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Development of a Prototype Tongue Strength Measurement Device and Evaluation of the Test–Retest Reliability of Tongue Strength and Isometric Endurance: A Psychometric Study

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Original Article

Abstract

Introduction: The tongue plays a vital role in swallowing and speech, and neurological disorders such as stroke may cause tongue weakness and functional impairment. Conventional tongue strength assessment is predominantly qualitative and dependent on clinical judgment, limiting its ability to quantify tongue pressure and monitor functional changes. Given the lack of commercially available tongue-strength measurement devices in Iran, this study aimed to design and develop a prototype device and to evaluate the test–retest reliability of tongue-strength and isometric-endurance measurements in healthy young adults.

Materials and Methods: The study comprised two phases. In the first phase, a prototype device was designed and developed. In the second phase, the test–retest reliability of tongue strength and isometric endurance measurements was assessed in 50 healthy young adults.

Results: A device incorporating a thin, flexible sensor was developed. The device was easy to use in healthy individuals and was designed to measure four indices of tongue function: strength, isometric endurance, isotonic endurance, and power. Test–retest analysis demonstrated statistically significant agreement between measurements obtained at the two assessment sessions for both tongue strength and isometric endurance. The intraclass correlation coefficients were 90% for tongue strength and 91% for isometric endurance.

Conclusion: The prototype was designed to assess four indices of tongue function: strength, isometric endurance, isotonic endurance, and power. The reliability assessment demonstrated very high reproducibility of tongue strength and isometric endurance measurements in healthy young adults. Further studies are needed to examine reliability in older adults and in individuals with oropharyngeal impairments, and to establish the validity of measurements obtained with the device.

Keywords: Dysphagia; Instrumental assessment; Tongue; Strength; Endurance

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Introduction

Swallowing is a highly complex process involving the coordinated activity of the oral, pharyngeal, laryngeal, and esophageal muscles. Normal swallowing is therefore commonly divided into three phases: oral, pharyngeal, and esophageal (1, 2). Dysphagia, which may affect any of these phases, is a common consequence of stroke and many other neurological conditions. It may lead to weight loss, malnutrition, increased healthcare costs, pneumonia, and death (3, 4).

The tongue plays a central role in the oral and pharyngeal phases of swallowing, contributing to

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mastication, bolus formation and manipulation, residue clearance, and bolus transport from the oral cavity to the pharynx (5, 6). Impairment of the tongue musculature resulting from conditions such as neurological diseases may lead to oral or pharyngeal dysphagia (7). Tongue strength and endurance are therefore essential for normal and safe swallowing (8). During swallowing, tongue compression against the hard palate generates the force required to propel the bolus toward the pharynx. Increasing tongue–palate pressure thus plays an important role in enhancing overall swallowing strength (9).

Accordingly, isometric lingual strengthening exercises have received considerable attention in dysphagia rehabilitation (10). Studies have shown that interventions involving progressive resistance lingual exercises can increase tongue strength, improve oral swallowing, and enhance swallowing safety during the pharyngeal phase (11). However, according to the overload principle, the demands placed on a muscle during a strengthening program must increase progressively in relation to its force-generating capacity to sustain strength gains (12). Consequently, implementing tongue-strengthening exercises first requires measuring the pressure the tongue exerts against the palate.

Despite the importance of the tongue in swallowing and the need to apply exercise principles in treatment programs, tongue function is commonly assessed in speech-language pathology clinics through clinicians' subjective judgments, which have limited validity and precision (13, 14). Furthermore, tongue strength assessments frequently involve protruding the tongue beyond the oral cavity, a movement that differs from the upward movement toward the hard palate that occurs during swallowing. Clinicians also cannot estimate the pressure exerted by the tongue against the hard palate through observation alone.

In Iran, assessment of tongue function similarly relies on traditional qualitative approaches. Tongue strength is generally assessed using a tongue depressor or the examiner's finger, with the findings largely dependent on the clinician's experience. This increases the likelihood of error in measurement and reporting.

A limited number of commercial instruments have been developed to measure tongue force against the palate, including the Iowa Oral Performance Instrument (IOPI) and the Madison Oral Strengthening Therapeutic (MOST) device; none of these instruments are manufactured in Iran. These instruments have been used to assess isometric tongue strength (ITS) and isometric tongue endurance (ITE) (13). Previous studies have identified limitations associated with these instruments, including difficulty maintaining a consistent sensor position with the IOPI, the high cost of disposable sensors for the IOPI and MOST, and issues related to portability, hardware costs, and ease of use (13, 15, 16).

Given the importance of tongue function in swallowing, the need for precisely quantified strengthening programs, and the lack of commercially available tongue-strength measurement devices in Iran, this study aimed to design and develop a locally manufactured prototype to measure tongue force against the palate. A further objective was to assess the test–retest reliability of measurements obtained using the device.

Materials and Methods

This study comprised two main phases: the design and development of a prototype device for measuring tongue strength and endurance, followed by an assessment of the test–retest reliability of tongue strength and isometric endurance measurements in healthy young adults.

Phase 1: Device Design and Development

Hardware Specifications: The main components of the device included a signal acquisition, processing, and transmission board; a display; a force sensor; a power supply; a keypad; and an analog-to-digital conversion module. An Arduino board equipped with an ATmega328T microcontroller and an FSR402 force sensor was used (Figure 1).

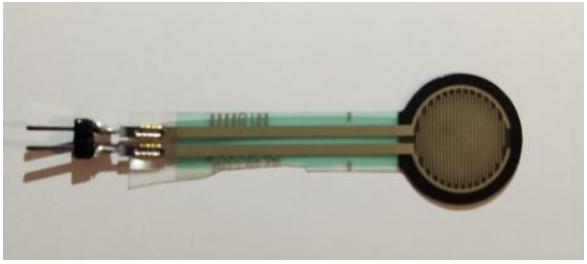


Figure 1. FSR402 force sensor

Placement of a sensor in the posterior palate may elicit the gag reflex and reduce patient cooperation. Therefore, the device incorporated a single sensor positioned on the anterior hard palate. Previous studies have also shown that, during tongue-to-palate pressing tasks, the anterior tongue exerts greater pressure against the palate than the middle and posterior regions (17). During normal swallowing, pressure generated by the anterior tongue against the palate is also a major contributor to posterior bolus propulsion (18).

The FSR402 is a force-sensitive resistor. In the unloaded state, its resistance is extremely high,

approaching infinity; resistance decreases when force is applied. The sensor has a sensing area with a diameter of 12.7 mm and a thickness of 0.45 mm. The sensor used in this device measures forces ranging from 0 to 100 N, with a minimum activation force of 0.1 N.

Sensors of this type are suitable for use in medical instruments. Because the sensor needed to be positioned inside the mouth, its minimal thickness and high flexibility were particularly advantageous. Similar sensors have been used in previous studies to measure tongue and dental forces (19-22).

The sensor operates by detecting force-dependent changes in resistance, which are reflected in corresponding changes in voltage, and records force measurements over time. Force applied to the sensor changes its resistance, which in turn changes the measured voltage. These voltage changes are subsequently converted into force values expressed in newtons.

Because the sensor was placed intraorally, it was covered with plastic film to protect it from moisture and minimize moisture-related measurement errors. It was then attached to the palate immediately posterior to the alveolar ridge using Professional denture adhesive, manufactured by Bonyf, Switzerland.

Software Specifications: The device was programmed to measure tongue strength, isometric endurance, isotonic endurance, and power.

Tongue strength: To assess maximum tongue strength, the participant presses the tongue against the sensor with maximal effort for a predefined 5 s period on this device (6, 13, 23). This interval was incorporated into the software and timed automatically so that neither the participant nor the clinician needed to monitor the duration manually.

Force and time recording begins only when the force applied to the sensor exceeds 0.1 N, defined as the force threshold. Recording stops automatically after 5 s. To improve measurement precision, the software excludes values recorded during the first and final seconds and calculates the mean force over the remaining 3 s. This value is displayed as the tongue strength index.

Isometric endurance: Endurance is generally assessed during sustained or repeated submaximal contractions. To measure isometric endurance, the participant is instructed to press against the sensor for as long as possible at a force of at least 50% of the previously measured tongue strength (23). This target is automatically calculated by the device using the force recorded during the strength assessment.

Recording begins when the applied force first exceeds 50% of tongue strength. When the force remains below this threshold for 2 consecutive seconds, recording stops. The elapsed time is displayed in seconds as the participant's isometric endurance.

Isotonic endurance: The target force for isotonic endurance is the same as that used in the isometric endurance task. However, isotonic endurance is quantified as the number of repetitions during which the participant can apply the required force to the sensor (23).

The device counts the number of presses reaching at least 50% of tongue strength and displays this count as isotonic endurance. As in the preceding task, the target force is calculated automatically. The task ends when the participant fails to achieve the target force on two consecutive attempts.

Tongue power: Power is defined here as the ability of a muscle to produce rapid contractions at a specified force level (24). For the tongue power task, the target force was set at 75% of maximum tongue strength (23). The software automatically calculates this threshold.

The participant is instructed to press against the sensor as rapidly and as many times as possible within 10 s, reaching 75% of maximum tongue strength on each repetition (23). The device counts repetitions that meet the criterion and displays the total at the end of the 10-s interval.

Phase 2: Reliability Assessment

Following approval from the Ethics Committee of Isfahan University of Medical Sciences, 50 healthy individuals were recruited through convenience sampling from university staff and students.

The inclusion criteria were an age between 20 and 50 years, no self-reported history of dysphagia or neurological disorders, and no structural abnormalities of the oral cavity or tongue. The exclusion criteria were an excessively sensitive gag reflex that made sensor placement difficult or intolerable and a participant's request to withdraw. No participants withdrew during either the test or retest session.

Recruitment took place from December 2021 to April 2022. The study procedures were fully explained, and informed consent was obtained from all participants.

To assess the test–retest reliability of tongue strength and isometric endurance, participants were seated with their heads in a neutral position, without lateral deviation or anterior–posterior tilt, while looking straight ahead.

After being covered with plastic film, the sensor was secured with denture adhesive to the anterior hard palate immediately posterior to the alveolar ridge, over the anatomical location of the incisive foramen (Figure 2). Before formal testing, each participant completed one familiarization trial by pressing the tongue against the sensor with maximal effort for 5 s.

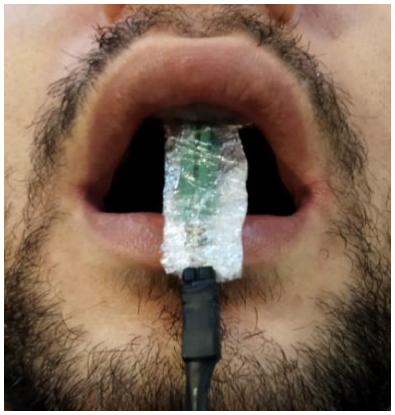


Figure 2. Attachment of the sensor to the palate using denture adhesive

The strength task was then performed three times, with a 1-min rest interval between trials. The sensor remained in place throughout testing, and its stability was checked. The force displayed by the device was recorded for each trial, and the mean of the three trials was calculated as tongue strength.

All tasks were performed with the mouth nearly closed. The device display was positioned within the participant's field of view to provide visual feedback.

After the third strength trial, isometric tongue endurance was assessed using the force recorded during that trial as the reference value. Participants were instructed to press the tongue against the sensor for as long as possible at a force of at least 50% of the value recorded during the third strength trial. The duration for which this force was maintained, as displayed by the device, was recorded in seconds as isometric tongue endurance. The sensor was then removed.

Retesting was performed at least 1 h and no more than 1 day after the initial assessment. All procedures were repeated, and tongue strength and isometric endurance were recorded again.

The test–retest reliability of tongue strength and isometric endurance measurements was assessed using the intraclass correlation coefficient (ICC), calculated with a two-way random-effects model, absolute agreement, and average measures.

Statistical significance was set at $p < 0.05$. Data were analyzed using IBM SPSS Statistics for Windows, version 21.0 (IBM Corp., Armonk, NY, USA; 2012).

Results

Phase 1: Device Development

At the end of the first phase, a device capable of quantifying four indices of tongue function—strength, isometric endurance, isotonic endurance, and power—had been developed (Figure 3). The device was registered with the Intellectual Property Office of the State Organization for Registration of Deeds and Properties of Iran under patent number 105784.



Figure 3. Prototype tongue strength measurement device

The sensor was connected to the main unit by a cable and transmitted signals to the internal processing board. The external housing included a display for presenting measurements and an LED indicator for visual feedback. Four buttons were provided to select and perform the different tasks.

For strength assessment, the device was connected to a power supply and the "Strength" mode was selected. The sensor was covered with plastic film, coated with a small amount of denture adhesive, and secured to the anterior hard palate immediately posterior to the alveolar ridge.

Once the device was ready, the timer started when the first recordable force was detected. The participant then pressed against the sensor with maximal effort for 5 s. At the end of the interval, recording stopped automatically, and the strength value was displayed in newtons.

In "Endurance" mode, the device automatically calculated 50% of the recorded strength value as the target force. The participant maintained the force at this level for as long as possible. If the force remained below the target for 2 consecutive seconds, the task ended, and the duration was displayed in seconds as the isometric endurance index.

For isotonic endurance, the device counted and displayed the number of valid repetitions reaching at least 50% of tongue strength. For power, the target force was set at 75% of tongue strength, and the number of valid repetitions completed within 10 s was automatically counted and displayed.

Phase 2: Test–Retest Reliability

In the second phase, 50 healthy individuals, including 24 women and 26 men, completed the tongue-strength and isometric-endurance tasks. Their mean age was 32.2 ± 6.0 years, with a range of 23–46 years.

Table 1 presents the descriptive statistics and test–retest reliability results for tongue strength and isometric endurance. Measurements obtained using the device demonstrated very high reliability for both tasks in healthy young adults (25).

Discussion

This study had two related objectives: to develop a locally manufactured prototype for measuring tongue force against the palate and to assess the reproducibility of its tongue strength and isometric endurance measurements in healthy individuals. The first phase demonstrated the feasibility of developing a device to assess four indices of tongue function. In the second phase, measurements of tongue strength and isometric endurance demonstrated very high test–retest reliability.

One of the principal features of the prototype was the use of a thin, highly flexible FSR402 sensor. These characteristics facilitated attachment to the hard palate and allowed participants to perform tongue-pressing tasks with the mouth nearly closed, a position more closely resembling oral posture during swallowing. In addition, covering the sensor with plastic film eliminated the need to replace the sensor for each participant, reducing operating costs. However, carefully covering the sensor to prevent moisture penetration was time-consuming. Custom-molded sensor covers are therefore recommended for subsequent versions of the device.

Another advantage was the integration of four indices—strength, isometric endurance, isotonic endurance, and power—within a single system. The algorithms for these indices were based primarily on the definitions described by Clark (23). The target force was fixed at 50% of tongue strength for both isometric and isotonic endurance and at 75% for power.

From a clinical perspective, these fixed thresholds may simplify operation because the reference values are predefined in the software and do not need to be entered separately by the clinician. For research purposes, however, allowing users to adjust target thresholds and assessment intervals could improve the device's flexibility.

The prototype reports tongue strength in newtons, whereas the IOPI, a widely recognized instrument for assessing tongue function, reports measurements in kilopascals. This difference in units may hinder direct comparison with IOPI measurements. Moreover, because a commercial IOPI device was unavailable in Iran, simultaneous comparison with a reference instrument was not possible in the present study. Future development should therefore examine the feasibility of expressing the output in kilopascals and conducting direct comparisons with an established instrument.

The LED indicator provided visual feedback during testing, with light intensity increasing as tongue force against the palate increased. This feedback was particularly useful during the endurance task. In future versions, a computer or smartphone application displaying real-time performance graphs could provide more comprehensive visual feedback.

The findings from the second phase were particularly relevant to measurement reproducibility. Sensor placement was a potential source of variability because substantial differences in placement between sessions could affect the results. Nevertheless, ICCs of 0.90 for strength and 0.91 for isometric endurance indicated that the standardized procedures and sensor placement protocol yielded highly consistent measurements in healthy individuals.

According to Munro's classification, both coefficients indicate very high reliability (25). These findings are consistent with those reported by Clark et al., who measured tongue strength using the IOPI in 12 participants with dysphagia on two occasions separated by 36 h and reported a correlation of 0.97 between sessions (26).

Limitations

This study had several methodological limitations that should be addressed in future research.A principal limitation was the lack of access to a comparable commercially available device because of its high cost and restrictions on international procurement.

Table 1. Descriptive statistics and test–retest reliability of tongue strength and isometric endurance measurements

Variable	Session	Mean ± SD	Range	ICC (lower–upper bound)	p-value
Tongue strength (N)	Test	8.82 ± 1.62	4.92–12.03	0.90 (0.83–0.95)	<0.001
	Retest	8.87 ± 1.58	5.61–12.16	—	—
Isometric tongue endurance (s)	Test	30.84 ± 5.60	17–42	0.91 (0.84–0.95)	<0.001
	Retest	31.12 ± 5.61	15–44	—	—

ICC: Intraclass correlation coefficient; SD: Standard deviation
ICC values represent agreement between the test and retest sessions

Consequently, direct examination of the design and operating mechanisms of existing devices and simultaneous comparison of the prototype with a reference instrument were not possible. Information about existing devices was therefore obtained from published articles and descriptive sources. Furthermore, reliability was assessed only among healthy adults aged 20–50 years. The reproducibility findings, therefore, cannot be directly generalized to older adults or to individuals with oropharyngeal impairments.

Recommendations

Further studies should investigate the reproducibility of measurements obtained with this device in older adults and in patients with oropharyngeal impairments resulting from various neurological and structural conditions. Additional research is also needed to assess discriminative validity, examine the effects of age and sex on the measurements, and establish normative values for tongue strength and endurance across age groups.

Conclusion

This study led to the development of a prototype device to measure tongue force against the palate and assess four indices of tongue function: strength, isometric endurance, isotonic endurance, and power. The device was easy for clinicians to use, at least in healthy individuals, and no major practical difficulties were encountered. Tongue strength and isometric endurance measurements demonstrated very high test–retest reliability in healthy young adults. Nevertheless, further studies are required in older adults and individuals with oropharyngeal impairments.

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Authors' Contribution

Design and conceptualization: Marzieh Poorjavad, Peyman Amirifar
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Analysis and interpretation of results: Marzieh Poorjavad
Statistical expert services: Marzieh Poorjavad
Manuscript preparation: Marzieh Poorjavad, Peyman Amirifar
Expert evaluation of the manuscript in terms of scientific content: Marzieh Poorjavad, Peyman Amirifar
Final approval of the manuscript: Marzieh Poorjavad, Peyman Amirifar
Responsibility for the integrity of the study from inception to publication and for responding to reviewers' comments: Marzieh Poorjavad, Peyman Amirifar

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Conflict of Interest

The authors did not have a conflict of interest.

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