 Work. Mob. Augment. Real. Robot. Technol. Syst., 2014, pp. 17–18.
[132] F. Ofli, G. Kurillo, Š. Obdržálek, R. Bajcsy, H.B. Jimison, M. Pavel, Design and evaluation of an interactive exercise coaching system for older adults: lessons learned, IEEE J. Biomed. Heal. Inform. 20 (1) (2016) 201–212.
[133] L.C. de Oliveira, A.O. Andrade, E.C. de Oliveira, A. Soares, A. Cardoso, E. Lamounier, Indoor navigation with mobile augmented reality and beacon technology for wheelchair users, 2017 IEEE EMBS International Conference on Biomedical & Health Informatics (BHI), 2017, pp. 37–40.
[134] S. Ortiz, A. Uribe-Quevedo, B. Kapralos, Hand VR exergame for occupational health care, Stud. Heal. Technol. Inform. 220 (2016) 281–284.
[135] J.M. Saez, F. Escolano, M.A. Lozano, Aerial obstacle detection with 3-D mobile devices, IEEE J. Biomed. Heal. Inform. 19 (1) (2015) 74–80.
[136] P. Sigam, M. Denz, Reliability and Accuracy of Wound Surface Measurement Using Mobile Technology, 2015, pp. 1–5.
[137] J. Soeiro, A.P. Claudio, M.B. Carmo, H.A. Ferreira, Visualizing the brain on a mixed reality smartphone application, in: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, vol. 2015–Novem, 2015, pp. 5090–5093.
[138] S. Yeom, Augmented Reality for Learning Anatomy, ascilite 2011 Chang. Demands, Chang. Dir., vol. 1, 2011, pp. 1377–1383.
[139] M.Y. Zhao, S.K. Ong, A.Y.C. Nee, An augmented reality-assisted therapeutic healthcare exercise system based on bare-hand interaction, Int. J. Hum. Comput. Interact. 32 (9) (2016) 708–721.
[140] M. Zilverschoon, K.L. Vincken, R.L.A.W. Bleys, The virtual dissecting room: creating highly detailed anatomy models for educational purposes, J. Biomed. Inform. 65 (Jan.) (2017) 58–75.
[141] S. Sakellariou, B.M. Ward, V. Charissis, D. Chanock, P. Anderson, 20-Design and Implementation of Augmented Reality environment for complex anatomy training-inguinal canal case study, Shumaker R. Virtual Mix. Reality, VMR 2009, vol. 5622, 2009, pp. 605–614.
[142] R.H. Harper, M. Lamming, W. Newman, Locating systems at work: implications for the development of active badge applications, Interact. Comput. 4 (3) (1992) 343–363.
[143] V. Bellotti, A. Sellen, Design for privacy in ubiquitous computing environments, in: Proceedings of the Third European Conference on Computer-Supported Cooperative Work 13–17 September 1993, Milan, Italy ECSCW '93, Springer Netherlands, Dordrecht, 1993, pp. 77–92.
[144] K.E. Caine, W.A. Rogers, A.D. Fisk, Privacy perceptions of an aware home with visual sensing devices, in: Proc. Hum. Factors Ergon. Soc. Annu. Meet., vol. 49, no. 21, 2005, pp. 1856–1858.
[145] S. Park, S. Park, H. Kautz, Privacy-preserving recognition of activities in daily

living from multi-view silhouettes and RFID-based training, in: AAAI Symp. AI Eldercare NEW Solut. TO OLD Probl., 2008.
[146] G. Demiris, D.P. Oliver, J. Giger, M. Skubic, M. Rantz, Older adults' privacy considerations for vision based recognition methods of eldercare applications, Technol. Heal. Care 17 (1) (2009) 41–48.
[147] J. Hamm, A.G. Money, A. Atwal, I. Paraskevopoulos, Fall Prevention Intervention Technologies: A Conceptual Framework and Survey of the State of the Art, 2016.
[148] Apple Inc, Creating Face-Based AR Experiences – Apple Developer Documentation, 2018. Available: < https://developer.apple.com/documentation/arkit/creating_face_based_ar_experiences > (accessed: 30-Mar-2018).
[149] K.A. Nguyen, Z. Luo, On assessing the positioning accuracy of Google Tango in challenging indoor environments, in: 2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 2017, pp. 1–8.
[150] i9finite, Google's Project Tango : All you need to know! - i9finite, 2016.
[151] Github, Github Open-Sourced ARkit Solutions, 2018. Available: < https://github.com/search?utf8=&q=ARkit&type= > .