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REVIEW

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Methods to assess lower limb prosthetic adaptation: a systematic review

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Abstract

Background Lower limb amputation is a disabling condition with serious psychological, physical, and functional consequences. The adaptation of a prosthetic device can either mitigate or exacerbate these effects. Although many individuals receive lower limb prostheses, rejection rates remain high. Furthermore, while numerous objective and quantitative methods are available to assess the interface between the residual limb and the prosthetic socket, as well as the device performance, prosthetic fitting largely relies on prosthetists' observation and expertise. Accordingly, this review describes the most commonly employed methods for evaluating prosthetic fitting, emphasizing frequently used combinations of tools, devices, procedures, and tests for characterizing residual limbs and clinical outcomes, which indirectly contribute to prosthetic fitting evaluation.

Main body In July 2023, searches were conducted across the Taylor & Francis, SpringerLink, Sage, ScienceDirect, and Scopus databases, focusing on research papers, case reports, and technical briefs published between 2011 and 2023. Studies were selected by four reviewers, and any discrepancies were resolved through group discussions. The Rayyan tool was employed to ensure that the retrieved publications evaluated residual limb variables involved in prosthetic fitting. The predominant methods for assessing lower-limb prosthetic fitting include mobility evaluation, gait analysis, measurement of physical variables, and stability assessment. Functional tests and self-report questionnaires, which do not require specialized equipment or great expertise, are the most widely utilized techniques.

Conclusions The results demonstrate that, within clinical practice, mobility evaluation is the primary predictor of prosthetic fitting. Since methodologies for measuring more specific variables are often restricted to laboratory settings, future studies should analyze factors that could enable their implementation in clinical contexts.

Keywords prosthetic fitting, assessment of persons with amputation, lower limb, residual lower limb, evaluation of the stump

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Background

Persons with amputations require prosthetic devices that restore as much functionality and independence as possible while providing comfort and safety at the socket interface [1]. Among amputations, those of the lower limbs are the most prevalent [2] and have a dramatic physical, functional, and emotional impact [3], thereby compromising the quality of life of many individuals worldwide [4, 5].

Despite recent advancements in prosthetic technology, many individuals with amputations still reject or express dissatisfaction with their prostheses [6–10]. Although 49–95% of persons with lower-limb amputation use a prosthesis [11], estimates suggest that up to 50% do not wear it regularly [7]. Additionally, 40–60% report dissatisfaction, and over 50% claim to feel pain during use—issues often associated with poor prosthetic fitting [8]. A comfortable and functional prosthesis reduces the likelihood of rejection or abandonment [8, 12, 13]; therefore, special attention should be paid to prosthesis design and the factors influencing fitting [6, 7].

The team in charge of prescribing, fabricating, and adapting prostheses are also responsible for the fitting process. This clinical practice is grounded in years of empirical evidence and relies largely on practitioners' expertise, clinical judgment, and feedback from users during follow-up assessments [7]. In this process, prosthetists and clinicians employ various tools, methodologies, and tests to assess outcomes related to prosthetic adaptation.

Some studies have investigated prosthetic device adjustment, consistently concluding that there is considerable variability in the tools and methods used for fitting these devices. However, most studies have focused only on subjective clinical tools, such as questionnaires, functional tests, or quantitative assessments conducted in laboratory environments using specialized devices [6, 8, 14]. Therefore, this systematic review aims to present the most common combinations of tools, devices, methodologies, and tests used in residual limb assessment that indirectly relate to prosthetic fitting evaluation, independent of factors like comorbidities, age, amputation cause, or specific methodology applications.

Methods

This systematic review follows the PRISMA guidelines and reports the required information accordingly (see Supplementary Checklist). Rayyan, an AI-powered collaborative platform, was used to screen and select studies. Research papers, case reports, and technical briefs published in English or Spanish between January 1, 2011, and July 7, 2023, were retrieved from five databases: Taylor & Francis, SpringerLink, Sage, ScienceDirect, and Scopus. The following search string was employed: (("assessment" OR "evaluation") AND ("prosthetic fitting" OR "prosthetic adaptation") AND (("lower Limb" OR "residual limb") AND NOT (upper AND limb))).

Article screening and selection

Research papers, case reports, and technical briefs published in English or Spanish between 2011 and 2023 were considered. Materials were retrieved from five databases: Taylor & Francis, SpringerLink, Sage, ScienceDirect, and Scopus. Only papers that reported measurements of the residual limb or variables related to prosthetic adaptation were selected for inclusion. Conversely, the review excluded studies that: (1) did not assess any residual limb variable; (2) did not report data on prosthetic fitting; (3) focused on clinical aspects, such as diagnosis and treatment protocols; surgical aspects, including techniques and outcomes; or psychological aspects, like patient wellbeing and therapy effectiveness; (4) analyzed osseointegrated prostheses; (5) validated the translation of clinical questionnaires; or (6) addressed pediatric disarticulations or bilateral amputations.

A blind review was performed by four reviewers in two stages to minimize bias, as reviewers were unaware of each other's decisions. In the first stage, they reviewed the titles and abstracts of all retrieved papers to identify those meeting the inclusion criteria. In the second stage, if the decision to include a document was not unanimous, the full text was analyzed.

Data extraction and critical appraisal

All papers included in this review were equally distributed among the four reviewers, who entered relevant information into an Excel spreadsheet. Recorded information included key data such as title, author(s), year of publication, amputation level and cause, study setting, main variable measured, methodology and tools used, significant findings, future research recommendations, and study limitations. This information was then analyzed in group discussions to consolidate the results. From this analysis, three main categories were established: (1) Variables analyzed in each study, (2) Instruments employed, and (3) Conclusions regarding each variable and instrument.

Results

The literature search described above yielded 181 publications. Figure 1 shows a PRISMA flow diagram that summarizes the selection process, which ultimately led to the inclusion of 48 documents focused on residual limb measurements related to prosthetic fitting (See Supplementary Material - Article Review Table). These publications addressed various factors associated with prosthetic fitting at the socket–residual limb interface from several perspectives across clinical and laboratory settings.

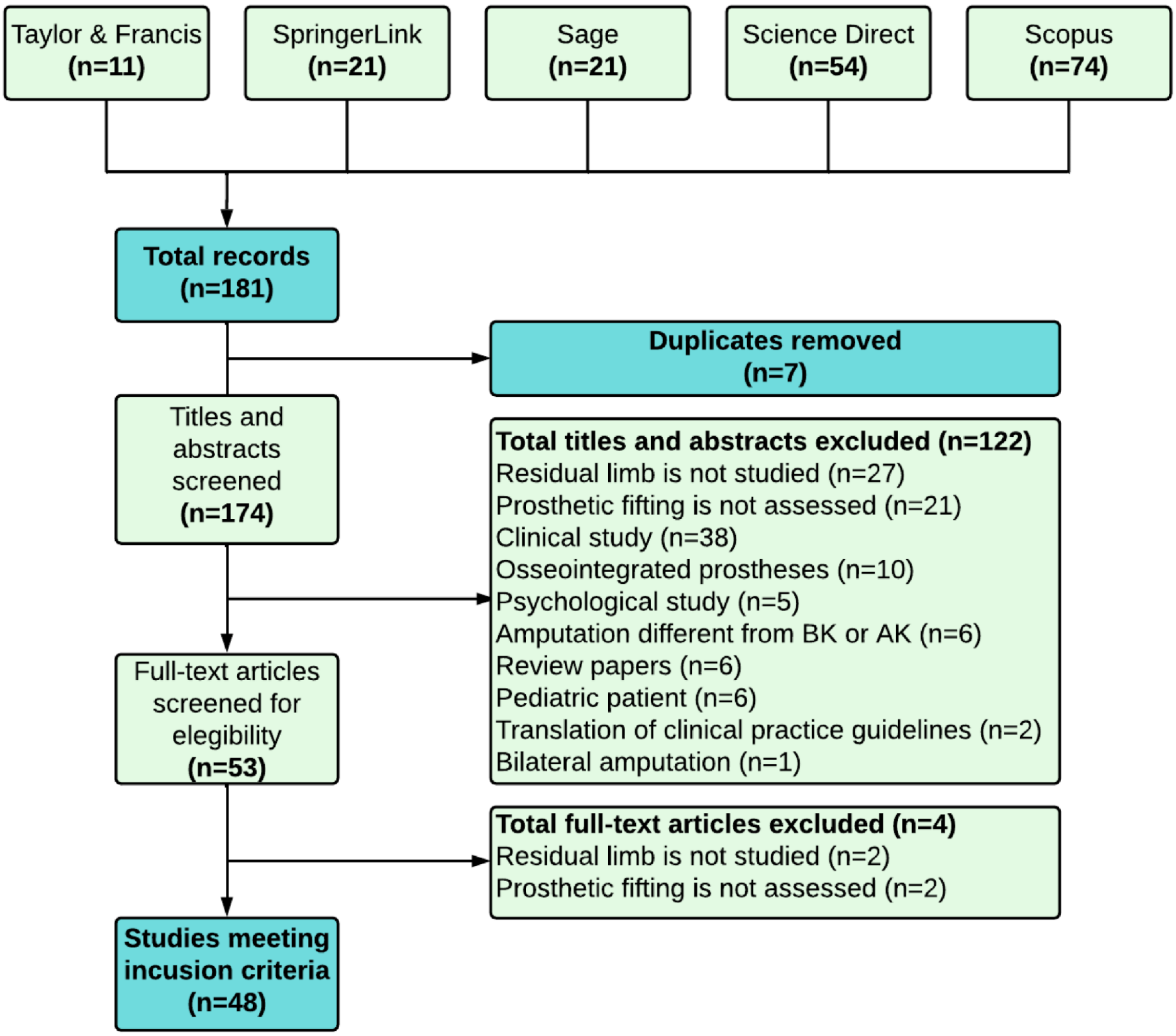

Fig. 1 PRISMA flow diagram summarizing the literature search, screening, and selection process

Figure 2 is a Sankey diagram illustrating the most frequently analyzed variables in studies on prosthetic fitting. The width of each link in the diagram reflects the strength of the connection between nodes. The following are the most significant connections of these variables with the instruments employed to measure them: Mobility [12, 15–32] with functional tests and questionnaires; Kinetics [20, 22, 33–44] with motion capture systems and functional tests; Physical values [22, 26, 28, 38, 42, 45–52] with specialized equipment and sensors; Prosthesis use [16, 23, 24, 26, 29, 31, 42, 50, 53, 54] with questionnaires; Kinetics related to gait [20, 33, 35, 39, 43, 44, 52, 55, 56] with instrumented surfaces; Postural stability [12, 19, 31, 43, 44, 57] with functional tests; and Prosthetic alignment [58, 59] with alignment-specific tools.

After analyzing these variables with the instruments listed above, the authors of the selected studies reported findings related to kinematic and kinetic aspects of walking, amputation and residual limb characteristics, tool and device validation, prosthetic components, functional abilities, prosthetic alignment, and user satisfaction.

As shown in Fig. 3, mobility-related predictors of prosthetic adaptation most commonly include functional capacity [12, 16, 17, 19, 22, 24–26, 28, 29] and functionality with the prosthesis [15, 18, 20, 21, 23, 27, 30–32], accounting for 21.6% of the variables analyzed. Velocity [22, 33–37, 41] is the most frequently reported kinematic variable, representing 29.2% of all measurements. Among physical variables, volume is the most commonly analyzed, accounting for 46.1% of the observations [26, 42, 45–47, 49], followed by distance [28, 48–50], pressure

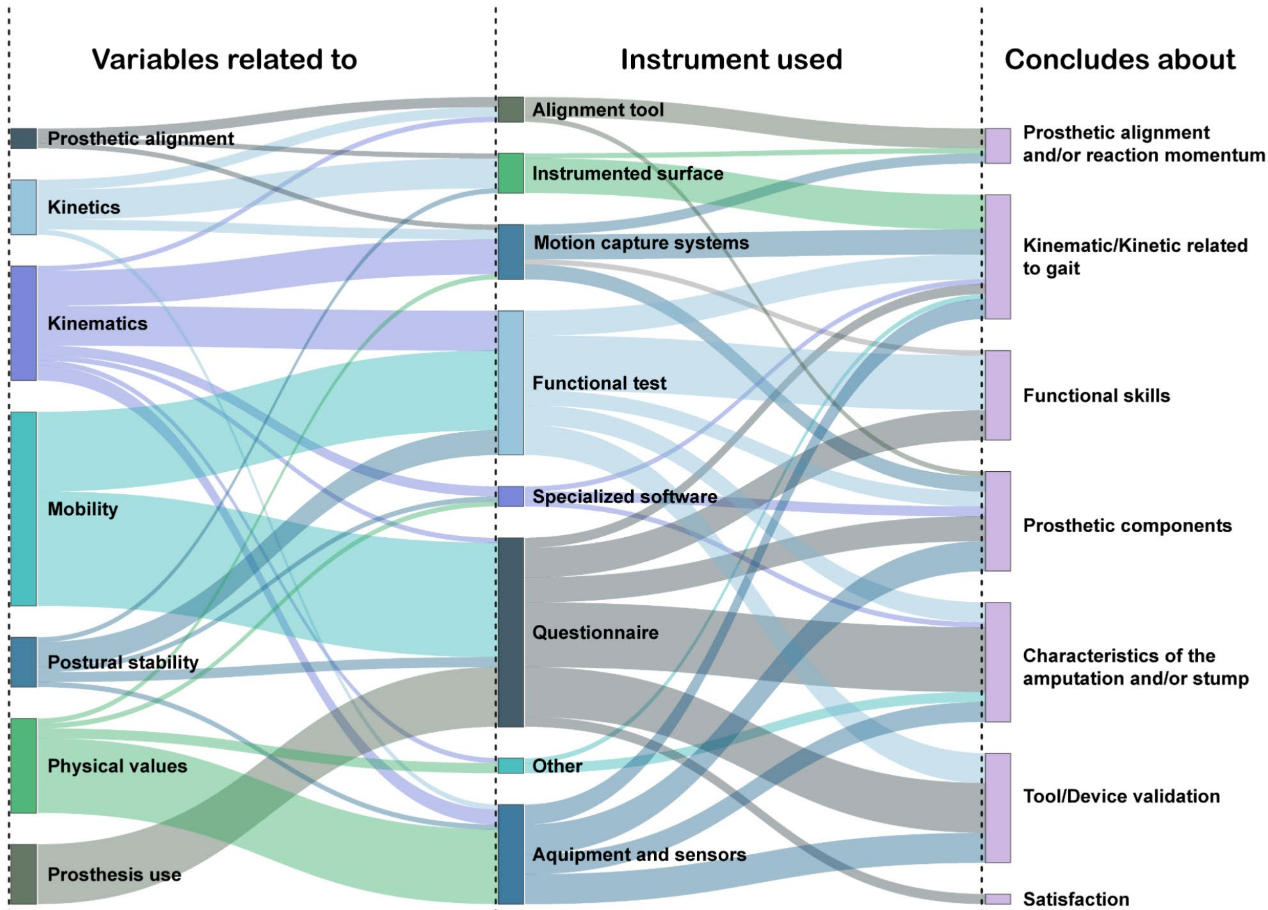

Fig. 2 Combinations of [1] prosthesis fitting variables [2], instruments, and [3] conclusions in the selected studies. Link width indicates the number of studies addressing each combination

[22, 38, 52], and temperature [38], collectively representing another 46.1%.

The primary kinetic variables identified include ground reaction forces [20, 35, 55], which represent 38.5% of observations, and angular momentum [33, 39, 44], accounting for 30.8%. Among prosthesis use variables, adaptation and fit [16, 31, 54] are the most frequently evaluated, making up 61.5%, while comfort [26, 29, 50] represents 23.1%. To a lesser extent, balance [12, 31, 57] is reported among postural stability variables, accounting for 37.5%. Finally, factors related to prosthetic alignment are also examined in a few studies [58, 59].

The variables mentioned above have been assessed using specialized devices and software. Figure 4 presents a treemap chart showing that questionnaires and functional tests are the most popular instruments (57.8%), followed by equipment and sensors (16.9%), motion capture systems (9.3%), instrumented surfaces (6.8%), alignment tools (4.2%), and specialized software (3.4%).

The Prosthesis Evaluation Questionnaire (PEQ) [22, 24–26, 28, 29, 32, 45] is the most commonly used questionnaire (21.0%), followed by the Trinity Amputation and Prosthesis Experience Scales (TAPES, 15.8%) [23, 24, 26, 31, 42, 54], the Houghton Scale (HS, 13.1%) [12, 15, 16, 23, 32], and the Activities-Specific Balance Confidence (ABC) scale (7.9%) [19, 27, 44]. Regarding functional tests, the Two-Minute Walk Test (2MWT) and its variations [12, 18, 19, 25, 29, 32, 38, 41, 44] are the most widely applied (34.5%), followed by the Timed Up and Go (TUG) test (24.1%) [12, 16–19, 27].

Specialized devices include 3D scanners [42, 45, 47, 49], pressure sensors [22, 38, 52], videogrammetry- and accelerometry-based motion capture systems [20, 22, 28, 33, 35, 36, 38, 40, 42–44, 52, 55, 56, 59] complemented with force platforms [20, 35, 43, 44, 55–57, 59], and devices for measuring postural stability [12, 19, 31, 43, 44, 57] and prosthetic alignment [58, 59]. In addition, specialized software has been used to edit and process videos and images, allowing for the quantification of specific variables of interest [36, 47, 57].

The studies cited above reported limitations in terms of sample characteristics, including size [22, 23, 27, 28, 33–35, 37, 39, 42, 45, 51], heterogeneity [12, 17–19, 24, 31, 36, 41, 54, 59], non-randomization [58, 60], and potential

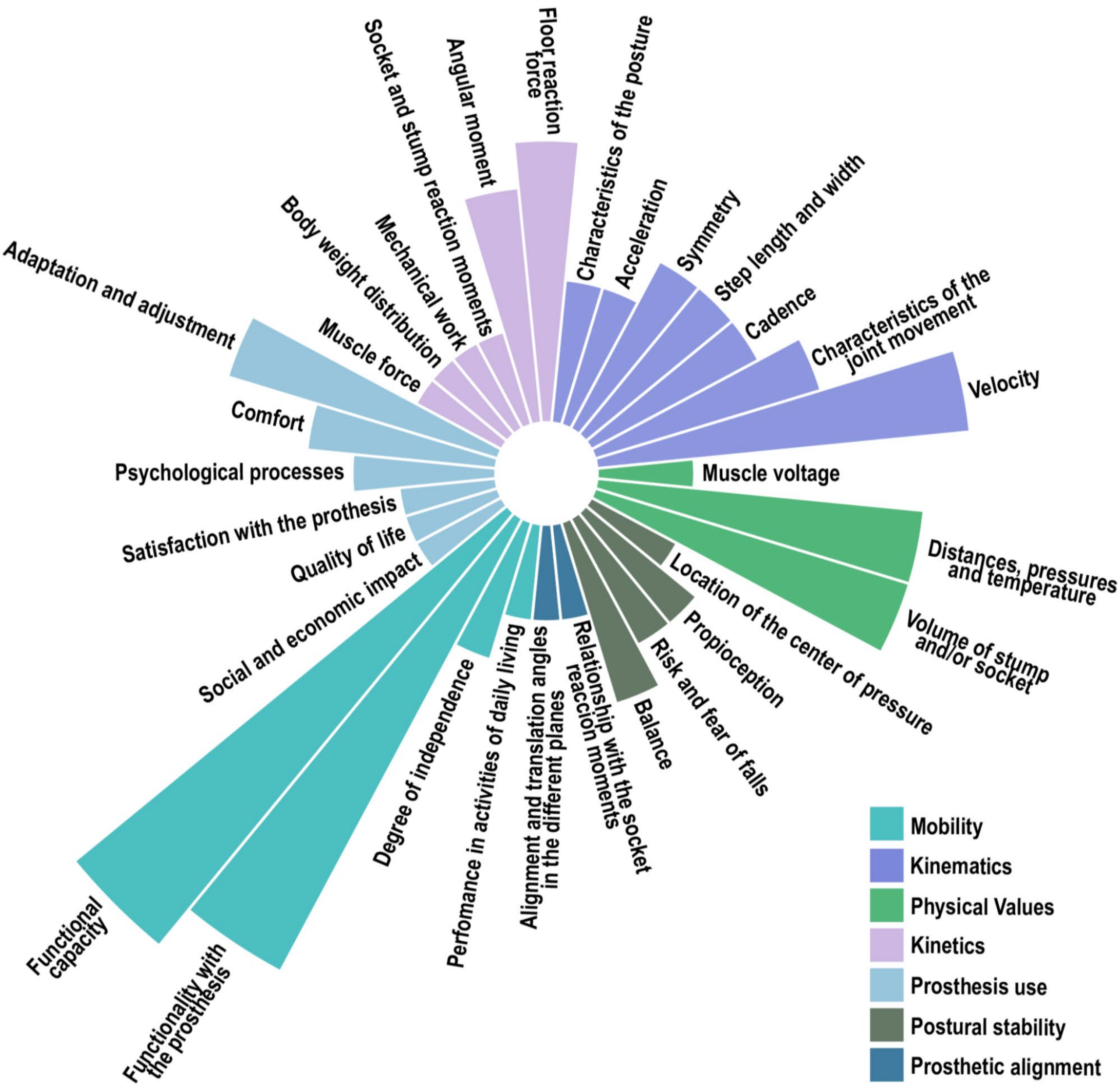

Fig. 3 Classification of parameters found in the selected documents by type of variable

biases [29, 46]. Moreover, limitations were encountered in data collection methods [15, 16, 29, 33, 38, 48, 50–52] and experimental design issues [17, 21, 22, 26, 28–31, 34, 38, 39, 43–45, 47, 49, 53–58]. Future studies should address these barriers and focus on areas such as reducing reliance on prosthetist expertise [33, 60, 61], enhancing understanding of prosthetic biomechanics [20, 33, 35, 43, 58, 59], improving stability for prosthetic users [44, 55, 57], and increasing the reliability of measurement instruments or tools [15, 21, 28, 30, 39, 40, 45, 48, 52, 53].

Discussion

Multiple tools have been employed to assess ambulation, functionality, and other patient-centered outcomes in individuals with prosthetic devices. Mobility evaluation remains the primary predictor of physical adaptation, often surpassing other methodologies that assess residual limb characteristics [46]. Ensuring the validity and reliability of these tools is crucial to ensure accurate measurements, consistent results, and enhanced patient safety, which ultimately contributes to improved functional outcomes and quality of life. Furthermore, reliable tools receive greater acceptance within the scientific

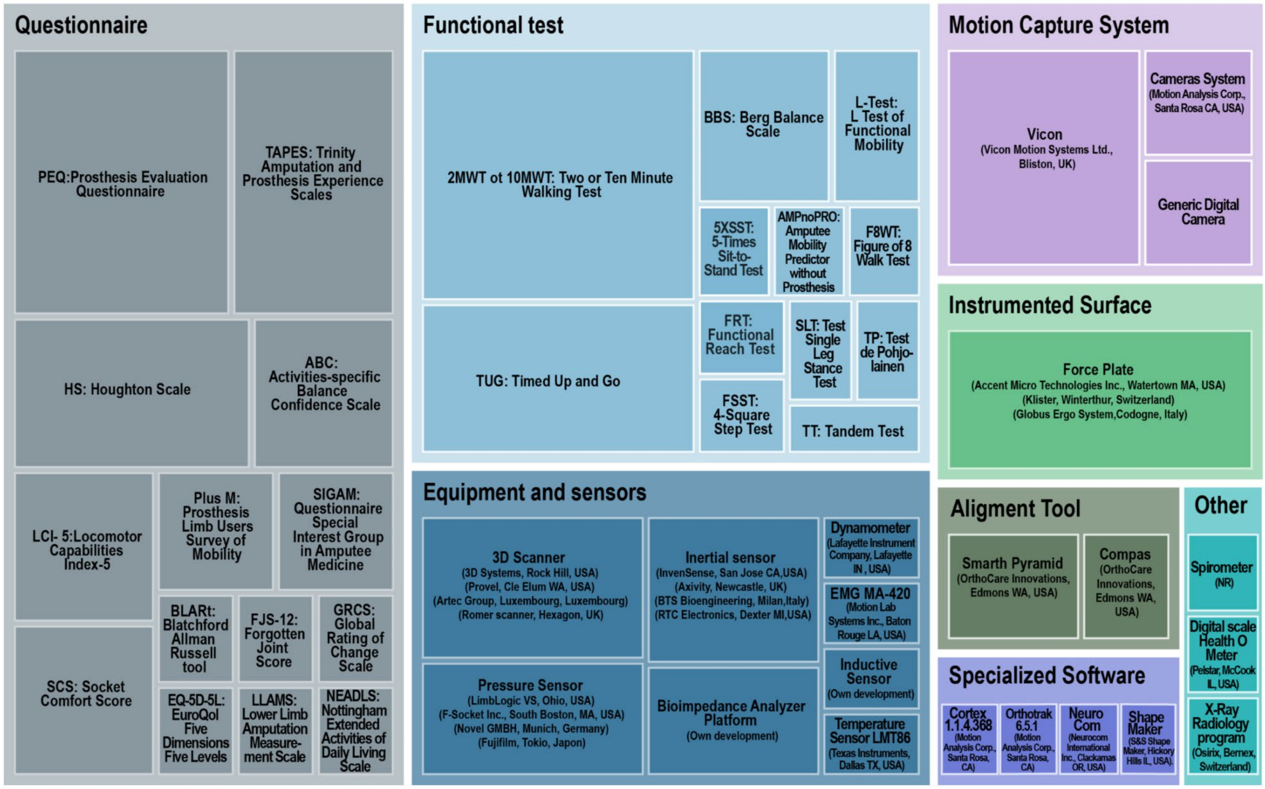

Fig. 4 Tools used in the selected studies. Rectangle size indicates the number of studies that employed each tool

community, facilitating their adoption in clinical practice [62].

Self-report questionnaires provide valuable qualitative insights into user experience and satisfaction, indirectly assessing prosthetic fitting. While they are cost-effective and straightforward to administer, their subjective nature may introduce bias and fail to capture all factors affecting prosthetic use. Similarly, functional tests offer a practical approach for mobility assessment in clinical settings without requiring advanced equipment or specialized training. However, these tests might not comprehensively evaluate all dimensions of prosthetic performance and may be influenced by external factors like fatigue or motivation [12, 63].

Many evaluation tools have not been specifically designed for prosthetic users. Rather, they are adaptations of tests originally intended for other mobility-related health conditions [10]. This adaptation can limit the accuracy of prosthetic fitting assessments, making them heavily reliant on prosthetists' expertise and user feedback [8, 64, 65]. Conversely, advanced tools such as gait analysis cameras, instrumented platforms, 3D scanners, alignment systems, and accelerometers offer precise measurements. However, their use is typically restricted to laboratory settings due to high costs and the need for trained personnel [66]. These limitations, along with reduced sample sizes, underscore the importance of integrating advanced tools into clinical environments to optimize the fitting process. Future studies should involve larger participant groups to address this need [67].

Quantitative measurements, such as those obtained from motion capture systems or pressure sensors, often require expensive specialized equipment, creating financial barriers for many facilities [68]. To overcome these challenges, experimental designs could benefit from incorporating doubled-barrelled tools—such as combining questionnaires, functional tests, and objective measurements—tailored to the study's scope.

Conclusions

This review highlights that, while mobility evaluation remains the most common predictor of adaptation to prosthetic devices, functional tests and self-report questionnaires, though widely used, have limitations due to their subjective nature. Furthermore, many assessment tools are not tailored for prosthetic users, which may affect their accuracy.

To improve prosthetic fitting evaluations, future research should integrate doubled-barrelled measures and advanced technologies within clinical settings. As these tools become more accessible, clinical staff training will be essential for standardizing the fitting process and improving outcomes for individuals with lower-limb amputations. A comprehensive approach that combines various assessment methods will be crucial to gain a deeper understanding and enhancing prosthetic adaptation.

Limitations

This systematic review was limited by the number of studies included. Many publications were excluded due to the lack of information on prosthetic fitting, and papers addressing partial foot amputations, disarticulations, or bilateral amputations were not considered. Consequently, these findings should not be generalized to individuals with these amputation characteristics. Likewise, as studies written in languages other than English and Spanish were not analyzed, potentially relevant publications may have been left out.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-024-01530-7.

Supplementary Material 1

Supplementary Material 2

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Author contributions

All authors searched the documents in scientific databases. NOM and MGH created the document database on the Rayyan platform for subsequent review and created the graphs included in this document. All authors reviewed the papers for the inclusion decision, performed the data analysis, interpreted the results, and wrote and approved the final manuscript.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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