REVIEW ARTICLE

The Convergence of Artificial Intelligence, Digital Therapeutics, and Biomedical Electronics in the field of Speech-Language Therapy

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Abstract

Speech-language therapy (SLT) has traditionally relied on the art of human expertise and manual, traditional therapeutic techniques. Recent developments in artificial intelligence (AI), digital therapeutics, and biomedical electronics have changed this landscape. This paper reviews how all these technologies are combined, focusing on their current applications, potential benefits, and future directions in speech-language therapy. AI applications in speech recognition and natural language processing provide evaluations and treatment tailored to the needs of the patients. Digital therapeutics, such as applications and online platforms, complement these traditional techniques with interactive exercises and real-time feedback. Biomedical electronics like biofeedback, wearable devices, and brain-computer interfaces have offered novel solutions in diagnostics and therapy. Improvements like these have raised patient outcomes and access to therapy, thus enabling data-driven therapy plans. Many ethical concerns, especially regarding the accuracy of the AI models and technology integration into the clinic, are of high priority. These barriers can be overcome in further research to benefit SLT from these technologies.

Keywords

Artificial Intelligence, Brain-Computer Interface, Digital Therapeutics, Speech-language Therapy.

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Introduction

Speech-language therapy (SLT) is an essential area of study for diagnosing and treating speech disorders that might profoundly affect individuals experiencing trouble with language or speech[1-2]. The disorders are represented by speech sound, language, voice, and fluency difficulties. They all refer to all ages—from little children with developmental delays to adults with neurological insults like stroke[2]. Effective SLT is crucial in enabling people to achieve their full potential for communication, underpinning personal, educational, and occupational success, as communication is a fundamental human enterprise. Addressing those kinds of disorders thus improves individual outcomes and interpersonal and community integration. SLT thus enables the opening for fully active participation of different persons with different abilities, enhancing well-being in society as a whole.

It is expected to strengthen the research work in this subject field, as it is the driver of innovations of landmark diagnostic and therapeutic methodologies[3-4]. Over the last couple of years, impressive improvements have made this field a much more feasible business avenue, particularly in artificial intelligence and machine learning. This technology holds high hopes for advancing the diagnosis and treatment of speech and language disorders to be more user-friendly, accessible, and tailored to specific needs[5]. Additionally, current work is refining existing methodologies and approaches, focusing on interventions based on current evidence and best practice guidelines available[6-7]. Continuous work and clinical application help improve therapy outcomes and contribute to our understanding of human communication and its disorders. SLT and research promote health, education, and social participation for individuals with developmental delays or neurogenic diseases (Figure 1).

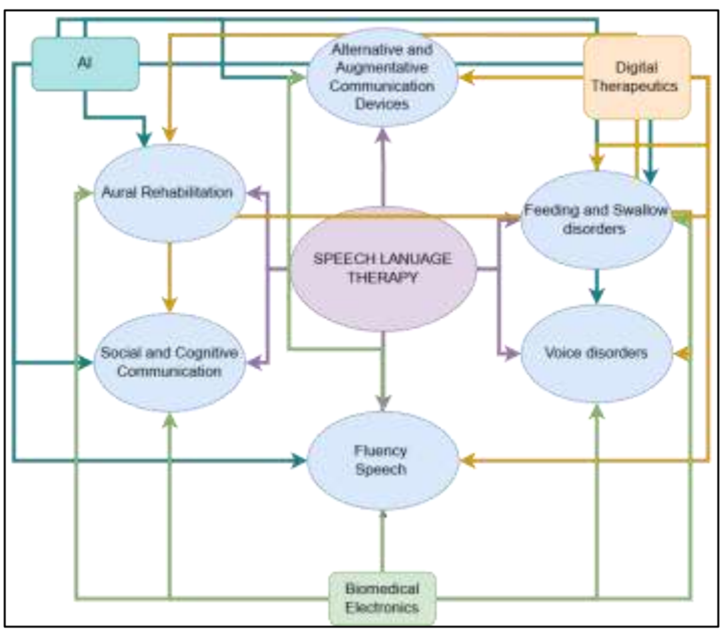

Figure-1 Applications of AI, Digital therapeutics, and Biomedical Electronics in various areas of Speech-Language Pathology

Previously, there has been a lack of research on the frequency of onset of speech and language disorders due to the complex nature of the disease[8-9]. However, in recent years, there has been significant technological advancement in SLT and a surge in research studies. For example, in the United States, 7.7% of all children had a communication disorder in 2012. Among these, 5.0% suffered from speech disorders, while swallowing disorders were the least common, affecting 0.9% of all children[10]. The situation is particularly concerning for Pakistan, as there are no recent statistics available for the prevalence of speech-language impairment, and there is a shortage of therapists and facilities[11]. This underscores the need to explore digital solutions. Digital therapeutics, artificial intelligence (AI), and biomedical electronics are emerging as potential tools to improve diagnostic accuracy, treatment effectiveness, and patient engagement in SLT[12]. This review aims to summarize these developments and discuss their implications, as well as outline future research directions.

Artificial Intelligence in Speech-Language Therapy

AI is used in SLT for automatic assessment, personal therapy, and predictive analytics. Garcia et al.[13] provided a comprehensive review of the role of AI in speech processing for Alzheimer's Disease (AD) monitoring. They noted that AD is closely associated with severe language impairment, a symptom that has not been extensively studied for diagnostics due to its correlation with neurodegeneration. The review summarized the latest findings and described the current methodologies in the research, including limitations and proposed strategies to address these challenges. The authors conducted a systematic review covering the period from 2000 to 2019, searching six databases and identifying 51 articles meeting their eligibility criteria. They analyzed the studies in four main areas: study details, data details, methodology, and clinical applicability. The results indicated that AI shows promise in using speech data to predict cognitive decline, but only some of these methods have been implemented in clinical settings. Notable limitations include poor standardization, low comparability of results, and a gap between research goals and clinical applications. The authors emphasized the need to standardize methodologies and bridge the gap between research and clinical practice to enable the translation of these technologies into tools for AD monitoring in practice.

Duffy[14] outlined the future landscape for Musculoskeletal Disorders (MSD) research and practice. The author stated that the current understanding, assessment, and treatment of MSDs were expected to undergo an evolutionary development of thought and practice rather than a revolutionary change. The author made critical predictions about an increasing understanding of the genetic and neurological basis of MSDs and the potential impact of this on more precise diagnosis and therapeutics. The paper emphasized the necessity of developing a differential diagnosis within the medical community, especially for cases where an MSD could be the first indication of neurodegenerative diseases. Also highlighted were the role of technological advancements, telepractice, data management, and online libraries of speech samples for clinical practice and research. The author also discussed the potential for more widespread and effective use of perceptual and acoustic measures in diagnosing and managing MSDs. While auditory perceptual analysis is predominant, with reliability issues, a more comprehensive inclusion of acoustic and physiological measures to enhance clinical measures could be expected. The paper also mentioned the likely development of treatments, mainly through a clearer understanding of diseases such as primary progressive apraxia of speech and the need for consensus criteria to diagnose different types of MSDs.

Further, the author has commented on the applicability of these developments from a larger perspective like the changes in the healthcare system and continuous technological developments will significantly impact the field. Disorders like dysphonia are widespread but are neglected. Mobile healthcare systems may be expected to tackle this by giving fast and effortless support to diagnose voice disorders. Rehman et al.[15] developed an algorithm that allowed the reliable classification of healthy and pathological voices using the majority of voice databases through many datasets, such as the Saarbruecken Voice Database, Massachusetts Eye and Ear Infirmary database, and private datasets, with machine learning models for voice analysis. The authors used many datasets, like the Saarbruecken Voice Database, the Massachusetts Eye and Ear Infirmary database, and private datasets. They applied machine learning algorithms, including decision trees, random forests, and support vector machines, to determine the best accuracy in detecting voice disorder. In this respect, using the SVM algorithm with the appropriate method of selecting features was reported to be the most accurate in voice disorder detection. This model can distinguish efficiently between healthy voices and several pathologies like dysphonia, vocal fold granuloma, and functional dysphonia, among others. Deka et al.[16] conducted a systematic review of AI-based automated tools for offering help in speech therapy for Speech Sound Disorders. The importance of automated tools is highlighted, especially after COVID-19 pointed out the need for accessible and affordable speech therapy solutions. The review presented four primary research questions:

- **The type of Somatic Symptom Disorders (SSDs) being treated under AI tool use**
- **The autonomy level of such tools in terms of the intervention modes characterized their effectiveness compared to traditional speech therapy provided by SLPs.**

The paper covered four main areas: types of SSDs, autonomy levels, intervention methods, and effectiveness. The most common SSDs addressed were articulation disorders, but the tools also targeted hearing impairments, dysarthria, and motor speech disorders. Many AI-based tools were fully automated and did not involve therapists, caregivers, or parents. However, this raised concerns about data bias, privacy, and the potential to replace speech-language pathologists (SLPs). The most common intervention involved using mobile or computer applications, software, or programs with gamified or storytelling features, primarily aimed at children for motivation. Few studies have compared the effectiveness of AI intervention to traditional speech therapy. AI can potentially be a valuable supplement to speech therapy due to its high compatibility with SLPs. The paper also suggested future research directions such as tools for underrepresented languages, specific SSD design, involving stakeholders in the design process, and usability studies. The study by Lin et al.[17] highlighted the use of digital learning in medical fields, specifically in speech-language pathology (SLP), phoniatrics, and otolaryngology. The research showed that these digital learning formats comprised interactive modules, video lectures, and virtual simulations. According to the analysis, various advantages of such a course include increased access, flexibility in the learning schedule, and the possibility for standardization of education across different locations. However, challenges in controlling the quality and relevance, integrating the existing curriculum, and technical barriers were also identified. The study pointed out that inter-professional collaboration was a precondition for achieving comprehensive educational and practice-relevant results in developing and managing digital learning resources. In summary, the study indicates that digital learning has enormous potential to improve the education and training of SLP, phoniatrics, and otolaryngology professionals.

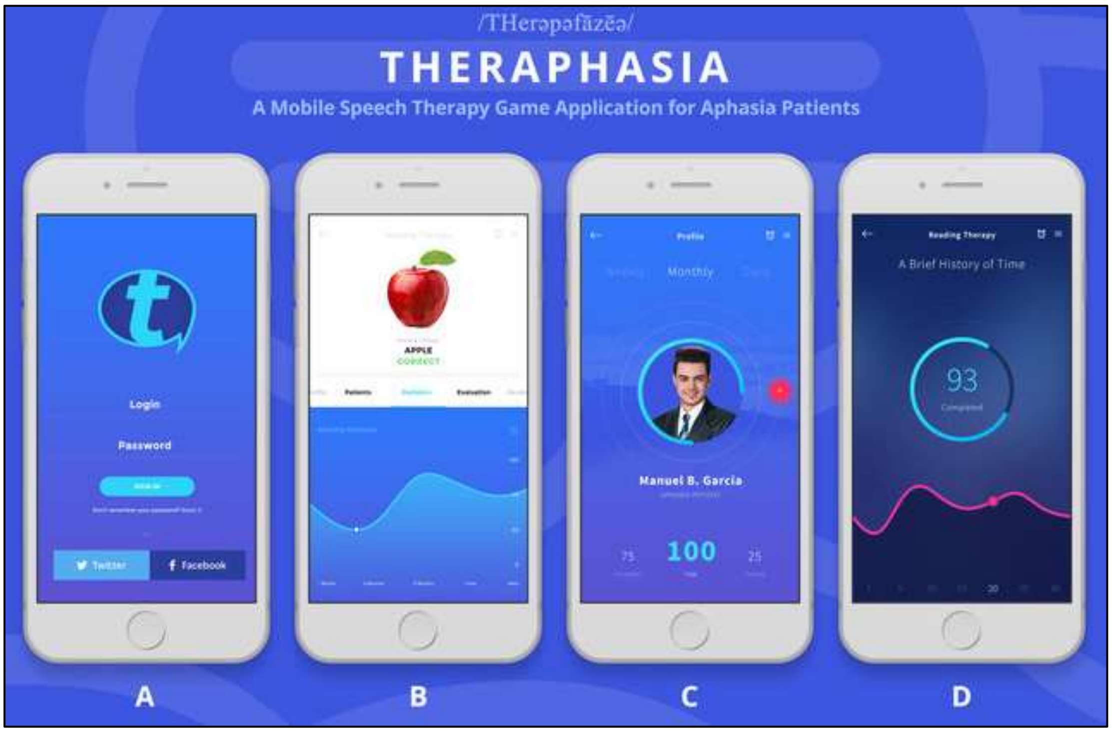

Figure-2 A visual representation of speech therapy game tool for Aphasia patients (Developed by Gracia et al.[18])

Pierce et al.[19] explored the clinical utility of AI-created images within speech pathology to assess and intervene in aphasias. Aphasias are language disorders emanating from brain damage, generally resulting from stroke, often causing impairments in understanding, reading, writing, and speaking. This pilot study examined if AI-created images could be used to create individualized therapy materials to enhance treatment efficiency and flexibility for individuals with aphasias[20]. It has been shown that AI technologies can create context-relevant images for treatment use. That means integrating AI tools into speech pathology may negate some of the limitations found in traditional methods and provide flexible, adaptive resources for clinicians and patients.

- ***Applications***

It is revolutionizing SLP with the help of high-ended applications that assist in diagnosis and treatment. One such critical application is the Automated Speech Recognition (ASR) System, which transcribes and analyzes speech and objectively describes speech and language disorders. This technology provides exact and consistent analysis, thereby reducing subjectivity in human analysis. Natural Language Processing (NLP) algorithms enhance the capabilities of AI in analyzing the use of language for diagnosing disorders and tailoring treatment syntax, semantics, and pragmatics. Machine Learning models predict the outcome of therapy and individualize interventions based on patient data, proposing real-life therapeutic approaches that could be applied in each case. These applications enable speech and language therapy to be reshaped into much more accurate, individual, and successful fields. The advantages of AI in speech and language therapy are:

- **Consistent and objective assessment.**
- **Personalized therapeutic plans.**
- **Data-driven treatment planning in decision-making.**
- **Design of individualized materials for users who have a variety of speech and language disorders.**

- ***The Challenges***

It places great emphasis on the need for high standards in developing standardization and integration of AI and speech processing about their application in a clinical setting. However, AI's application in SLP challenges fairness and ethical justification. Ensuring that models of AI are fair and effective remains one major challenge. For example, the training data should be diverse enough not to produce biased results when dealing with understudied populations. Another challenge is bringing AI technologies into the workflow of medical practices. There is a need for intuitive and easy-to-use tools that offer real value to the services provided by SLPs, not at the cost of extensive retraining. Other ethical concerns related to protecting patient privacy and transparency of AI decisions must be considered if trust is to be developed and high professional standards are to be maintained. There are, of course, challenges to the successful application of AI in SLP that need to be negotiated if it is going to assist rather than hinder clinical practice. Several machine-learning-based systems, such as those used to identify voice disorders, have performed highly in the differentiation between normal and abnormal voices in various disorders. This makes them valuable tools for early detection and assessment of voice pathology. Future research should focus on expanding the database and updating machine-learning algorithms to enhance performance.

Digital Therapeutics in Speech-Language Therapy

Digital therapeutics are evidence-based interventions that cure, manage, and treat numerous medical conditions. In SLT digital therapeutics include software applications, apps, and webbased tools that help enforce and enhance existing therapy methods. Heyman[21] utilized a mixed-method approach to evaluate the suitability and usability of various mobile apps for SLT. The applications' ease of use and appropriateness were assessed through cognitive interviews, which were conducted via Skype and FaceTime. One participant was interviewed using Skype-Out due to limited WiFi access. The data was descriptively analyzed to gain a preliminary understanding. All variables were categorized and summarized using frequency and percentage tabulation, with bar charts for illustration. The interviews were audio-recorded and transcribed verbatim, followed by a theoretical thematic analysis. A qualitative codebook was created using predetermined codes, and the level of agreement between the primary author and an independent SLP rater was assessed. Another notable feature identified was the inclusion of a shot record feature to promote self-assessment and metalinguistic awareness, along with the use of sound and video recordings to make learning visible through self-assessment and monitoring. Both studies highlighted the need for a more robust framework to identify app features that can facilitate intervention goals. Additionally, the users' tendency to view apps solely as tools without considering the specific application indicates a demand for a higher level of understanding related to the use and applications of these apps. The study participants were experienced clinicians. The central research issue identified in the study data is the theory-practice gap in the usability of information technology and multimedia tools within SLP practice. Respondents preferred a consensus information approach to app selection, highlighting the need

for greater understanding and awareness regarding the use and applications of these apps.

Figure-3 A digital therapy platform for post-stroke dysarthria

The study conducted by Munsell et al.[22] extracted data from Constant Therapy, a cloud-based speech-language rehabilitation program. The data included patient demographics, therapy session activities, and usability logs. The study focused on patients with stroke or TBI who used Constant Therapy. Descriptive statistics were used to analyze patient demographics and activity metrics. Three multiple linear regression models explored the relationship between patient demographic characteristics (age, sex, diagnosis, time from disease onset, and geographic location) and usage patterns. The findings revealed that patients with their disease for more than six months completed more therapeutic sessions and weeks of therapy than acute patients. The study also found that stroke or TBI diagnosis and gender did not significantly affect activity metrics. Moreover, age, gender, diagnosis, and geographic location did not significantly impact therapy engagement levels. The study emphasized the importance of understanding how different factors influence patients' engagement in digital therapy. It suggested that chronic patients are more likely to participate in digital therapy, highlighting the need to address the digital divide in speech, language, and cognitive therapy. Braley et al.[23] conducted a randomized, controlled virtual trial of a speech, language, and cognitive intervention digital therapeutic for post-stroke individuals with aphasia. The study involved 17 participants in the experimental group, where patients used the Constant Therapy app for home-based therapy with biweekly check-ins, and 15 in the control group who practiced workbooks at home with biweekly check-ins. The primary outcome measures were the Western Aphasia Battery-Revised, Brief Test of Adult Cognition by Telephone, and Stroke and Aphasia Quality of Life Scale-39[24-26]. The experimental group showed a 6.75-point gain on the WAB-AQ, considered clinically meaningful. After adjusting for age and time post-stroke, the experimental group demonstrated a 6.43-point more significant improvement in the WAB-AQ than controls. The experimental group showed more significant improvements in spontaneous speech, auditory comprehension, repetition, and naming subtests. This virtual trial provided Class III evidence that a digital therapeutic improves language outcomes in post-stroke aphasia. However, additional studies are needed in a larger, definitive clinical trial to replicate the findings.

Applications

Digital therapeutics are changing the field of speech and language therapy. They use technology to make therapy more accessible and practical. Teletherapy platforms allow therapists to provide services from a distance, which helps people in areas with few resources. Therapeutic apps offer interactive exercises and feedback so patients can practice their skills between therapy sessions. Virtual reality (VR) technology creates realistic environments for practicing speech, improving skills transfer to real-life situations. These new approaches show the potential for digital therapeutics to change speech and language therapy. The benefits of digital therapeutics, as shown in the above studies, can be summarized as follows:

- **Increased access to therapy services.**
- **Greater patient engagement and motivation.**
- **Real-time monitoring and feedback.**

- **Individualized, home-based treatment with remote guidance.**
- **Consistent practice with high adherence.**

- ***Challenges***

The studies indicated a need for further research on the discrepancy between best practices. It is essential to understand the principles of the therapy techniques chosen, as they can serve as a foundation for integrating evidence-based practices into speech-language pathology interventions. More research is necessary to understand what influences the adoption and usage of digital rehabilitation platforms. This information can be utilized to develop more effective strategies for improving access to therapy and enhancing patient outcomes with speech-language disorders. Many studies have been conducted with sample sizes that need to be more significant. In randomized controlled trials, it is challenging to blind interventions from participants and experimenters.

Biomedical Electronics in Speech-Language Pathology

Biomedical electronics refers to devices or technologies that interface with biological systems for either diagnosis or treatment. SLT includes wearable devices, biofeedback systems, and brain-computer interfaces. Latif et al.[27] reviewed the current state of speech technology, describing recent progress, expected benefits, and barriers to integrating the technology into health care. Their findings showed that speech technology could significantly contribute to various healthcare applications, spanning support for diagnostics, patient monitoring, and improving access to healthcare services. The technology at hand includes ASR, NLP, and TTS systems, all set up in order to aid This technology encompasses ASR, NLP, and Text-to-Speech (TTS) systems designed to enhance communication between patients and clinicians, streamline clinical documentation, and support telehealth services. However, practical integration challenges must be addressed to ensure seamless interoperability with electronic health records and other medical systems. The authors emphasized the need for interdisciplinary collaboration, rigorous clinical trials, and establishing regulatory frameworks to guide the development and deployment of speech technologies in healthcare settings.

The most significant advancement of biomedical electronics in speech-language therapy is the creation of various augmentative and alternative communication (AAC) devices. Over 2 million individuals with conditions such as autism, cerebral palsy, hearing impairment, and stroke use AAC as these conditions hinder their ability to communicate effectively through speech[28]. Choosing the right AAC system involves assessing the patient's abilities, strengths, and requirements. This is an ongoing process since an individual's communication skills and needs change over time[29]. Depending on the situation, AAC allows people to utilize multiple communication methods, such as speech, signs, and devices. Advanced AAC systems incorporating speech synthesis, machine learning, and brain-computer interfaces are under development, but they still face challenges related to cost and portability[30]. Latif et al. have addressed outstanding issues in speech technology and provided recommendations[31]. The significant potential of speech technology in healthcare has been explored, driven by advancements in deep learning. This study thoroughly examined current methods for automatic speech recognition, text-to-speech, and health monitoring using speech signals. These advancements face challenges such as high implementation costs, technical complexities, and the need for specialized training, which hinder the widespread adoption of speech-based healthcare solutions. The paper discussed unresolved issues and suggested future research directions to enhance the effectiveness and accessibility of speech-based healthcare technologies. These technologies have the potential to significantly improve remote diagnostics, management of chronic diseases, and independent care for the elderly, addressing critical challenges faced by the healthcare system today (Figure-4).

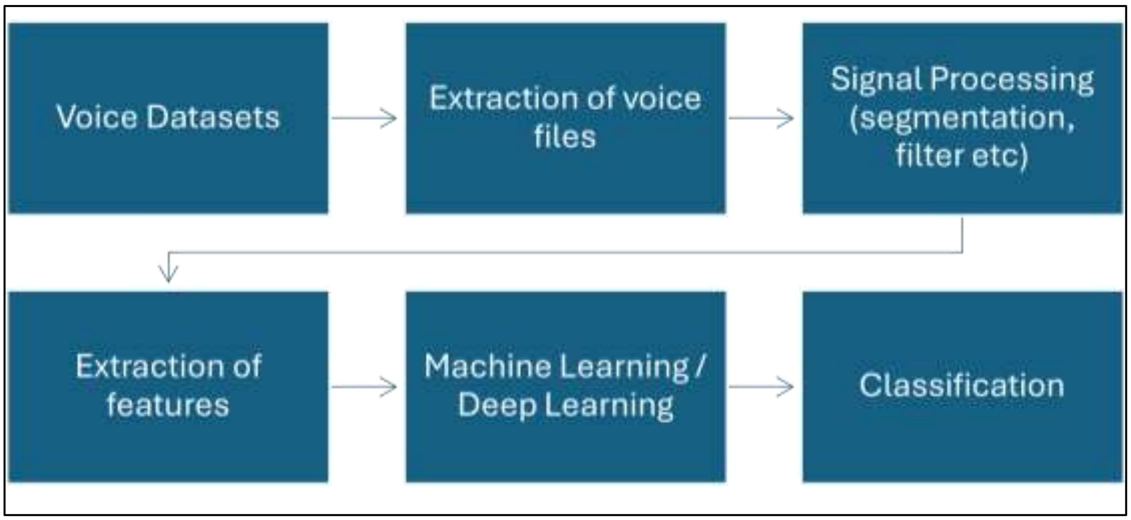

Figure-4 Generic flow diagram for the automated voice disorder diagnosis

In a study, Deepa et al. examined the use of machine learning and biomedical electronics in detecting voice disorders and conducted a comprehensive survey on speech technology[32]. However, they noted that although research has been redeveloped on speech solutions, these systems still need to be implemented in real-time real-world problems. This area holds significant promise for researchers in biomedical sensors, instrumentation, and devices, as most of the tools used by SLTs are manual, and these therapists rely on their judgment when assessing patient outcomes. For instance, the TalkTools tongue lateralization and elevation tool, equipped with EMG sensors and a displacement sensor, can measure muscle strength and the distance a patient displaces, aiding clinicians in quantifying patient outcomes[33]. This illustrates the potential for collaboration between biomedical electronics, AI, digital therapeutics, and speech-language therapy to advance the field.

- ***Applications***

  Advancements in biomedical electronics have greatly improved speech-language pathology and treatment. They have led to the development of various tools and technologies that enhance diagnostic and therapeutic processes. For example, AAC devices are now available to aid people with severe speech or language impairments. These come in many devices, from simple communication boards to sophisticated, state-of-the-art speech-generating devices that use speech recognition and synthesis technologies. They work by translating text or symbols into speech, thus enabling users to integrate better into society and maintain a good quality of life. Biomedical sensors and mobile applications are applied for speech therapy by real-time monitoring of speech patterns, vocal intensity, and articulation. For example, instrumented gloves are translating sign language. Speech-language pathologists can use data from these devices to individualize treatment plans and, more precisely, document progress34. A second significant application of biomedical electronics in speech-language pathology involves biofeedback systems.

Biofeedback uses multiple sensors to capture a number of physiological parameters of speech production processes, including muscle activity, airflow, and vocal-fold vibration. For instance, electromyography sensors can detect muscle movements involved in speech articulation and project it visually before the patient. It provides instant patient feedback about producing speech techniques, thereby making speech therapy sessions more interactive and functional. In addition, biofeedback technology integrates high-end audio and video features while allowing remote therapy sessions, thus assisting therapists to reach out to patients with limited access to in-person services. This makes most platforms have assessment tools and interactive exercises that patients can work on at home, thus ascertaining continuity of care. Consequently, biomedical electronics in speech-language pathology increase the efficiency and access to speech treatment, giving the patient the best results.

- ***Challenges***

Ideally, speech recognition by biomedical electronics should be attuned to the needs of an individual despite noisy or diversified contexts. This is still one of the critical technical challenges toward applying biomedical electronics in speech-language pathology. Despite the various advantages of high-technology augmentative and alternative communication devices, they have several challenges. First and foremost, the high cost could be more affordable for many families and institutions. Technical complexities trouble most devices and require regular maintenance, which may involve endless hours of training for the users and caregivers. More than that, how to use the devices is a steep learning curve, especially for the cognitively impaired. This adds complexity to the already-mentioned ethical considerations, such as patient privacy and data security from possible biases in AI algorithms. Interoperability issues may result in seamless integration with and data exchange to already operating health systems. Still, ease of use by users is another critical factor for wide diffusion, which these technologies can achieve, which is generally overlooked during the design of these devices. One downside for data management and privacy concerns is that more attention is needed to keep sensitive patient information safe. Finally, more research is required to make more affordable and better intelligent AAC solutions that support more natural conversation in order to make them more accessible and effective for those who are in real need.

Future Directions and Research Opportunities

The integrated applications of digital therapeutics, artificial intelligence, and biomedical electronics have enormous potential for SLP and SLT. This innovation also comes with essential challenges that can be overcome in the future by R&D. There is a need for interdisciplinary collaboration among SLPs, engineers, and computer scientists to design novel solutions that are both clinically effective and technologically sophisticated. This may range from developing diagnostic tools with high clinical merit to advanced therapeutic devices integrating AI and biomedical technologies and personalized therapy plans. Another area that is highly expected to evolve is the clinical validation of these new technologies. The effectiveness and safety of AI-driven tools and digital therapeutics concerning speech-language therapy will be validated through rigorous clinical trials.

The implementation of AI and DTs in speech-language pathology must be thoroughly evaluated with the help of RCTs to provide an understanding of immediate outcomes and determine the benefits and risks of these technologies over the long term. Clinical validation is necessary before it is earned and implemented by healthcare providers and patients as a trusted tool that is effective and safe for general use.

The elementary approach to ethical aspects such as data privacy, AI algorithm biases, and informed consent should be followed in this research area. The data and algorithms must be developed to appear transparent and unbiased and have robust data protection features. All these issues should be resolved in this area of research due to its pace of development, the respect of patients, and public trust. Scalability and accessibility will be critical to widespread acceptance and impact of these innovative solutions. Cost-effective technologies must be available to diverse populations, particularly in low-resource settings. Future research needs should include developing inexpensive devices and digital platforms with greater accessibility to AAC and further development of digital therapeutic space. This will include friendly interfaces and proper training of patients and healthcare providers toward effective adoption of such technologies. Apart from that, these technologies must be developed based on an individual patient, like more significant advancements in speech recognition and synthesis, real-time biofeedback systems, and comprehensive data analytics in personalized treatment plans.

It is also essential to monitor the latest technological changes and update the tools available in SLP. This will enable us to provide more effective, accessible, and tailored care for individuals with speech and language disorders. Future generations of AI, digital therapeutics, and biomedical electronics will keep transforming SLT, providing new avenues for speech-language pathologists to help patients achieve better outcomes. These combined technologies can propel speech-language pathologists towards customized, effective, and accessible therapy solutions for their patients. However, this calls for tackling the associated challenges to reap the full potential of such innovations.

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Conflict of Interest
None.

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AUTHORS' CONTRIBUTION

The following authors have made substantial contributions to the manuscript as under:

Conception or Design: Kanwal K

Acquisition, Analysis or Interpretation of Data: Ibrahim Z, Siddiqui AA

Manuscript Writing & Approval: Kanwal K, Siddiqui AA

All the authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.