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REVIEW

Design for assistive technology oriented to design methodology: a systematic review on user-centered design and 3D printing approaches

A. V. F. Santos[1] · **Z. C. Silveira**[1]

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Abstract

This paper presents a systematic review whose objective is to map the design development of assistive devices through user's participation, use of design methodology and also 3D printing support. The development of multidisciplinary engineering design has increasingly demanded the need for effective participation of different stakeholders throughout product development cycle. Assistive Technology represents this multidisciplinary domain in the context of design for customization. This design approach requires the co-participation of the users, both occupational therapists and end users and also family members. This interactive process is fundamental in the early phases of the design and in the iterations to promote improvements between conceptual and functional prototypes. The research methodology is based on the three-stage systematic literature review, followed by a critical analysis grounded on content analysis procedures. The 30 approaches identified were classified according to their theoretical and practical characteristics (short descriptions, design development phases, design methods and techniques used and evaluation tools). The results point to the gap in the conceptual phase related to use of design methods and techniques, precisely the design early level where there is greatest potential to add value with innovation and functionality to the final product. This systematic review reinforces the increasingly importance of this integration between engineering and assistive technology, seeking to establish a systematization of the process of development of ADs that incorporates the qualities of both the areas: the technical knowledge, tools and development methodology and the user-centered approach together with the knowledge of therapeutic needs and occupational performance.

Keywords User-centered design · UCD · Participatory design · Co-design · Design for additive manufacturing · Assistive technology

Abbreviations

ACMC	Assessment of Capacity for Myoelectric Control
ADs	Assistive Devices
AM	Additive Manufacturing
AT	Assistive Technology
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CHEQ	Children's Hand-use Experience Questionnaire
COPM	Canadian Occupational Performance Measure
DfAM	Design for Additive Manufacturing
DfAT	Design for Assistive Technology
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
DFX	Design for Excellence
DIY	Do It Yourself
FES	Functional electrical stimulation
GREAT	Global Research, Innovation and Education in Assistive Technology
GATE	Global Cooperation in Assistive Technology
IDEF	Integration Definition Language for Function Modeling
JTHF	Jebsen–Taylor Hand Function Test
FMEA	Failure Mode and Effect Analysis
HVM	Hierarchical Value Map

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✉ Z. C. Silveira
silveira@sc.usp.br

A. V. F. Santos
artur.santos@usp.br

[1] Department of Mechanical Engineering, University of São Paulo, São Carlos, Brazil

MEC	Means-End Chain
PedsQL	Pediatric Quality of Life Inventory
PIADS	Psychosocial Impact of Assistive Devices Scale
QFD	Quality Function Deployment
QUEST	Quebec User Evaluation of Satisfaction with Assistive Technology
SHAP-C	Southampton Hand Assessment Procedure
SR	Systematic Review
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving
UCD	User-Centered Design
UX	User Experience
WHO	World Health Organization

1 Introduction

The World Health Organization (WHO) and its initiative for Global Research, Innovation and Education in Assistive Technology (GREAT), coordinated by the Global Cooperation in Assistive Technology (GATE), defines assistive technology (AT) as the application of knowledge and skills to the development of assistive products, including systems and services, which are aimed at maintaining or improving the functioning and independence of an individual [1]. In addition to greater independence, there is evidence of physical, psychological and economic positive impacts of AT on quality of life, social inclusion and reduced costs of care [2], as well as on education and employment, being a foundational support that produces multiple and life-changing benefits [3].

Despite the growing demand for AT products, in view of the worldwide [4] and also national (Brazil) [5] trend of population aging, many challenges are still identified in this area, such as: the lack of match between demand and supply; the needs of users, often little known and unsatisfactorily met; problems with product reliability; the stigmatization caused by an unsatisfactory design. The lack of specialized distribution networks, the multiple profit margins and, in many cases, the monopolistic market are other difficulties to be mentioned [6].

Therefore, it is estimated that there are approximately 600 million individuals with disabilities living with assistive devices (ADs) not properly adjusted or even without devices [7].

Specifically in the Brazilian context, taken as a starting point for this work, it was possible to identify a tradition of unsystematic development [8], leading to a technological stagnation in the area. The development in the country continues to be more based on the adoption of incomplete models or the adaptation of existing objects, often generating products that do not effectively meet users' demands. Some of the main problems identified were: lack of design method, disregard of the importance of aesthetic parameters for the user, non-involvement of other important parts in the design process, empiricism in the evaluation process.

These difficulties lead to another significant problem: the abandonment of devices. One of the first studies on the abandonment of assistive devices [9] identified an abandonment rate of 29.3% for devices of the most varied types, associated with four main factors: (1) lack of consideration of user opinion; (2) easy device procurement; (3) poor device performance; (4) change in user needs or priorities. As a consequence of this abandonment, loss of functional skills, freedom and user autonomy can be mentioned, at the individual level, in addition to higher expenses; another consequence is the ineffective use of resources by the federal, state and local governments and by other provider organizations, causing a waste of funds that grows with the increase in demand for these types of products.

On the other hand, with the growth of the AT field and with the increase in the complexity of the users' needs, a very favorable niche for collaboration between engineering professionals and AT professionals emerges. [10], aiming to obtain better solutions and products for AT users. In this case, engineers collaborate with their knowledge about technology and product development methods, while occupational therapists contribute with their user-centered practice and their knowledge of occupational performance.

In this sense, the elaboration of a proposed methodology for the design of assistive devices, with a user-centered approach that incorporates perspectives, methods, tools and possibilities of engineering and so-called 3D technologies, such as additive manufacturing (AM), presents itself as an important demand in the search for better quality products that really meet the users' needs, avoiding abandonment and waste of resources.

A systematic review (SR), in turn, plays a leading role in research where originality is required, since, when conducted in a systematic and rigorous manner; it contributes to the development of a solid knowledge base, facilitating the organization of a large amount of information and the understanding of the state-of-the-art on a given subject. As a consequence, it also favors the development of theory in areas where research already exists and allows identifying opportunities for new research in other areas. [11].

Therefore, this work presents the development of a SR, whose objective was to carry out a survey on the current scenario of the product development process with a user-centered approach and the use of AM in the context of AT, serving as support for the elaboration of a methodological proposal for the development of assistive devices, called AT-d8sign [12, 13].

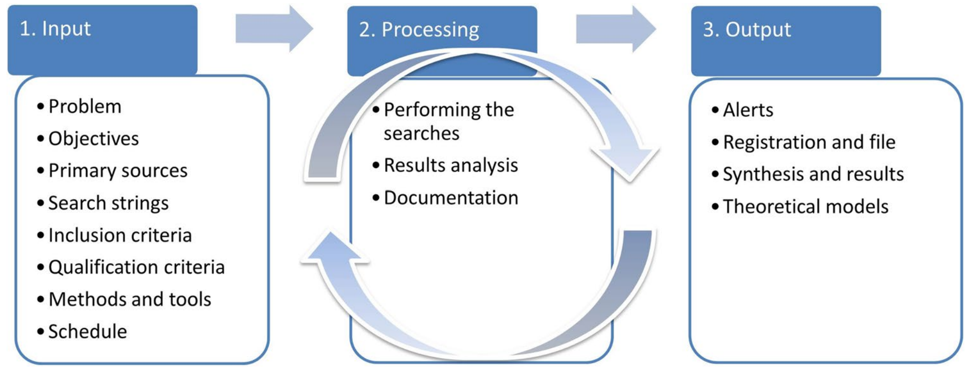

Fig. 1 RBS Roadmap scheme

2 Method

As a reference for conducting the systematic review, the script called RBS Roadmap [11] was used, proposed for carrying out reviews with a focus especially on research in the area of product development and design management, as is the case in this work.

The script is divided into three main phases: Input, Processing and Output, which are also subdivided into steps, totaling 15, according to Fig. 1:

The steps taken in the first phase, Input, are defined as follows:

1. *Problem*: Definition of the problem to be solved through the research, that is, which research questions are to be answered;
2. *Objectives*: In alignment with the objectives of the research project, establishment of the SR objectives, which will be the basis for the analysis of the papers found;
3. *Primary sources*: Choice of primary sources for the review (papers, journals or databases) and identification of the main authors and relevant papers, either through consultations with experts and senior researchers or through a preliminary review;
4. *Search strings*: Identification of the keywords and terms related to the research topic, based on a preliminary study of primary sources and consultation with specialists and researchers. Preparation, testing and adaptation of strings, according to the rules of search and use of logical operators in each database to be used;
5. *Inclusion criteria*: In line with the research objectives, define the inclusion criteria for the papers found in the searches;
6. *Qualification criteria*: In order to assess the relative importance of each paper for the study, establish qualification criteria, such as: research method adopted, size and diversity of the sample used, number of citations of the paper, impact factor of the journal where it was published, among others;
7. *Method and tools*: Definition of the steps, filters and search procedures to be used, as well as the method for storing the results. It is worth mentioning that the search process must be iterative, through cycles that favor the search refinement;
8. *Schedule*: Establish a schedule for the realization of the SR, bearing in mind the objectives and deadlines of the project;

In the second phase of the script, Processing, the following steps are performed:

9. *Conducting searches*: Performing searches on primary sources iteratively and, from the selected material, also perform cross-searches;
10. *Analysis of results*: Application of search filters to the material obtained. In Filter 1, only the title, summary and keywords of the papers found are read. Those that align with the research and SR objectives are selected for the next filter. Filter 2 is characterized by reading the introduction and conclusion of the papers, with the re-reading of the items of the first filter. Papers that do not meet the search objectives and inclusion criteria are then eliminated. Finally, in Filter 3, papers are submitted to complete reading, focusing on the objectives and inclusion criteria. The papers selected after this filter will certainly be relevant to the research, in addition to contributing to the cross-search, with the tracking and identification of other important papers through the citations of the authors;
11. *Documentation*: Cataloging and storing the selected papers using a reference management software or other means;

Finally, the steps of the third phase, Output, are:

12. *Alerts*: Insertion of alerts in the databases and in the main journals found in SR to track new relevant papers;
13. *Registration and archive*: Inclusion of the papers documented in the previous phase in the repository of research papers;

14. *Synthesis and results*: Preparation of a report with a synthesis of the analyzed bibliography, containing information such as: description of the main authors in the area, number of papers directly related to the topic, evolution of concepts and definitions of terms, theoretical models, case studies, among others;
15. *Theoretical models*: Construction of theoretical models and definition of research hypotheses based on the results of the SR and the elaborated synthesis.

3 Results

3.1 Input

3.1.1 Problem

The key question to be answered by the research was: what would be a recommended methodology proposal, from an engineering perspective, for the development of products with a user-centered approach and the aid of AM in the context of AT?

3.1.2 Objectives

In harmony with the research objectives, the objective of this SR was to investigate, analyze and describe, based on searches in primary sources and multidisciplinary databases, the methodologies that have been developed and proposed for the development of products with an user-centered approach and the aid of AM in the context of AT.

3.1.3 Primary sources

After a preliminary review on the topic and through the guidance of more experienced researchers in both the AT and the design methodology areas, the following multidisciplinary databases were defined as primary sources: ScienceDirect, Scopus, PubMed and Web of Science. Relevant papers and references were also obtained directly by indication of the researchers in the mentioned areas.

3.1.4 Search strings

Based on the preliminary review and the guidance from more experienced researchers in their respective areas, the following combination of keywords was defined for the search strings: design, user-centered design, user-center design, UCD, personalized design, customized design, participatory design, inclusive design, universal design, design for, user experience, UX, assistive technology, assistive device, additive manufacturing, 3D printing, rapid prototyping.

The strings were then prepared taking into account the necessary terminology and operator adjustments (AND and OR), in accordance with the research tools of each of the four multidisciplinary databases used.

3.1.5 Inclusion criteria

Considering the objectives of the SR, papers or references since 1998 (twenty years ago from the start of the SR) that studied the methodology of development of ADs were included, regardless of the specificities (type, application, etc.) of the devices and the knowledge area (health, engineering), since the focus is the study of the design methods in the eminently multidisciplinary context of AT. The use of AM, in some way, in the process, was also an important inclusion criterion. In specific cases, however, in which AM was not used, but the study of the method was well designed and relevant to the research, the works were included. References in English as well as in Portuguese were considered.

Those papers that deal with the development of ADs, but that did not present a methodology itself, as in the case of some works that report the digital fabrication of ADs obtained in virtual databases through the Do It Yourself (DIY) method, were not included. In some cases, however, although the methodology was not clearly outlined, it was understood that the papers made significant contributions to the methodological study of the AT design and, for this reason, they were included. Paid papers were only considered when really closely aligned with the research objectives.

3.1.6 Qualification criteria

Observing the eminently investigative and descriptive purpose of this work, all papers and references found that presented some proposal for systematizing the process of design of ADs were considered qualified, being more relevant, however, those whose description of the methodology was more complete and detailed.

3.1.7 Methods and tools

The three filters were applied, sequentially, to the papers obtained through searches performed in the databases. The result of each filtering step was filed in specific folders. References from other primary sources—for example, from indication of experienced researchers in their fields or from cross-references—were also subjected to the same process.

At the end, the selected references were analyzed in more detail and synthesized for the preparation of the final results and conclusions of the SR.

3.1.8 Schedule

The SR was developed from mid-2018 until the end of 2019, close to the completion of the PhD work [12] in which it was inserted. The searches in the databases were carried out until mid-2020, with the aim of extending the scope of the research as much as possible and including the largest number of references of interest. Two additional papers (the last ones) were found after the conclusion of the PhD thesis and added in this work.

3.2 Processing

3.2.1 Performing the searches

After defining the strings, the criteria and the search method, as well as the primary sources, the searches for the references were then conducted in a direct and crossed way. The process was repeated iteratively throughout the development of the work, in order to ensure that new papers of interest could be incorporated into the research as they were published.

3.2.2 Results analysis

During the searches in the databases, the three described filters were applied successively. The first one was applied still in the database environment, since only the papers that were validated by this filter were archived. These papers were then stored in a specific folder, and subsequently submitted to the second filter, with the reading of the introduction and summary. Those that were validated after the second filter, were then transferred to another specific folder and submitted to the third filter, which consisted of reading the full paper. Finally, another folder was assigned to the selected papers after going through all the filters, which were analyzed in more detail for the preparation of the synthesis and the final results of the SR.

3.2.3 Documentation

In addition to the strings used in each database, with their specific characteristics, statistical data on the searches and on the filters application were also documented, such as: number of papers found after searching in each database, number of papers archived, number of papers selected, time distribution of the selected papers, number of those obtained by other primary sources or by cross-reference.

3.3 Output

3.3.1 Alerts

In order to monitor the publication of new papers of interest throughout the work, alerts were created in the search tools of the databases used.

3.3.2 Registration and archive

The papers and references selected by the SR were properly registered in a spreadsheet of references, synthesized and archived in the references repository, within specific folders.

3.3.3 Synthesis and results

The searches in the databases presented the following results:

1. PubMed: 25 papers found, of which 10 were selected (first Filter);
2. ScienceDirect[1]: 18 papers found, of which 6 were selected (first Filter);
3. Scopus: 107 papers found, of which 38 were selected (first Filter);
4. Web of Science: 61 papers found, of which 17 were selected (first Filter).

All papers selected after the application of the first Filter were then collected in a folder, with the removal of duplicates, reaching a total of 44 in this first step.

After being submitted to the second Filter, by reading the introduction and conclusion, a total of 37 papers were selected and relocated to another folder.

The cross-references totaled 25 and those from other primary sources (indications from experienced researchers in the field, specific journals, books, reports, etc.) totaled 12.

Finally, after reading all the references in the third Filter, 30 were selected and directed to a third folder.

Thus, the application of the RBS Roadmap script resulted in the selection of a total of 30 references of interest for the research, as outlined in Fig. 2.

[1] In mid-2018, ScienceDirect changed its search engines, removing the advanced search field through the use of strings. It was therefore not possible to perform the iterative search after that date, remaining only the results of the first searches.

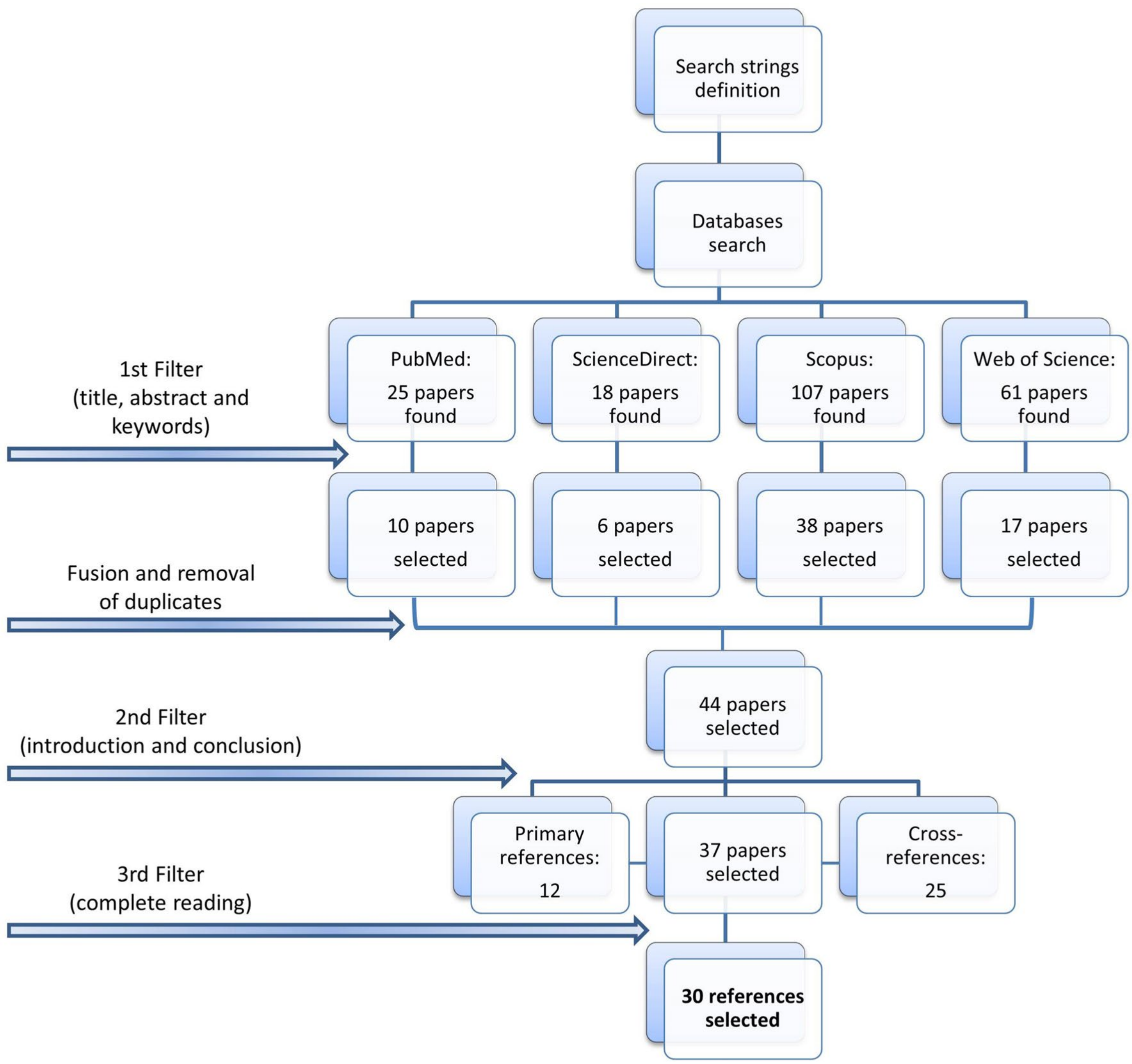

Fig. 2 SR Flowchart

3.3.4 Theoretical models

After a thorough reading of the 30 selected references, a synthesis of each was elaborated, seeking to highlight the main characteristics of the analyzed methodologies.

In order to facilitate visualization and comparison between them, for further discussion and elaboration of hypotheses, theoretical models and conclusions, the comparative table (Table 1) presented below was elaborated.

In a general analysis of the selected references it was possible to notice that many of them presented more a sequential description of the steps of the development process of an AD than properly a methodological proposal. It would be rather a sequencing of activities rather than a design method. In some works, although a planned sequence of activities is noted, it was not expressly presented or described. On the other hand, some very complete and structured proposals could also be identified, such as, for example: Ostuzzi et al. (2015) [25], Gherardini et al. (2018) [32] e Schwartz et al. (2019) [38].

As previously mentioned in the description of the inclusion criteria, some only theoretical works—without case studies or manufacturing of ADs—were considered due to their relevance and, in some cases, originality, in the methodological study of the AT design. The same happened with some studies in which there was no use of AD as a tool to aid the design.

Among the identified limitations, one of the most significant, even in the case of more structured methodologies, is the lack of use or the lack of a more detailed description of the application of technical design tools, especially in the initial stages of the process, such as, for example, in the identification and treatment of users' requirements, in the ideation and elaboration of product concepts, in the proper

Table 1 Comparative table of the references selected by the SR

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
Poulson e Richardson (1998) [14]	USERfit	(1) Problem Definition (2) Functional Specification (3) Build (4) Test	- No case study - Brainstorming - Interviewing techniques - Task Analysis - User Trials
Manzini e Santos (2002) [15]	Flowchart for development of technical aids	(1) Understand the situation (2) Generate ideas (3) Choose alternatives (4) Represent the idea (5) Build the object (6) Evaluate the use (7) Follow the use	- No case study - Interviews - Observation - Researches of interest (existing solutions, alternatives, materials, etc.)
Demirbilek e Demirkan (2004) [16]	USAP – Usability, Safety, Attractiveness Participatory Model	(1) Concept Development (2) Concept Refinement (3) Prototype Construction (4) User Trial Session (5) Production	- Case study - Brainstorming - Idea writing and sketching - Quality function deployment matrix - Scenario building - Unstructured interviews and pre-set questions
Wang e Chou (2007) [17]	MPC – Multi-professional collaboration approach	(1) User Needs Elicitation Module (2) Design Knowledge Interaction Module (3) Product Concept Clarification Module (4) Optimal Concept Alternative Module	- Case study - Additive manufacturing - Hierarchical value map (HVM) - Laddering - Means-end chain (MEC) - Morphological analysis - Multi-professional team - QFD
Carvalho, Okumura e Canciglieri Junior (2010) [18]	Framework for development of AT products based on the concepts of Simultaneous Engineering	(1) Informational Design (2) Conceptual Design (3) Detailed Design (4) Preparation for Production (5) Product Launch	- No case study - CAD/CAE/CAM - Design for Assembly (DFA) - Design for Manufacturing (DFM) - Multidisciplinary team - Simultaneous Engineering - Total Quality Management (TQM)
De Couvreur e Goossens (2011) [7]	Design for (every)one	(1) Performance (2) Economy (3) Convenience (4) Identity (5) Pleasure	- Case study - Additive manufacturing - Brainstorming - Co-creation and co-construction sessions - Multidisciplinary team - Stigmergic communication - Universal design

Table 1 (continued)

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
CGEE (2012) [19]	AT products design model	(1) User Need (2) Device Design and Conception (3) Product Design (4) Design Development (5) Manufacturing (6) Market	- No case study - Adoption of transversal technologies - Collaboration with experts - Material selection - Sketches and drawings
Medola et al. (2012) [20]	Design based on ergonomic principles	(1) Conception and Virtual Modeling (2) Prototype Manufacturing (3) Evaluation	- Case study - Additive manufacturing - CAD - Ergonomic and anthropometric study - Silicone mold - Study of the acting forces
Plos et al. (2012) [6]	EMFASIS – Extended Modularity, Functional Accessibility, and Social Integration Strategy	(1) Extended Market (2) Modular Design (3) Functional Acceptability (4) Accessibility (5) Social Integration	- Case study - Creativity sessions - Interviews and questionnaires - Multidisciplinary team - Semantic and emotional analysis
Buehler, Hurst e Hofmann (2014) [21]	3D Printing for Accessibility	(1) Gathering Requirements (2) Prototyping and Iteration	- Case study - 3D scanning - Additive manufacturing - CAD - Clay models - Interviews - Multidisciplinary team - Observation - Software for generating parametric models
Chavarriaga et al. (2014) [22]	Multidisciplinary Design of Suitable Assistive Technologies	(1) Characterization of the problem and socio-cultural aspects of the population (2) State-of-the-art research and development of technology-based assistive solutions (3) Community building through the involvement of different stake holders	- Case study - Axiomatic Design - CAD - Conferences, workshops, courses and papers - Functional electrical stimulation (FES) - Interdisciplinary team - State-of-the-art research - TRIZ
Coton et al. (2014) [23]	DFD—Design for Disability	(1) Knowledge of end users (2) Active participation of users (3) Appropriate repartition of functions between users and technology (4) Iterative approach to design (5) Intervention of a multidisciplinary team	- Case study - Additive manufacturing - Multidisciplinary team - Discussions - Observation

Table 1 (continued)

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
Maia e Freitas (2014) [8]	Flowchart for AT products development process	(1) Problematization (2) Data Survey (3) Data Analysis (4) Product Design (5) Product Evaluation and Validation (6) Detail Design (7) Production Planning (8) Product Production (9) Usability Assessment	- No case study - Comparison, functionality and ergonomics tests - Functional modeling - Observation - Physical and cognitive assessment - Simulation
Okumura e Canciglieri Junior (2015) [24]	Design for AT—Integrated Product Development for AT	(1) Pre-Design (2) Design Development (Informational design, Concept design, Preliminary design, Detailed design) (3) Post-Design	- No case study - Concurrent engineering - Design for Assembly (DFA) - Design for Excellence (DFX) - Design for Manufacturing (DFM) - Integration Definition Language for Function Modeling (IDEF) - Multidisciplinary team - Product ergonomics - Universal Design - Usability
Ostuzzi et al. (2015) [25]	+ TUO Project	(1) Questionnaire (2) Design of Reference Products (3) Activation Stage (4) Generative Session (co-design and co-production)	- Case study - Additive manufacturing - Brainstorming - CAD - Intermediate product prototyping - Interviews and questionnaires - Multidisciplinary team - Sketches and drawings
Hofmann et al. (2016) [26]	Rapid iterative prototyping of prosthetic devices	(1) Initial Interviews (2) Design Interviews (3) Prototyping Sessions (4) Testing	- Case study - Additive manufacturing - CAD - Modularity - Multidisciplinary team - Prototyping with alternative materials (clay, foam, Lego, etc.)
Thomnn, Morais e Werba (2017) [27]	Multidisciplinary Project focused on Assistive Technology	(1) User-Centered Design (UCD) (2) Iterative Design (3) Scenario Based Design (4) Tools from Ergonomics	- Case study - Activity analysis - Additive manufacturing - CAD - Direct observations - Interdisciplinary team - Interviews and researches - Prototyping with alternative materials - Usability testing

Table 1 (continued)

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
Harris (2017) [28]	Pathway for development of assistive technologies	(1) Feasibility (2) Concept Development (3) Prototying and Testing (4) Development (5) Commercialization	- No case study - Additive manufacturing - Decision matrix (House of Quality) - Design for Manufacturing and Assembly (DFMA) - Direct observation - FMEA - Functional and performance tests - Mock-ups and prototypes - Multidisciplinary team - State-of-the-art and technical feasibility - Unstructured or structured interviews
Berger et al. (2018) [29]	3D printing of Personalized AT	(1) Participatory Design	- Case study - Additive manufacturing - Focus groups - Parametric design - Questionnaires - Web tool - Workshops
Da Silva et al. (2018) [30]	Interdisciplinary-based Development of user-friendly customized 3D printed upper limb prosthesis	(1) Exploring (2) Briefing (3) Concept design (4) Prototyping (5) Testing (6) Provision	- Case study - 3D Scanning - Additive manufacturing - CAD - Interdisciplinary team - Interviews - Open-source design - Study of available technologies - Usability test
Day e Riley (2018) [31]	Utilizing three-dimensional printing techniques when providing unique assistive devices	(1) Shape Capture (2) 3D Scanning (3) 3D Modeling (4) Finite Element Analysis (5) 3D Print (6) Product Evaluation	- Case study - 3D scanning - Additive manufacturing - Alginate cast - CAD - Finite element analysis - Intermediate material prototype - Lengthy consultation - Multidisciplinary team - Photogrammetry - Pugh's Matrix

Table 1 (continued)

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
Gherardini et al. (2018) [32]	Co-Design Method for the Additive Manufacturing of Customized Assistive Devices	(1) Mapping of the patient's therapeutic needs (2) Co-design of the customized AD (3) Parametric modeling of the AD (4) Preliminary validation of the AD (5) Delivery of the AD and patient's training, (6) 6 months follow-up (7) Finalization of the AD modeling and documentation	- Case study - Additive manufacturing - CAD - Interdisciplinary team - Intermediate materials prototyping - Interviews - PIADS - QFD - QUEST - Storytelling - Training sessions - USERfit Product Analysis - Virtual models (3D) library
Haring et al. (2018) [33]	Development of an Adaptive Device	(1) Physical and virtual modeling (2) Preliminary evaluation and training program (3) Comparative test	- Case study - 3D scanning - Additive manufacturing - CAD - Interviews and observations - Mold and cast - SHAP-C
Portnova et al. (2018) [34]	Design of a 3D-printed, open-source wrist-driven orthosis	(1) Device design (2) Fabrication testing (3) User testing	- Case study - Additive manufacturing - CAD - Interviews and survey - Multidisciplinary team - Parametric design - Step-by-step manual (for measurements and CAD input) - Box-and-Blocks Test - Jebsen–Taylor Hand Function Test (JTHF) - Pinch dynamometry
Gordes e Waller (2019) [35]	Strategies for improving the development of patient-centered 3D printed adaptive equipment	(1) Session One: Discipline Introductions (2) Session Two: Modeling adaptive equipment (simulated patients) (3) Session Three: Revise 3D printed product (simulated patients) (4) Session Four: Review final 3D printed product (simulated patients) (5) Session Five: Modeling adaptive equipment (actual patients) (6) Session Six: Review 3D printed product (actual patients)	- Case study - Additive manufacturing - Follow-up online surveys - Interviews - Interdisciplinary team - IPEC Core Competencies - Lectures and open sessions discussions - Playdough and clay molds - Simulated scenarios

Table 1 (continued)

Authors	Short description	Phases/principles of the methodology	Tools and techniques used
Lee et al. (2019) [36]	Personalized assistive device manufactured by 3D modeling and printing techniques	(1) Patient analysis (2) Designing and printing (3) Evaluation	- Case study - 3D scanning - Additive manufacturing - CAD - Interviews - Grip, force and flexion tests - Jebsen–Taylor Hand Function Test (JHFT) - QUEST
Manero et al. (2019) [37]	Participatory design – Cooperative expression	(1) Core Design (2) Participation (3) Engineering Integration (4) Interdisciplinary Manufacturing	- Case study - Additive manufacturing - Artistic customization - CHEQ - Game-based training - Interactive website - Interdisciplinary team - Assessment of Capacity for Myoelectric Control (ACMC) - PedsQL
Schwartz et al. (2019) [38]	Methodology and feasibility of a 3D printed assistive technology intervention	(1) Identify habits and routines (2) Attain user's AT preferences (3) Design and manufacture the device (4) Train the user	- Case study - 3D printed objects digital repository - Additive manufacturing - ARMS - CAD - Cohen's D - QUEST 2.0 - Semi-structured interviews and questionnaires
Binedell et al. (2020) [39]	User-centered and iterative process of prosthesis design	(1) Patient Needs (2) Capture Geometry (3) Geometry Processing (4) Prosthesis Design (5) 3D Printing (6) Verification and Fitting (7) Delivery and Survey	- Case study - 3D scanning - Additive manufacturing - CAD - Interviews - User shadowing - QUEST 2.0
Degerli et al. (2020) [40]		(1) Identifying the problematic activity (2) Design and planning (3) Scanning (4) 3D modeling (5) 3D printing (6) Teaching how to use	- Case study - 3D scanning - Additive manufacturing - CAD - COPM - Sketch drawings

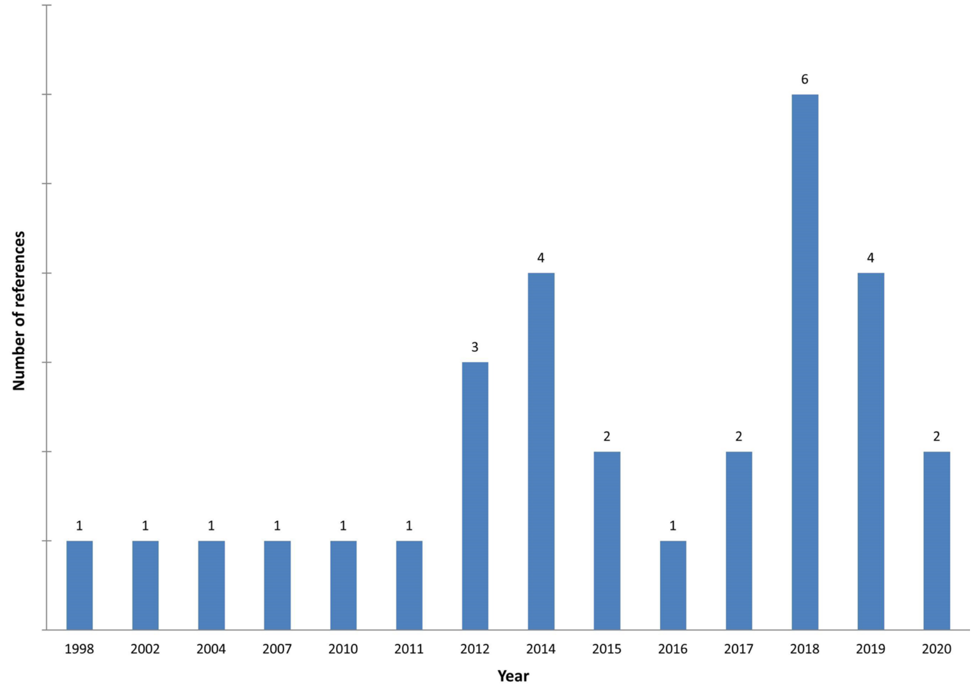

Fig. 3 Number of SR references per year

understanding of its functions and in the selection of the most appropriate and viable solutions, among others.

It is interesting to note that a great number of works (19 of 30) already highlighted the importance of a multidisciplinary/interdisciplinary team for carrying out this type of design, although not all works that mention this characteristic seek to present the composition of the team and its process of formation, integration and interaction. The use of AM as an important tool to support the design in this area could also be seen through many (21 of 30) of the selected references. Only seven of the selected references did not present a case study.

It is also worth mentioning, based on an analysis of the selected references, the increase in studies and methodological proposals over time, especially from 2018 onward, as shown by Fig. 3, thus highlighting the topicality of this type of research.

Finally, it is also important to consider the limitations of this SR, which, despite being systematic, mainly focused on papers from journals and congresses found in multidisciplinary databases, not focusing on searching specific journals, books, theses, dissertations or other sources. Even so, some of these references were incorporated thanks to the cross-searches and the indications of professionals and experienced researchers in the areas of interest.

From what has been presented, it is clear that there are some research gaps in this area, especially with regard to the structuring and more detailed description of design methodologies for ADs, as well as the validation of these methodologies through case studies. Many methodologies are presented only theoretically, while many AD development case studies are conducted without an outlined methodology. On the other hand, it was possible to notice an increasing trend in the use of AM as an aid tool in AT design, as well as in the approach through multidisciplinary/interdisciplinary teams for this type of design.

4 Conclusions

The realization of a SR proved to be very important for the development of the work for which it was thought, both for the elucidation of the research and development scenario in the area, as well as for the organization of the information and the subsidies it offered to the process of elaborating the AT-d8sign methodology [13]. The script used, RBS Roadmap [11], also proved to be very useful, making it easier to carry out the review thanks to the detailed and very pragmatic description of the process.

Through the SR, an increase in the number of studies and research related to the AT design methodology could be seen in recent years, indicating a trend that reinforces the importance and the topicality of the theme, in view of the growing demand for ADs in the world. This also indicates an increasing concern with the quality of the devices generated and, therefore, with the systematization of development processes, so that they can guarantee the generation of products that really meet the users' needs and desires, promoting their autonomy and independence and avoiding the waste of resources.

Despite this, it was still possible to identify some important gaps in the process of development of ADs, especially with regard to the more structured and well-described use of tools, techniques and design practices, aiming to favor the interaction between the different parts and areas involved in this type of design, the flow of information throughout the process, the maintenance and observance of quality criteria and goals and, finally, the achievement of satisfactory results.

Finally, it became possible to conclude from the SR the increasingly clear and necessary importance of this integration between engineering and AT, seeking to establish a systematization of the process of development of ADs that incorporates, at the same time, the qualities of both the areas: technical knowledge, tools and development methodology, in the case of the former; the user-centered approach and the knowledge of therapeutic needs and occupational performance, in the case of the second.

5 Search strings

5.1 PubMed

(((design OR development OR user-centered OR user-centered OR UCD OR personalized OR customized OR participatory OR co-design OR inclusive OR universal OR design for OR user experience OR UX)) AND (additive manufacturing OR 3D printing OR three-dimensional printing OR rapid prototyping)) AND (assistive technology OR assistive device).

5.2 Scopus

TITLE-ABS-KEY (design OR development OR "user-centered" OR "user-centred" OR UCD OR personalized OR customized OR participatory OR inclusive OR universal OR "design for" OR "co-design" OR "user experience" OR UX AND "additive manufacturing" OR "3D print*" OR "three-dimensional print*" OR "rapid prototyping" AND "assistive technology" OR "assistive device*").

5.3 ScienceDirect[2]

TITLE-ABS-KEY design OR development OR "user-centered" OR "user-centred" OR UCD OR personalized OR customized OR participatory OR inclusive OR universal OR "design for" OR "co-design" OR "user experience" OR UX AND "additive manufacturing" OR "3D printing" OR "three-dimensional printing" OR "rapid prototyping" AND "assistive technology" OR "assistive device".

5.4 Web of science

TS = ((design OR development OR "user-centered" OR "user-centred" OR UCD OR personalized OR customized OR participatory OR inclusive OR universal OR "design for" OR "co-design" OR "user experience" OR UX) AND ("additive manufacturing" OR "3D print*" OR "three-dimensional print*" OR "rapid prototyping") AND ("assistive technology" OR "assistive device*")).

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[2] In mid-2018, ScienceDirect changed its search engines, removing the advanced search field through the use of strings.

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