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Guidetomeasure-OT: A mobile 3D application to improve the accuracy, consistency, and efficiency of clinician-led home-based falls-risk assessments

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ABSTRACT

Background: A key falls prevention intervention delivered within occupational therapy is the home environment falls-risk assessment process. This involves the clinician visiting the patient's home and using a 2D paper-based measurement guidance booklet to ensure that all measurements are taken and recorded accurately. However, 30% of all assistive devices installed within the home are abandoned by patients, in part as a result of the inaccurate measurements being recorded as part of the home environment falls-risk assessment process. In the absence of more appropriate and effective guidance, high levels of device abandonment are likely to persist.
Aim: This study presents guidetomeasure-OT, a mobile 3D measurement guidance application designed to support occupational therapists in carrying out home environment falls-risk assessments. Furthermore, this study aims to empirically evaluate the performance of guidetomeasure-OT compared with an equivalent paper-based measurement guidance booklet.
Methods: Thirty-five occupational therapists took part in this within-subjects repeated measures study, delivered within a living lab setting. Participants carried out the home environment falls-risk assessment process under two counterbalanced treatment conditions; using 3D guidetomeasure-OT; and using a 2D paper-based guide. Systems Usability Scale questionnaires and semi-structured interviews were completed at the end of both task. A comparative statistical analysis explored performance relating to measurement accuracy, measurement accuracy consistency, task completion time, and overall system usability, learnability, and effectiveness of guidance. Interview transcripts were analysed using inductive and deductive thematic analysis, the latter was informed by the Unified Theory of Acceptance and Use of Technology model.
Results: The guidetomeasure-OT application significantly outperformed the 2D paper-based guidance in terms task efficiency ($p < 0.001$), learnability ($p < 0.001$), system usability ($p < 0.001$), effectiveness of guidance ($p = 0.001$). Regarding accuracy, in absolute terms, guidetomeasure-OT produced lower mean error differences for 11 out of 12 items and performed significantly better for six out of 12 items ($p = < 0.05$). In terms of SUS, guidetomeasure-OT scored 83.7 compared with 70.4 achieved by the booklet. Five high-level themes emerged from interviews: Performance Expectancy, Effort Expectancy, Social Influence, Clinical Benefits, and Augmentation of Clinical Practice. Participants reported that guidetomeasure-OT delivered clearer measurement guidance that was more realistic, intuitive, precise and usable than the paper-based equivalent. Audio instructions and animated prompts were seen as being helpful in reducing the learning overhead required to comprehend measurement guidance and maintain awareness of task progression.
Conclusions: This study reveals that guidetomeasure-OT enables occupational therapists to carry out significantly more accurate and efficient home environment falls-risk assessments, whilst also providing a measurement guide tool that is considered more usable compared with the paper-based measurement guide that is currently used by clinicians in practice. These results are significant as they indicate that mobile 3D visualisation technologies can be effectively deployed to improve clinical practice, particularly within the home environment falls-risk assessment context. Furthermore, the empirical findings constitute overcoming the challenges associated with the digitisation of health care and delivery of new innovative and enabling technological solutions that health providers and policy makers so urgently need to ease the ever-increasing burden on existing public resources. Future work will focus on the development and empirical evaluation of a mobile 3D application for patient self-assessment and automated assistive equipment prescription. Furthermore, broader User Experience

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aspects of the application design and the interaction mechanisms that are made available to the user could be considered so as to minimize the effect of cognitive overloading and optimise user performance.

1. Introduction

The demand for healthcare resources is rising steadily, largely as a consequence of an ageing global population, coupled with increasingly constrained public health resource budgets [1,2]. Innovations in technology for healthcare are seen as one of the few areas that promise efficiency gains, a reduction in costs, whilst also delivering improvements in quality of service and care for patients [1]. In the UK, the government's commitment to innovation via the use of Information and Communication Technology has been made clear and is seen as a key lever in delivering more efficient, person-centred, preventative, reabling and personalised care [3]. The area falls prevention is by no means exempt from the global health challenges being faced [4], and the development of technology assisted falls prevention interventions remains as key area of research focus [5–8]. The number of falls related injuries has increased in recent years, in part as a result of an ageing population [9]. In the UK alone, the annual cost of falls to the National Health Service is estimated as being in excess of £2.3 billion and it is anticipated that this figure will continue to rise [3]. Approximately 30% of older adults over 65 years and 50% of adults over 80, who live independently, fall each year [9]. One of the key fall prevention interventions used to reduce the risk of falling within the home setting is the prescription of assistive devices such as stair handrails, toilet raisers, chair raisers, bath boards, and bathroom grab rails. Assistive devices are growing in importance for falls prevention activities, as they are believed to reduce the risk of falling [10,11], promote functional independence [12],and increase self-efficacy [13] and quality of life [14,15]. The assistive devices market was valued at USD 12.37 billion in 2012 and is expected to reach an estimated value of USD 19.68 billion by 2019 [16]. This is perhaps not surprising given that the risk of falls and the use of AD increases with age [17]. There is also evidence that indicates, assuming the correct prescription of AD, substantial cost savings for health care providers can be made by promoting the use of such devices [18,19]. Despite the apparent benefits, there appear to be a number of barriers to ensuring that assistive devices are successfully adopted and used. These barriers can include lack of knowledge about the device, lack of patient involvement in the process of selecting it, attitude towards the use of such devices, and a poor fit between service users, the assistive devices, and the home environment [20,21]. As a consequence, it is estimated that on average, 30% of all assistive devices prescribed are abandoned by patients within the first year of being fitted [22].

2. Related work

2.1. Home-environment falls-risk assessments

Home-environment falls risk assessment process (HEFAP) is the key process via which assistive devices are prescribed to patients. HEFAP has the primary aim of promoting independent living by identifying and mitigating falls risk factors via the appropriate provision of assistive devices (also referred to as assistive equipment/assistive technology) [23]. Current HEFAP practice involves a clinician working with the patient to identify falls risks within the home that impact on the patient's ability to effectively carry out activities of daily living (ADLs). In order to carry out the HEFAP, a clinician (often an Occupational Therapist) visits the patient home to gather information about the patient's functional abilities. An important part of the process is to take and record accurate measurements of the key items of furniture around the home and the patient (typically popliteal height). These measurements are then used to prescribe adaptations to the patient's home in accordance with the information recorded during the home visit. Prescribed adaptations typically include the provision of assistive equipment tailored to the needs of the individual, such as the installation of appropriately sized bath boards, shower chairs, toilet raisers, chair raisers, bed raisers, and grab rails to help with transfers when bathing or climbing stairs [24]. Accurate prescription of assistive equipment is therefore of paramount importance to both the acceptance of the functional changes by the patient and also a key strategy to mitigate the adverse impact of functional decline. Successful provision of assistive equipment will sustain independent living and quality of life, whereas miscarried assessment and inefficacy of home modifications can lead to increasing the probability of falls [25]. In order to ensure accurate measurement, current best practice supports the use of paper-based measurement guidance booklets, which provide measurement instruction and help ensure that all appropriate measurements are recorded during the visit [22]. Paper-based measurement guidance provides two-dimensional (2D) illustrations of information that must be collected from key items of home furniture, fittings and the patient. The paper-2D illustrations are typically annotated with measurement arrows that serve as prompts to indicate the precise points in three-dimensional (3D) space that must be accurately identified and measured in order to gather the necessary data to formulate an assessment and to accurately prescribe the necessary assistive devices [26]. A recent study funded UK Occupational Therapy Research Foundation has developed and published a 2D paper-based measurement guidance tool which has been specifically designed to enhance and standardise the quality of paper-based guidance and improve the accuracy of assistive device self-assessment measurements recorded by patients and practitioners [22,27]. The 2D paper-based guidance represents the current state-of-the-art in 2D paper-based clinical measurement guidance, offering measurement guidance for the five items of furniture (bed, bath, toilet, chair, and stairs) that are most frequently associated with falls within the home and hence most commonly measured as part of HEFAP [28,29].

Despite the prominent use of 2D paper-based clinical measurement guidance, almost a third of assistive devices prescribed by clinicians are abandoned by patients within one year [22,30,31]. This is a significant proportion, which may be attributed to a failure on the part of the health service that has prescribed the equipment, and has direct and real consequences on levels of patient independence and overall quality of life [32]. One of the key reasons for this equipment abandonment is "poor fit" between the assistive device and the person it is prescribed for [20,21]. The impact of poor fit of assistive devices is wide-spread and significantly affects healthcare objectives by potentially accelerating functional decline, increasing overall exposure to falls risks in the home, and, more generally, unnecessarily depleting already scarce and valuable health care resources [32,33].

2.2. 3D visualisation solutions for enhanced clinical assessment

Three dimensional (3D) visualisation refers to computer generated graphics and software applications that exploit certain characterisitics of human vision to enhance visual representation of 3D objects through a 2D presentation device (such as computer monitors) and create the illusion of depth. Furthermore, the visual representation of objects in 3D graphics, enable the user to interact with these objects in a more natural manner and control them within the virtual 3D space. The added value of 3D graphics and visualisation, and more specifically their application to healthcare related challenges is well documented in the recent years. Studies that have exploited 3D graphics in the modality for physical rehabilitation of a variety of conditions and targeted cohorts have been prominently appearing in the literature throughout the recent years. For example, Uzor et al. [34] and Doyle et al. [35] aim to improve uptake and adherence to home-based falls prevention exercise programmes by replacing traditional paper-based 2D illustrated exercises with equivalent interactive 3D visualisation of these programmes. One existing study explores the potential of exploiting 3D visualisation technologies to assist clinicians in identifying extrinsic fall hazards. Du et al. [36] developed a robotic system to automatically model patients' home environments in 3D space. A 3D visualisation of the environment is constructed, with the help of the robot, to assist clinicians in identifying the precise location and nature of extrinsic fall hazards. Examples in other areas of healthcare include the work of Spyridonis et al. [37] who found that enabling patients to carry out self-assessments by reporting the type and precise location of back pain by using a 3D visualisation of the human body was more accurate and intuitive than the traditional paper-based 2D model of the human body typically used in practice. Other studies have found similar benefits in utilising 3D visualisations to communicate other forms of pain to clinicians. For example, Jang et al. [38] enable clinicians and patients work more collaboratively and express their symptoms of pain to clinicians by annotating specific regions on an on-screen 3D representation of the human body using free-hand drawing. De Heras Ciechomski et al. [39] propose a preoperative surgical 3D visualisation system for breast augmentation using 2D digital photographs of the patient's torso and reconstructing these into 3D models. This system helps clinicians to perform virtual clinical analysis without the patient being present and visualises the required measurements on the modeled body in order to facilitate accurate measurements for the treatment. Other research efforts have focused on how to utilize 3D visualisation for healthcare personnel training, with surgical training being one of the most prominent areas [40,41]. The use of 3D graphics and visualisation in various modalities has been indicated in the research literature as a promising solution to overcome the challenges of existing, conventional 2D-based clinical tools and to sufficiently provide the visual quality necessary to conceptualise visual cues as part of a particular treatment and assessment [23,42]. In the field of occupational therapy, a qualitative study exploring clinicians' perceptions of using mobile 3D visualisation technologies for facilitating home assessments has suggested that clinicians see potential benefits of applying such technologies in practice [43]. However, no existing research has developed a fully functional mobile 3D measurement guidance application and explored the clinical utility of its performance in terms of measurement accuracy and consistency, efficiency, usability and user satisfaction, compared with the state of the art 2D paper-based equivalent.

There is a need to address the equipment abandonment issues currently faced within HEFAP. Therefore, there is a need to explore the potential application of 3D visualisation tools and applications developed specifically for use by clinicians to better guide the HEFAP process and to ensure that accurate and appropriate measurements are taken and recorded as part of this process.

2.3. Research aims

The aim of this study is to evaluate the performance of the guidetomeasure-OT application (developed specifically for Occupational Therapists), compared with existing 2D paper-based measurement guidance tools that are currently used in practice. This study explores, from the clinicians' perspective, the relative effectiveness and efficiency of the application, and perceptions of the application in terms of user satisfaction and attitudes towards adopting and using this new technology in practice. Specifically, the following research questions are addressed in this study: ***R1***: Does 3D guidetomeasure-OT produce more accurate recording of measurements, on average, compared with the paper-based equivalent guidance, when used by clinicians?; ***R2***: Does guidetomeasure-OT produce more consistently accurate measurements, compared with the paper-based equivalent, when used by clinicians? ***R3***: Does guidetomeasure-OT support the more efficient recording of measurements, compared with the paper-cased equivalent, when used by clinicians? ***R4***: How satisfied are clinicians with the guidetomeasure-OT compared with the paper-based equivalent, in terms of system usability? ***R5***: What are clinicians' views of guidetomeasure-OT with regards to the perceived challenges, opportunities, and their intention to adopt and use this application in practice?

3. Guidetomeasure-OT

This section presents details about guidetomeasure-OT, the system design and development process is presented in Section 3.1. The system architecture is presented in Section 3.2, and a full application walkthrough is presented in Section 3.3.

3.1. System design and development process

Designing usable applications that deliver functionality that are aligned with user needs, is as important as the innovation itself [44,45]. It is more likely that practitioners will engage with and use new technologies if they are usable and are perceived to be compatible with user needs [46,47]. Therefore, it is crucial when developing healthcare applications, that the practitioner needs are understood and included at every stage of the application design and development process [48,49].

The guidetomeasure-OT system has been designed and developed iteratively, using a range of user-centred design methods, over a number of years and has progressed through numerous user centred design and usability testing phases prior to completing the development of the full-scale version of the guidetomeasure-OT application that is presented and empirically evaluated here. Fig. 1 presents the user-centred design process that has been followed in order to develop the guidetomeasure-OT application which is presented and empirically evaluated here.

The first step in the user-centred design and development process

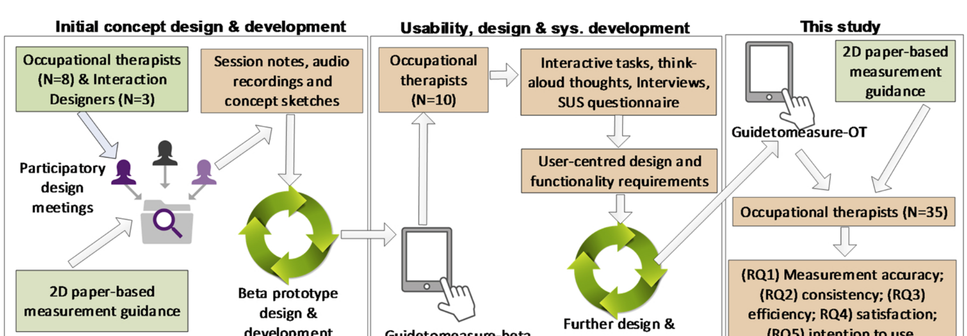

Fig. 1. User centred design process for guidetomeasure-OT.

involved a *concept design and development* phase. Eight occupational therapists and three interaction designers took part in series of participatory design session. Participants were provided with a sample of existing representative 2D paper-based measurement guidance leaflets to use as a point of reference and a low fidelity prototype application (deployed on a mobile phone, tablet and laptop) was also provided to demonstrate how 2D measurement guidance leaflets may be feasibly presented using 3D visualisation technologies. Participants were tasked with the challenge of exploring the idea of replacing the 2D paper-based measurement guidance leaflet with a digital equivalent and were asked to identify the key features and functionality that would be necessary in a digital equivalent application. With the help of the interaction designers, participants were also asked to develop annotated concept sketches of the suggested application user interface including requirements and functionality of a potential application interface and associated requirements and functionality. All sessions were observed, audio recorded, and notes were taken by two researchers during the sessions.

The outputs of the concept design and development phase were used to inform the design and development of the first beta-prototype version of the guidetomeasure-OT application. The beta version of the application was then used in a second phase of *usability, design and system development*. This involved carrying out user trials with 10 occupational therapists who were presented with the beta version of guidetomeasure-OT and were asked to complete a series of measurement tasks using the application. Participants were asked to 'think-aloud' as they completed the measurement tasks and were also interviewed and asked to complete the Systems Usability Scale (SUS) at the end of the measurement task. Our previous work provides a detailed description of the beta prototype, and the results of the user-based trials that were carried out to inform the development of the final version of guidetomeasure-OT, which has subsequently been developed and is presented in the remainder of this section [43].

3.2. System architecture

The *guidetomeasure-OT system architecture* and associated *measurement guidance module*, presented in Fig. 2, provides users with 3D visualisation measurement guidance by displaying 3D models of the five furniture items (bed, bath, toilet, chair, and stairs) most commonly associated with falls within the home and hence are measured as part of HEFAP [28,29].

Rendering 3D models: The *Unity3D engine* is responsible for rendering the furniture scenes which contain objects such as the *avatar model*, *3D furniture models,* and *arrow prompts* of the application. Like the previous design stage, the prototype was further developed using the Unity3D, a game engine with cross platform capabilities developed by Unity technologies, which allows content to be developed and deployed on Android, IOS, desktop or the web. The other tool which was utilised for the design of 3D furniture models was Blender. This is an open-source 3D authoring tool that allows 3D graphics/objects to be developed and integrated into any game engine e.g. Unity3D. It allows 3D objects to be imported and designed in accordance to the needs of the end-users. The version of Blender used was v2.76 [50]. *Scenes*: There are in total five furniture scenes: *bath, chair, stairs, toilet, bed* and an *'About You'* scene where users record their popliteal height dimensions. *GameObjects* represent custom coded models and functionality within each scene. MonoDevelop, which is an open source IDE editor, was used to develop the behaviour via scripts for the GameObject. The *3D guidance models* located in each scene are used to facilitate users to record accurate

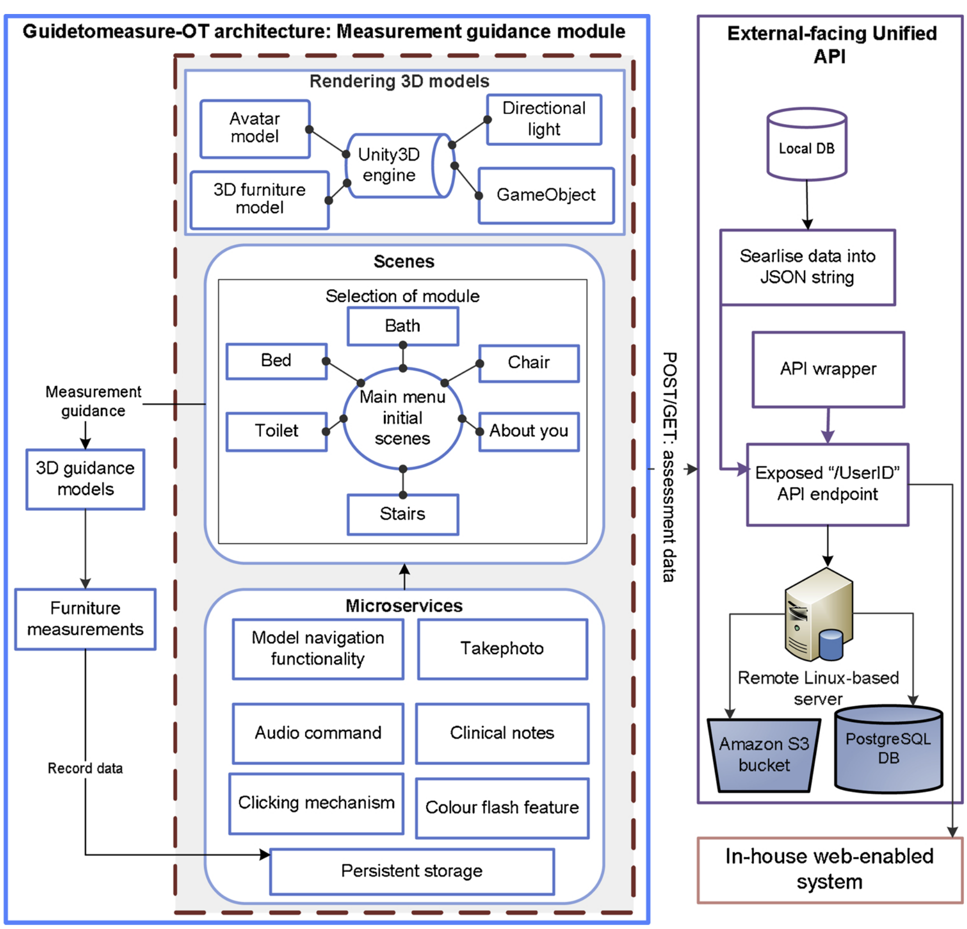

Fig. 2. System architecture of the guidetomeasure-OT application.

furniture measurements and stored in local persistent storage.

Microservices: The application contains the core application functionality which has been decoupled into microservices and attached to the GameObjects in the furniture scene which are invoked by the UI component in the presentation layer. This adopts an essentially polymorphic principle of allowing scenes to use (overload and override) these services in the context in which they are used. *Model navigation functionality* contains two sub-functions. First, the 3D model rotation which uses the input touch library to detect user's finger-swipe gestures on the screen to rotate the model along the x axis from its relative position. Second, egocentric navigation is used to allow the camera in the scene to rotate around the model itself along with the zoom-in/out function. *Takephoto* uses the android plugin to access the Android device's camera to take photos through the application. *Audio command* contains a corpus of pre- recorded measurement instructions in a. mp3 audio format to match each corresponding arrow prompt in the furniture scenes. *Notepad* is simply a UI GameObject which allows users to input their notes using the device's virtual keyboard and then stores the notes

to the local database for reporting purposes. *Clicking mechanism* registers each of the arrow prompts as components which allow users to click on the arrows to activate the audio guides. *Colour flash feature* is an animation developed using transitions and events to loop through colours in the RGB colour model. The service is attached to the arrow prompts and executed once the scene is initiated. *Persistent storage* is responsible for storing the measurements and the photographs taken on the device and then transmitting the data to a local repository and *local SQLite database.*

External-facing Unified API: The built-in application programming interface (API) provides an *exposed API endpoint* to enable clinicians to retrieve patient assessments and self-directed equipment prescriptions. The naming of the endpoints is the service user ID concatenated onto the URL base address of the API (e.g. /UserID). These endpoints require special permissions to be accessed. Any client used to access the API must be secured using a digital security certificate. The measurement guidance module performs a *POST request* to the *API wrapper* with *serialised dataset in a JSON string* which is then consumed by a script which runs on the *remote Linux-based server* and stored to the *PostgreSQL database* or *Amazon S3 bucket* if any photographs were taken. Given that an *in-house web-based system* used by clinicians in their practice supports API requests (or could be configured to do so), a GET request would be required to retrieve patient assessments from the app. Recorded assessments are merged with the corresponding patient record, which is stored on a *PostgreSQL database* located on a remote *Linux-based server*. Any supporting photographs (aiding clinical reasoning) taken of the patients' home furniture is stored in the Amazon S3 bucket to be viewed by clinicians who have access via an API request call. There are two scripts located on the server which handle data that is stored to the remote DB and S3 bucket.

3.3. Application walkthrough

This section provides a walkthrough of the 3D measurement guidance application. In addition, the measurement 3D guidance is showcased as a side-by-side comparison with the items included in the current state-of-the-art 2D evidence-based booklet, which is used by patients and clinicians as part of the HEFAP process [27].

3.3.1. Launch screen and main menu

The first screen that users are presented with is the launch screen. They receive brief audio instructions, welcoming them to the application and to touch the image in the centre of the screen to proceed, which takes them to the main menu. The main menu presents the five home furniture items and an 'About you' option which relates specifically to the patient user interacting with the application. Each of the six options can be accessed by touching the appropriate representative icon displayed on the main menu screen. Audio instructions prompt the user to select the item that they would like to measure. Fig. 3 presents both the launch screen and the main menu screen as it appears to the user.

3.3.2. Measurement recording and guidance

Once an option is selected, the application displays a 3D model of the item selected to be measured, complete with measurement guidance. All six measurement guidance screens that may be accessed via the Main menu are presented in Fig. 4.

The 3D furniture model presented in each scene includes arrow prompts which indicate visually where the measurements should be taken from and to. For example, in the toilet measurement scene, there are two pairs of measurements that must be taken and recorded on this screen, those relating to points A to B and points C to D. All arrow prompts are carefully positioned so that they mirror the necessary measurement points indicated for this item in the state-of-the-art 2D measurement guidance booklet [27]. The arrow prompts are embedded with flashing colour animation (pulsating through the full RGB colour spectrum with a few milliseconds transition between each colour) to indicate to the user that the arrow is awaiting selection. The arrow prompts have a built in mechanism that handles errors and will only stop the pulsating colour transition once an appropriate numeric measurement value has been provided. After the measurement is recorded, the static colour state is restored with the measurement recorded being displayed on the arrow. Once the arrow is selected, instructions specific to the arrow are delivered via a voice prompt and a numeric virtual keyboard is presented to the user to insert the measurement value. Existing healthcare studies recommend the use of a numeric keyboard

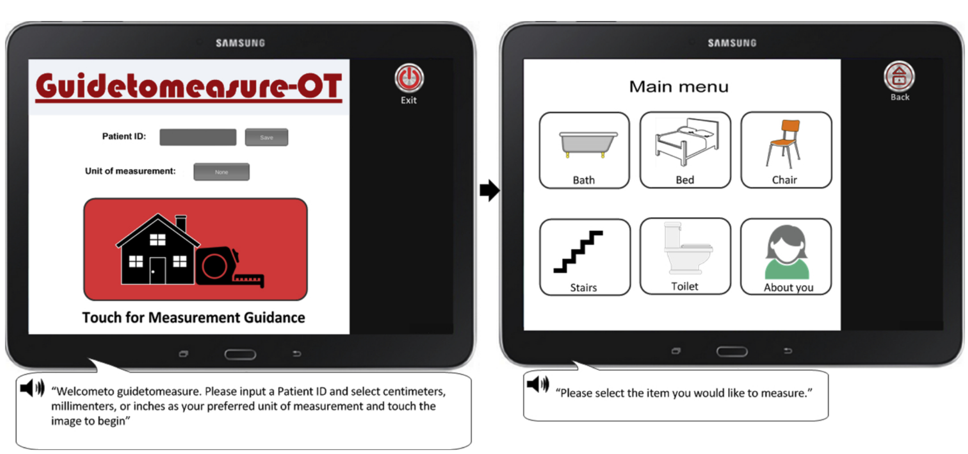

Fig. 3. Launch screen (Left), and Main Menu (Right).

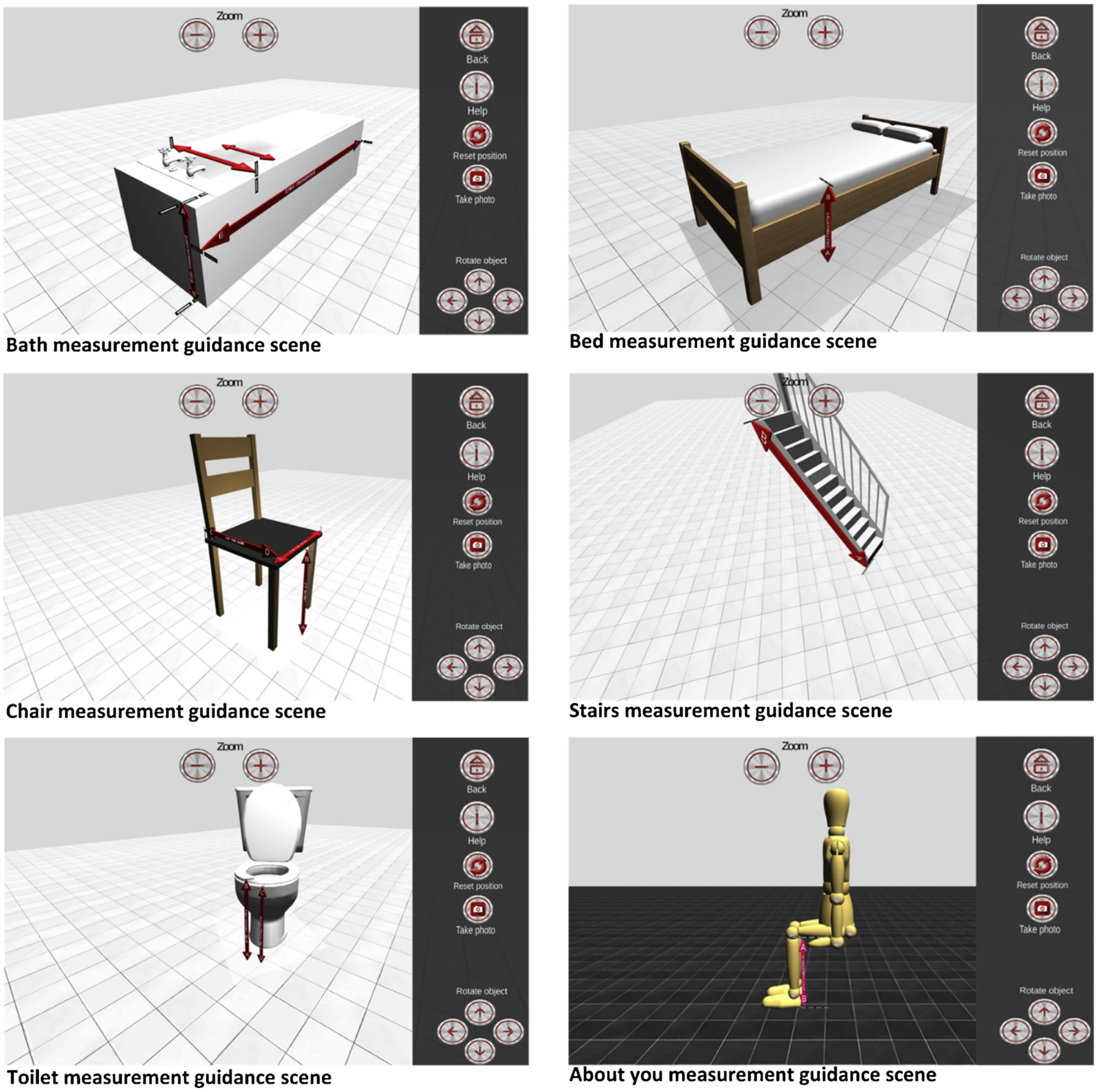

Fig. 4. Six measurement guidance scenes.

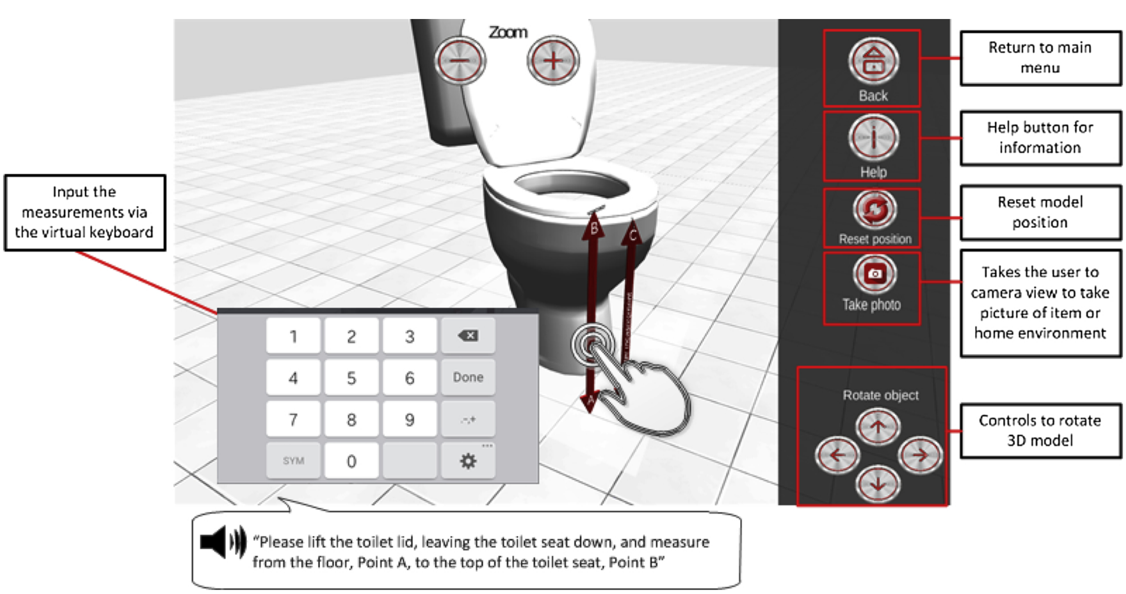

Fig. 5. Annotated measurement guidance screen.

for such tasks [51]. Fig. 5 presents an annotated toilet model measurement showcasing the range of functionality offered.

3.3.3. Navigation

A range of functionality is provided on the right hand side of the application, including a 'Back' button, which returns the user to the main menu a 'Help' button, which provides additional audio-based instruction for the task at hand. A 'Reset position' button allows the user to reset the orientation of the 3D model back to its original position and the 'Take photo' button takes the user to camera view and enables them to take a picture of the item they are measuring. Exocentric rotation of the 3D model is made possible via two interaction mechanisms, firstly the directional arrows positioned on the bottom left of the control pane, and secondly by performing the swipe gesture i.e. moving a finger across the touchscreen to orbit the view perspective of the 3D model. Fig. 6 shows both of the rotation features within the context of the chair measurement guidance screen.

There are also two interaction mechanisms for zooming in and out of the target. This can be done, either by touching the 'Zoom +' (zoom in) or 'Zoom –' (zoom out) buttons positioned centrally at the top of the screen or by using pinch gestures. Fig. 7 showcases the zoom in function via the 'pinch out' gesture (applying two fingers on the screen and gradually moving them apart) or touching the 'Zoom +' button. Conversely, Fig. 8 showcases the zoom out function, both within the context of the bath measurement guidance screen.

3.3.4. Additional 'About you' information

Once the popliteal height has been entered within the 'about you' measurement guidance scene, the clinician is presented with an assessment questionnaire in order to collect baseline demographic information and information relating to activities of daily living, functional abilities and furniture/associated assistive equipment. The clinician is prompted to enter answers to the questions about the patient through the text fields, multiple choice items, and binary options (yes or no) answers. Fig. 9 presents the assessment notes function which allows the clinician to record free text notes about the assessment if necessary (A), and shows the assessment questionnaire window in the 'About You' screen (B).

4. Method

This section provides details of the data collection and analysis protocol used to address the specific research aims of this study. Fig. 10 provides an overview of the protocol.

4.1. Study participants

Thirty-five Occupational Therapist participants were recruited to via hospital and community-based occupational therapy services in the UK in an online search through the NHS service directories page. To recruit more participants, contact was made with 'gatekeepers' (such as clinical leaders and heads of occupational therapy services) in the first instance in order to disseminate the invite to colleagues that work with older adults. Occupational therapy teams working within the social care sector, as part of local authorities, were also identified by an online search. In addition, the invite was distributed through the College of Occupational Therapists on their website in the specialist sections and made available on the College of Occupational Therapists social networking pages (e.g. Facebook and LinkedIn). The number of participants required was estimated by carrying out an a priori power analysis using G* power 3.1 software, which to ensure a power of 0.80 with a medium effect size of 0.5 (dz) and for a 2-tailed hypothesis was calculated as $N = 34$ participants, of which 35 occupational therapist participants were recruited. The inclusion criteria were that participants: (1) had the relevant clinical experience of working with community-dwelling older adults within a hospital or other clinical setting (e.g. falls service and social care and health services) or in the community; (2) experience in the provision of assistive equipment and minor adaptions; (3) carried out home visit assessments; (4) used a range of technology; (5) were registered healthcare practitioners; and (6) were proficient English speakers. Participants' demographic details reveal that the majority of the participants were female *(93.9%, $n = 31$)*. This may be justified by the view that the occupational therapy field is identified as a female-dominated profession [52]. The mean score of clinicians' years of experience equated to 14.2. All clinicians reported experience working with community-dwelling older adults, specialising in a range of areas that fall within the community or hospital. Table 1 presents a summary of occupational therapist participant profiles for this study.

4.2. Protocol and instrumentation

A within subjects counterbalanced design was used to verify the accuracy and consistency of measurements recorded using the guidetomeasure-OT application (measurement guidance module) compared with paper-based booklet measurement guidance. It is worthy to note that a pilot study was carried out with seven clinicians in the same setting in which the main study were conducted. This trial run was to identify any issues with the experimental design and to rectify these accordingly prior to the main trial. The study was conducted in a controlled Living Lab space located in the Stoke on Trent Mobility and Independent Living Centre. The living lab hosted a bedroom, bathroom, lounge, kitchen, dining area and full-length stairs. In preparation for the trials, the living lab was assembled by expert clinicians to represent a typical daily living environment whilst ensuring that all necessary items were in place for the measurement task. Four expert clinicians took measurements for each item and reached consensus on the true mean values (gold standard) against which measurements recorded by participants could be compared. Informed consent was obtained at the start of each session. Initially, participants were given a brief demonstration

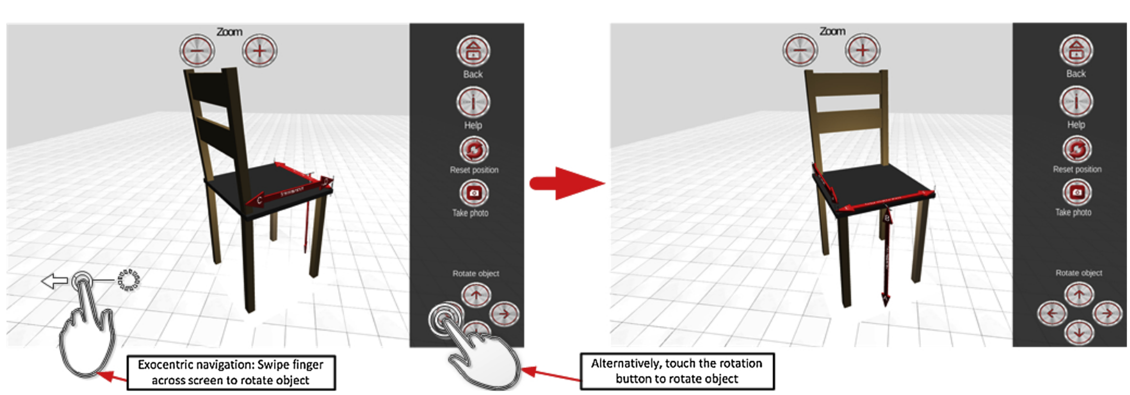

Fig. 6. Exocentric navigation (using the drag touch gesture) and rotation button.

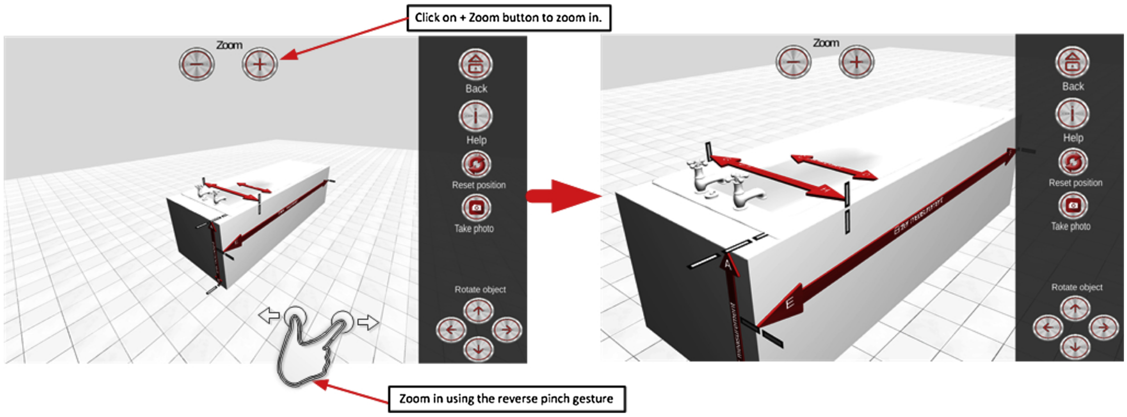

Fig. 7. Chair measurement screen demonstrating Zoom in function.

of the two measurement guidance tools (i.e. the guidetomeasure-OT application and booklet) and were given a tour of the living lab environment. They were then issued with one of the measurement guidance tools, a tape measure and asked to record the measurements of items as indicated as by the measurement guidance tool. For the popliteal height, participants were asked to measure a seated person's popliteal height to allow comparisons for testing accuracy between the two measurement guidance tools. The total amount of time taken was noted on completion of the measurement task. Participants were then asked to complete an adapted Systems Usability Scale (SUS) questionnaire [53] which included the 10 standard SUS statements and four additional bespoke statements specifically about the clarity of guidance they feel the respective measurement tools provide for the task of taking measurements. Participants were required to rate all statements using a 5-point Likert type scale ranging from 1 (strongly disagree) to 5 (strongly agree). Each participant then engaged in a second iteration of this procedure, using the alternative measurement guidance tool. A counterbalanced design was employed to control for order effects, i.e. alternating the order in which respective measurement tools were issued to participants at the start of each session. Once both measurement guidance tools had been used and associated SUS questionnaires completed, a post task interview was conducted with each participant to discuss their experiences of using the measurement guidance tools and the perceived challenges and opportunities of using these in practice. All interviews were recorded and transcribed verbatim.

4.3. Data analysis

IBM SPSS statistics package Version 20.0.0 was used to analyse the measurement data, task completion times, and SUS questionnaire survey responses. Measurement error values were calculated as the difference between participant measurement values and corresponding true mean values. One-sample t-tests were applied to verify measurement accuracy (R1) i.e. whether the mean error differences were significantly different from the true mean values for each measurement guidance tool respectively. Error values were converted to absolute error values. To establish whether there was a significant difference between the two measurement guidance tools, in terms of the accuracy consistency (R2), the Wilcoxon signed-rank test was applied to compare the ranked differences of absolute error values generated by both tools. The Wilcoxon signed rank test was conducted as the datasets were not normally distributed [54]. Paired sample t-tests were applied to test for differences in task completion times (R3) and to compare differences in individual SUS item responses (R4) and the two subscales that SUS is said to be made up of [55,56] i.e. Usability (SUS items 1–3, 5–9) and Learnability (SUS items 4 & 10). Furthermore, overall SUS scores were calculated and interpreted according to the acceptability range, and the adjective and school grading scales [53]. This involved calculating a mean SUS representative value on a 100-point rating scale for each sample. These scores were then mapped to descriptive adjectives (Best imaginable, Excellent, Good, OK, Poor, Worst Imaginable), an acceptability range (Acceptable, Marginal-High, Marginal-Low, Not acceptable) and a school grading scale (i.e. 90–100 = A, 80–89 = B etc.). The baseline adjective and acceptability ranges are derived from a sample of over 3000 software applications [57]. Thematic template analysis [58] was used to analyse interview transcripts (R5). Thematic template analysis [58] was used to analyse interview transcripts (R5). Analysis of the transcripts, 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) [59,60]. The first stage involved creating a template which used three key determinants of technology use as

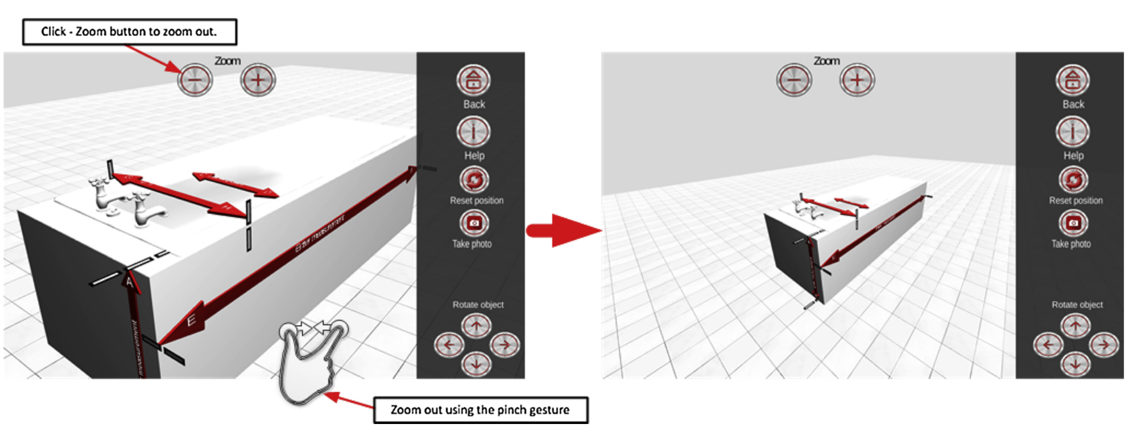

Fig. 8. Chair measurement screen Zoom out feature.

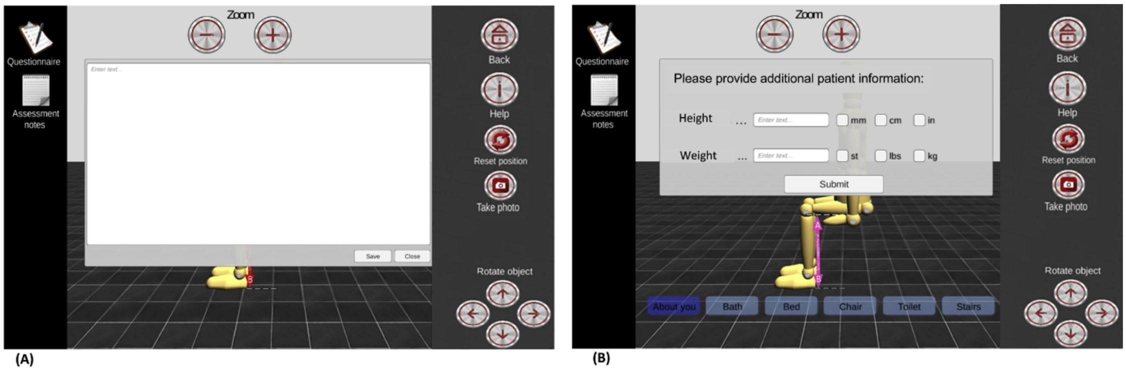

Fig. 9. (A) Note-taking facility for clinicians, (B) Assessment questionnaire on the 'About You' screen.

defined by the Unified Theory of Acceptance and Use of Technology (UTAUT) Model [61]. UTAUT is a widely used and empirically validated model of technology acceptance which integrates eight existing models and has been shown to account for 70% of user intentions to adopt and use new technologies [62]. Hence the analysis considered the three key UTAUT determinants of intention to adopt new technology: Performance Expectancy (PE); Effort Expectancy (EE); Social Influence (SI). The entire corpus was perused and coded; identifying specific extracts from the data that related to the three UTAUT themes and other high-level themes that emerged, moving and grouping similar texts in one place and re-reading segments to ensure that groupings were justified. The corpus was then perused iteratively through several stages of splicing, linking, deleting and reassigning texts to high-level themes and sub-themes. Finally, a template covering the finalised themes and sub-themes was proposed. Conducting such analysis in this way is in congruent with 'contextual constructivism', a stance of which accepts that there are multiple interpretations of a given phenomenon that is dependent on the context in which data were collected and analysed [63].

5. Results

5.1. Measurement accuracy

The first research question was to compare the relative accuracy of measurements recorded using guidetomeasure-OTand booklet measurement guidance tools. The results of the comparison between the guidetomeasure-OT and booklet, and the extent to which the respective recorded measurements are significantly different from the true mean values are presented in Table 2.

Comparing the measurement guidance results, in all cases, with the exception of bath-external width, bath-internal width and chair-width, standard deviation values (denoted as SD) for guidetomeasure-OT were smaller than that of the booklet. Therefore, as an initial observation, this suggests that guidetomeasure-OT tended to generate more precise (but not necessarily accurate) measurements compared with the booklet. In reference to accuracy, for all cases, in absolute terms, the mean error differences were larger for the booklet compared with the app, with the exception of bed-height which was smaller for the booklet. This therefore means in absolute terms that the application generated more accurate measurements compared with the booklet for 11 out of the 12 home furniture measurements.

The one sampled comparison of the guidetomeasure-OT app mean error differences against the true mean, reveals that in the majority of cases (i.e. 10 out of 12), the mean error differences are not significantly different from the true means: bath-internal width ($p =$ 0.097); bath-height ($p =$ 0.469); chair-height ($p =$ 0.462); chair-width ($p =$ 0.879); chair-depth ($p =$ 0.790); toilet-height-A ($p =$ 0.915); toilet-height-B ($p =$ 0.076); stairs-length ($p =$ 0.104); bed-height ($p =$ 0.153); anthropometric-popliteal-height ($p =$ 0.346). This indicates that in these cases, there is no evidence that guidetomeasure-OT produces inaccurate measurements at the < 0.05 significance level. Two of the 12 cases are significantly different from the true mean values, suggesting that in these cases, guidetomeasure-OT produced inaccurate measurements at the < 0.05 significance level.

The one sampled comparison of the booklet mean error differences with true mean reveals that four out of the 12 mean error differences are not significantly different from the true means: chair-width ($p =$

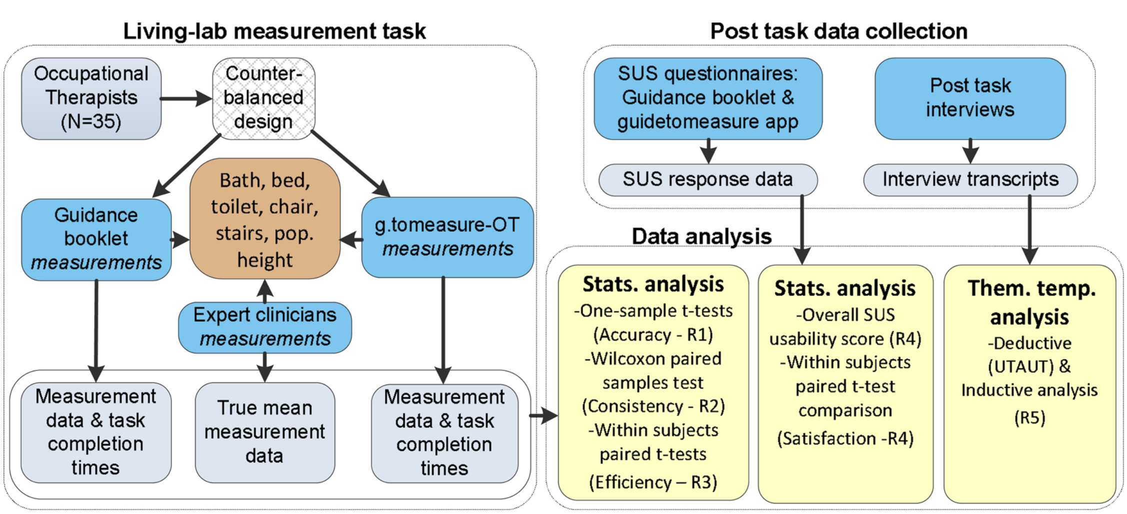

Fig. 10. Overview of the user trial session, methods and process.

Table 1
Summary of occupational therapist participant profiles.

Part. ID	Gender	Years exp.	Specialty
#P1	F	20	Community
#P2	F	6	Neuro
#P3	F	12	Local Authority/community work
#P4	F	10	Community
#P5	M	2.5	Older people
#P6	M	7	Adult social care, manual handling
#P7	F	17	Adult social care, assistive equipment
#P8	F	4	AT/telecare
#P9	F	15	Intermediate care
#P10	F	19	Community/Renal
#P11	F	21	Information and Communication Technology
#P12	F	7	Trauma Orthopaedics
#P13	F	35	Community/physical adults
#P14	F	24	Community
#P15	F	10	Social care, equipment and adaptations
#P16	F	20	Social care
#P17	F	14	Respiratory
#P18	F	1	Intermediate care
#P19	F	12	Neurosurgery, renal, stroke, CT
#P20	F	23	Physiotherapy
#P21	F	5	Intermediate care
#P22	F	14	Acute medicine
#P23	F	16	Community
#P24	F	27	Equipment, primary care
#P25	F	29	Primary care-Community
#P26	F	29	Community housing
#P27	F	6	Primary care(Community)
#P28	F	25	Community enablement/older people
#P29	F	11	Research
#P30	F	15	Intermediate care
#P31	F	13	Community
#P32	F	8	Community Nursing
#P33	F	6	Social care
#P34	F	4	Community enablement/older people
#P35	F	11	Community

0.455); chair-depth ($p = 0.186$); stairs-length ($p = 0.226$); bed-height ($p = 0.812$). The majority of cases (i.e. eight out of 12) are significantly different from the true mean values, indicating that the booklet produced inaccurate measurements at < 0.05 significance level.

Overall, comparing the performance of the two conditions, the booklet produced inaccurate values for six more measurement items, compared with guidetomeasure-OT, i.e. for the bath-internal width; bath-height; chair-height; toilet-height-A; toilet-height-B; patient-popliteal height items. Both measurement guidance tools produced inaccurate measurements for two similar items: bath-length; bath-external width. The key difference between the two measurement guidance tools was that the booklet produced inaccurate measurements at < 0.05 level for all bath measurement items: bath-length ($p = 0.002$); bath-internal width ($p = 0.001$); bath-external width ($p = 0.001$); bath-height ($p = 0.002$), all toilet measurement items: toilet-height-A ($p = 0.005$); toilet-height-B ($p = 0.001$), one of the chair measurements: chair-height ($p = 0.010$) and patient-popliteal height ($p = 0.004$). With regards to the app, a total of two inaccurate measurements were produced; bath-length ($p = 0.010$); bath-external width ($p = 0.022$), there was, however, no evidence of inaccurate values for any of the remaining measurement items.

5.2. Measurement accuracy consistency

The second research question was to compare the accuracy consistency of measurements recorded using the two respective guidance tools. The results of this analysis are presented in Table 3.

When considering the median error differences between the two measurement guidance tools, in 8 of the 12 cases the median error value for the booklet was larger than that for the guidetomeasure-OT, hence resulting in a negative median error difference in all eight cases: bath-internal width: (md err. diff. -0.97); bath-height (Md = -0.08); chair-height (Md = -1.10); chair-width (Md = -1.00); chair-depth (Md = -0.11); stairs-length (Md = -0.10); bed-height (Md = -0.18); anthropometric-popliteal height (Md = -0.10). In the remaining four cases, there was no evidence of any difference between the median error values for guidetomeasure-OT and the booklet. This indicates that the mid-point error values tended to be lower for guidetomeasure-OT compared with the booklet.

The Wilcoxon signed-rank test comparing the absolute error differences of guidetomeasure-OT and booklet measurements reveals that in three out of the 12 cases, guidetomeasure-OT produced more consistently accurate measurements than the booklet: chair-height, z = -3.667, $p < 0.001$, with a large effect size $r = 0.63$; toilet-height-B, z = -2.024, $p = 0.043$, with a large effect size $r = 0.35$; patient-popliteal height, z = -2.821, $p = 0.005$, with a medium-large effect size $r = 0.48$. All z scores were based on positive ranks, with the exception

Table 2
Measurement accuracy for guidetomeasure-OT (App.) and booklet guidance for occupational therapist cohort.

		App.						Booklet					
	True mean (cm)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)	Mean (cm)	St. Dev.	Mean error diff. (cm)	Df	t	Sig. (2-tail)
Bath													
Length	170.00	169.52	1.05	0.48	34	−2.71	0.010*	169.41	1.12	0.59	33	3.44	0.002*
Internal Width	57.00	56.78	0.95	0.22	34	−1.71	0.097	56.36	0.78	0.64	34	−5.16	0.000*
External Width	70.00	69.79	0.65	0.21	34	−2.40	0.022*	69.63	0.49	0.37	34	−5.42	0.000*
Height	55.60	55.55	0.49	0.05	33	−0.73	0.469	56.01	0.71	−0.41	34	3.44	0.002*
Chair													
Height	46.50	46.64	1.09	−0.14	34	0.74	0.462	45.46	2.25	1.04	34	−2.74	0.010*
Width	45.60	45.50	3.74	0.10	34	−0.15	0.879	45.22	2.98	0.38	34	−0.75	0.455
Depth	53.40	53.30	2.31	0.10	34	−0.27	0.790	53.86	2.02	−0.46	34	1.35	0.186
Toilet													
Height A (floor - bowl)	45.00	45.02	0.94	−0.02	34	0.11	0.915	44.26	1.18	0.74	34	−2.99	0.005*
Height B (floor - seat)	47.50	47.16	1.09	0.34	34	−1.83	0.076	46.66	1.66	0.84	34	−3.71	0.001*
Stairs													
Length	152.00	152.84	2.99	−0.84	34	1.67	0.104	150.71	6.17	1.29	34	−1.23	0.226
Bed													
Height	45.00	44.28	2.93	0.72	34	−1.46	0.153	44.85	3.59	0.15	34	−0.24	0.812
Anthropometric													
Popliteal height	44.50	44.28	0.79	0.22	34	−0.96	0.346	43.47	1.97	1.03	34	−3.11	0.004*

* Indicates statistically significant at < 0.05 level.

Table 3
Comparison of accuracy consistency for guidetomeasure-OT (App.) and booklet.

	App.	Booklet	Paired differences					
	Md err. (cm)	Md err. (cm)	Md err. diff. (cm)	Df	Z	Sig. (2-tail)	Effect size (r)	Effect size magnitude
Bath								
Length	0.18	0.18	0.00	33	−0.035[b]	0.972	0.01	Trivial
Internal Width	0.15	1.12	−0.97	34	−1.857[b]	0.063	0.32	Medium - Large
External Width	0.15	0.15	0.00	34	−0.581[b]	0.561	0.10	Small
Height	0.32	0.40	−0.08	33	−1.162[b]	0.245	0.20	Small - Medium
Chair								
Height	0.70	1.80	−1.10	34	−3.667[b]	0.000*	0.63	Large
Width	1.26	2.26	−1.00	34	−0.725[b]	0.468	0.12	Small
Depth	0.94	1.05	−0.11	34	−1.046[b]	0.295	0.18	Small - Medium
Toilet								
Height A (floor - bowl)	0.51	0.51	0.00	34	−0.624[b]	0.532	0.11	Small
Height B (floor - seat)	0.55	0.55	0.00	34	−2.024[b]	0.043*	0.35	Medium - Large
Stairs								
Length	0.50	0.60	−0.10	34	−0.019[a]	0.985	0.00	Trivial
Bed								
Height	1.82	2.00	−0.18	34	−1.430[b]	0.153	0.25	Small - Medium
Anthropometric								
Popliteal height	1.22	1.32	−0.10	34	−2.821[b]	0.005*	0.48	Medium - Large

[a] Based on negative ranks.
[b] Based on positive ranks.
* Indicates statistically significant at < 0.05 level.

of stairs-length, which further confirms that which was indicated by the negative median error differences, that in the majority of cases (11 of the 12), the sum of ranked positive differences was lower than the sum of negative ranked differences, indicating that the app consistently produced more accurate (i.e. lower measurement error differences) compared with the booklet.

Overall, comparing the performance of guidetomeasure-OT and booklet in terms of accuracy consistency, guidetomeasure-OT outperformed the booklet in three of the 12 cases, hence generating significantly more consistently accurate measurements compared with the booklet. In six of the remaining nine cases, although the differences were not significantly different in statistical terms, guidetomeasure-OT tended to generate smaller error differences than the booklet (indicated by the z values being based on positive ranks). In the one remaining case (stairs-length) booklet tended to generate smaller error differences than the guidetomeasure-OT (indicated by the *z* value being based on negative ranks), however, there was no significant difference in the error differences for this particular measure. In four of the 12 cases, there were no differences in the error differences (indicated by the 0.00 median difference scores). However, one of the four cases was significantly different at the < .05 significance level.

5.3. Task completion time

The third research question was to consider whether there are any significant differences in the overall task completion time (measured in seconds) when using the respective measurement guidance tools. The results of this analysis are presented Table 4.

The result of the paired samples *t*-test comparing task completion times for guidetomeasure-OT and the booklet measurement guidance tools, reveals that participants required significantly less time to complete the interactive task when using guidetomeasure-OT (M = 404.29, SD 151.68) compared with the booklet (M = 681.33, SD 276.99), t (34) = -5.95 $p <$ 0.001. The *SD* scores for the application and booklet revealed a high variance indicating that the amount of time it took participants to complete the measurements using both the guidance tools which varied more between participants using the booklet than using the application. A Pearson's *r* correlation coefficient comparison was performed to determine whether the relationship between years of experience, measurement accuracy, and task completion time may provide further insight into the large variance for the two tools.

5.4. Satisfaction and overall usability

The total SUS score for the guidetomeasure-OT application was 83.7 out of 100 (SD = 11.0), which, according to the evaluation criteria for SUS [57], indicates that the application delivers 'excellent' (Descriptive adjective), 'acceptable' (Acceptability range), and 'Grade B' (School grading scale) levels of usability. The total SUS score for the booklet was 70.4 (SD = 10.1), indicating 'good', 'acceptable', and 'Grade C' levels of usability

Follow-up analysis of individual SUS items for the application and the booklet were conducted to identify any specific usability issues that the participants experienced during the interactive task. Table 5 presents the individual SUS item results, differences (denoted as gap score) and corresponding significance values. All 10 SUS individual mean item scores and all four clarity of guidance items were above the neutral mid-point of 3.00, indicating that overall, participants tended to be positive about both measurement guidance tools. In all cases (i.e. SUS items and clarity of guidance items), guidetomeasure-OT achieved higher absolute mean scores compared with the booklet, which is signified by the positive gap scores. This further indicates that for all of the

Table 4
Statistics of the task completion time using guidetomeasure-OT (App.) and booklet.

	App.		Booklet		Piared differences			
	Mean (Seconds)	St. Dev.	Mean (Seconds)	St. Dev.	Mean diff. (Seconds)	Df	t	Sig (2-tail)
Time	404.29	151.68	681.33	276.99	−277.04	34	−5.95	0.000*

* Statistically significant < 0.05 level.

Table 5
Comparison of SUS scores for guidetomeasure-OT (App.) and booklet.

SUS item	App. Mean	Booklet Mean	Gap score	Df	t	Sig. (2-tail)
S1: I think that I would like to use the app/booklet frequently.	4.23	3.83	0.40	34	1.48	0.147
S2: I found the app/booklet unnecessarily complex.[a]	4.51	3.83	0.68	34	3.86	0.000*
S3: I thought the app/booklet was easy to use.	4.34	3.34	1.00	34	4.18	0.000*
S4: I think that I would need the support of a technical person to be able to use the app/booklet.[a]	4.57	3.26	1.31	34	5.29	0.000*
S5: I found the various functions in the app/booklet were well integrated.	4.09	3.89	0.20	34	0.77	0.445
S6: I thought there was too much inconsistency in the app/booklet.[a]	4.46	4.17	0.29	34	1.89	0.067
S7: I would imagine that most people would learn to use the app/booklet very quickly.	4.11	3.66	0.45	34	2.02	0.051
S8: I found the app/booklet very awkward to use.[a]	4.31	4.29	0.02	34	0.14	0.893
S9: I felt very confident using the app/booklet.	4.37	4.11	0.26	34	1.20	0.239
S10: I needed to learn a lot of things before I could get going with the app/booklet.[a]	4.49	3.43	1.06	34	4.24	0.000*
Clarity of guidance (additional items)						
A1: Using prompts (arrows) on the diagrams to assist with measurement was clear and easy.	4.57	3.94	0.63	34	3.51	0.001*
A2: Using the app/booklet improves the way I measure home furniture.	4.03	3.54	0.49	34	2.35	0.025*
A3: The instructions were clear and helpful.	4.23	3.80	0.43	34	2.12	0.041*
A4: I felt the diagrams clearly illustrated where I had to measure on the item/object.	4.34	3.86	0.48	34	2.62	0.013*

A1 – A4 bespoke items presented in addition to the 10 standard SUS items to evaluate clarity of guidance.
[a] Responses of negative items reversed to align with positive items, higher scores indicate positive responses.
* Indicates statistically significant < 0.05 level.

ten SUS items, participants tended to be more positive about the application compared with the booklet. Whilst the participants tended to respond more positively for the application compared with the booklet in relation to SUS items S1, S5, S6, S7, S8 and S9, the differences however in statistical terms were not significant. Four of the ten SUS items (S2-S4, and S10) were significantly different, and in all these cases, the application significantly outperformed the booklet. For the clarity of guidance items, all of the items (A1-A4) were significantly higher for guidetomeasure-OT compared with the booklet. Above all, participants tended to be more enthusiastic about the application and felt that it delivered a better user experience for conducting their clinical work in relation to usability and learnability, hence the general trend from the descriptive statistical results, showing that the application outperformed the booklet.

Results for item S2, reveal that participants tended to be more positive about the application and that it was significantly less unnecessarily complex than the booklet ($p < 0.001$). Responses for S3, show that participants found the application to be significantly easier to use compared to the booklet ($p < 0.001$). For S4, participants responded that using the application is significantly less likely to require the support of a technical person to be able to use it compared to using the booklet ($p < 0.001$). Results for item S10 suggest that participants disagreed with having to learn a lot of things before being able to use the application, compared with the booklet ($p < 0.001$). Item A1, indicates that the arrow prompts in the application were significantly clearer and easier to use than the prompts presented on the booklet ($p = 0.001$). Responses to item A2 show that the application is significantly more likely to improve the way they measure home furniture, more so than the booklet ($p = 0.025$). For A3, results suggest that the instructions provided by the application were more clear and helpful as compared to the booklet ($p = 0.041$), and that the application clearly illustrated the instructions to measure home furniture significantly more compared to the booklet ($p = 0.013$).

With regards to the paired samples t-tests comparing SUS Learnability, Usability and Clarity and helpfulness of guidance constructs, the Cronbach's alpha scores for all of the respective SUS constructs and effectiveness of guidance construct were above the acceptable threshold value of 0.6 for small sample studies [64], however, item S2 for the usability construct was deleted from both questionnaire tool responses, so that the Cronbach's alpha score for the usability met the acceptable reliability threshold. The reason the corresponding item S2 was deleted for both tool was so that a like-for-like comparison could therefore be made between the giodetomeasre-OT and booklet usability construct. Table 6 presents the results of the comparison of these respective constructs.

Guidetomeasure-OT achieved a significantly higher Usability score ($M = 4.31$, SD = 0.50) compared with the booklet ($M = 3.89$, SD 0.40), t (34) = 3.93 $p < 0.001$. For Learnability, guidetomeasure-OT achieved a significantly higher score ($M = 4.53$, $SD = 0.70$) compared with the booklet ($M = 3.34$, $SD = 0.94$), t (34) = 5.643, $p < 0.001$. For effectiveness of guidance, guidetomeasure-OT achieved a significantly higher score ($M = 4.29$, $SD = 0.61$) compared with the booklet ($M = 3.79$, $SD = 0.70$), t (34) = 3.801, $p < 0.001$. Indicating that overall, guidetomeasure-OT was considered to be significantly more usable, learnable, and delivered more effective guidance compared with the booklet.

5.5. Perceived challenges, opportunities, adoption and use

Five high-level themes emerged as a result of the thematic analysis. Three of these themes emerged as a result deductive thematic template analysis related to the UTAUT model: Performance Expectancy; Effort

Table 6
Comparison of SUS constructs for guidetomeasure-OT (App.) and booklet.

Construct	Items	Cronbach's alpha		App. Mean	Booklet Mean	Gap score (App. - Booklet)	Sig. (2-tail)
		App	Booklet				
Usability	SUS items 1-3, 5-9	0.61 (item 2 deleted)	0.65 (item 2 deleted)	4.31	3.89	0.42	0.000*
Learnability	SUS items 4,10	0.69	0.61	4.53	3.34	1.19	0.000*
Effectiveness of guidance	Effectiveness of guidance items 1-4	0.70	0.74	4.29	3.79	0.50	0.001*

A1 – A4: items presented in addition to the 10 standard SUS items to evaluate effectiveness of guidance.
* Statistically significant < 0.05 level.

Expectancy; Social Influence. The remaining two high-level themes emerged as a result of the inductive thematic analysis: Clinical Benefits; Augment Clinical Practice. The unique Participant ID is included in parentheses alongside quotes from the interview transcripts may be used to cross-reference Table 1 which includes additional participant profile information.

5.5.1. Performance expectancy

Participants reported that the guidetomeasure-OT provided *enhanced measurement guidance*, which achieved a closer to reality representation of precise measurements that should be taken, in turn helping to users to better interpret the guidance instruction. Furthermore, the 3D visualisation element of the application was perceived as being clear and easy to use. Particularly the 3D models of the chair and toilet items were perceived as being clearer and more detailed in a 3D format and hence more useful in identifying precise measurement points. Participants reported the clarity of the *3D models* in guidetomeasure-OT, particularly its additional dimension helped enable users to make sense of the measurement guidance. One participant commented on the enhanced look and feel of the 3D model as being a notable improvement compared with the paper-based equivalent, and in particular having the option to manipulate the viewing perspective helped to better conceptualise the measurement guidance. Another participant highlighted the benefit of 3D in capturing the height of furniture items and other modifications to the home that are otherwise not effectively mediated in 2D form.

> "… 3D's great. The more real life it is, the easier it is to interpret … the clearer the instruction and the clearer the visual part, would make it easier to use. So hopefully, that would make it easier for everybody to adapt to and use." (#P35)
> "…the 3D images were really good … I think they [the app and booklet] were similar … it was just more 3D in the app than it was on the paperwork … in the booklet it wasn't as clear as what the 3D app was and you couldn't move the diagrams on the booklet to get a better views of the measurements" (#P6)

Most participants felt that guidetomeasure-OT served as a useful *measurement aid* that supports HEFAP. Given that guidetomeasure-OT provides, in essence, digital 3D alternative to the booklet, participants saw potential in it being used to generate digital records of assessments which may support inter-professional collaboration. More generally, the interactive and multimodal nature of the application was seen as delivering notable benefits in practice, for example features such as being able to choose the preferred unit of measurement.

> "…in terms of clinically, it's definitely useful, it's a quick prompt guide and you can decide whether its centimeters, inches and so on ... as you go room to room, you know what to measure, and that you've got all the right measurements … and if you don't do one measurement, it will sort of prompt you a bit … It's something that can't necessarily go missing, like paper sometimes can, especially if the app can be used to generate reports and these could be shared with other staff and teams." (#P22)

5.5.2. Effort expectancy

Participants reported that they were satisfied with the *clarity* and *ease of use* of the guidetomeasure-OT's instructions and navigation controls and that they found it intuitive and were able start use guidetomeasure-OT for its intended purpose. Some noted that perhaps their familiarity with touch-screen devices and technology more generally, may have helped with the overall usability of the application. Participants found the app's interface is *user friendly* to interact with and its associated functionality. For example, one participant noted that the arrow prompts were helpful and clear in providing instructions for taking measurements in the form of 3D visualisation and audio guide. Another participant felt that guidetomeasure-OT was just as easy to use as the booklet which hence made it user-friendly with no learning overhead required.

> "I liked the clearness of the models, the arrows to show you where to measure, and the simplicity of the instructions. I think people would find it easy because of its easy to use, and it instructs you to do what you need to do quite clearly." (#P9)
> "I thought it was easy to use and not more complicated certainly than a pen and pad or a form that you would otherwise fill in by hand … and the arrows telling you where you're measuring from. So yeah, the simplicity of it I think is makes it user-friendly." (#P27)

5.5.3. Social influence

Participants felt that guidetomeasure-OT could be used by family members to help *facilitate discharge* of older patients from hospital so that clinicians could use such information gathered for appropriate assessments. Different *user types* were highlighted as possible beneficiaries of guidetomeasure-OT. One participant felt that, as a practitioner, they saw value in using the application on their own, however, they may feel it a useful collaborative tool that could be used with patients patients or the patient's family members/carers, in which case a guided walkthrough of the application may be necessary or useful.

> "As a practitioner, I would use it on my own, or to facilitate discharge. But if I were showing it to a client or a family member … I think I might walk them through it, although I don't know how much that's really needed. But usually people just like a little bit of instruction, just so they get a vague of what they're doing, even if you just explain why you're taking the measurements." (#P5)

Participants felt *confident* using guidetomeasure-OT to perform measurement tasks as part of the HEFAP. One participant reported that their confidence of using guidetomeasure-OT is a direct result of their role as an occupational therapist because it complements the tasks they perform during home assessments and could use it independently, without the need for technical intervention. One participant, however, explains that clinical users could become familiar with what to measure which may render the detailed guidance offered by guidetomeasure-OT less necessary, but nevertheless serves as a valuable way of recording measurements.

> "I was confident using the application, but the thing is because obviously I'm an OT, I knew what I was using it for, so I felt it supplemented what I was doing. So yeah, I'm fairly happy with using that on my own." (P23)
> "I would recommend it for use but not sure if I would use it all the time myself. Purely because if you do it every day, you become very accustomed to knowing what you have to measure and you don't need to keep looking back, although it's a valuable way of storing information … it would be more appropriate for people that didn't do it very often." (#P12)

5.5.4. Clinical Benefits

It was suggested that using the Guidetomeasure-OT application in practice could improve *collaboration* with service users and other clinicians. It was felt that guidetomeasure-OT could be utilised by community-dwelling service users to self-assess their needs and share the resultant assessment data, which may enable clinicians to collaborate with users on possible options for recommendations which surface from analysis of the data collected. Guidetomeasure-OT was also seen as a solution for reducing paper usage and sending patient assessment records to other clinicians based in different hospitals to deal with and prescribe equipment for patients that are sent by other clinicians.

> "I think it's something that would probably start with the client themselves, so they could use it at home and they could even send it in before the assessment … if there are queries … more assessments

could be done perhaps a little bit more efficiently. So there might be a little bit more dialogue with the patient too." (#P3)

"It cuts down on paper usage and you've got an electronic record then of any assessments, to share this with colleagues through the system. Because there's a lot of times we'll have patients that end up going into hospital and they'll have a different OT (occupational therapy) team looking after them there, so it would be useful for sending to other teams so they can prescribe correct equipment when the need arises." (#P34)

Participants felt that guidetomeasure-OT is a useful tool for *standardisation* and the to the provision of assistive equipment in promoting consistency of measurements taken among stakeholders involved in this particular intervention.

"I think if it could become something that's used as a standard nationally, it would mean it would help ensure that there's more consistency between the measurements that professionals and patients and relatives have take. Because although we're all OTs (occupational therapists), we will all do it very differently."(#P7)

5.5.5. Augment Clinical Practice

It was felt that most people could become skillful at using guidetomeasure-OT and that it provided *efficiency* in terms of reducing effort in recording measurements. Participants reported that one of the benefits of guidetomeasure-OT was the ability to correlate the recorded assessment data to the *patient record*. They commented that as guidetomeasure-OT is electronic it could help with documenting the assessments more effectively, particularly with storing assessment data directly to the patient's record. One of the key benefits was arrow prompt functionality, as it instructs users on how to conduct measurement tasks via audio advice which is triggered by clicking on the arrow prompt, a valuable functionality which is not offered in the booklet. It was also noted that the *tracking progress and offering support during assessment* was also made easier via the visual arrow prompts that change colour and revert to a static state once a valid measurement is entered helped them to keep track of progress.

"It would also benefit that if it was electronic, in the team I work for, we use electronic records, so if we could upload the data and attach it to the person's record, it would be of benefit and give us a clear document assessment really." (#P12)

"…The arrows kind of changed colour and stayed permanently marked when a measurement is entered, so you knew what you'd recorded … I know through experience when you're actually doing a home visit with somebody and they're asking you questions about their home oryou've got an anxious spouse asking you questions … it's just kind of really difficult to keep a thread of yourself … so with this, you've got a, almost like a tick box process going on." (#P22)

6. Discussion

The guidetomeasure-OT application, a 3D mobile application which provides 3D interactive guidance to enable clinicians to carry out HEFAP falls prevention interventions, has been presented in this study. The application architecture and Web API is designed to support integration directly into health care providers' existing in-house web-enabled applications. The performance of the application was evaluated via a user-based study involving 35 occupational therapists conducted within a living lab environment which explored how effectively (accuracy, and accuracy consistency) and efficiently (task completion time) HEFAP measurements can be taken and recorded by the guidetomeasure-OT compared with a 2D paper-based measurement equivalent which is currently used in practice. Furthermore, usability measures (SUS) and user perceptions of the guidance tools (post-task interviews) were also considered to investigate comparative user satisfaction, the perceived challenges, opportunities and intention to adopt the new application in practice.

The first research question explored the accuracy of recorded measurements taken using guidetomeasure-OT and the booklet. The results indicate that in most cases (11 out of 12), in terms of absolute mean error differences, the guidetomeasure-OT condition generated more accurate measurements. Regarding the results of the one-sample t-tests comparison against true mean values, guidetomeasure-OT produced accurate measurements for six measurement items that the booklet did not: bath-internal width; bath-height; chair-height; toilet-height-A; toilet-height-B; popliteal-height. The booklet and guidetomeasure-OT performed equally well for four measurement items by producing accurate measurements for: chair-width; chair-depth; stairs-length; bed-height. Both produced inaccurate measurements for bath-length and bath-external-width. Therefore, guidetomeasure-OT generated accurate measurements for all three chair measurements, compared with the booklet, which only generated accurate measurements for two out of three chair measurements (chair-width, chair-depth). With regards to the toilet measurements, guidetomeasure-OT generated accurate measurements for both toilet measurements, compared with the booklet, which did not produce accurate measurements for either of the toilet measurements. The height of the toilet and chair are important as they reduce fall risk factors when they are at the correct height, and assist patients with safe on and off transfers [65–67]. The raised toilet seat which is prescribed via obtaining the toilet's height is found to be the most used item of assistive equipment, with its use increasing with advanced ageing [68]. Furthermore, incorrect toilet height can lead to falls and impact patients ability to use the toilet [69]. The anthropomorphic measurement is also an important measurement as it is used as a key value in the formula to adapt the height of multiple furniture items (e.g. toilet, bed and chair) [28]. The development of a measurement guidance tool that improves the accuracy of measurements taken by occupational therapists as part of HEFAP is an important outcome. More accurate measurements are likely to lead to the prescription of home adaptations that achieve a better fit between the patient, the prescribed assistive equipment and the home environment, which is one of the contributing factors to equipment being abandoned [70].

The second research question compared the relative accuracy consistency of the two measurement guidance tools. The results revealed that, when considering both absolute median error differences and indeed differences in terms of statistical significance, guidetomeasure-OT performed either equally well, or better than the paper-based measurement booklet equivalent. For eight out of 12 measurement items, guitetomeasure-OT produced smaller median error values, and equal median error values in the remaining four cases. In three of the 12 measurement items, guidetomeasure-OT achieved significantly better levels of accuracy consistency, and there was no significant difference in the other nine items. Eleven of the 12 z scores were based on positive ranks, which further confirms that guidetomeasure-OT consistently produced more accurate measurements. In practical terms, a notable difference in performance was seen in the chair measurement, which demonstrated a large effect size in favour of guidetomeasure-OT for the chair height measurement. Achieving accurate/optimal chair height is important in the context of fall prevention interventions to ensure the frequent task of transferring to and from a chair can be carried out safely [71]. The enhanced visualisation and spoken instruction functions provided by guidetomeasure-OT may provide an explanation for why more accurate measurements were taken. Furthermore, this finding supports the and indeed highlights the significant potential practical value that may be realised by replacing existing paper-based measurement guidance with 3D measurement guidance. Further investigation into the relative costs and benefits of utilising 3D measurement guidance in practice is therefore needed, if this is to be successfully adopted by occupational therapists to help augment assessments. The medium - large effect size achieved for the toilet height B and anthropomorphic measurements (popliteal height) adds further support to the potential value of deploying mobile 3D applications for such clinical assessment tasks. Although obtaining consistently accurate chair height measurements is a key [71], obtaining consistently accurate popliteal height measurements is perhaps most crucial, as it is the combination of popliteal height and furniture height (i.e. chair, toilet, bed) that determines the final prescribed adaptation [72]. Improving accuracy consistency in HEFAP is also a particularly important outcome as it addresses the variability of assessment techniques used in health and social care across the country [73], which is also one of the contributing factors to high levels of equipment being abandoned.

The third research question compared the task completion time for guidetomeasure-OT compared with the booklet. The results revealed that guidetomeasure-OT enabled participants to complete measurement tasks significantly faster compared with the booklet. In reference to efficiency, this represents a clear benefit of using the 3D measurement guidance tool. Furthermore, the results indicate that guidetomeasure-OT may serve as a promising alternative, which if used, requires a lower time overhead from clinicians, and in the context of accuracy and accuracy consistency, enables more effective interpretation of measurement guidance, in addition to the benefit of efficiency. Indeed, existing research has shown interest in improving the time spent performing assessments by augmenting home visits with mobile devices to improve service capacity in a health service [74]. Increasing the efficiency of measurement tasks for clinicians is an important finding which has benefits to health and social care services as some home visits are perceived as “time consuming” which are considered to impact negatively upon occupational therapy practice [75].

The fourth research question evaluated the usability of the respective measurement guides via the Systems Usability Scale (SUS). The results revealed that guidetomeasure-OT achieved a higher overall SUS score versus the booklet (83.7 vs 70.4 respectively). The individual SUS item results revealed that guidetomeasure-OT significantly outperformed the booklet on four of the ten SUS items (S2, S3, S4, S10) and there was no significant difference for all remaining items. In terms of SUS sub-scales, guidetomeasure-OT was reported to be significantly more usable, easy to learn, and provided significantly more effective guidance. These results are encouraging particularly as new technologies must be perceived as useful, and easy to use if clinicians and patients are to accept and adopt the technology in clinical practice [76–78]. Furthermore, in light of the growing resource constraints and the need for clinicians to integrate a wider range of new technologies that help to automate and optimise practice and move towards a more patient-centred model, these results are encouraging particularly with regards to such tools being adopted as part of future practice [76].

The fifth research question investigated clinicians’ views of guidetomeasure-OT and the perceived challenges, opportunities and intention to adopt the measurement tool in practice. In terms of *Performance Expectancy*, participants reported that the visual quality of measurement guidance were notably improved in 3D form. More specifically, guidetomeasure-OT was seen to provide a more realistic/real-life, precise and detailed measurement guidance that enabled discrete measurement points to be identified more intuitively. This finding is promising, but perhaps not surprising considering that there is some existing health technology-based research that has demonstrated benefits of applying 3D visualisation technologies conventional paper-based assessment practices which have led improved patient satisfaction and treatment outcomes [79]. In terms of *Effort Expectancy*, participants were enthusiastic about the look and feel and clarity of the instructions that the application provides, specifically the ability to manipulate the viewing perspective of the 3D guidance models and the audio-based instructions were seen as helping to reduce the learning overhead required to understand the instructions and take measurements confidently. Furthermore, the animated arrow prompts illustrating areas to measure and those which had already been recorded (static) were seen as reducing the required effort overhead further. Factors that affect practice and relating to *Social Influence* included occupational therapists seeing that the guidetomeasure-OT tool has potential to be repurposed as a patient-facing measurement guidance tool, which may be used by family members/carers to help facilitate the discharge of patients from hospital to home. This would likely lead to a smoother transition from hospital. Indeed, it is becoming increasingly common for clinicians to request that family members take preliminary HEFAP measurements prior to patient discharge [80]. Therefore, providing HEFAP novice family members with a 3D measurement guide may help ensure more accurate information is recorded, particularly given that trained occupational therapists regularly record inaccurate measurements using paper-based guidance. Although most occupational therapist participants reported they could use guidetomeasure-OT independently, some expressed that it would be useful to offer a patient a guided walkthrough of the application before expecting them to use the application. In terms of *Clinical Benefits*, clinicians reported that they felt guidetomeasure-OT could improve collaboration with other clinicians and service services, all of which could equally contribute to identifying the optimum equipment recommendations based on the data collected. The application was perceived as an ‘environmentally friendly’ solution in terms of reducing excess paper usage in practice and as means of integrating either clinician-led assessments or self-assessment data to patient record available in a centralised location whereby other clinicians have access to these records to deal with patient uptake. This is an important finding as it is consistent with the government mandate for the NHS to ‘go paperless’ by 2020 [81] and highlights the existing issues of the healthcare system being fragmented in terms of NHS trusts running as separate entities [81]. The standardised approach to HEFAP that participants felt guidetomeasure-OT could help to achieve is further evidence that the adoption of this tool in practice could help to address the current heterogeneous and inconsistent practice of HEFAP delivery across the UK NHS trusts. This is a particularly crucial as equipment prescribed to patients is rejected in part due to the inappropriate fit of equipment as a result of misinterpretation of guidance and absence of standardised measurement practice [82], of which previous research emphasise on the need for improved quality and standardised approach to the equipment provision [82]. Finally, with regards to *augmentation of clinical practice*, participants expressed their preference of using guidetomeasure-OT to carry out the HEFAP as the significant benefits it offers over the 2D booklet such as the depth cues, arrow prompts and audio instructions providing guidance to users, all of which the booklet currently lacks.

7. Conclusions

This study has presented guidetomeasure-OT, a mobile 3D application which provides interactive measurement guidance to enable clinicians to carry out HEFAP more efficiently and effectively. An empirical evaluation of the performance of the application compared with paper-based measurement guidance revealed that in terms of measurement accuracy, accuracy consistency, and task efficiency, and usability the guidetomeasure-OT delivers significant performance gains over the paper-based equivalent. The development of a usable mobile 3D application that achieves significant improvements in measurement accuracy and usability is an important finding, given challenge of poor fit of assistive equipment and equipment abandonment that the field of occupational therapy has faced for several years. Furthermore, the application and empirical findings in this study represent an important case example of how 3D visualisation technologies may be used as the innovative and enabling technological solutions that health care providers and policy makers so urgently need to ease the ever-increasing ageing population related burden that is being placed on existing health care resources. Given the clarity and intuitiveness of the guidance measurement delivered by guidetomeasure-OT, in terms of future work, occupational therapists suggested that there is potential to repurpose the application as a patient-centred measurement guide to enable patients/family members to carry out HEFAP self-assessments, hence reducing the time and resource constraints placed on occupational therapists even further. Further research is required to redevelop the application in-line with patient needs and to subsequently empirically evaluate the performance of a mobile 3D measurement application deployed specifically for this user cohort. Furthermore, there is potential to incorporate new functionality into the application, such as an automated assistive equipment recommendation function, which if implemented effectively, could help to further reduce the burden on occupational therapists of carrying out HEFAP assessments and potentially move HEFAP closer towards becoming a patient self-assessment task.

The primary focus of this study was to explore the clinical utility of guidetomeasure-OT and also to gain some insights into its usability and intentions to adopt the application in practice. Whilst numerous user-centred design methods were utilised to incrementally develop the application, such as participatory design sessions, the think-aloud protocol, interviews, focus groups, questionnaires, there remain numerous other avenues that may be focused on to further develop, improve, and optimise the application for the target user groups. For example, from a methodological perspective, exploring the broader concept of User Experience (UX), as opposed to the usability of the application, is likely to reveal numerous additional insights into how useful, usable, findable, credible, accessible, desirable, valuable the application is perceived to be, and from which a range of further requirements may be identified [83]. Perhaps focusing on some additional UX elements that have been suggested as being more relevant to m-health, such as integration, sustainability and security may also be fruitful areas of focus when looking to further develop the application [84]. Any future development of this application, i.e. for clinicians or patients, should also consider aspects relating to cognitive overloading of the user when using an application that presents a 3D environment to the user. For example, Jorge, Sarmiento, Maciel, Nedel, Collazos, Faria and Oliveira [85] explored the effect that constraining the number of degrees of freedom the user has, with respect to interacting and navigating through a 3D environment, has on the user's ability to complete risk perception tasks. Surprisingly, they found that constraining the degrees of freedom available to the user, reduced the user's ability to carry out cognitively complex risk perception tasks effectively. Contrary to these findings, some research has found that constraining the degrees of freedom improves user performance when carrying out 3D environment orientation tasks [86]. Therefore, in order to optimise the effectiveness of the 3D measurement guidance provided to patient and clinician users delivered by guidetomeasure-OT, there is a need for further research to establish the optimum number of degrees of freedom provided to the user for this application and indeed explore what the effect of, for example, degrees of freedom separation [87] may have on the user's ability to follow measurement guidance more effectively.

Summary points

What was already known on the topic

- The home environment falls-risk assessment process (HEFAP) results in 30% of assistive equipment being abandoned by patients in the 1st year, in part due to poor fit between assistive equipment, the patient and the environment in which it is installed.
- There is a need to more effective and efficient HEFAP measurement guidance for clinicians, to help overcome high levels of equipment abandonment.
- The use of 3D visualisation technologies has potential in being applied to improve the HEFAP process.

What this study adds

- The guidetomeasure-OT application, a mobile 3D measurement guidance application that serves as an alternative to existing state of the art paper-based measurement guidance tools is presented.
- Measurement accuracy (11 out of 12 items) and accuracy consistency (8 out of 12 items) was improved in absolute terms when clinicians used guitetomeasure-OT.
- guidetomeasure-OT significantly outperformed the 2D paper-based measurement guide in statistical terms for task efficiency ($p < 0.001$), usability ($p < 0.001$), learnability ($p < 0.001$), effectiveness of guidance ($p = 0.001$), and for measurement accuracy for six out of 12 items.
- The results show that mobile 3D visualisation technologies can be effectively deployed to improve clinical practice.

Authorship statement

All authors contributed equally to the study conception, design, acquisition of data, analysis and interpretation, drafting of the manuscript, and approval of the final version submitted.

References

[1] J. Dixon, J. Hurst, J. Smith, S. Williams, Can NHS Hospitals Do More With Less? Nuffield Trust, London, UK, 2016.
[2] A. Darzi, High Quality Care For All NHS Next Stage Review Final Report, Department of Health, London, 2008.
[3] DoH, Equity and Excellence: Liberating the NHS (White Paper), The Stationery Office, London, UK, 2010.
[4] H. Hawley-Hague, E. Boulton, A. Hall, K. Pfeiffer, C. Todd, Older adults' perceptions of technologies aimed at falls prevention, detection or monitoring: a systematic review, Int. J. Med. Inform. 83 (2014) 416–426.
[5] N.M. Kosse, K.K. Brands, J.M. Bauer, T. Hortobagyi, C. Lamoth, Sensor technologies aiming at fall prevention in institutionalized old adults: a synthesis of current knowledge, Int. J. Med. Inform. 82 (2013).
[6] N. Lapierre, N. Neubauer, A. Miguel-Cruz, A. Rios Rincon, L. Liu, J. Rousseau, The state of knowledge on technologies and their use for fall detection: a scoping review, Int. J. Med. Inform. 111 (2018) 58–71.
[7] C. Siegel, T. Dorner, Information technologies for active and assisted living—influences to the quality of life of an ageing society, Int. J. Med. Inform. 100 (2017) 32–45.
[8] J. Hilbe, E. Schulc, B. Linder, C. Them, Development and alarm threshold evaluation of a side rail integrated sensor technology for the prevention of falls, Int. J. Med. Inform. 79 (2010) 173–180.
[9] P.A. Logan, C.A. Coupland, J.R. Gladman, O. Sahota, V. Stoner-Hobbs, K. Robertson, V. Tomlinson, M. Ward, T. Sach, A. Avery, Community falls prevention for people who call an emergency ambulance after a fall: randomised controlled trial, BMJ Br. Med. J. 340 (2010).
[10] A.F. Ambrose, G. Paul, J.M. Hausdorff, Risk factors for falls among older adults: a review of the literature, Maturitas 75 (2013) 51–61.
[11] A. Atwal, A. Mcintyre, G. Spiliotopoulou, A. Money, I. Paraskevopulos, How are service users instructed to measure home furniture for provision of minor assistive devices? Disabil. Rehabil. Assist. Technol. 12 (2016) 153–159.
[12] J.M. Mitchell, D.J. Wilson, B.J. Kemp, R.H. Adkins, W. Mann, Effects of assistive technology on functional decline in people aging with a disability, Assist. Technol. 21 (2009) 208–217.
[13] J.A. Sanford, P.C. Griffiths, P. Richardson, K. Hargraves, T. Butterfield, H. Hoenig, The effects of in-home rehabilitation on task self-efficacy in mobility-impaired adults: a randomized clinical trial, J. Am. Geriatr. Soc. 54 (2006) 1641–1648.
[14] J. Damant, M. Knapp, S. Watters, P. Freddolino, M. Ellis, D. King, The impact of ICT services on perceptions of the quality of life of older people, J. Assist. Technol. 7 (2013) 5–21.
[15] C. Siegel, B.G. 112, Contributions of ambient assisted living for health and quality of life in the elderly and care services–a qualitative analysis from the experts' perspective of care service professionals, BMC Geriatr. 14 (2014).
[16] Transparency Market Research, Elderly and Disabled Assistive Devices Market, (2015).
[17] S. Dahlin-Ivanoff, U. Sonn, Use of assistive devices in daily activities among 85-year-olds living at home focusing especially on the visually impaired, Disabil. Rehabil. 26 (2004) 1423–1430.
[18] W.C. Mann, K.J. Ottenbacher, L. Fraas, M. Tomita, C.V. Granger, Effectiveness of assistive technology and environmental interventions in maintaining independence and reducing home care costs for the frail elderly, Arch. Fam. Med. 8 (1999) 210–217.
[19] G. Gosman-Hedström, L. Claesson, C. Blomstrand, B. Fagerberg, B. Lundgren-Lindquist, Use and cost of assistive technology the first year after stroke: a randomized controlled trial, Int. J. Technol. Assess. Health Care 18 (2002) 20–27.
[20] J.K. Martin, L.G. Martin, N.J. Stumbo, J.H. Morrill, The impact of consumer involvement on satisfaction with and use of assistive technology, Disabil. Rehabil. Assist. Technol. 6 (2011) 225–242.
[21] T. Wielandt, J. Strong, Compliance with prescribed adaptive equipment: a literature review, Br. J. Occup. Ther. 63 (2000) 65–75.
[22] G. Spiliotopoulou, A. Atwal, A. McIntyre, The use of evidence-based guidance to enable reliable and accurate measurements of the home environment, Br. J. Occup. Ther. 81 (2017) 32–41.
[23] A.G. Money, A. Atwal, K.L. Young, Y. Day, L. Wilson, K.G. Money, Using the Technology Acceptance Model to explore community dwelling older adults' perceptions of a 3D interior design application to facilitate pre-discharge home adaptations, BMC Med. Inform. Decis. Mak. 15 (2015) 73.
[24] M. Scherer, J., Assistive Technology: Matching Device and Consumer for Successful Rehabilitation, American Psychological Association, Washington, USA, 2002.
[25] S.D. Lord, H.B. Menz, C. Sherrington, Home environment risk factors for falls in older people and the efficacy of home modifications, Age Ageing 35 (2006).
[26] A. Atwal, A. Luke, N. Plastow, Evaluation of occupational therapy pre-discharge home visit information leaflets for older adults, Br. J. Occup. Ther. 74 (2011) 383–386.
[27] G. Spiliotopoulou, National Guidance for Measuring Home Furniture and Fittings to Enable User Self-Assessment and Successful Fit of Minor Assistive Devices, UK Occupational Therapy Research Foundation, 2016.
[28] A. Atwal, I. Paraskevopoulos, G. Spiliotopoulou, A. Money, A. McIntyre, How are

service users instructed to measure home furniture for provision of minor assistive devices? Disabil. Rehabil. Assist. Technol. 12 (2017) 153–159.
[29] J.D. Williamson, L.P. Fried, Characterization of older adults who attribute functional decrements to "old age", J. Am. Geriatric Soc. 44 (1996) 1429–1434.
[30] M.L. Riemer Reiss, R. Walker, Factors associated with assistive technology discontinuance among individuals with disabilities, J. Rehabil. 66 (2000) 44–50.
[31] S. Federici, F. Meloni, S. Borsci, The abandonment of assistive technology in Italy: a survey of National Health Service users, Eur. J. Phys. Rehabil. Med. 52 (2016) 516–526.
[32] R. Verza, M.L. Carvalho, M. Battaglia, M.M. Uccelli, An interdisciplinary approach to evaluating the need for assistive technology reduces equipment abandonment, Mult. Scler. 12 (2006) 88–93.
[33] K. Goodacre, C. McCreadie, S. Flanagan, P. Lansley, Enabling older people to stay at home: the costs of substituting and supplementing care with assistive technology, Br. J. Occup. Ther. 71 (2008) 130–140.
[34] S. Uzor, L. Baillie, Exploring & designing tools to enhance falls rehabilitation in the home, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (2013) 1233–1242.
[35] J. Doyle, C. Bailey, B. Dromey, C.N. Scanaill, BASE-an interactive technology solution to deliver balance and strength exercises to older adults, International Conference on Pervasive Computing Technologies for Healthcare (Pervasive Health), 2010 (2010) 1–5.
[36] R. Du, V. Jagtap, Y. Long, O. Onwuka, T. Padir, Robotics enabled in-home environment screening for fall risks, Proceedings of the 2014 Workshop on Mobile Augmented Reality and Robotic Technology-Based Systems (2014) 9–12.
[37] F. Spyridonis, G. Ghinea, A.O. Frank, Attitudes of patients toward adoption of 3D technology in pain assessment: qualitative perspective, J. Med. Internet Res. 15 (2013).
[38] A. Jang, D.L. MacLean, J. Heer, BodyDiagrams: improving communication of pain symptoms through drawing, Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems (2014) 1153–1162.
[39] P. de Heras Ciechomski, M. Constantinescu, J. Garcia, R. Olariu, I. Dindoyal, S. Le Huu, M. Reyes, Development and implementation of a web-enabled 3D consultation tool for breast augmentation surgery based on 3D-image reconstruction of 2D pictures, J. Med. Internet Res. 14 (2012).
[40] Y. Pulijala, M. Ma, A. Ayoub, V.R. Surgery, Interactive Virtual Reality Application for Training Oral and Maxillofacial Surgeons Using Oculus Rift and Leap Motion, Springer, Cham, Switzerland, 2017.
[41] C. Luciano, P. Banerjee, T. DeFenti, Haptics-based virtual reality periodontal training simulator, Virtual Real. 13 (2009) 69–85.
[42] A. Macdonald, D. Loudon, P.J. Rowe, Visualisation of biomechanical data to assist therapeutic rehabilitation, Gerontechnology 9 (2010) 98–99.
[43] J. Hamm, A.G. Money, A. Atwal, G. Ghinea, Mobile three-dimensional visualisation technologies for clinician-led fall prevention assessments, Health Informatics J. (2017) 1460458217723170.
[44] A.G. Money, J. Barnett, J. Kuljis, M.P. Craven, J.L. Martin, T. Young, The role of the user within the medical device design and development process: medical device manufacturers' perspectives, BMC Med. Inform. Decis. Mak. 11 (2011).
[45] T. Greenhalgh, R. Procter, J. Wherton, P. Sugarhood, S. Hinder, M. Rouncefield, What is quality in assisted living technology? The ARCHIE framework for effective telehealth and telecare services, BMC Med. 13 (2015) 91.
[46] K.L. Calvin, K. Ben-Tzion, A systematic review of patient acceptance of consumer health information technology, J. Am. Med. Inf. Soc. 16 (2009) 550–560.
[47] J. Barnett, M. Harricharan, D. Fletcher, B. Gilchrist, J. Coughlan, Mypace: an integrative health platform for supporting weight loss and maintenance behaviors, IEEE J. Biomed. Health Inform. 19 (2015) 109–116.
[48] A. Atwal, A. McIntyre, C. Craik, J. Hunt, Occupational therapists' perceptions of predischarge home assessments with older adults in acute care, Br. J. Occup. Ther. 71 (2008) 52–58.
[49] A. Atwal, A. Money, M. Harvey, Occupational therapists' views on using a virtual reality interior design application within the pre-discharge home visit process, J. Med. Internet Res. 16 (2014).
[50] Blender.
[51] P. Curzon, A. Blandford, H. Thimbleby, A. Cox, Safer interactive medical device design: insights from the CHI+ MED project, Proceedings of the 5th EAI International Conference on Wireless Mobile Communication and Healthcare, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), (2015), pp. 34–37.
[52] T. Brown, B. Williams, L. Jolliffe, Leadership style preference of undergraduate occupational therapy students in Australia, Hong Kong J. Occup. Ther. 24 (2014) 35–42.
[53] J. Brooke, SUS-A Quick and Dirty Usability Scale, Usability Evaluation in Industry Vol. 189 (1996), pp. 4–7.
[54] A. Field, Discovering Statistics Using IBM SPSS Statistics, Sage, 2013.
[55] J.R. Lewis, J. Sauro, The Factor Structure of the System Usability Scale, Human Centered Design, Springer, 2009, pp. 94–103.
[56] S. Czarnuch, A. Mihailidis, The design of intelligent in-home assistive technologies: assessing the needs of older adults with dementia and their caregivers, Gerontechnology 10 (2011) 169–182.
[57] A. Bangor, P. Kortum, J. Miller, Determining what individual SUS scores mean: adding an adjective rating scale, J. Usability Stud. 4 (2009) 114–123.
[58] R.E. Boyatzis, Transforming Qualitative Information: Thematic Analysis and Code Development, Sage, 1998.
[59] B.F. Crabtree, W.F. Miller, A Template Approach to Text Analysis: Developing and Using Codebooks, (1992).
[60] J. Fereday, E. Muir-Cochrane, Demonstrating rigor using thematic analysis: a hybrid approach of inductive and deductive coding and theme development, Int. J. Qual. Methods 5 (2008) 80–92.
[61] V. Venkatesh, M.G. Morris, G.B. Davis, F.D. Davis, User acceptance of information technology: toward a unified view, Mis Q. (2003) 425–478.
[62] M. Cimperman, M. Makovec Brenčič, P. Trkman, Analyzing older users' home telehealth services acceptance behavior-applying an Extended UTAUT model, Int. J. Med. Inform. 90 (2016) 22–31.
[63] B.F. Crabtree, W.L. Miller, Doing Qualitative Research, Sage Publications, 1999.
[64] J.F. Hair, W.C. Black, B.J. Babin, R.E. Anderson, R.L. Tatham, Multivariate Data Analysis, Pearson Prentice Hall Upper Saddle River, NJ, 2006.
[65] T. Hoffmann, T. Russell, Pre-admission orthopaedic occupational therapy home visits conducted using the Internet, J. Telemed. Telecare 14 (2008) 83–87.
[66] N. Alexander, A. Galecki, L. Nyquist, M. Hofmeyer, J. Grunawalt, M. Grenier, J. Medell, Chair and bed rise performance in ADL-impaired congregate housing residents, J. Am. Geriatr. Soc. 48 (2000) 526–533.
[67] M. Hughes, D. Weiner, M. Schenkman, R. Long, S. Studenski, Chair rise strategies in the elderly, Clin. Biomech. 9 (1994) 187–192.
[68] J.C. Cornman, V.A. Freedman, E.M. Agree, Measurement of assistive device use: implications for estimates of device use and disability in late life, Gerontologist 45 (2005) 347–358.
[69] E. Capezuti, L. Wagner, B.L. Brush, M. Boltz, S. Renz, M. Secic, Bed and toilet height as potential environmental risk factors, Clin. Nurs. Res. 17 (2008) 50–66.
[70] W.B. Mortenson, L. Demers, M.J. Fuhrer, J.W. Jutai, J. Lenker, F. DeRuyter, Effects of an assistive technology intervention on older adults with disabilities and their informal caregivers: an exploratory randomized controlled trial, Am. J. Phys. Med. Rehabil. 92 (2013) 297–306.
[71] N. Reider, C. Gaul, Fall risk screening in the elderly: a comparison of the minimal chair height standing ability test and 5-repetition sit-to-stand test, Arch. Gerontol. Geriatr. 65 (2016) 133–139.
[72] M. Stevens, C.A.J. Holman, N. Bennett, Preventing falls in older people: impact of an intervention to reduce environmental hazards in the home, J. Am. Geriatr. Soc. 49 (2001) 1442–1447.
[73] S. Federici, F. Meloni, S. Borsci, The abandonment of assistive technology in Italy: a survey of National Health Service users, Eur. J. Phys. Rehabil. Med. 52 (2016) 516–526.
[74] J. Nix, T. Comans, Home quick–Occupational therapy home visits using mHealth, to facilitate discharge from acute admission back to the community, Int. J. Telerehabil. 9 (2017) 47.
[75] A. Atwal, G. Spiliotopoulou, J. Stradden, V. Fellows, E. Anako, L. Robinson, A. McIntyre, Factors influencing occupational therapy home visit practice: a qualitative study, Scand. J. Occup. Ther. (2013) 1–8.
[76] L. Liu, A. Miguel Cruz, A. Rios Rincon, V. Buttar, Q. Ranson, D. Goertzen, What factors determine therapists' acceptance of new technologies for rehabilitation–a study using the Unified Theory of Acceptance and Use of Technology (UTAUT), Disabil. Rehabil. 37 (2015) 447–455.
[77] C. McGrath, M. Ellis, S. Harney-Levine, D. Wright, E.A. Williams, F. Hwang, A. Astell, Investigating the enabling factors influencing occupational therapists' adoption of assisted living technology, Br. J. Occup. Ther. (2017) 0308022617711669.
[78] T. Heart, E. Kalderon, Older adults: are they ready to adopt health-related ICT? Int. J. Med. Inform. 82 (2013) e209–e231.
[79] F. Spyridonis, J. Gawronski, G. Ghinea, A.O. Frank, An interactive 3-D application for pain management: results from a pilot study in spinal cord injury rehabilitation, Comput. Methods Programs Biomed. 108 (2012) 356–366.
[80] M. Isaacson, Best practices by occupational and physical therapists performing seating and mobility evaluations, Assist. Technol. 23 (2011) 13–21.
[81] M. Honeyman, P. Dunn, H. McKenna, A Digital NHS? An Introduction to the Digital Agenda and Plans for Implementation, The Kings Fund, 2016.
[82] G. Spiliotopoulou, A. Atwal, Embedding the personalization agenda in service users' self-assessment for provision of assistive devices, Br. J. Occup. Ther. 77 (2014) 483-483.
[83] P. Bate, G. Robert, Bringing User Experience to Healthcare Improvement: The Concepts, Methods and Practices of Experience-Based Design, Radcliffe Publishing, Abingdon, UK, 2007.
[84] S. Ouma, M. Herselman, D. Greunen, Essential UX metrics to be considered when designing m-health applications in order to provide positive user experiences, Proceedings of the IADIS International Conference e-Health 2010Freiburg (2010) 271–274.
[85] V.A.M. Jorge, W.J. Sarmiento, A. Maciel, L. Nedel, S.A. Collazos, F. Faria, J. Oliveira, Interacting with danger in an immersive environment: issues on cognitive load and risk perception, Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology (2013) 83–92.
[86] M. Veit, A. Capobianco, D. Bechmann, Influence of degrees of freedom's manipulation on performances during orientation tasks in virtual reality environments, Proceedings of the 16th ACM Symposium on Virtual Reality Software Technology (2009) 51–58.
[87] D. Mendes, F. Relvas, A. Ferreira, J. Jorge, The benefits of DOF separation in mid-air 3D object manipulation, Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (2016) 261–268.