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Automatic, computer-based speech assessment on edentulous patients with and without complete dentures – preliminary results

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SUMMARY Dental rehabilitation of edentulous patients with complete dentures includes not only aesthetics and mastication of food, but also speech quality. It was the aim of this study to introduce and validate a computer-based speech recognition system (ASR) for automatic speech assessment in edentulous patients after dental rehabilitation with complete dentures. To examine the impact of dentures on speech production, the speech outcome of edentulous patients with and without complete dentures was compared. Twenty-eight patients reading a standardized text were recorded twice – with and without their complete dentures *in situ*. A control group of 40 healthy subjects with natural dentition was recorded under the same conditions. Speech quality was evaluated by means of a polyphone-based ASR according to the percentage of the word accuracy (WA). Speech acceptability assessment by expert listeners and the automatic rating of the WA by the ASR showed a high correlation (*corr* = 0·71). Word accuracy was significantly reduced in edentulous speakers (55·42 ± 13·1) compared to the control group's WA (69·79 ± 10·6). On the other hand, wearing complete dentures significantly increased the WA of the edentulous patients (60·00 ± 15·6). Speech production quality is significantly reduced after complete loss of teeth. Reconstitution of speech production quality is an important part of dental rehabilitation and can be improved for edentulous patients by means of complete dentures. The ASR has proven to be a useful and easily applicable tool for automatic speech assessment in a standardized way.

KEYWORDS: speech quality, automatic speech recognition, objective speech assessment, edentulism, complete dentures, oral rehabilitation

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Introduction

Complete loss of teeth can cause a persistent speech disorder by altering dental articulation areas. This severely reduces the quality of speech (1). Particularly, the alteration of frontal maxillary morphology leads to impairment of speech production (2). Removable complete dentures can partly solve this problem (3). However, they disturb speech production themselves as they restrict the flexibility of the tongue, narrow the oral cavity and alter the articulation areas of the palate and teeth (1, 4, 5). Speech production has a significant effect on patients' general satisfaction with dentures. The patients' contentment correlates with the acceptance of the denture (6). Therefore, speech production quality is an essential criterion for success or failure of dental rehabilitation.

There is no standardized assessment of speech disorders in adults or children at the national or international level (7, 8). Semi-standardized instruments for the analysis of speech disorders are well known (9, 10). The auditory speech evaluation by speech therapists is

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Table 1. Studies using automatic, technical analysis of speech

Authors	Automatic spectral analysis of	Automatic analysis of speech intelligibility	Study design	Number of patients
Molly *et al.* (16)	/s/sound	No	Clinical	10
Ungvári *et al.* (17)	Dental sounds	No	Clinical	x
Stojcevic *et al.* (18)	Dental/post-alveolar sounds	No	Clinical	30
Runte *et al.* (2)	/s/sound	No	Experimental	20
Seifert *et al.* (19)	/s/sound	No	Experimental	10
Ichikawa *et al.* (1)	/s/sound/consonants	No	Experimental	7
Lundqvist *et al.* (12)	/s/sound	No	Clinical	21
Petrović (5)	Test word:/ivica/	No	Experimental	x
Altmann (21)	/s/sound, vocals	No	Experimental	10

x = not specified.

state of the art in analysing speech quality as an overall phonetic outcome of dental rehabilitation (3, 11–13). But the assessment of speech disorders or intelligibility is performed perceptually and therefore lacks reliability because of differences in the speech therapists' experience (14). This is accompanied by the problem of reproducibility of the evaluation results. For more reliable results, transcription tasks and multiple-choice tasks for several listeners have been found to be appropriate (15). Hence, the use of several listeners is rather time-consuming and is thus mainly used for research projects. For clinical purposes, a single expert usually evaluates the patient's speech.

Technology-based and independent diagnostic tools for the assessment of speech ability regarding alteration of the dental arch or dental rehabilitation have only been utilized for single parameters of speech (Table 1; 1, 2, 5, 12, 16, 17, 18, 19, 20, 21). However, these methods do not allow for a global assessment of speech quality as an important factor for quality of life. A new technique for an automatic and standardized speech assessment has been tested as a diagnostic tool in adult patients who suffered from neurological diseases (22), who stuttered (23), in laryngectomees with trachea-oesophageal speech (24) and in children with cleft lip and palate (25). This method is based on a statistical analysis of speech with established methods of automatic speech recognition. A validation of the automatic analysis system demonstrated strong correlations between the experts' ratings of intelligibility and the automatic assessment of the word accuracy (WA) (24–26) for each of the different pathologies. These studies demonstrated that the rating of the automatic system is in the same order as the inter-rater agreement, i.e., the correlation of the ratings of an expert to the mean value of the other raters, between five different expert raters.

It was the aim of this study to introduce and validate a computer-based speech recognition system for the standardized and automatic speech assessment in edentulous patients after dental rehabilitation with complete dentures. To examine the impact of dentures on speech production, the speech quality according to the WA of edentulous patients with and without complete dentures was analysed by the automatic system and compared to each other. To meet the requirements of an easier standardization by avoiding the influence of different kinds of dentures, only patients with removable complete dentures were accepted as participants in this study.

Materials and methods

Patients and control group

The study group consisted of 28 edentulous patients with complete dentures (Table 2). All patients were native German speakers, using a local dialect. None of the patients had speech disorders caused by medical problems other than dental, psychological problems or any reported hearing impairment. Patients with any speech mannerisms were excluded from the study. The control group was randomly selected from a population matched by age and gender and consisted of 40 German native speakers without speech disorders and no alteration of the oral cavity or the dental arch, speaking the same local dialect as the patient group (Table 2).

Table 2. Data of patients and control group

Patients	Age*	Sex		Prosthesis *in situ*†		Control group	Age*	Sex	
Mean ±	64 ± 10	Male	13	Mean ±	59 ± 49	Mean ±	58 ± 13	Male	30
Min	43	Female	15	Min	1	Min	28	Female	10
Max	83	*N*	28	Max	240	Max	82·1	Total	40

*Years.
†Month.

The study respected the principles of the ethics committee in charge as well as the 1975/1983 Helsinki declaration and was approved by the ethics committee of the University of Erlangen-Nuremberg (approval Nr. 3816).

Assessment of dental rehabilitation

Only patients wearing their dentures for at least 1 month were chosen to ensure patient habituation to new dentures. All complete dentures were constructed according to the guidelines of the All-oral procedure. The following criteria for the success of a complete denture were defined as follows:

1 Absence of pain concerning the chewing muscles, the soft and hard tissue in functional and non-functional situations.
2 Absence of variances of the soft tissue like redness or ulcer.
3 Ability to chew and swallow without restrictions.
4 Balanced occlusion relationship under function.
5 An interocclusal distance of 2 mm in a physiological rest position.
6 Excellent fit proved by a soft pattern.
7 Patient satisfaction.

Every parameter was rated as sufficient/insufficient, i.e., correct/not correct by the same senior dentist from the Department of Prosthodontics, Dental school, University of Erlangen-Nuremberg. The complete denture was rated as insufficient if one of the seven parameters was rated as insufficient/not correct and a new denture was recommended following the speech evaluation. Based on this assessment, patients were divided into two groups: 18 patients with sufficient complete dentures and 10 patients with insufficient complete dentures.

Speech recording

The data were assessed during regular outpatient examinations. All patients and the control group subjects read the German text 'Der Nordwind und die Sonne', a tale by Aesop, which acts as reference text for the International Phonetic Alphabet by the International Phonetic Association. It is phonetically balanced and contains 108 words that include all phonemes of the German language. For recording, the text was split up into 10 paragraphs according to syntactic boundaries.

The patients read the text with their complete dentures inserted at first. The second recording was subsequently performed without complete dentures. To take the influence of habituation into account, six randomly chosen patients performed six consecutive recordings each, three with and three without inserted complete dentures, in random order.

The text was presented on a computer screen in large letters, to ensure that it was also easy to read for elderly people without disturbing the reading flow. The people were asked to speak in standard German. The recordings were performed using a close-talk microphone (Call 4U*) at a sampling frequency of 16 kHz and quantized with 16 bit.

Perceptual evaluation of edentulous patients

A panel of three professional speech therapists performed speech acceptability judgements. For each of the 28 patients, two recordings were performed: one with and one without complete dentures *in situ*. Each recording was divided into 10 utterances with a duration period of 5–6 s each. Therefore a total of $(28 \times 10) \times 2 = 560$ utterances was available. Each pair of recordings, i.e., the two corresponding utterances by the same person, with and without dentures *in situ*, where presented to the three professionals. They had to decide which one of the two utterances was more acceptable concerning speech production quality in a binary way. The sum of these binary

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decisions for every utterance, described by percentage, was used as the speech acceptability judgment score for each single patient with and without dentures inserted. To avoid a training effect for the speech therapists, all pairs were played randomly. The order of the 560 pairs was completely random. Additionally, we randomized the sequence of the recordings with dentures, i.e., in half of the pairs, the therapists listened to the recordings with dentures first and in half of the pairs, the therapists listened to the recordings without inserted dentures first. For the purpose of measuring the correlation in the human experts' speech ratings and the correlation between human and machine, we applied different measures. To compare an arbitrary number of raters, we used the weighted multirater κ, an extension of Cohen's κ. Two raters' scores x and y are weighted with $w(x, y) = 1-(x-y)/(C-1)$, where C is the number of different rating grades (here: 10). The minimum value of κ is below 0 and depends on the input data, and the maximum of 1 means perfect agreement. We also measured the % agreement of the 280 binary decisions for each pair of raters. Finally, we calculated the Pearson correlation coefficients of the speech acceptability score described previously.

Automatic speech recognition system

An objective speech assessment was achieved by means of a state-of-the-art automatic speech recognition (ASR) system, developed in the Department of Computer Science, Chair of Pattern Recognition, University of Erlangen-Nuremberg (27). In a first acoustic analysis, the ASR system segments the data into temporal units of 16 ms (10 ms frame rate) and transforms the speech signal into Mel-Frequency Cepstrum Coefficients (MFCCs) that uniquely represent the spoken utterance. These feature vectors are analysed regarding temporal and spectral characteristics and compared to statistical word models in the form of Hidden Markov Models (HMMs). These word models can be regarded as an internal 'dictionary', which was trained with dialogues from the VERBMOBIL project, a dataset that contains data from speakers all over Germany and thus covers most dialectal aspects (28). Each word in the 'dictionary' is represented by a sequence of elementary HMMs. So HMMs allow mapping from the acoustic signal of a word to its text form. The statistical word models are trained on 578 speakers; 304 men and 274 women. The dataset contains 27 h of speech (11 714 utterances, 257 810 words). Modern ASR systems use this acoustic information in combination with linguistic information, i.e., stochastic language models. Stochastic language models take the word frequency in a text into consideration. Typically ASR systems use so-called bigram or trigram models. Bigram-language models analyse the probability that a word follows the last spoken word, trigram models take the last two words spoken into consideration. We used a unigram-language model trained on the 'Nordwind und Sonne' text. It assumes that the current word is independent of previously spoken words. Thus, recognition mainly depends on the acoustic signal of each single word.

We computed the so-called word accuracy (WA) of the speech data as a benchmark of speech recognition quality separately for each recording. The WA describes the percentage of correctly recognized words in the whole text and takes the number of falsely inserted words into consideration. It is calculated as follows: WA (%) = $(C-W)/R \times 100\%$, whereby C denotes the number of correctly recognized words, W the number of wrongly inserted words and R the number of words in the reference text.

Beside the 'global' WA for each recording, we calculated the WA in the same manner as the perceptual evaluations. The WA is calculated for each of the 280 pairs and a score is given according to the difference of the two WA values.

Statistics

For statistical variance analysis, the Levene test was used, and for proof of normal distribution, the Kolmogorov-Smirnov and Shapiro tests were used. The comparison of word recognition values was performed by the *t*-test when appropriate. For paired samples, the paired *t*-test was utilized. For unpaired small samples sizes, the Wilcoxon-rank-test was used and the Mann–Whitney-*U*-test for paired sample sizes. For the correlation analysis, the Pearson correlation coefficient was used. *P*-values equal to or smaller than 0·05 were considered to be significant. These calculations were made using SPSS Version 16 for Windows†.

†SPSS®, Chicago, IL, USA.

Results

Three different types of experiments were performed. First, the speech acceptability judgments of edentulous persons with and without complete dentures *in situ*, received from different speech therapists, were compared to each other. Second, these scores were compared to the WA scores obtained by the ASR system. Third, the speech recognition scores of edentulous persons with and without complete dentures *in situ* were compared to each other, using the WA as a standardized speech quality score by the ASR.

Percentage agreement of the binary decisions of the human raters

The percentage agreement between the different raters is shown in Table 3. Rater 1 and rater 2 achieved an agreement of 75·4%. The agreement between rater 1 and rater 3 was 77·5%, and rater 2 achieved an agreement of 73·6% with rater 3. These values were not significant amongst each other ($P > 0{\cdot}1$).

Inter-rater correlation

An inter-rater correlation between each of the single raters was performed according to the speech acceptability judgements. Rater 1 correlated to rater 2 with 0·78, rater 1 and rater 3 achieved 0·84 and rater 2 achieved a correlation coefficient to rater 3 of 0·82 (Table 4). The three correlation coefficients showed no significant differences amongst each other ($P > 0{\cdot}05$). The comparison between the ratings of the different experts showed a moderate agreement with a multi-rater κ of 0·54.

Table 3. Percentage agreement of the binary decisions paired raters

Rater	1–2	1–3	2–3
Correlation	75·4%	77·5%	73·6%

Table 4. Correlation of the speech acceptability judgements of all raters against each other and of the word accuracy (WA) scores of the automatic speech recognition (ASR) to the mean values of the experts ratings

Rater	1–2	1–3	2–3	ASR to 1/2/3
Correlation	0·78	0·84	0·82	0·71

Correlation between ASR system and human ratings

The ASR system achieved a correlation coefficient of 0·71 to the mean scores of all raters (Table 4). The difference of correlation between the inter-rater comparisons and the ASR system was found to be not significant for the comparison between the mean experts' score to the system ($P > 0{\cdot}05$).

Automatic, standardized scoring of the WA

The WA of edentulous patients without complete dentures *in situ* [WA: 55·43% ± 13·1 (min/max %: 13·89/73·15)] was significantly reduced compared to the subjects with complete dental arches [WA: 69·79% 10·6 (min/max %: 32·40/88·00)] (Table 5). The WA improved to a significantly higher level by wearing complete dentures [WA: 60·00% ± 15·6 (min/max %: 0·56/85·19)] but did not reach that of the control group (Table 5). Still, there was a significant difference. Ten of 28 complete dentures were found to be insufficient. That caused a lowering of the WA [WA: 50·89% ± 19·1 (min/max %: 0·56/65·74)] and showed significance compared to the WA of patients with sufficient complete dentures [WA: 65·07% ± 10·90 (min/max %: 0·56/65·74)]. Speaking with insufficient complete dentures turned out to produce an insignificantly higher WA than edentulous speech production (Table 5). The randomly repeated speech recordings of similar patients with and without dentures showed no significant differences concerning the WA (*P*-value: 0·984; Wilcoxon-Rank-Test).

Discussion

In the present study, a new method for automatic, standardized speech assessment in patients with alteration of the dental arch is introduced. This speech recognition technique is based on the WA of spoken language as a means of representing speech production quality. Of course WA is not similar, but akin to the quality of speech production. Both are influenced by voice quality, phonematic and morpho-syntactic structure, amplitudes and speaking velocity. Speech quality additionally includes the 'human factor' which is addressed by the judgement of speech acceptability performed by the expert listeners. Even if the listener does not understand every word or syllable of a spoken sequence, the meaning can be understood by

Table 5. Word accuracy (WA)/Comparison of groups

			P-values			
Patients/control	*n*	WA % ± (min/max)	Edentulous	Dentures-all	Dentures-suff	Dentures-insuff
Control group	40	69·79 ± 10·6 (32·40/88·00)	5·32E-06**	0·0012**	0·0817**	0·0001**
Edentulous	28	55·42 ± 13·1 (13·89/73·15)	–	0·0068*	0·0008*	0·9056*
Dentures – all	28	60·00 ± 15·6 (0·56/85·19)	–	–	–	–
Dentures – suff	18	65·07 ± 10·9 (47·22/85·19)	–	–	–	–
Dentures – insuff	10	50·89 ± 19·1 (0·56/65·74)	–	–	0·0344**	–

*Wilcoxon-Rank-Test.
**Mann–Whitney-*U*-Test; $P < 0{\cdot}05$ = sig.

extrapolating from contextual, pragmatic and prosodic characteristics. Although there is a good correlation of intra-individual listeners' evaluation of speech acceptability, it shows considerable variability, which reveals the limitations of listeners' speech assessment (14, 15).

However, our results presented a high correlation between the experts' rating of the speech acceptability scores and the WA analysed by the ASR-system. There was no significant difference in comparison to the inter-expert rating as well as the expert rating and the ASR-scores. Similar results with high correlation between the expert ratings and the WA scores were found when the automatic speech analysing system was validated in laryngectomees with trachea-oesophageal speech (24), in children with cleft lip and palate (25) and in patients with oral squamous cell carcinoma (26).

Applying the automatic system, we found significantly reduced speech recognition scores in edentulous patients compared to the control group. These results confirm prior studies, which used perceptual expert ratings for the assessment of speech intelligibility (1) or spectral analysis to assess single distorted sounds (5, 9, 17). In these studies, edentulous speakers were not able to properly articulate fricative sounds or consonant, which may be an explanation for reduced speech intelligibility.

The dental rehabilitation of edentulous patients with complete dentures is followed by an advancement of speech intelligibility, which could be demonstrated by expert ratings (3, 11, 13, 17). We found comparable results in our study, as there were no significant differences of speech recognition between the control group and patients with inserted dentures that were evaluated as sufficient. On the other hand, complete dentures as well as oral implant supported prostheses turned out to increase pronunciation difficulties in expert listener ratings (5, 9, 12). Again, fricatives were mainly altered concerning timing, amplitude and frequency distortion (2, 12, 16, 19). These studies indicate that the/s/-sound production is most affected by prostheses at the anterior upper jaw region, but seems to not be directly connected to an impairment of speech intelligibility (3). The contribution of other altered single sounds to intelligibility of speech is not clear so far. Labio-dental articulation is influenced by the position and angulation of the maxillary incisors (2–4) and fricative production in general by the thickness and shape of the palate plate of removable dentures (1, 3, 5, 21). Variations in teeth positioning as well as shape of teeth and resin base have not been part of the present study, but their influence on speech production is an interesting aspect for a further standardized investigation with the automatic speech recognition system.

However, complete dentures that were rated as insufficient according to our evaluation criteria caused a significant decrease of speech recognition, compared to sufficient complete dentures. As every alteration in the oral cavity can influence speech production (1) that may especially apply to dentures without exact fit and stability of position, as the patient has to compensate for these factors while speaking. An assumption which is supported by the results of a patient questionnaire study that showed that implant-fixed prostheses provide better speech intelligibility than complete dentures, because of the better fixation of the prostheses in the oral cavity (20). Hence, there is only little information concerning speech production quality in relation to the sufficiency of complete dentures in literature, so far.

Different studies refer to an increase of the quality of speech production after a period of habituation to prostheses (3, 11, 21). Ninety per cent of the patients seem to reach a steady state of speech quality after a period of at least 4 weeks (3, 21). Other studies assume a longer habituation period, but have acquired these results only for single sounds, like/s/- and/th/(11) or in patients with implant-supported prostheses (12, 16). In the present study, the earliest speech recordings were performed 4 weeks after a habituation period to the insertion of new complete dentures. However, the influence of a longer oral habituation period on overall speech quality should be part of further research. The short-time habituation of the patients regarding the repeated reproduction of the reference text with and without complete dentures turned out to be of no significant influence.

The WA showed a high variance for the patient group. Hence, equal results can be found for the control group which demonstrates the high variability of 'normal' (Table 5). Some of the speakers of the control group had poor results, which is not surprising as the recognizer was trained with mainly young people. Elderly people and children may deviate from the 'normal' standard of speech quality (29). To avoid any influence from age or gender, the control group of this study was matched to these factors. However, absolute WA is not crucial, as it is dependent on the training population as well as on the adaption of the system, and therefore presents a result of relative comparison. Another aspect may be the influence of different dialects on speech recognition assessment. Therefore, the automatic recognition system was trained on an initial dataset which contained data from speakers from all over Germany. It was shown in a former study that there are no significant differences between the WA in different German dialects (30).

In this study, we were able to demonstrate that the computer-based speech analysis system can automatically rate the speech recognition depending on speech production quality of edentulous patients with and without complete dentures. It evaluates every single word independently of prosodic, pragmatic and contextual information that may influence perceptual rating and can facilitate the comparison between different speech samples independent of time and place of the recording. Therefore, the system can be an easily applicable method to measure the outcome of speech ability regarding dental rehabilitation in daily practice. Nevertheless, it is not the actual goal to replace the examination and detailed interpretation of an expert with the presented system. In fact, the system can support the dentist, or, in cases of more severe articulation problems, the speech pathologist to quantify the speech assessment and monitor the process of dental rehabilitation in terms of quality management.

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