prosthesis

Review

Applying 3D Scanning and Printing Techniques to Produce Upper Limb Prostheses: Bibliometric Analysis and Scoping Review

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Abstract: Background/Objectives: Three-dimensional scanning and printing techniques have gained prominence in the fabrication of upper limb prostheses. This paper provides an overview of various studies on the current utilization of 3D scanning and 3D printing techniques in upper limb prostheses. **Methods**: A scoping review of the literature was performed following the PRISMA-ScR guidelines in Scopus, PubMed, Google Scholar, and Web of Science, with a total of 274 papers included. A bibliometric analysis was conducted, analyzing the field via keyword co-occurrence visualized using VOSviewer software. **Results**: Keyword co-occurrence analysis identified four key areas, "prosthesis design and evaluation for people", "prosthesis control and sensing technologies", "robotics and mechanical prostheses design", and "accessibility for prosthesis". Temporal analysis identified three trends: a focus on fingers, advancement of control systems, and the rise of 3D scanning. In addition, qualitative analysis was conducted to discuss the areas and trends that were shown from the bibliometric analysis, highlighting several studies. **Conclusions**: This review shows the utilization and notable success of 3D printing and scanning techniques when making upper limb prostheses, with the contents of this article informing healthcare professionals and the general public about the field.

Keywords: prosthetics; prosthesis; 3D scanning; 3D printing; upper limb

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1. Introduction

Three-dimensional scanning and printing techniques have become popular over the years, especially in the medical field [1]. Three-dimensional scanning is used to collect three-dimensional data on an object's shape and appearance, while three-dimensional printing constructs three-dimensional objects from computer-generated models by adding layers of materials. A key area where the usage of these techniques has been adopted is the prosthetics field [2]. Conventional techniques for making prostheses involve casting molds using silicones or plaster and manufacturing the prostheses using techniques like injection molding and vacuum forming. These processes can take a lot of time and money to generate a finished product for the person in need [3]. Prefabricated prostheses are commercially available in parts of the world; however, without the measurements of individual limbs, these alternatives will most likely not fit what the person needs. More expensive custom-made prostheses are required for a better fit with the wearer's characteristics [4].

Custom-made prostheses require wearers to have their residual limb specifically measured to make molds [3]. Specialists are needed for the fabrication of these custom-made prostheses, as specially fitting prostheses to suit a person's body requires considerable skills and experiences. However, there are insufficient specialists to match the number of patients in need [5]. Furthermore, patients are required to visit those specialists, incurring the financial and time costs of traveling [6].

This is a cause for concern, as a considerable number of people need prostheses of some kind. In 2017, the WHO estimated that around 35–40 million people needed prosthetic or orthotic services. However, only 1 in 10 people have access to the required services [5]. Not having a prosthesis often negatively impacts the life of the person with a limb difference. The loss of function of the missing body part can affect the level of autonomy of an individual and limit their capability to carry out work and daily activities [7]. There are also societal and emotional drawbacks in day-to-day life that need to be considered [8].

Three-dimensional scanning and printing techniques bring several advantages [9,10]. The biggest advantage is shortening the time required to fabricate a prosthesis. Traditionally, patients have needed to travel to specialized clinics, have their limbs cast, and wait for the casts to dry, all of which takes time. Furthermore, the prosthesis needs to be made and fitted, potentially requiring further adjustments to the design to fit the patient's specifications. Three-dimensional scanning technology enables precise measuring to create custom prostheses in significantly less time. Computer software can design and, more importantly, adjust the design, reducing the time needed to create the prostheses compared to conventional methods. These techniques also bring a great degree of customizability, allowing more complex shapes and designs to be manufactured. Prostheses can be directly printed with various materials, or molds can be made to cast silicone-based prostheses. Furthermore, they enable people to build their prostheses, shifting some of the needs of professionals to the individuals themselves, which is further enabled by open-source designs [11].

As the costs of 3D scanners and printers have reduced significantly over the last 10 years [12], the utilization of these techniques in the prosthetic field should grow in the foreseeable future. The prosthetic field itself is broad, consisting of different types of prostheses for different body parts. This paper will focus on upper limb prostheses, as that field is a popular one with a large number of people needing devices. The functions of upper limb body parts are more difficult to reproduce than those of the lower limbs [13]. Upper limb body parts are frequently used for gross and fine motor activities, requiring large degrees of freedom. The restoration of these functions can only be partial, with active types of prostheses restoring more functions than passive types. Regardless, having a prosthesis of any type has been shown to help individuals in at least one or two basic functions [14].

Research on prostheses made using 3D printing and scanning techniques is abundant, covering a broad range of cases from clinical use, prototype development, and commercial application to community-led development. A general overview of the field is lacking, which can make entry into the field confusing. Scoping reviews have been widely adopted as a method for researchers to map existing knowledge and empirically assess a research topic [15]. This paper aims to provide an overview of the current utilization of 3D scanning and printing techniques in making upper limb prostheses, serving as a basis for further research. Additionally, this paper aims to identify the key areas and trends in the field, which could serve as directions for future research.

2. Materials and Methods

A scoping review was conducted on published papers written about upper limb prostheses that involved using 3D scanning and printing techniques in the process. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR). The PRISMA guidelines help ensure better reporting of the wide array of research [16]. A protocol was developed and can be accessed at https://bit.ly/3EFePox.

Four predetermined inclusion criteria had to be met. First, the paper had to involve 3D scanning or printing at some stage in the production process of upper limb prostheses. Review and evaluation papers were excluded. Secondly, the prostheses were limited to external prostheses; bone or other internal prostheses were excluded. Thirdly, the paper had to be available in full length to review. Lastly, the paper had to be written in English. Additionally, the scope of research was restricted to published papers from 2018 to the time of the search. This was to create a better overview of the recent utilization of 3D scanning and printing techniques.

The literature search was conducted using three databases: Scopus, PubMed, and Google Scholar. Multiple databases were used to ensure that the search was more comprehensive than relying on a single source. The initial literature search across these databases was conducted on 22 October 2023. An additional search was conducted to include the Web of Science database and newer research on 24 January 2025.

The database search was performed using several keywords to find papers covering 3D scanning and printing techniques in relation to upper limb prostheses. Keywords were searched within the title, abstract, and keywords of the literature. Several keywords were identified to find papers relevant to the study. The keywords identified were "3D printed", "3D printing", "prostheses", "prosthesis", "prosthetic", "arm", "hand", and "finger". The keyword "3D scanning" was not used as the use of 3D scanning is usually followed by 3D printing to create the prosthesis and, therefore, would likely contain the keywords "3D printing" or "3D printed". This exclusion may exclude papers that discuss the accuracy of 3D scanners, but this paper will primarily focus on the practical use of the scanners. Boolean operators were used to combine keywords and limit the search to the scope of the study.

The final string used for searching the Scopus database was [("3D print *") AND ("prosthe *") AND ("arm" OR "hand" OR "finger")]. Additionally, the search was limited by the time criteria of 2018–2023, to full-text papers, and to papers written in English using the built-in feature. The same string was used for PubMed. The search in Google Scholar was performed with additional modifications to exclude papers outside the scope of the study. The final string used was ["3D print *" prosthetic prosthesis prostheses arm OR hand OR finger-gripper-"lower limb"-"dent *"]. The additional search in Web of Science used the string [((TS = ("3d print *")OR TS = ("3d scan *")) AND TS = ("prosthe *") AND (TS = ("upper limb *") OR TS = ("arm *") OR TS = ("hand *") OR TS = ("finger *"))) NOT TS = ("lower limb *")].

The search results were then imported to the reference manager Zotero to be narrowed down. Manual screening was conducted by a group of four researchers. First, the titles and abstracts of the papers were screened to exclude papers outside of upper limb prostheses and those not utilizing 3D scanning or printing techniques. Title and abstract screening were performed independently by two researchers. Papers that the researchers were unsure of at this stage were included for full-text screening. These papers were then screened in full by two researchers and assisted by two more. Disagreements between reviewers were resolved through discussion. Only papers that passed both screenings were used.

The selected papers were analyzed both qualitatively and quantitatively. Each included paper was carefully read, and information about prosthesis type, limb deficiency type, materials, and techniques used was recorded in a shared sheet. Missing information and noteworthy observations were flagged and highlighted in a separate column.

A quantitative bibliometric analysis was conducted to statistically assess the field's status. Bibliometric analysis has been used in multiple studies as a method for evaluating research topics [17]. Keyword co-occurrence analysis and temporal analysis were conducted to identify key areas and trends in the field. Both analyses were conducted using VOSviewer, a software developed by Nees Jan van Eck and Ludo Waltman at Leiden University's Centre for Science and Technology Studies (CWTS) [18], which has been extensively used to construct and visualize bibliometric networks.

The software was used to identify keywords from the titles and the abstracts of the included papers. Keyword co-occurrences resulted in links between keywords that were visualized as a network map. Temporal analysis of the map was visualized by the average publication date of each keyword. The binary counting method was chosen, which counts each keyword's occurrence at least once without including repetitions. This approach prevents bias towards frequently repeated words and was considered more appropriate for this review [19,20]. Additionally, a thesaurus was created to group words that meant the same thing, for example, "3-D printing", "3D-printing", and "three-dimensional printing" were grouped as "3D printing".

3. Results

3.1. Search Results

The initial database search resulted in 418 documents from Scopus, 156 documents from PubMed, and 2040 documents from Google Scholar. A total of 2614 papers were imported to Zotero for screening. After removing duplicates, a total of 2430 papers were screened by the title and abstract, resulting in 260 papers that were read in full. After assessing the papers based on the inclusion–exclusion criteria, 104 papers were included for review.

The follow-up search conducted on Web of Science resulted in 412 documents. After removing duplicates from the initial search, 352 documents were screened based on the same inclusion–exclusion criteria. This resulted in a total of 170 documents being added to the review. The final selection of literature included a total of 274 documents from Scopus, PubMed, Google Scholar, and Web of Science. Figure 1 depicts the document collection procedure at each stage.

Figure 2 depicts the year of publication of the 274 papers that were included in the review. Papers published in 2020 was the category with the highest number of papers included, followed by those published in 2019 and 2018. A decline in the number of publications can be seen in the years after 2020, which could indicate a decrease in research activity in the field. Only one paper published in 2025 was included, as the latest search was conducted in January. Having papers from multiple years helps ensure that the literature reviewed represents the broad utilization over the time frame.

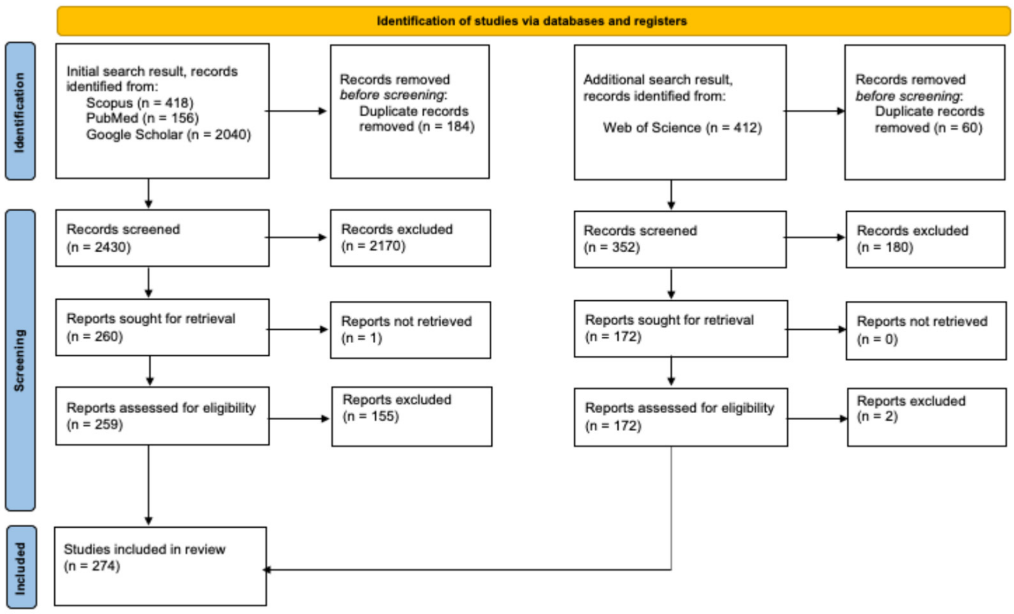

Figure 1. Flow diagram of document collection process.

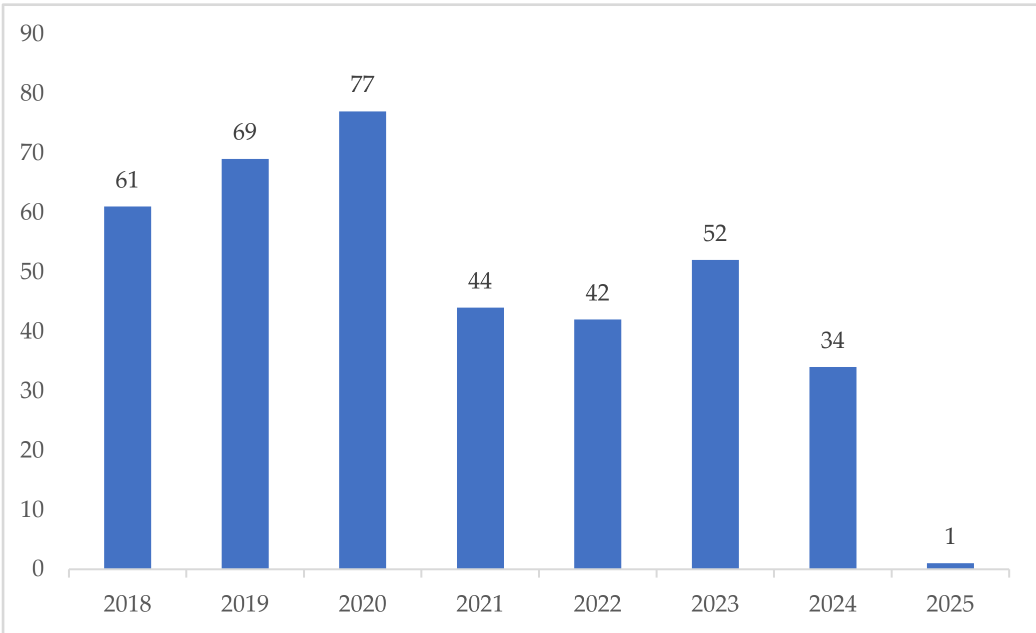

Figure 2. Year of document publication.

3.2. Summary of the Literature

Table 1 provides a summary of the types of prostheses from the papers included in the review. Upper limb prosthesis is a broad term that includes several different types of prostheses with different intended uses [21]. Prostheses can generally be categorized into two broad types: passive and active. Active prostheses can be further split into two categories, body-powered and externally powered [22]. An additional category was added to categorize activity-specific prostheses. The reasoning for this category was that the prostheses developed for specific activities have different use cases and design approaches. Lastly, two more categories, components and scan-only, were used to group the papers that only discussed specific components or only discussed the use of 3D scanning techniques in the paper.

Table 1. Summary of the literature.

Papers	Prosthesis Type	Limb Deficiency Type Arm	Hand	Finger	Total
[23–43]	Passive	8	6	7	21
[44–75]	Body-powered	3	16	13	32
[76–223]	Externally powered	52	84	12	148
[224–229]	Activity-specific	5	0	1	6
[230–289]	Components				60
[290–296]	Scan-only				7
Total Papers		**29**	**50**	**12**	**274**

Additionally, the prostheses were classified by the limb deficiency that the prostheses were designed for. The three categories used were arm, hand, and finger. The techniques and materials used in the papers are listed and summarized in Table 2.

Table 2. Techniques and materials used.

Techniques/Materials	Use Cases/Comparison	Example Paper
3D scanning techniques		
CT Scan	Used in a clinical setting; special equipment is needed which hospitals generally already have	[24]
Commercial Scanner	Multiple commercial scanners are available to buy and have higher accuracy	[23,47,100,241]
Photogrammetry	Uses 2D photographs to create 3D models; cost-effective, requires minimal specialized equipment, lower accuracy	[45,46,240,292]
Printing methods		
Fused Filament Fabrication/Fused Deposition Modeling (FFM/FDM)	Mostly used in prototyping and low-cost manufacturing; affordable, easy to use, and compatible with various materials like PLA and ABS	[30,31,44,48,51,55,77]
Selective Laser Sintering (SLS)	Good for printing complex parts and detailed parts; uses powdered materials; durable prototype	[47,116,138,235]
Stereolithography (SLA)	High-resolution and smooth finish; commonly used in dentistry and precision engineering	[116,123]
Materials		
Polylactide (PLA)	Cheapest material; mostly used for quick, affordable prototyping or creating non-functional models	[27,29–31,46]
Acrylonitrile Butadiene Styrene (ABS)	Durable and resistant to impact; best for functional prototypes and mechanical parts	[52,53,56,77]
Thermoplastic Polyurethane (TPU)	Flexible and compliant; often used for soft robotics parts	[28,80,85,93,94,231]
Thermoplastic Elastomer (TPE)	Extremely flexible and stretchable; recommended for wearables	[51]
Polyethylene Terephthalate Glycol (PETG)	Durable, transparent, food-safe, and hard to tear	[57,78,241]

3.3. Bibliometric Analysis

Keyword co-occurrence analysis was performed on the selected papers to identify patterns and trends in the topic. Keyword co-occurrence refers to when words or terms appear together in a text and can indicate a relationship or association between the terms [297]. Strong relationships between terms can show areas of focus, providing insights into the research question [298]. VOSviewer software was used to conduct the analysis. The minimum threshold for occurrence was set at 12, and the analysis was performed using binary counting.

The software identified a total of 95 keywords with enough occurrences. Several irrelevant keywords (e.g., "paper", "research", "project") were removed to avoid unnecessary items in the network map, resulting in a total of 62 keywords representing the current field of research. VOSviewer then visualized a network map based on the keywords and their connection. Connections between keywords indicate co-occurrence and are visualized with connecting lines. Stronger connections are visualized with thicker lines. Figure 3 depicts the network map visualizing the relationship between keywords.

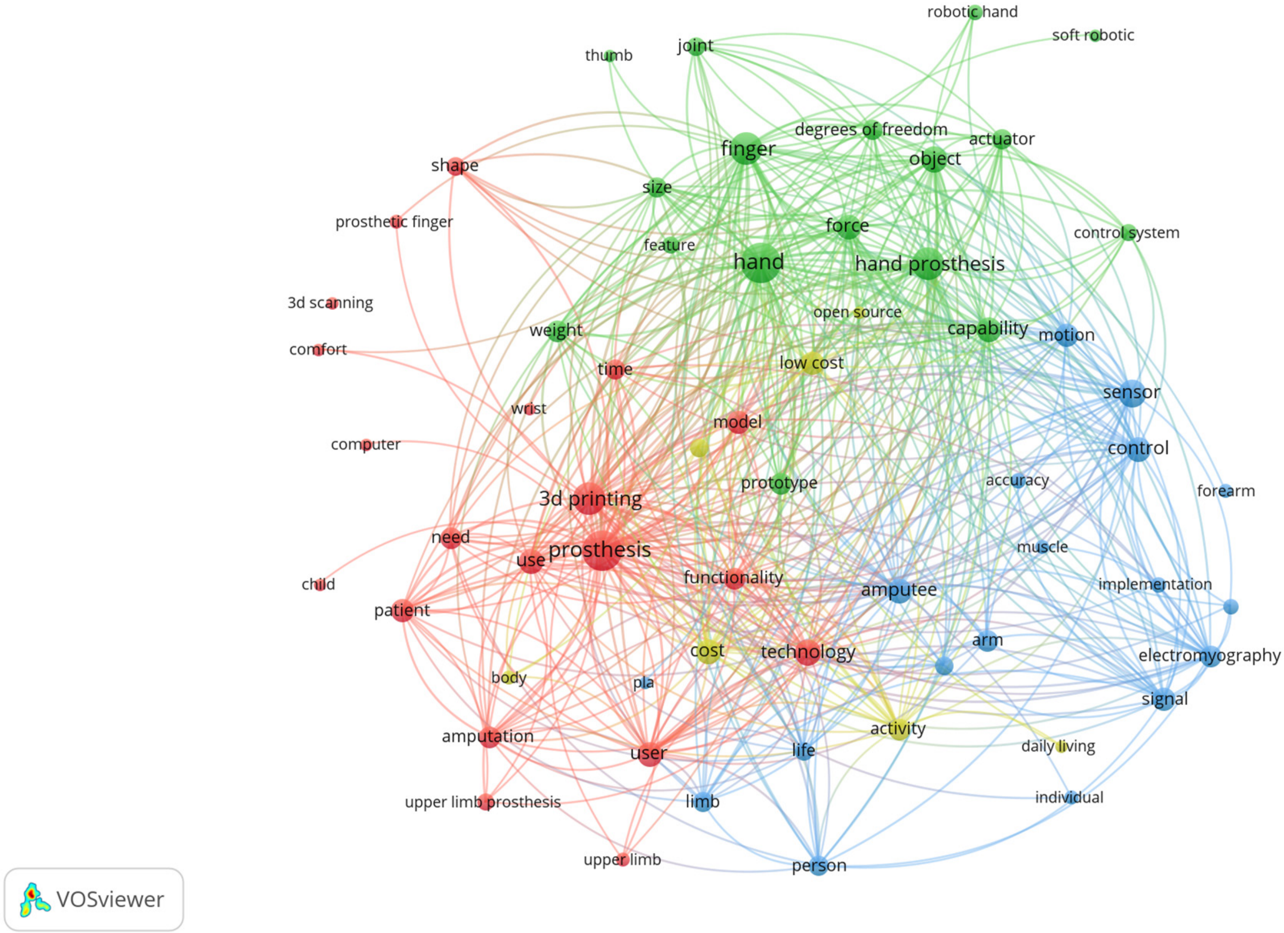

Figure 3. Network map visualization of keyword co-occurrence.

The network map shows several clusters highlighted in different colors. VOSviewer uses a matrix of the links between nodes to group items that it deems related [298]. This process results in clusters of keywords that may indicate key areas in the field. Literature reviews have used bibliometric analyses of these clusters to identify research areas of interest [19]. There are four clusters, shown by the colors red, green, blue, and yellow. Each cluster was analyzed, and a theme was assigned based on the keywords it contained. Table 3 shows the four clusters and the corresponding themes assigned.

Temporal analysis of the keywords was conducted to identify trends from keywords that have had more occurrences in recent years. To ensure that recent trends with fewer occurrences were considered, the minimum occurrence threshold was lowered to 5. Like before, binary counting was used, and irrelevant keywords were removed. A temporal network map was created with VOSviewer using the overlay visualization. Each keyword was visualized with a color gradient that shows its average publication year. Darker-colored nodes indicate an earlier average publication date, while lighter-colored nodes indicate more recent publications, likely signifying an emerging trend in the research. Figure 4 shows the temporal network map of the identified keywords.

Table 3. Clusters and assigned themes.

No	Cluster	Theme	Number of Keywords	Representative Keywords
1	Red	Prosthesis design and evaluation for people	20	child comfort functionality patient user 3d scanning
2	Blue	Prosthesis control and sensing technologies	18	control sensor electromyography surface electromyography
3	Green	Mechanical design and robotics	17	actuator degrees of freedom robotic hand soft robotics
4	Yellow	Accessibility for prosthesis	7	cost low cost daily living open source

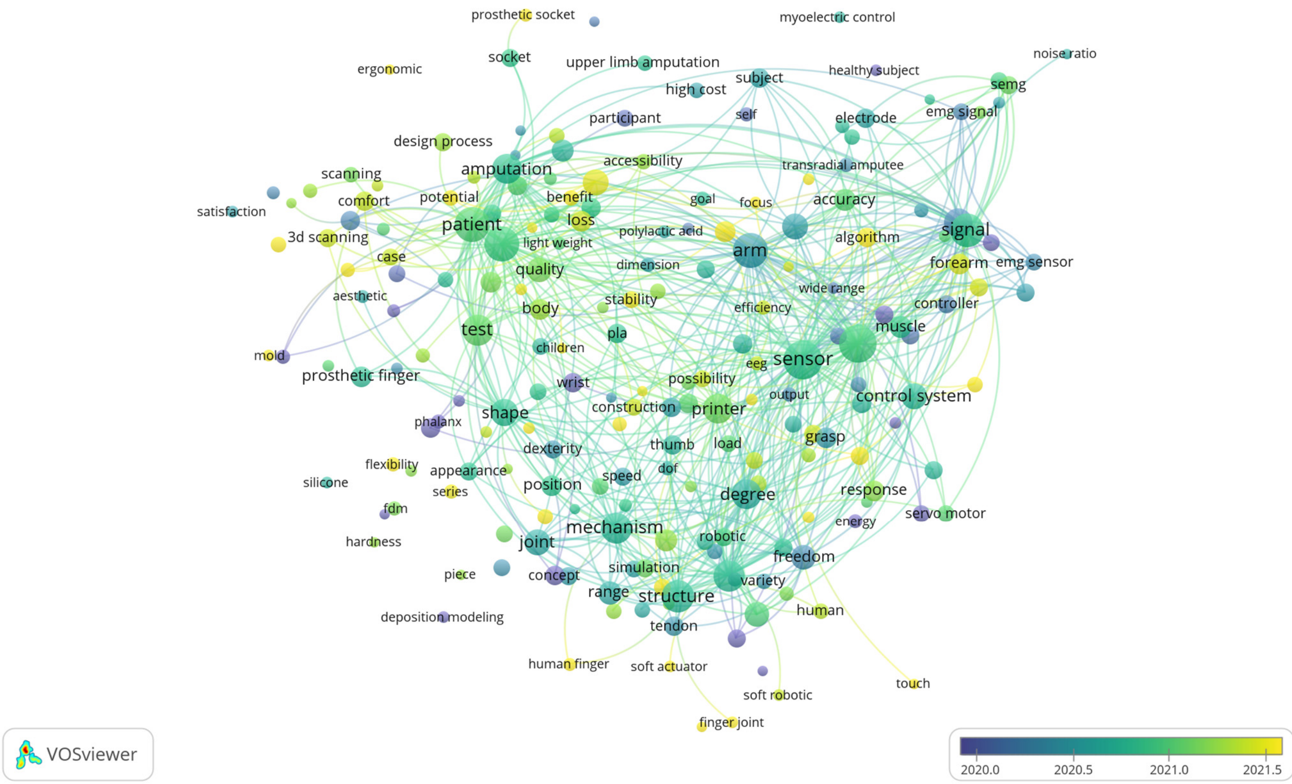

Figure 4. Temporal network map of keywords.

Several notable keywords in lighter colors are “finger prosthesis”, “finger joint”, “soft actuator”, “algorithm”, and “scanner”. These keywords have more recent occurrences in the papers included in the review and could indicate a trend in the field.

4. Discussion

4.1. Key Areas of Research

Keyword co-occurrence analysis of the selected papers resulted in four clusters, with each assigned a theme based on the keywords they contained. These clusters indicate the key areas of research in the field. Each cluster, along with its associated keywords and several selected studies, will be discussed in detail in this section.

4.1.1. Cluster 1: Prosthesis Design and Evaluation for People

The first cluster is called "Prosthesis Design and Evaluation for People", based on keywords that indicate a deliberate focus on designing prostheses for users. These keywords included "amputation", "patient", "user", and "child", which shows research involving patients at some stage of the prosthesis development. Patient involvement typically includes obtaining measurements and testing the resulting prototype. However, some studies employed a user-centered design approach involving patients throughout the development process. This area could also feature research more concerned with personalized prostheses than the ones in other clusters that focus on the technical aspect.

Several keywords in the network map indicate relevant areas of research. The first relevant keyword is "child", indicating a sub-area of research specifically for children's prostheses. Children's prostheses have been a significant area of interest since the early days of 3D-printed prostheses; the first 3D-printed prosthesis was designed as a solution for a child who could quickly outgrow traditional prostheses [2]. Development for children's prostheses remains an important area in the field as better prostheses are needed because children often have more needs to be considered. Some of the factors that need to be considered include mechanical properties, such as the weight and size of the prosthesis, and the growth of children, which leads to prostheses becoming ill-fitting over time. The emotional aspect should also be considered, such as ensuring the prosthesis is designed in a way that encourages the child to wear it. One study focusing on the development of children's prostheses was conducted by Ccorimanya et al. [109].

The researchers adopted a user-centered design approach, developing multiple iterations of 3D-printed prostheses for a child's different growth stages. The study reported that, thanks to 3D scanning and 3D printing technologies, the resulting prostheses were lighter in weight (85.1 g—less than 80% of the intact hand's weight, which was 86.3 g), which improved comfort when wearing. These technologies also allow the design to be scalable, allowing the model dimensions to be adjusted to produce prostheses in different sizes—an essential factor for children's prostheses. This allowed for multiple iterations to be customized to fit the patient better both physically and emotionally. Additionally, the study reported that the 3D-printed prosthesis cost, in total, around USD 1600, which is significantly more affordable compared to the USD 14,000 device that the patient previously used. More research involving children in the design process could greatly benefit the development and availability of prostheses that better suit the needs of children.

The next keywords notably present in this cluster are "comfort" and "functionality", indicating two important aspects of evaluation for prostheses. The evaluation of prostheses is usually performed after prosthesis development and was reported in many of the papers. The functionality of prostheses is typically evaluated by the device's ability to assist hand function in daily life activities. The evaluation of hand function gained from the prosthesis can be performed using available standardized tests such as the Sollerman hand function test, Jebsen–Taylor hand function test, box and block test, etc. Evaluating hand function is crucial for assessing whether the prosthesis will bring significant improvement to a patient's life. Additionally, the comfort of a prosthesis also factors greatly in whether patients consistently choose to wear it in their day-to-day life.

The presence of the two keywords aligns with the findings of Smail et al. [299], which identified lack of comfort and function as the two main reasons for product abandonment in upper limb prostheses. Furthermore, evaluation results will also aid future improvement, both for the prosthesis itself and for the field in general. Several relevant evaluation metrics should be used, as multiple aspects affect a patient's satisfaction with the prosthesis. In the previously highlighted research by Ccorimanya et al., six performance evaluations were performed, namely EMG signal, desired and undesired movements, electromechanical delay, box and block test, grip force and opening distance, and full opening and closing times. The results showed that the developed prosthesis has adequate performance to be used as an early intervention for children with congenital below-elbow deficiency. The researchers noted that although the prosthesis has adequate grip force for light objects, it is still inadequate for heavier ones, indicating an area for future development.

The last notable keyword in this cluster is "3d scanning", which is a main part of this study's aim. Three-dimensional scanning is being used to take precise measurements of patients' bodies, helping create better-fitting prostheses in a shorter time. There are three main methods for capturing these measurements, which are outlined in Table 3: CT scanners, commercial 3D scanners, and photogrammetry. CT scanners are often found in hospitals and usually use X-rays to capture internal images of organs. However, they can also be used to capture external geometry to create high-resolution 3D models [24].

On the other hand, commercial 3D scanners are now widely available for purchase and use light to capture surface geometry with high resolution. This can be seen in references [241], where 3D scanners were used to capture the geometry of the patient. The study by Baron et al. [100] noted that using 3D scanning results in a more anthropometric prosthesis but briefly discussed challenges in obtaining the best scan results from the patient's hand. Procedures for 3D scanning are usually just briefly mentioned in the papers; further research comparing the procedures and results of 3D scanning could be useful for future researchers to obtain the best scan results.

Lastly, photogrammetry is a method for capturing patients' geometry to create a 3D model from 2D photographs. There are four studies from the included literature that utilized photogrammetry, varying from using only patients' photographs, using a digital camera, to a full setup with multiple cameras. The studies by Young et al. [45] and Dumitrescu et al. [46] managed to generate a 3D model from just patient photographs. However, both studies provide little details on how accurate the measurements are, making it difficult to assess the effectiveness of this technique. The study by Ismail et al. [240] utilized one digital camera, with scan results showing 5–19% of deviation compared to standard casting methods, but was reported to be more time- and cost-effective. The study by Yang et al. [292], however, took it a step further and built a system with 50 cameras that has comparable performance with a commercial scanner, suggesting that photogrammetry could be viable to provide accurate measurements.

The use of 3D scanning shows promise as an alternative to traditional measurement techniques and the variety of scanning options available further aids the accessibility of the technique. However, the study by Olsen et al. [241] highlighted that optical scanning alone is insufficient to capture the nuanced physical features that could affect the prostheses' fit, such as sensitive skin, among others. Therefore, utilizing 3D scanning should still take into account other aspects that affect the patient's comfort when designing prostheses.

4.1.2. Cluster 2: Prosthesis Control and Sensing Technologies

The second cluster is called "Prosthesis Control and Sensing Technologies" and was based on keywords that included "control", "sensor", "signal", "electromyography", and "surface electromyography". The keywords "control", "signal", and "sensor" indicate an area of focus on improving prosthesis control based on various signal-based methods. The keyword "sensor" also includes research performed to enable sensing capabilities in prostheses. Externally powered prostheses rely on processing control signals from the body to instruct the movement of actuators. The control methods for prostheses discussed in the literature included popular methods such as electromyography and electroencephalography, as well as less popular methods such as force myography and acoustic myography.

Only the keywords "electromyography" and "surface electromyography" had enough occurrences to show in the network map, showing that more research is being performed on electromyography than the other control methods. The occurrences of these keywords also coincide with research on externally powered prostheses, comprising more than half of the studies included in this review, which indicates that externally powered prostheses, particularly ones controlled with electromyography, are a more popular development area for upper limb prostheses. This could be a natural research progression from body-powered prostheses to developing more advanced technologies that can provide more power and control than a mechanical setup.

Prostheses controlled with electromyography (EMG) are called myoelectric prostheses, and various research is being performed on them. The development of myoelectric prostheses shows some shared advantages, and several studies will be highlighted here. One popular myoelectric prosthesis in the included literature is the Galileo Hand, which was proposed by Fajardo et al. [90]. The device utilized surface EMG sensors to detect muscle contraction to signal the control system to perform movement. Another myoelectric prosthesis proposed is SIMPA, short for Soft-Grasp Infant Myoelectric Prosthetic Arm, proposed by De Barrie et al. [95]. This prosthetic arm is specifically designed for early infant adoption, following a lack of focus on the category, as stated by the researchers. The device was predominantly manufactured using 3D printing and produced consistent grasping results using signals from surface EMG armbands. The study demonstrated the viability of using myoelectric prostheses not just for adults but also for infants.

Another interesting study was conducted by Hussian et al. [82], where a myoelectric prosthetic arm was developed with EMG sensors, similar to other research but also featuring a self-charging capability. A piezoelectric generator was implemented in the device, allowing it to charge itself while the wearer is walking. The study reported that the generator could fully charge the battery during a one-and-a-half-mile walk. The study could be beneficial as most myoelectric prostheses rely on electricity to power actuators that allow movement. A self-charging prosthetic arm could help remove some of the efforts needed to maintain the prosthesis. Moreover, this study shows that there are many ways that development could be achieved to improve prostheses, not just through better design but also through features that could help the day-to-day lives of patients.

Although less popular, several studies in the literature have explored alternative control methods. A study by Ali et al. [88] developed an electroencephalography (EEG)-controlled prosthesis that utilized the electrical activity of neurons in the brain collected through a headset. The signals were then processed to control the drivers that move the hand. The study by Cortes et al. [247] used force myography (FMG) as the control signal for the prosthetic hand. Force myography uses variations in muscle stiffness during different movement patterns as signals [300]. Cortes et al. employed sensors to detect these variations and send processed signals to contract and expand a linear motor. Lastly, a study by Al-Timemy et al. [253] proposed acoustic myography (AMG), which uses acoustic signals as a control source. The study utilized eight high-sensitivity array microphones with custom 3D-printed housing to collect the AMG signals. The study suggests that acoustic myography could be a reliable control source. Research on these alternative control methods has shown promise, and further development could lead to a greater variety of prosthesis control technologies.

The other challenge regarding prostheses that is being tackled is the lack of feedback or sensing capabilities from devices. The development of sensing technologies is indicated to be a sub-area of focus in this cluster. Sensory feedback could help the prostheses feel more like a human hand, letting the wearers feel sensations from the environment. Sensors include piezoresistive, temperature, and pneumatic sensors, among others. One study by Rahiminejad et al. [262] proposed a biomimetic circuit replicating the spiking response for tactile feedback in prostheses. Another study by Saqib et al. [91] equipped a temperature sensor in the proposed prosthetic hand, providing users with input for hot or cold temperatures. More research could be performed to develop prostheses that can provide a variety of different sensations that a human hand could feel. However, adding sensing capabilities could add to the complexity involved in developing prostheses; as sensing technologies progress, more prostheses would be able to include them in the fabrication.

From the included research, 3D printing is generally utilized to create rapid prototypes for prostheses. Rapid prototyping allows researchers to test multiple iterations and fine-tune the prototype to achieve better results. Another use is to fabricate components or structures for the sensors. One study by Wolterink et al. [238] demonstrated the use of 3D printing to create flexible, personalized sensing structures that could be implemented in prostheses or assistive devices. The component was printed from thermoplastic polyurethane (TPU) doped with carbon and performed comparably to standard gold electrodes. This work illustrates how 3D printing can be applied not only to develop prostheses themselves but also to produce components during the fabrication process.

4.1.3. Cluster 3: Robotics and Mechanical Design

The third cluster is called "Robotics and Mechanical Design", and is based on keywords that include "robotic", "soft robotic", "degrees of freedom", "actuator", "capability", "joint", and "force". These keywords indicate an area of research concerned with developing better mechanics for 3D-printed upper limb prostheses. The keywords "degrees of freedom" and "actuator" show the effort towards developing prostheses with a higher degree of freedom. Degrees of freedom refer to the dimension in which the prostheses can move; a higher degree of freedom means that the prosthesis has a broader range of motion. Better actuators are needed for prostheses to move and, therefore, play an important role in achieving higher degrees of freedom. Additionally, the keywords "force" and "capability" indicate that aside from degrees of freedom, the prosthesis's ability to generate sufficient gripping force and have other capabilities are also areas of interest.

The approaches researchers take to develop these prostheses can be seen in the keywords in the cluster. One of the keywords is "joint". The keyword has enough occurrence to show up on the network map and shows that developing better joints for active prostheses is an area of focus in the field. Joints are as important as actuators in enabling more complex movements. Several studies included in the review specifically develop joint mechanisms. One such investigation was performed by Mohammadi et al. [233] that shows a 3D-printable, bioinspired flexure joint. The joint was made from thermoplastic polyurethane (TPU) material and printed using fused deposition modeling (FDM). The developed joint can be tuned to have different bending stiffness behaviors, allowing for a broader range of motion. The joint was tested in a soft robotic hand, enabling complex motions and the ability to grasp a wide range of objects without the need for bulky actuators or complex control systems. Although the joint was not tested by a human patient, this and other similar research can be beneficial for further applications by other researchers when designing better-moving prosthetic hands or fingers.

Additionally, in this cluster, the keywords "robotic" and "soft robotic" indicate an overlap between the fields of robotics and prostheses. The development of robotics, especially robotic arms and hands, often has use cases in prostheses. Robotic arms that can move and perform fine motor tasks could be used to replace hand functions as prostheses. Soft robotics, a more recent field, uses compliant materials rather than rigid ones. Soft robotics makes sense to be implemented in prostheses, whereas traditional robotics materials are too heavy and rigid for wearers. One study was performed by Zhou et al. [80], who designed a 3D-printed soft robotic hand. The fingers were printed from the softer thermoplastic polyurethane (TPU) material, while the palm was printed from acrylonitrile butadiene styrene (ABS), which offers more stability. The robotic hand is equipped with actuators programmed for seven grasps/gestures common for daily activities. Free transitions between gestures were programmed, allowing the hand to perform multi-stage grasps.

Another soft robotic hand was developed by Mohammadi et al. [110]. The device was also printed from TPU and features a monolithic structure with a membrane covering. The device can perform three grasp types with the capability of individual finger movement. The durability was tested with a prediction of a minimum lifetime of one year. In both cases, the application of 3D printing for the soft robotics part resulted in a lightweight device; the one by Zhou et al. weighed 313 g, and the one by Mohammadi et al. weighed only 235 g, which are both lighter than the reported average weight of 400 g for similar prostheses. Three-dimensional printing was also reported to lower the cost of prostheses with the device by Mohammadi et al., which cost around USD 200 to produce. Although promising results have been shown, work in this area primarily focuses on developing hand functions with robotics and lacks research on usability with real users. This research gap should be further explored to implement the functionality gained from robotics to help wearers in day-to-day life.

4.1.4. Cluster 4: Accessibility for Prosthesis

The fourth cluster only consists of seven keywords (“cost”, “low cost”, “activity”, “daily living”, “body”, “task”, and “open source”) and is called “Accessibility for Prosthesis”. This cluster indicates a sub-area concerned with making cost-effective prostheses for day-to-day life. The cost of prostheses is often stated to be expensive, making prosthesis accessibility a well-established challenge in the field. Inspection of the connection of the keywords “cost” and “low cost” shows connections to many other keywords in the network map. These connections suggest that cost considerations are relevant to much of the research included. Lower costs have always been an important value offered by 3D-printed prostheses, with researchers aiming to create affordable options for users. The research found in this cluster includes works that explore making cheaper working prostheses with 3D-printable material or components. Some studies explore ways to reduce the cost along the fabrication process, from 3D scanning to parameterizing measurements.

The cost of the prostheses varies depending on the type of prosthesis, the complexity, and the materials used. In several studies on passive prostheses, lower costs were reported. For example, the studies by Alturkistani et al. [29] and Alvial et al. [27] developed passive prosthetic fingers that cost around USD 20 and USD 12, respectively. Both are considered affordable compared to commercial finger prostheses that could range from USD 40 to over USD 100. Active myoelectric prostheses, which contain more components, naturally incur higher costs. Myoelectric prosthetic arm development was common in the included review, with several papers reporting the total cost of the prostheses developed. The prosthetic arm proposed by Bishay et al. [85] costs around USD 300, while the one proposed by Hussian et al. [82] costs around USD 350, and the device proposed by Kenza et al. [92] costs around USD 375. These three prostheses are similarly made and cost significantly less than commercial active prostheses, which could cost thousands of dollars.

The lower total cost of the prostheses was often reported to be highly attributed to the cheaper cost of materials. Three-dimensional printing materials like PLA and TPU are relatively affordable. However, most papers ignored the cost of 3D printers when reporting the total cost. While some individuals may already own 3D printers or have access to affordable 3D printing services, including these costs would provide a more accurate estimate for those looking to 3D print their own prostheses. The faster fabrication process can also indirectly lower costs by reducing expenses such as traveling to a clinic and taking time off work.

The keyword "open source" highlights a significant effort to improve accessibility in the field. Open-source prostheses are publicly available designs, usually in the form of 3D models, that anyone can use without legal restrictions. This means that researchers, and even the broader community, can use and develop existing prosthesis models. Several papers in this review based their designs on existing open-source models, benefiting from previous work to develop new prostheses. Alternatively, researchers can develop prostheses and release them as open source so that others can build on them. One example is the Federica Hand developed by the University of Naples "Federico II" [135]. The development of specific components, such as joints or sensors, can also be made open source, allowing future researchers to incorporate these components into their work.

Another use case can be seen in multiple papers in the literature, where researchers utilized open-source models to create prototype prostheses to house specific technologies. For example, the study by Hasan et al. [96] focused on developing an EEG control headset. An open-source prosthesis by Inmoov was printed to house and test the component. Research for developing specific components accounts for more than one-fifth of the included literature, showing a strong area of focus for researchers. Using open-source models can save researchers significant time by eliminating the need to create their own prostheses from scratch.

Popular open-source projects, from communities to individual works, are available online. One project, the InMoov arm, is a component of an open-source robot created as a personal project by Gael Langevin. In contrast, some of the most popular open-source designs—such as the Cyborg Beast hand and Phoenix hand—originate from the online community E-Nable. E-Nable offers over 40 designs for download, including hand, arm, and shoulder prostheses. These widely adopted models can serve as an excellent starting point for new researchers entering the field.

Open-source designs like those provided by communities, universities, and even individuals could play a significant role in developing these prostheses by having various developments performed by different people. Work could be shared and implemented by other researchers, creating a collaborative environment that could enhance prosthesis design. Furthermore, anyone with a 3D printer could print out open-source prostheses, making prostheses more accessible without the need to go to specialized prosthesis makers. Popular open-source models could also be parameterized to create prostheses that fit a wide range of patients. Patients with 3D CAD software skills could further modify the prostheses to their size and liking. Open-source projects could lead to more development and more prostheses in the hands of people in need.

4.2. Trends

Temporal analysis of keyword co-occurrence shows multiple keywords with more recent average occurrences, several of which will be highlighted in this section. These keywords could give an insight into the emerging trends in recent research regarding 3D printing in the prosthesis field. The six keywords highlighted are "finger joint", "soft actuator", "hand gesture", "scanner", and "algorithm". It can be observed from Figure 2, however, that the number of publications included in the review decreased after 2020. This might indicate that less scientific research is being performed in the field overall. The following trends, therefore, could highlight emerging areas that could serve as directions for future research.

4.2.1. Trend 1: Focus on Fingers

The first trend that could be indicated is the focus on fingers in prosthesis development. In addition to the keyword “finger joint”, the keywords “finger prosthesis” and “human finger” also showed more recent average publication dates in the temporal analysis, suggesting an emerging popularity of finger prostheses or the incorporation of fingers in hand prostheses in research publications. However, the presence of the keyword “finger joint” implies that the research is not solely focused on replacing fingers but also on developing finger movement in prosthetic hands. As previously discussed, joints (usually at the fingers) are essential for making a prosthesis with a greater range of motion. A recent study by Attaoui et al. [213] illustrates this focus, demonstrating a robotic hand with high grasping capabilities developed through a tendon-driven mechanism that precisely controls finger joints. Studies like this could drive further development in the future as researchers aim to create prostheses with improved degrees of freedom through enhanced finger joints.

4.2.2. Trend 2: Advancement of Control Systems

The second trend that could be indicated is the continued development of control systems and pattern recognition systems, as suggested by the keywords "hand gesture" and “algorithm”. Hand gestures in prostheses are important for creating different positions for gripping. Developing finer hand gestures and control would improve a prosthesis’s ability to perform more hand functions. However, advanced control systems require good pattern recognition systems to command gestures based on the control signals used. Machine learning algorithms are often utilized to analyze signals and recognize patterns. The study by Zhou et al. [80] shows the development of a 3D-printed soft robotic hand that is capable of directly transitioning between hand gestures, improving grasping variety and capability. This was made possible through the development of better control system that utilized embedded soft sensors. A more recent study by Zhou et al. [287] developed a human–machine interface using force myography that can be used for prosthesis control systems, using machine learning algorithm to process the signals from pressure sensors. This trend aligns with the previously discussed second cluster, “Prosthesis Control and Sensing Technologies”, and shows promises for further advancement in control systems for prostheses.

4.2.3. Trend 3: The Rise of 3D Scanning

The third trend indicated is the increasing use of 3D scanners in the field. The keywords “scanner” and “3D scanning” have more recent average publication dates, suggesting that an increasing amount of research on upper limb prostheses incorporates 3D scanning. In recent years, the prices of commercial 3D scanners have dropped significantly, with models available for under USD 1000 on e-commerce sites. These scanners are also now being adopted in local clinics, making them more accessible to a wider range of patients and prosthesis makers. The utilization of 3D scanning has already been discussed in the first cluster, and this trend suggests that utilization will continue to grow in the future.

4.3. Limitations and Implications of Work

This study faced several limitations. Although the review was conducted using various databases and literature sources to be as comprehensive as possible, some potentially relevant research was inaccessible to the authors. Furthermore, the review did not cover proprietary technologies developed by private companies, meaning that novel innovations, which are often better supported and published, might have been missed. Additionally, only studies in English were included, thereby excluding localized studies in other languages. Finally, open-source prostheses and the community that develops, makes, and uses them outside the formal research scope did not appear in the literature search. The study was also conducted with a time gap between the search and the writing of the discussion, which may have resulted in newer research being excluded. Moreover, the review was carried out by multiple reviewers with varying thought processes and potential biases, although every effort was made to remain as objective as possible.

This study carries several implications for future research and applications in the field. As intended, the review provides an overview of the current landscape in making upper limb prostheses using 3D printing and scanning techniques, highlighting four cluster themes and three recent trends. Further development addressing challenges in key areas, such as designing and evaluating suitable prostheses for patients, achieving finer control, developing higher degrees of freedom, and improving accessibility, is anticipated. Emerging technologies like soft robotics and new sensors require additional research, particularly in applying these technologies to prostheses that people use every day. This overview can serve as a foundation for upcoming researchers. The identified key areas and trends may help pinpoint gaps or intriguing topics for further investigation. Lastly, this review demonstrates that the development of 3D printing and scanning techniques for creating upper limb prostheses has achieved notable success, enabling healthcare professionals and the general public to be informed about the latest technologies available.

5. Conclusions

This study conducted a scoping review following the PRISMA-ScR guidelines on the use of 3D printing and scanning techniques in the fabrication of external upper limb prostheses. A total of 274 documents from journals, conferences, and gray literature were analyzed both bibliometrically and qualitatively. The review demonstrated a broad interest in the topic, with many researchers using these techniques to develop upper limb prostheses. Keyword co-occurrence analysis was performed and visualized with a network map, revealing clusters of related terms. Four themes were identified from these clusters: Prosthesis Design and Evaluation for People; Prosthesis Control and Sensing Technologies; Robotics and Mechanical Design; and Accessibility for Prostheses. These themes represent the key areas of interest in the field, each facing its own set of challenges. Temporal analysis indicates a decrease in overall research activity; however, three trends emerged: a focus on fingers, advancements in control systems, and the growing use of 3D scanning. Further developments in these areas are needed to achieve higher degrees of freedom, finer control, and more affordable prostheses. Overall, the utilization of 3D printing and scanning techniques shows promise by enabling rapid prototyping, which accelerates development and reduces costs. The continued adoption of these techniques is expected to enhance the quality of upper limb prostheses, making them more affordable and quicker to produce, ultimately benefiting the millions of people who need these devices.

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