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REVIEW ARTICLE

A Systematic Review and Meta-analysis of Measurements of Tongue and Hand Strength and Endurance Using the Iowa Oral Performance Instrument (IOPI)

Valerie Adams · Bernice Mathisen · Surinder Baines · Cathy Lazarus · Robin Callister

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Abstract The purpose of this systematic review was to examine the evidence for the use of the Iowa Oral Performance Instrument (IOPI) to measure strength and endurance of the tongue and hand in healthy populations and those with medical conditions. A systematic search of the scientific literature published since 1991 yielded 38 studies that addressed this purpose. The IOPI was used primarily for tongue strength (38 studies) and endurance (15 studies) measurement; relatively few studies measured hand strength (9 studies) or endurance (6 studies). The majority of the studies identified used the IOPI as an evaluation tool, although four used it as an intervention tool. Half the studies were conducted in healthy people, primarily adults. Most of the other participants had disorders with dysphagia, primarily Parkinson's disease or head or neck cancer. Age and gender, as well as a number of medical conditions, influence the values of tongue and hand strength. There is sufficient evidence to support the use of the IOPI as a suitable tool for measuring tongue strength and endurance and as an assessment tool for intervention studies, and there is growing support for its use to assess hand strength and endurance in healthy and clinical populations.

Keywords Tongue strength · Iowa Oral Performance Instrument · Systematic review · Meta-analysis · Deglutition · Deglutition disorders

V. Adams · R. Callister (✉)
Priority Research Centre in Physical Activity and Nutrition, School of Biomedical Sciences and Pharmacy, Faculty of Health, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia
e-mail: Robin.Callister@newcastle.edu.au

B. Mathisen
LaTrobe Rural Health School, Faculty of Health Sciences, LaTrobe University, Bendigo, VIC 3552, Australia

S. Baines
School of Health Sciences, Faculty of Health, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia

C. Lazarus
Department of Otorhinolaryngology Head & Neck Surgery, Albert Einstein College of Medicine of Yeshiva University, and Thyroid Head and Neck Cancer (THANC) Foundation, Beth Israel Medical Center, 10 Union Square East Suite 5B, New York, NY 10003, USA

Introduction

In the early 1990s, new tools to measure the pressure generated by contact between the tongue and palate were developed which offered speech-language pathologists an objective means of assessing tongue strength and endurance. One such tool was the Iowa Oral Performance Instrument (IOPI) [1], which has been used primarily in the US over the past two decades. The IOPI was originally developed to examine the relationships between tongue strength or endurance and speech motor control; its role has subsequently been extended to examine relationships with swallowing. Over this time a number of research studies have been conducted using the IOPI on both healthy and clinical populations to provide data that can be used to establish normative IOPI values for tongue strength and endurance and to investigate the possible influences of age, gender, and medical condition on these values [2–30].

The IOPI is a portable, handheld device that uses an air-filled pliable plastic tongue bulb (approximately 3.5 cm long and 4.5 cm in diameter with an approximate internal volume of 2.8 ml) connected via an 11.5-cm-long clear plastic tube to measure peak pressure [in kilopascals (kPa)] exerted on the tongue bulb. It contains pressure-sensing circuitry, a peak-hold function, and a timer. Researchers have used this device in many studies to measure tongue strength and endurance with excellent interrater reliability [2, 3]. Currently it is one of the most commonly used measurement techniques available to objectively measure tongue strength and endurance [31]. A hand bulb has also been developed for use with the IOPI, to assess hand strength and endurance.

Therefore, the primary aim of this systematic review was to evaluate the utility of the IOPI as an effective tool for assessing both tongue and hand strength and endurance in healthy and clinical populations and, if possible, to identify representative values of these measures. Secondary aims were to investigate the effects of age and gender on the measured values and, the impact of clinical conditions, and to determine how the IOPI can be used as an intervention tool to improve tongue strength and/or endurance. Meta-analyses to consolidate these effects were conducted where appropriate.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [32] and the Consolidated Standards of Reporting Trials (CONSORT) statement [33] guided the conduct and reporting of this review.

Eligibility Criteria

A systematic computer-based search of 21 databases (Table 1) and Google Scholar was conducted between January 1990 and April 2012. The search terms used were "Iowa Oral Performance Instrument" and "IOPI." The search was limited to publications in English and peer-reviewed journals. An additional search of the databases using "tongue strength" was conducted to ensure maximum inclusion of potential articles. All reference lists in selected journal articles were screened for additional potentially relevant articles that met the eligibility criteria. The first authors of two relevant journal articles [3, 16] were contacted in April and June 2012 to obtain participant numbers, gender balance, and standard deviations from those studies to allow them to be included in the review. Eligible studies included cross-sectional, time series, prospective cohort, and randomized controlled studies that provided values for tongue or hand strength or endurance measured with the IOPI, and studies that evaluated the IOPI as an intervention tool in measuring strength/endurance in healthy or disordered populations. Exclusion criteria were studies that did not use the IOPI as a measurement device; abstracts, theses, posters or conference papers; or papers that contained no relevant data.

Table 1 A systematic computer-based search of electronic databases and vendors

Cochrane library (Wiley Interscience)
CINAHL
EBSCO (Academic search complete, Communications & mass, media complete, Education resources complete, Health source: Nursing, Masterfile premier, Psyc & Behavioural sciences collection, SportsDiscus)
Embase (Elsevier)
Linguistics Language Behavior Abstracts (LLBA)
Medline
OVID
Proquest
PubMed
ScienceDirect
Scopus
SpringerLink
Taylor & Francis
Web of knowledge (science citation index; social science citation index)

Study Selection

After duplicates were deleted, eligibility assessment was performed independently in an unblinded standardized manner by the first author (VA), with any uncertainties resolved by a second author (RC). Retrieved records were screened for relevance and inclusion by title and abstract.

Data Extraction Process and Data Items

All data were extracted from the studies by one author (VA). If available, statistics such as 95 % confidence interval (CI) or standard error (SE) were converted to the required form [mean ± standard deviation (SD)] according to the calculations outlined in the Cochrane Handbook for Systematic Reviews of Interventions (Sects. 7.7 and 16.1.3.2) [34]. Information extracted included (1) authors and year of publication, (2) setting, (3) groups if appropriate, (4) number of participants, (5) gender, (6) mean age, (7) age range, (8) means and standard deviations (SD) of IOPI measures, (9) outcomes of any comparisons between groups and whether p values were reported, (10) effect size of any comparisons, and (11) a clear population description (healthy or with disorders).

Studies that were published after 2000 used the second-generation IOPI tongue bulbs (soft vinyl blue plastic bulbs attached to a polyethylene tube with a 2-mm inner diameter). Studies measuring tongue strength published prior to 2000 were further examined to determine bulb texture and

Table 2 A 10-item quality checklist scale and explanation of scoring for randomized control trials

Indicator	Quality marker
Study design	Controlled trial*
	Cohort study
	Retrospective case control or single-subject design
	Case series
	Case study
Blinding	Assessors blinded*
	Assessors not blinded or not stated
Sampling/allocation	Random sample adequately described*
	Random sample inadequately described
	Convenience sample adequately described
	Convenience sample inadequately described or hand-picked sample or not stated
Group/participant comparability	Groups/participants at baseline on important factors (between-subject design) or participant(s) adequately described (within-subject design)*
	Groups/participants not comparable at baseline or comparability not reported or participant(s) not adequately described
Outcomes	At least one primary outcome measure is valid and reliable*
	Validity unknown but appears reasonable; measure is reliable
	Invalid and/or unreliable
Significance	*p* value reported or calculable*
	p value neither reported or calculable
Precision	Effect size and confidence interval reported or calculable*
	Effect size or confidence interval, but not both, reported or calculable
Intention to treat (controlled trials only)	Analysed by intention to treat*
	Not analysed by intention to treat or not stated

* Indicates highest level of quality

colour. Because of slightly different internal volumes and surface areas, pressure values obtained from first-generation clear air-filled tongue bulbs or latex bulbs must be multiplied by 0.87 to be comparable to the data from the second-generation bulb [19]; this correction was made where required to the values reported in this review. Whether this correction adequately addresses all variations in the materials in the early years is uncertain.

Risk of Bias in Intervention Studies

Risk of bias was assessed for randomized controlled trials and prospective cohort studies by two authors (VA and RC) using a 10-item quality checklist adapted from the CONSORT statement [35]. In the case of disagreement, discussion took place until a consensus was reached. The items and explanations of the scoring for each item are reported in Table 2. Each item was scored with a "1" for "yes" or "0" for "no." The studies were then classified as having a low (score $\geq$ 6) or high risk of bias (score $\leq$ 5).

Summary Measures and Synthesis of Results

The primary outcome measures for this review were the means $\pm$ SD of the IOPI measures [tongue and hand strength (kPa) and endurance (seconds, s)] for the described population samples. Differences between population groups and the effects of intervention studies were examined using statistical comparisons and effect sizes such as Cohen's *d*. Meta-analyses of healthy participants with outcomes for tongue strength (kPa) and tongue endurance (s) were conducted on eligible evaluation studies. Results were pooled in separate meta-analyses using RevMan 5.1.4 for Windows (The Cochrane Collaboration). All data were continuous and reported on the same scale for age and gender. The aggregate result was calculated as the weighted mean difference (WMD) between age and/or gender. Funnel plots to assess publication bias were generated if more than ten studies were included in the meta-analysis [34]. Meta-analysis was deemed inappropriate if results from fewer than three studies were compatible for analysis.

Results

Study Selection

A search across 21 databases identified a total of 295 articles for inclusion in the review (Fig. 1). An additional 47 articles were identified from searching the reference lists of the included articles. After deleting duplications, 162 remained. Of these, 126 studies were excluded as they did not meet the eligibility criteria. The full texts of the remaining 42 articles were examined in greater detail. Four of these articles did not meet the inclusion criteria as they did not provide IOPI data on tongue or hand strength or endurance. Thirty-eight studies met the inclusion criteria and were included in the systematic review.

Study Characteristics

Of the 38 included studies, 36 were conducted in the US, one in Brazil, and one in Taiwan. The collective sample size was 1,729 participants, with 882 males (51 %) and 847 females. Participants consisted of 53 % healthy people and 47 % from disordered populations [Parkinson's disease (PD), head and neck cancer (HNC), multiple sclerosis (MS), motor neuron disease (MND), traumatic brain injury (TBI), nasopharyngeal cancer (NPC), oculopharyngeal muscular dystrophy (OPMD), cerebrovascular accident (CVA), developmental apraxia of speech (DAS), developmental verbal dyspraxia (DVD)]. The participants were recruited from the community (24 %), clinics (21 %), had no setting stated (21 %), hospitals (16 %), schools or universities (13 %), or from other research projects (5 %). Age ranges included children and adolescents (3–17 years) and adults (18–96 years). Included studies were classified as evaluation studies 87 % ($n = 33$) or intervention studies 13 % ($n = 5$).

Evaluation Studies

Tongue Strength in Healthy Populations

Sixteen studies (adults $n = 14$ and children $n = 2$) reported measures of tongue strength in healthy individuals (Table 3). Mean values ranged from 43 to 78 kPa in healthy adults.

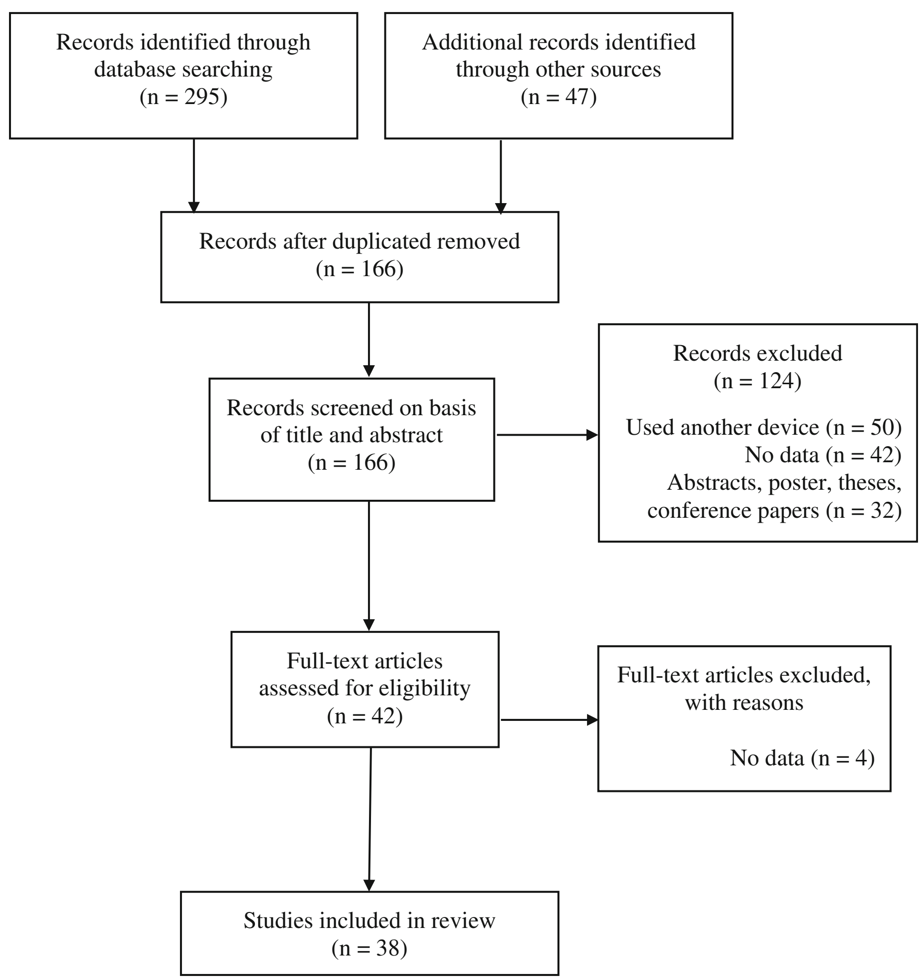

Fig. 1 A flowchart of the literature search pertaining to the IOPI for measuring tongue and hand strength and endurance

Twelve studies reported data for healthy adult males and females; mean values for tongue strength in healthy males ranged from 49.25 ± 18.64 to 73.33 ± 12.03 kPa compared to moderately lower values for healthy females (37.00 ± 11.36–66.96 ± 11.60 kPa) at similar ages. Values of tongue strength in the healthy adult population were reported primarily for anterior elevation and secondarily for posterior elevation. Reports of other tongue strength measures using the IOPI (i.e., lateralization and protrusion) were not considered for this review. Three studies [5, 7, 15] measured tongue strength in both the anterior and the posterior position. Two studies [5, 15] investigated tongue strength anteriorly and posteriorly and reported values 4–9 kPa below the norm. Tongue strength measured in the anterior position (56.50 ± 13.60–73.33 ± 12.03 kPa) was typically stronger than in the posterior position (52.00 ± 15.20–55.75 ± 13.58 kPa). In addition, findings from these three studies indicated that males (57.50 ± 15.10–73.33 ± 12.03 kPa) were stronger than females (56.50 ± 13.60–61.27 ± 14.80 kPa) anteriorly but not posteriorly.

One study [14] reported values of tongue strength that were much lower than those reported by previous studies of healthy participants. Measures of tongue strength in this study were obtained while simultaneously recording from intramuscular electrodes inserted into the muscles of the tongue. No pre-electrode-insertion measures had been obtained but one female participant was measured when only a few electrodes were inserted (43 kPa) and again with all electrodes in place (29 kPa); a substantial decrease in tongue strength was observed with more electrodes, which explains the low values reported in this study. Males (range = 34–72 kPa, mean = 49 kPa) again were found to be stronger than females (range = 32–50 kPa, mean = 37 kPa).

Maximum tongue strength was observed to decrease with increasing age in nine studies involving healthy adults [2–4, 6, 7, 9, 10, 15, 36]. Results from these studies indicated that maximum tongue strength of the oldest adults was, on average, 10–15 kPa lower than that of young adults. Two studies investigated tongue strength in healthy children. Potter et al. [37] studied children aged 3–5 years and found tongue strength increased with age ($p < 0.001$). In another article, Potter et al. [38] reported tongue strength in children and adolescents (3–17 years) and found significant differences in tongue strength with age up to 10 years, after which no significant age-related differences were observed [38].

Tongue Strength in Populations with Disorders

Seventeen studies (adults $n = 15$ and children $n = 2$) reported measures of tongue strength (kPa) in populations with a disorder (Table 4). The main disorders were PD ($n = 5$), HNC ($n = 3$), and OPMD ($n = 2$). Mean values for PD ranged from 44.26 ± 3.22 to 55.11 ± 13.82 kPa, with higher tongue strength values in males than in females. Three studies investigated HNC [18, 20, 25], with values ranging from 37.05 ± 14.42 to 56.00 kPa. Lazarus et al. [25] reported that mean maximum tongue strength at 1 month after treatment was not significantly different than that at pretreatment but did increase significantly 6 and 12 months after treatment. Two studies investigated OPMD [23, 30] and found values much lower (19.50 ± 0.71–26.90 ± 7.80 kPa) than those of healthy controls and those with other disorders such as PD.

Tongue Endurance in Healthy Populations

Tongue endurance (s) was measured isometrically at 50 % of maximal tongue strength (P_{max}) in the anterior position (unless otherwise stated) and reported in four studies (Table 3) in healthy people. The effect of age on tongue endurance in males and females in four age groups (young, middle-aged, older, and elderly) was examined [10]. Regardless of age or sex, overall mean tongue endurance was 44.80 ± 28.00 s, and no significant differences in tongue endurance with age were observed ($p = 0.67$). Mean tongue endurance values ranged from 15.72 ± 5.86 to 37.85 ± 23.55 s for males and from 16.23 ± 7.07 to 36.35 ± 11.74 s for females, with no significant age effects in either males ($p = 0.61$) or females ($p = 0.33$). A comparison of tongue endurance in two age groups (20–35 and 65–82 years) and in two positions on the tongue (anterior and posterior) was conducted [15]. Significant differences in tongue endurance between the anterior and posterior position were observed ($p = 0.0005$) but no significant age or gender differences were reported. Neel and Palmer [6] examined tongue endurance in males and females in two age groups (20–40 and 42–78 years). Males had higher values than females ($p < 0.03$) and there was a trend for older adults to have higher values than younger adults ($p < 0.10$). The mean values for each subgroup were as follows: older males, 44.70 ± 28.40 s; younger males, 31.00 ± 17.40 s; older females, 27.70 ± 17.70 s; and younger females, 23.20 ± 9.20 s. Vitorino et al. [4] measured the tongue endurances of three age groups (20–40, 41–60, and 61–80 years) and found that they were lower than those in other studies; however, no significant differences were reported across age ($p > 0.05$) or gender ($p > 0.05$). Robin et al. [8] investigated tongue endurance in individuals with high tongue skills levels (e.g., trumpet players and debaters). Although values were not provided (other than in a figure), they reported that both debaters and trumpet players had substantially higher endurance values than healthy controls.

Table 3 Studies investigating tongue strength and endurance in a healthy population

Study name	Year	Age range (years)	*n*	Gender	Tongue strength (kPa)			Tongue endurance (s) @ 50 % Pmax		
					M and F across age groups	Males	Females	M and F across age groups	Males	Females
Adult studies										
IOPI website										
Young						65.00	60.00		35.00	35.00
Old						65.00	60.00		35.00	30.00
Robin et al. [8][a]	1992		12	8M, 4F						
Trumpeters		18–48			65.25 ± 11.74					
Control		18–49			65.98 ± 12.70					
Debaters		16–17	5	3M, 2F	77.63 ± 4.17					
Control		16–17			76.76 ± 6.00					
Robbins et al. [9][a]	1995		24	24M						
Young		22–33				49.30 ± 7.21				
Old		67–83				41.04 ± 2.17				
Crow and Ship[a]	1996		99	52M, 47F		65.08 ± 18.90	56.29 ± 19.60			
		19–39			65.85 ± 17.30			43.90 ± 21.30		
		40–59			65.42 ± 23.60			41.90 ± 24.30		
		60–79			60.47 ± 17.30			48.00 ± 40.80		
		80–96			46.72 ± 13.30			45.20 ± 25.50		
Solomon et al. [11][a]	1996	18–23	12	6M, 6F	60.47 ± 9.62	67.14 ± 9.13	53.80 ± 10.09			
Solomon et al. [12]	2002	19–26	10	5M, 5F	61.29 ± 8.80	65.82 ± 10.64	56.76 ± 6.45			
Solomon et al. [13]	2004	20–38	10	2M, 8F	61.60 ± 9.88		61.75 ± 9.53			
Youmans and Stierwalt [2]	2006		90	45M, 45F		64.00 ± 2.03	55.90 ± 1.86			
		20–39				72.00 ± 13.40	55.70 ± 12.50			
		40–59				63.90 ± 11.80	59.10 ± 14.00			
		60–96				56.10 ± 11.60	52.90 ± 10.70			
Palmer et al. [14]	2008		7	4M, 3F						
		24–37				49.25 ± 18.64				
		21–30					37.00 ± 11.36			
Youmans et al. [3]	2008		96	48M, 48F						
		20–39				77.65 ± 18.50	73.25 ± 10.42			
		40–59				69.63 ± 7.39	70.06 ± 11.52			
		60–79				62.69 ± 13.04	57.56 ± 12.73			

Table 3 continued

					Tongue strength (kPa)			Tongue endurance (s) @ 50 % Pmax		
Study name	Year	Age range (years)	*n*	Gender	M and F across age groups	Males	Females	M and F across age groups	Males	Females
Vitorino [4]	2010		75	35M, 40F	56.59 ± 2.73	56.81 ± 1.36	56.37 ± 4.07		15.72 ± 2.29	16.23 ± 2.11
Young		20–40				58.18 ± 7.07	57.05 ± 8.48		15.12 ± 6.73	17.30 ± 10.03
Middle		41–60				55.46 ± 7.69	60.06 ± 7.24		18.25 ± 7.32	17.60 ± 6.35
Old		61–80				56.80 ± 6.87	52.00 ± 5.00		13.80 ± 2.05	13.80 ± 3.03
Kays et al. [15]	2010		22	10M, 12F						
Young (anterior)		20–35				59.20 ± 5.20	67.80 ± 10.60		40.20 ± 14.00	37.50 ± 11.80
Young (posterior)						50.00 ± 7.90	62.50 ± 14.50		26.00 ± 19.50	29.60 ± 9.30
Old (anterior)		65–82				62.60 ± 8.80	50.30 ± 11.10		29.60 ± 12.50	34.30 ± 19.30
Old (posterior)						61.40 ± 7.50	49.00 ± 12.60		24.20 ± 13.60	24.40 ± 14.40
Neel and Palmer [6]	2011	20–78	57	29M, 28F	65.28 ± 12.04	69.35 ± 10.85	61.00 ± 10.10		37.85 ± 9.69	25.45 ± 3.18
		20–40				74.10 ± 11.80			31.00 ± 17.40	
		22–40					64.60 ± 9.80			23.20 ± 9.20
		42–78				64.80 ± 12.10			44.70 ± 28.40	
		42–74					57.20 ± 7.60			27.70 ± 17.70
Gingrich et al. [7]	2012	18–34	30	15M, 15F						
Anterior						73.33 ± 12.03	61.27 ± 14.80			
Posterior						53.60 ± 14.33	50.07 ± 14.44			
Clark and Solomon [5]	2012	18–89	171	88M, 83F						
All males (anterior)						57.50 ± 15.10				
All males (posterior)						52.00 ± 15.20	56.50 ± 13.60			
All females (anterior)					55.80 ± 13.50		53.60 ± 14.20			
All females (posterior)		18–29			52.30 ± 13.20					
Young (anterior)		30–59			62.80 ± 13.00					
Young (posterior)					57.90 ± 16.70					
Middle (anterior)		60–89			51.00 ± 15.00					
Middle (posterior)					47.40 ± 16.70					
Old (anterior)										
Old (posterior)										
Child studies										
Potter et al. [37]		3–5	48	24M, 24F	28.50 ± 8.77					
Potter et al. [38]		3–17	148	71M, 77F		48.08 ± 18.85	38.16 ± 8.14			

Values are mean ± SD unless stated otherwise

[a] Values in these studies multiplied by 0.87

Tongue Endurance in Populations with Disorders

Ten studies (adults $n = 9$ and children $n = 1$) measured tongue endurance (s) isometrically at 50 % of maximum tongue strength in populations with disorders (Table 4). Five disorders accounted for most of those measured: PD, HNC, OPMD, NPC, and TBI. Three studies' [16, 17, 19] endurance values ranged from 6.00 to 23.23 ± 11.14 s compared to those of a control group (23.14 ± 11.58–38.46 ± 32.05 s). Females in PD studies (22.20 ± 20.81 s) were better able to hold 50 % maximum tongue strength than males (21.10 ± 9.52 s). Stierwalt and Youmans [26] examined tongue endurance in patients with various medical conditions, including 29 participants following CVA, with males reporting longer endurance times (49.85 ± 52.27 s) than females (37.77 ± 37.30 s). No endurance data were available for individuals following CVA. One study [39] investigated children with DAS and/or DVD and found that males (14.50 ± 14.47 s) had better endurance than females (8.78 ± 10.54 s). Males in the control group (38.14 ± 17.10 s) also had longer endurance times than female controls (24.00 ± 19.91 s). This study also reported that children with DVD and/or DAS (9.10 ± 4.84 s) were not able to hold an endurance level similar to the control group (24.03 ± 4.13 s) [39].

Comparisons with healthy control groups indicate that populations with disorders have significantly lower tongue endurance, with the magnitude of the decrease dependent on the specific medical condition; this was demonstrated in a study on OPMD in older adults by Palmer et al. [30]. Compared to a control group, the OPMD group showed a decrease in tongue endurance; however, it was not significant [30].

Hand Strength in Healthy Populations

Only three studies (adults $n = 2$ and children $n = 1$) reported hand strength (kPa) in healthy individuals (Table 5). Such a small number of studies provides little basis for the establishment of normative hand strength values in healthy adults. Crow and Ship [10] investigated the effects of age and gender on hand strength in healthy adults, with males (155.10 ± 44.60 kPa) stronger ($p < 0.001$) than females (123.60 ± 27.20 kPa). Younger adults had the highest values (165.00 ± 43.80 kPa), followed by middle-aged (157.70 ± 34.10 kPa), older (129.00 ± 35.30 kPa), and elderly (110.00 ± 33.20 kPa) groups. Mean hand strength across broader age groups was also reported (140.43 ± 36.60 kPa) with a significant difference in strength ($p < 0.01$) between individuals older than 59 years and younger groups. Robin et al. [8] reported hand strength values for trumpet players (157.34 ± 25.74 kPa) and a control group (171.58 ± 23.32 kPa), with a significant difference observed ($p < 0.0001$). A debaters group (171.35 ± 13.20 kPa) showed values that were also significant ($p < 0.0002$) when compared to a control group (181.13 ± 23.32 kPa). Potter et al. [37] reported a mean hand strength of 48.41 ± 8.18 kPa in 48 children aged 3–5 years.

Hand Strength in Populations with Disorders

Five studies (adults) reported measures of hand strength (kPa) in populations with medical conditions (Table 6), primarily PD. Two studies [17, 19] examined hand strength in older adults with PD. Solomon et al. [17] reported that males (131.20 ± 29.84 kPa) were stronger than females (94.83 ± 35.36 kPa) but not as strong as the age- and gender-matched control groups (males 150.08 ± 34.13, and females 120.64 ± 25.16). Solomon et al. [19] reported values for males and females with PD (140.33 ± 23.46 and 98.25 ± 14.31 kPa respectively); however, these values were not significantly different ($p = 0.362$) from those of male and female control group participants (136.58 ± 23.75 and 101.75 ± 24.88 kPa, respectively).

Hand Endurance in Healthy Populations

Two studies (adults $n = 1$ and children $n = 1$) measured hand endurance at 50 % of maximum hand strength. One study [10] measured hand endurance in healthy adults (Table 5). Mean hand endurance, regardless of age, was 79.40 ± 45.25 s, and there were no significant differences in hand endurance with age whether analysed with all participants ($p = 0.41$) or by gender (males, $p = 0.38$, and females, $p = 0.56$). Mean values reported for different age groups were as follows: middle-aged adults, 88.50 ± 39.60 s; adults, 84.20 ± 46.60 s; elderly adults, 72.60 ± 50.50 s; and younger adults, 72.30 ± 44.30 s. There was a trend ($p = 0.08$) for females to sustain hand endurance longer (90.30 ± 49.80 s) than males (74.20 ± 38.30 s). Robin et al. [39] examined hand endurance in 26 healthy adults and 6 healthy children. Children sustained hand endurance for an average of 24.03 ± 4.13 s while adults averaged 36.31 ± 10.13 s ($p < 0.05$).

Hand Endurance in Populations with Disorders

Five studies (adults $n = 4$ and children $n = 1$) reported on hand endurance in populations with disorders (Table 6). Three studies examined PD [16, 17, 19]. Solomon et al. [16] reported three case studies (one male and two females) and found reduced or abnormal findings for hand endurance. In another study, Solomon et al. [17] reported hand endurance values for males (44.81 ± 45.95 s) and females (46.50 ± 18.48 s) with a statistically significant difference between PD and control groups ($p = 0.025$). In yet another study, Solomon et al. [19] reported hand

Table 4 Studies investigating tongue strength and endurance in populations with a disorder

Study name	Year	Medical condition	Age range (years)	*n*	Gender	Tongue strength (kPa)			Tongue endurance (s)		
						M and F across age groups	Males	Females	M and F across age groups	Males	Females
Adult studies											
Lazarus et al. [25][a]	2007	HNC	29–78	46	35M, 11F						
Baseline						47.00 ± 9.80					
1 month						41.70 ± 8.22					
3 months						51.00 ± 10.12					
6 months						57.50 ± 10.12					
12 months						54.70 ± 8.54					
Lazarus et al. [18]	2000	HNC	38–72	13	10M, 3F	37.05 ± 14.42			−40.62 ± 24.67		
		Control	36–77	13	10M, 3F	60.15 ± 3.68			−37.77 ± 3.18		
Lazarus et al. [20]	2002	HNC	72	1	1M		56.00			−4.00	
		Control	72	1	1M		30.00			13.00	
Chang et al. [27]	2008	NPC	33–63	12	11M, 1F	56.67 ± 9.35			−24.58 ± 10.72		
		Control	30–65	12	11M, 1F	64.50 ± 12.57			−18.75 ± 6.22		
Neel et al. [23]	2006	OPMD	57–67	8	2M, 6F		19.50 ± 0.71	24.67 ± 9.09			
		Control	61,67	2	2F			50.50 ± 0.71			
Palmer et al. [30]	2010	OPMD	50–76	11	3M, 8F		26.90 ± 7.80	26.90 ± 7.80			
		Control	52–76	9	4M, 5F		57.40 ± 10.40	57.40 ± 10.40			
Solomon et al. [16]	1994	PD	43–71	3	1M, 2F		53.00	49.50		6.00	50.00
		Control	43–64	3	1M, 2F		70.00	51.50		25.00	37.50
Solomon et al. [17]	1995	PD	46–73	19	10M, 9F		52.98 ± 19.93	50.07 ± 16.79		23.23 ± 11.14	34.32 ± 47.69
		Control	49–74	19	10M, 9F		63.25 ± 10.66	56.94 ± 9.68		23.14 ± 11.58	28.90 ± 11.44
Solomon et al. [19]	2000	PD	56–81	16	12M, 4F		48.25 ± 10.04	47.75 ± 10.21		21.10 ± 9.52	22.20 ± 20.81
		Control	55–93	16	12M, 4F		53.75 ± 6.18	60.75 ± 14.95		38.46 ± 32.05	32.05 ± 9.84
Solomon [24]	2006	PD	40–75	12	9M, 3F		55.11 ± 13.82	49.00 ± 20.42			
		Control	48–74	15	8M, 7F		63.75 ± 13.96	57.00 ± 7.59			

Table 4 continued

Study name	Year	Medical condition	Age range (years)	n	Gender	Tongue strength (kPa)			Tongue endurance (s)		
						M and F across age groups	Males	Females	M and F across age groups	Males	Females
O'Day et al. [22]	2005	PD	52–79	10	10M						
		day 1					38.70 ± 13.15				
		day 2					45.30 ± 13.55				
		day 3					47.10 ± 11.42				
		day 4					45.00 ± 12.89				
		day 5					45.20 ± 16.12				
		Control									
		day 1					55.10 ± 18.86				
		day 2					58.50 ± 14.65				
		day 3					62.10 ± 13.62				
		day 4					58.80 ± 15.59				
		day 5					59.00 ± 15.57				
Robin et al. [39]	1991	TBI	26	1	1F			38.28			25.00
		Control	20–49	26	5M, 21F	61.77					36.31 ± 10.13
Yeates et al. [29][a]	2008	TBI, HNC,	50–72	3	3M						
Anterior		CVA					45.25 ± 19.37				
Posterior							42.24 ± 21.95				
Clark et al. [21][a]	2003	Various	19–95	63	28M, 35F	32.75 ± 18.44					
Solomon et al. [28][a]	2008	Various	18–78	44	40M, 4F		43.18 ± 20.00	48.25 ± 13.82		38.28 ± 24.57	32.00 ± 21.83
Stierwalt and Youmans [26]	2007	Various	26–91	50	16M, 26F		42.89 ± 15.60	31.03 ± 15.85		49.85 ± 52.27	37.77 ± 37.30
		Control	26–90	50	16M, 26F		63.24 ± 13.86	57.15 ± 13.50		42.77 ± 16.14	37.15 ± 30.55
Child studies											
Robin et al. [39]	1991	DAS, DVD	8–10	5	4M, 1F	40.02			−9.10 ± 4.84		
		Control	6–12	6	4M, 2F	56.55			24.03 ± 4.13		
Stierwalt et al. [40]	1996	TBI	6–17	23	14M, 9F		56.24 ± 18.67	36.05 ± 13.58		14.50 ± 14.47	−8.78 ± 10.54
		Control	6–17	23	14M, 9F		64.44 ± 11.82	47.56 ± 9.73		38.14 ± 17.10	24.00 ± 19.91

Values are mean ± SD unless state otherwise

[a] No control group used

HNC head or neck cancer, *NPC* nasopharyngeal cancer, *OPMD* oculopharyngeal muscular dystrophy, *PD* Parkinson's disease, *TBI* traumatic brain injury, *DAS* developmental apraxia of speech, *DVD* developmental verbal dyspraxia

Table 5 Studies investigating hand strength and endurance in a healthy population

Study name	Year	Age range (years)	*n*	Gender	Hand strength (kPa)			Hand endurance (s)		
					M and F across age groups	Males	Females	M and F across age groups	Males	Females
Adult studies										
IOPI website						150.00	140.00		40.00–60.00	40.00–60.00
Robin et al. [8]	1992									
Trumpeters		18–48	12	8M, 4F	157.35 ± 25.74					
Control		18–49			171.58 ± 23.32					
Debaters		16–17	5	3M, 2F	171.35 ± 13.20					
Control		16–17			181.13 ± 23.32					
Crow and Ship [10]	1996	19–96	99	52M, 47F		155.10 ± 44.60	123.60 ± 27.20		74.20 ± 38.30	90.30 ± 49.80
		19–39			165.00 ± 43.80			72.30 ± 44.30		
		40–59			157.70 ± 34.10			88.50 ± 39.60		
		60–79			139.00 ± 35.30			84.20 ± 46.60		
		80–96			110.00 ± 33.20			72.60 ± 50.50		
Child study										
Potter et al. [38]	2009	3–5	48	24M, 24F	48.41 ± 8.18					

Values are mean ± SD unless stated otherwise

endurance values for males (53.18 ± 20.79 s) and females (63.40 ± 39.48 s) with no significant difference between the disordered and control groups ($p = 0.805$). Stierwalt et al. [40] measured hand endurance in 23 children with TBI compared to a control group and found a significant difference between groups ($p = 0.0001$). One study [39] reported hand endurance for children aged 8–10 years with DAS of 11.57 ± 6.96 s, which was significantly different ($p < 0.05$) to that for the healthy control group (48.00 ± 10.14 s). This study also reported values for one female with TBI (56.00 s) and found a comparable result to a control group (56.49 ± 13.70 s) (no p value reported).

Results of Meta-Analyses

Meta-analyses were conducted for tongue strength and endurance for age and gender. Funnel plot comparison for meta-analyses 2, 3, and 4 were not generated as fewer than ten studies were included. Meta-analysis was deemed inappropriate for younger participants (<60 years) versus older participants (60+ years) for males and females as results from fewer than three studies were compatible for analysis.

Tongue Strength

Meta-Analysis 1

A total of 816 participants (425 males and 391 females) from 17 studies, with an age range of 19–96 years, were included. The studies were statistically heterogeneous ($\tau^2 = 20.05$; $\chi^2 = 112.78$, df = 16, $p < 0.00001$, $I^2 = 86$ %), so the random-effects model was used. Meta-analysis (Fig. 2) revealed statistically significant greater tongue strength in males than in females [WMD = 5.21 kPa (95 % CI 2.26, 8.17), $Z = 3.46$, $p = 0.0005$]. As this meta-analysis used a random-effects estimate, a funnel plot comparison for tongue strength to assess publication bias was not generated even though more than ten studies were included. Random-effects estimates give greater relative weight to smaller studies and may lead to wider CIs [34].

Meta-Analysis 2

Two age groups were considered: <60 years (younger) and 60+ years (older). Younger adults ($n = 484$) were compared to older adults ($n = 275$) from eight studies (total 759). The studies were not statistically heterogeneous ($\chi^2 = 3.54$, df $= 7$, $p = 0.83$, $I^2 = 0$ %) so the fixed-effects model was used. Meta-analysis (Fig. 3) revealed statistically significant greater tongue strength in adults <60 years compared to adults 60+ years [WMD = 8.30 kPa (95 % CI 6.37, 10.23), $Z = 8.43$, $p < 0.00001$).

Table 6 Studies investigating hand strength and endurance in populations with a disorder

Study name	Medical condition	Age range (years)	*n*	Gender	M and F across ages	Hand strength (kPa)		Hand endurance (s)	
						Males	Females	Males	Females
Adult studies									
Robin et al. [39]	TBI	26	1	1F			132.00		56.00
	Control	20–49	26	5M, 21F	110.00				56.49 ± 13.70
Solomon et al. [16]	PD	43–71	3	1M, 2F		273.00	131.75	33.00	67.50
	Control					156.00	147.50	24.00	45.00
Solomon et al. [17]	PD	46–72	19	10M, 9F		131.20 ± 29.84	94.83 ± 35.36	44.81 ± 45.95	46.50 ± 18.48
	Control					150.08 ± 34.13	120.64 ± 25.16	41.67 ± 21.98	48.72 ± 20.24
Solomon et al. [19]	PD	56–81	16	12M, 4F		140.33 ± 23.46	98.25 ± 14.31	53.18 ± 20.79	63.40 ± 39.48
	Control					136.58 ± 23.75	101.75 ± 24.88	57.38 ± 16.19	60.63 ± 50.63
O'Day et al. [22]	PD	52–79	10	10M					
	day 1					105.90 ± 32.93			
	day 2					106.10 ± 28.93			
	day 3					110.50 ± 38.55			
	day 4					109.20 ± 31.62			
	day 5					111.70 ± 38.67			
	Control								
	day 1					133.20 ± 25.62			
	day 2					139.30 ± 25.27			
	day 3					136.90 ± 24.03			
	day 4					134.20 ± 23.71			
	day 5					137.50 ± 18.09			
Child study									
Robin et al. [39]	DAS, DVD	8–10	5	4M, 1F					11.57 ± 6.96
	Control	6–12	6	4M, 2F					48.00 ± 10.14

Values are mean ± SD unless stated otherwise

HNC head or neck cancer, *NPC* nasopharyngeal cancer, *OPMD* oculopharyngeal muscular dystrophy, *PD* Parkinson's disease, *TBI* traumatic brain injury, *DAS* developmental apraxia of speech, *DVD* developmental verbal dyspraxia

Meta-Analysis 3

Two age groups were considered for males ($n = 156$): <60 years (younger) and 60+ years (older). There were five studies that included 93 younger males and 63 older males. Studies were not statistically heterogeneous ($\chi^2 = 7.83$, df = 4, $p = 0.10$, $I^2 = 49$ %), so the fixed-effects model was used. Meta-analysis (Fig. 4) revealed that younger males had significantly stronger tongue strength than older males [WMD = 8.00 kPa (95 % CI 4.92, 11.08), $Z = 5.09$, $p < 0.00001$].

Meta-Analysis 4

Two age groups were considered for females ($n = 133$): <60 years (younger) and 60+ years (older). There were four studies that included 80 younger females and 53 older females. Studies were not statistically heterogeneous ($\chi^2 = 5.40$, df = 3, $p = 0.14$, $I^2 = 44\%$), so the fixed-effects model was used. Meta-analysis (Fig. 5) revealed that younger females had significantly stronger tongue strength than older females [WMD = 9.43 kPa (95 % CI 5.57, 13.28), $Z = 4.79$, $p < 0.00001$).

Tongue Endurance

We conducted one meta-analysis that included six studies with a total of 231 subjects (112 males and 119 females). The evaluation studies were statistically heterogeneous ($\chi^2 = 7.37$, df = 5, $p = 0.19$, $I^2 = 32\%$), so the fixed-effects model was used. The meta-analysis (Fig. 6) revealed no statistically significant difference in tongue endurance between adult males and females across all ages [WMD = −0.40 s (95 % CI −1.39, 0.58), $Z = 0.80$, $p = 0.42$].

	Adults < 60y			Adults 60+ y				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Fixed, 95% CI
Clark [43]	59.0812	13.6732	128	51	15	43	14.5%	8.08 [3.01, 13.15]
Crow [10]	65.58	21.2537	43	57.278	17.3625	56	6.1%	8.30 [0.49, 16.11]
Kays [15]	63.8909	9.3363	11	55.8909	11.569	11	4.8%	8.00 [-0.79, 16.79]
Neel [6]	70.0286	11.8069	28	60.6069	10.4156	29	11.1%	9.42 [3.63, 15.21]
Robbins [9]	49.3	7.21	10	41.04	2.17	14	17.5%	8.26 [3.65, 12.87]
Stierwalt [26]	61.5057	13.3688	140	55.01	14.32	60	20.6%	6.50 [2.25, 10.74]
Youmans [2]	62.675	13.5599	60	56.1	11.6	30	12.8%	6.57 [1.19, 11.96]
Youmans [3]	72.6475	12.7437	64	60.125	12.9415	32	12.5%	12.52 [7.06, 17.99]
Total (95% CI)			**484**			**275**	**100.0%**	**8.30 [6.37, 10.23]**

Heterogeneity: Chi² = 3.54, df = 7 (P = 0.83); I² = 0%
Test for overall effect: Z = 8.43 (P < 0.00001)

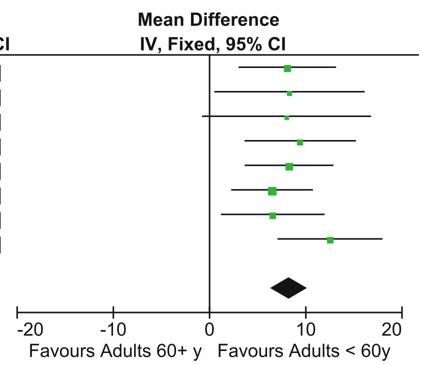

Fig. 2 Forest plot of comparison: tongue strength by age and gender, adults <60 years vs adults 60+ years

	Males			Females				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Youmans [2]	0	2.03	45	55.9	1.86	0		Not estimable
Solomon [13]	61	15.56	2	61.75	9.53	8	1.1%	-0.75 [-23.30, 21.80]
Palmer [14]	49.25	18.64	4	37	11.36	3	1.2%	12.25 [-10.09, 34.59]
Solomon [19]	53.75	6.18	12	60.75	14.95	4	2.4%	-7.00 [-22.06, 8.06]
Solomon [28]	43.18	20	40	48.25	13.82	4	2.4%	-5.07 [-19.96, 9.82]
Solomon [24]	63.75	13.96	8	57	7.59	7	3.9%	6.75 [-4.44, 17.94]
Solomon [12]	65.82	10.67	5	56.76	6.45	5	4.1%	9.06 [-1.87, 19.99]
Solomon [11]	67.14	9.13	6	53.8	10.09	6	4.1%	13.34 [2.45, 24.23]
Gingrich [7]	73.33	12.03	15	61.27	14.8	15	4.9%	12.06 [2.41, 21.71]
Solomon [17]	63.25	10.66	10	56.94	9.68	9	5.3%	6.31 [-2.84, 15.46]
Kays [15]	60.9	7.046	10	59.05	13.8058	12	5.5%	1.85 [-7.10, 10.80]
Stierwalt [26]	63.24	13.86	16	57.15	13.5	26	5.8%	6.09 [-2.46, 14.64]
Crow [10]	65.08	18.9	52	56.29	19.6	47	6.8%	8.79 [1.19, 16.39]
Neel [6]	69.931	12.6291	29	60.5172	9.2806	29	9.3%	9.41 [3.71, 15.12]
Clark [43]	57.5	15.1	88	56.5	13.6	83	11.8%	1.00 [-3.30, 5.30]
Youmans [3]	69.99	7.49	48	66.96	8.29	48	14.1%	3.03 [-0.13, 6.19]
Vitorino [4]	56.81	1.36	35	56.37	4.07	40	17.3%	0.44 [-0.90, 1.78]
Total (95% CI)			**425**			**346**	**100.0%**	**4.50 [2.00, 6.99]**

Heterogeneity: Tau² = 8.91; Chi² = 30.78, df = 15 (P = 0.009); I² = 51%
Test for overall effect: Z = 3.53 (P = 0.0004)

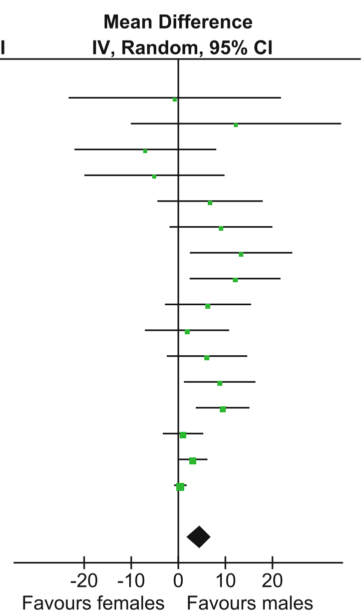

Fig. 3 Forest plot of comparison: tongue strength by age and gender, males vs females

Study or Subgroup	Younger males < 60y Mean	SD	Total	Older males 60+y Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
Kays [15]	59.2	5.2	5	62.6	8.8	5	11.8%	-3.40 [-12.36, 5.56]
Neel [6]	74.1	11.8	16	64.8	12.1	13	12.4%	9.30 [0.54, 18.06]
Robbins [9]	49.3	7.21	10	41.04	2.17	14	44.6%	8.26 [3.65, 12.87]
Youmans [2]	67.95	13.0718	30	56.1	11.6	15	16.8%	11.85 [4.34, 19.36]
Youmans [3]	73.64	14.444	32	62.69	13.04	16	14.4%	10.95 [2.83, 19.07]
Total (95% CI)			**93**			**63**	**100.0%**	**8.00 [4.92, 11.08]**

Heterogeneity: Chi² = 7.83, df = 4 (P = 0.10); I² = 49%
Test for overall effect: Z = 5.09 (P < 0.00001)

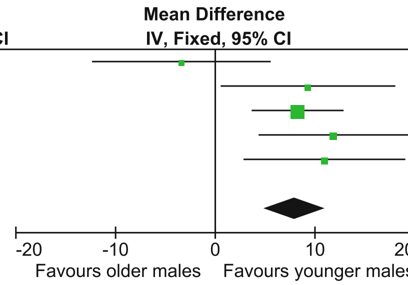

Fig. 4 Forest plot of comparison: tongue strength by age and gender, younger males vs older males

Study or Subgroup	Younger females < 60y Mean	SD	Total	Older females 60+y Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
Kays [15]	67.8	10.6	6	50.3	11.1	6	9.9%	17.50 [5.22, 29.78]
Neel [6]	64.6	9.8	12	57.2	7.6	16	33.3%	7.40 [0.72, 14.08]
Youmans [2]	57.4	13.1545	30	52.9	10.7	15	28.9%	4.50 [-2.67, 11.67]
Youmans [3]	71.655	10.926	32	57.56	12.73	16	27.9%	14.09 [6.80, 21.39]
Total (95% CI)			**80**			**53**	**100.0%**	**9.43 [5.57, 13.28]**

Heterogeneity: Chi² = 5.40, df = 3 (P = 0.14); I² = 44%
Test for overall effect: Z = 4.79 (P < 0.00001)

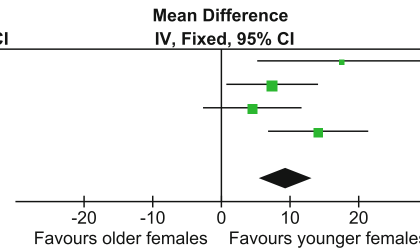

Fig. 5 Forest plot of comparison: tongue strength by age and gender, younger females vs older females

Study or Subgroup	Males Mean	SD	Total	Females Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
Kays [15]	34.9	13.7028	10	35.9	15.3427	12	0.7%	-1.00 [-13.14, 11.14]
Neel [6]	37.1414	23.5784	29	25.7714	14.6177	28	0.9%	11.37 [1.22, 21.52]
Solomon [17]	23.14	11.58	10	28.9	11.44	9	0.9%	-5.76 [-16.12, 4.60]
Solomon [19]	38.46	32.05	12	32.05	9.84	4	0.2%	6.41 [-14.13, 26.95]
Stierwalt [26]	42.77	16.14	16	37.15	30.55	26	0.5%	5.62 [-8.54, 19.78]
Vitorino [4]	15.72	2.29	35	16.23	2.11	40	96.8%	-0.51 [-1.51, 0.49]
Total (95% CI)			**112**			**119**	**100.0%**	**-0.40 [-1.39, 0.58]**

Heterogeneity: Chi² = 7.37, df = 5 (P = 0.19); I² = 32%
Test for overall effect: Z = 0.80 (P = 0.42)

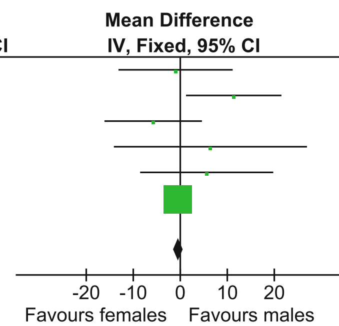

Fig. 6 Forest plot of comparison: tongue endurance by age and gender, males vs females

Intervention Studies

Five studies investigated the effects of intervention on the strength and endurance of the tongue (Table 7). Two RCTs [41, 42] used the IOPI as both an intervention and an evaluation tool and evaluated the effects of tongue-strengthening exercises on tongue strength and endurance in healthy adults. The third RCT [43] randomized participants to five tongue training groups (strength, endurance, power, speed, and no training) and used the IOPI to measure tongue strength, endurance, and power, but not speed, before and after training. Participants in the two prospective cohort studies [44, 45] used the IOPI to measure tongue strength and endurance following an 8-week tongue-strengthening exercise program in older-adult healthy and stroke populations.

Studies varied in the following areas: age groups (18–67, 19–57, 20–29, 51–90, 70–89 years), medical condition (healthy, stroke), gender imbalance (more females than males), study duration (4, 8, or 9 weeks), participant group size (10, 31, 31, and 39), frequency of measurements (time series, fortnightly, or monthly), exercise program (10 repetitions 3 times/day on 3 nonconsecutive days; 10 repetitions 3 times/day for 7 days/week; 10 repetitions 5 times/day for 5 days/week; or 3 sessions per week on 3 nonconsecutive days for 4 weeks). Outcome measures (tongue strength and endurance, only tongue strength, or tongue strength and endurance within specific training groups), tongue bulb position (anterior only or anterior and posterior), and training specificity (directional exercise—elevation, protrusion, lateralization, or none) were reported. The RCT by Clark [43] differed from the other four intervention studies in that it reported Cohen's *d* values as well as *p* values.

Table 7 Studies investigating the use of the IOPI in intervention studies

Study name	Study design	Groups	Health status	Age groups (years)	*n*	Gender	Tongue strength (kPa)		Tongue endurance (s)	
							Baseline	Post-exercise	Baseline	Post-exercise
Adult studies										
Robbins et al. [44]	Prospective cohort	IOPI	Healthy	70–89	10	4M, 6F	41.00	49.00		
Clark et al. [41]	RCT		Healthy	18–67	39	17M, 22F	59.63 ± 14.12			
		TD elevation						66.65 ± 14.50		
		TD protrusion						66.46 ± 14.13		
		TD lateral						66.45 ± 14.91		
Lazarus et al. [42]	RCT		Healthy	20–29	31	12M, 23F				
		TD					64.80 ± 9.48	74.00 ± 7.59	29.70 ± 16.44	43.70 ± 43.96
		IOPI					63.90 ± 6.96	72.10 ± 6.64	20.80 ± 10.75	26.00 ± 9.49
		IOPI & TD					64.40 ± 8.71	73.10 ± 7.33	25.00 ± 14.21	34.40 ± 31.62
		Control					69.80 ± 17.71	71.20 ± 17.08	17.90 ± 8.22	18.40 ± 8.54
Clark [43]	RCT	IOPI	Healthy	19–57	25	3M, 22F				
		Strength trg					65.80 ± 14.97	82.60 ± 13.39	45.20 ± 10.28	45.40 ± 10.16
		Endurance trg					65.60 ± 15.19	73.00 ± 18.40	81.20 ± 32.41	77.20 ± 12.09
		Power trg					60.20 ± 17.98	66.60 ± 17.05	71.60 ± 30.22	71.40 ± 12.58
		Speed trg					72.80 ± 14.72	80.40 ± 20.11	62.80 ± 9.07	64.40 ± 12.70
		Control					66.80 ± 13.18	73.60 ± 10.06	62.40 ± 5.18	59.80 ± 14.48
Robbins et al. [45]	Prospective cohort	IOPI	Stroke	51–90	10	5M, 5F				
		Anterior					35.6	51.7		
		Posterior					30.2	54.6		

Values are mean ± SD unless stated otherwise

TD tongue depressor, *RCT* randomised control trial

Tongue Strength

Four studies examined tongue strength before and after tongue-strengthening exercise programs (Table 7). Lazarus et al. [42] investigated the effects of IOPI or tongue depressor exercise training in young adults (20–29 years). The responses of the two exercise intervention groups did not differ, and when combined they showed significant improvements from baseline (64.40 ± 8.71 kPa) to 4 weeks (73.10 ± 7.33 kPa) compared to a no-exercise control group ($p = 0.04$). Robbins et al. [44] examined the effects of 6 weeks of IOPI exercise training on older adults (70–89 years). Significant increases in tongue strength were observed from baseline to 4 weeks ($p = 0.002$) and from baseline to 6 weeks ($p = 0.001$), with the following values reported: baseline, 41.00 kPa (range = 36–46); 2 weeks, 44.00 kPa (range = 39–49); 4 weeks, 47.00 kPa (range = 43–51); and 6 weeks, 49.00 kPa (range = 45–53). Clark et al. [41] examined the effects of 9 weeks of training, using three different directional exercise conditions (elevation, protrusion, and lateralization), on tongue strength in healthy adults (18–67 years) measured with the IOPI. Training effects were reported at 3 and 9 weeks. Significant increases in strength were observed, with a 6 % change in elevation strength ($p < 0.001$) compared to 26.6 % for lateralization ($p < 0.001$) and 13.4 % for protrusion ($p < 0.001$). Clark [41] also examined the specificity of exercise training effects using the IOPI in healthy adults (19–57 years). Large (Cohen's $d = 1.06$) improvements in strength were observed for the strength-training group only.

Tongue Endurance

Two intervention studies investigated the effects of exercise training on tongue endurance (Table 7). Lazarus et al. [42] examined the effects of IOPI or tongue depressor exercise training on tongue endurance in young adults (20–29 years). There was a trend of increased tongue endurance from baseline (25.00 ± 14.21 s) to 4 weeks (34.40 ± 31.62 s) ($p = 0.10$). Training included ten repetitions completed five times per day 5 days per week for 4 weeks, with each repetition held for 2 s and performed in four directions (i.e., left, right, on protrusion, and on elevation).

Clark [41] assessed tongue endurance using the IOPI to determine the effects of four different types of exercise training (including elevation exercises) that required the tongue to be pressed against the hard palate just behind the alveolar ridge with maximum effort. Training included ten repetitions each of elevation, protrusion, and lateralization 7 days per week. Clark [43] found that endurance training had a large effect ($d = 1.29$) on isotonic tongue endurance (repetitions) but no effect on isometric endurance.

Risk of Bias in Intervention Studies

The results of the 10-item risk-of-bias analysis for the five intervention studies are presented in Table 8. Interrater reliability between two reviewers (VA and RC) for the risk-of-bias items indicated a high level of agreement across all items (percentage agreement 100 %, Cohen's $\kappa = 1$). Each study received a point for each indicator that met the quality criteria. For the three randomized controlled trials, all eight quality indicators were relevant, leading to a maximum quality score of 8. For the other study designs, where an intention-to-treat analysis was not applicable, the highest quality score was 7. Randomization was described adequately and performed in two studies [41, 43], and a control group (randomized participants) was included in three studies [41–43]. Assessor blinding was carried out in only one study [41]; baseline characteristics were reported and at least one primary outcome measure was valid and reliable in all five studies [41–45]; p values were reported in five studies [41–45]. Effect sizes and/or precision estimates (e.g., 95 % CI) were reported in two studies [43, 45]; magnitude of effect size was determined in two studies [43, 45] using Cohen's benchmarks for small, medium, and large effects as 0.2, 0.5, and 0.8, respectively [46]. Summary results for individual study groups were presented in all studies cited. One study [43] indicated a low risk of bias with seven of the eight quality markers and one study [41] had a low risk of bias with six of the eight markers.

Discussion

This review systematically examined the state and quality of the evidence for using the Iowa Oral Performance Instrument (IOPI) to measure strength and endurance of the tongue and hand in healthy populations and those with a range of medical conditions. A systematic search of the scientific literature published since 1991 yielded 38 studies that addressed this purpose. The IOPI was used mostly for tongue strength (38 studies) and endurance (15 studies) measurements; relatively few studies measured hand strength (9 studies) or endurance (6 studies). Most of the studies used the IOPI as an evaluation tool, although four studies also used it as an intervention tool. Half the studies were conducted in healthy people, mostly adults. Most of the other participants had disorders associated with dysphagia, such as PD or HNC. In healthy populations, both age and gender influenced the tongue strength values obtained, but there was no gender difference in tongue endurance values.

Table 8 Risk of bias assessment of intervention studies

Studies	Did the study include a true control group (randomised participants not a comparison group)?	Were the assessors blinded to treatment allocation at baseline and posttest?	Was the randomisation procedure adequately described and carried out?	Were the subjects at baseline adequately described?	Was at least one primary outcome measure valid and reliable?	Did the study report or calculate a *p* value?	Did the study report effect size or confidence intervals?	Did the study report a power calculation and was the study adequately powered to detect intervention effects?
Clark et al. [41]	1	1	1	1	1	1	0	0
Clark [43]	1	0	1	1	1	1	1	1
Lazarus et al. [42]	1	0	0	1	1	1	0	0
Robbins et al. [45]	0	0	0	1	1	1	1	0
Robbins et al. [44]	0	0	0	1	1	1	0	0

1 yes, *0* no

Score of 0–5 = high risk of bias, score of 6–8 = low risk of bias

Consolidation of Results

Tongue Strength

The IOPI has been used mostly to measure tongue strength, which was the original reason for its development [39]. Tongue strength can be measured with the tongue in different positions, and anterior measurements produce higher values than posterior measurements. Measures of tongue strength taken with the tongue in the anterior position showed that males typically generate higher values than females, but this difference appears to be absent or substantially reduced when posterior measurements are used [5, 7, 15]. Where the bulb is in the mouth when recording tongue strength is important to note because of the possibility of slippage in the anterior and posterior positions. The average discrepancy between male and female values of tongue strength in healthy populations was 5.2 kPa, as suggested previously [1].

Age also influenced the values obtained, with strength increasing with age in children [37, 38] and decreasing with age in adults [2–7, 9, 10, 15]. A wide range of tongue strength values has been reported even in healthy populations, no doubt reflecting the influences of age and gender of the population sampled. Values ranged from 49 to 73 kPa for males and from 37 to 67 kPa for females. The analysis of gender showed that when younger adults (<60 years) were compared to older adults an average difference of 8 kPa for males and 9 kPa for females was indicated. There are likely to be differences between other age groups as well, but there are insufficient data to determine the magnitude of any differences. For future research studies, the age and gender effects on values mean that randomization to groups should consider stratifying by age and gender.

For clinical practice, there is a need to develop gender-based normative data in a number of age groups, including children and adolescents. Also, a systematic investigation of tongue strength and endurance in adults and children with medical conditions is required as there are limited normative values for individuals with a medical condition.

Three studies conducted in healthy populations reported lower than typical tongue strength measures. Palmer et al. [14] obtained much lower values during measurements obtained when intramuscular electrodes were inserted into specific muscles of the tongue. It is likely that the presence of the electrodes caused discomfort and muscle contractions were altered, thus reducing maximal strength performance. Vitorino [4] examined tongue strength in Portuguese speakers, with males (58.20 ± 7.10 kPa) and females (57.10 ± 8.50 kPa) showing 11 % lower tongue strength compared to English speakers. The inclusion of a small number ($n = 10$) of older Portuguese speakers may have contributed to the lower values as tongue strength has been shown to decrease in older people. Robbins et al. [9] measured strength of the tongue at three different positions (blade, dorsum, tip) in young (22–33 years) and old (67–83 years) healthy adults. Despite the values being lower than those reported in many other studies, the same trends were observed where older adults had lower tongue strength compared to younger adults.

Tongue Endurance

Of the 16 evaluation studies on healthy participants, five measured tongue endurance, which was measured mostly with the tongue in the anterior position. A wide range of values was observed, but there were no clear gender or age effect on tongue endurance. Two of the five studies reported values lower than those of other studies included in this review. Vitorino [4] reported a mean tongue endurance of 16.20 $\pm$ 8.57 s. There is no clear explanation for these low values. Neel et al. [6] reported values that were below the suggested normative range for males (37.85 $\pm$ 23.55 s) and females (25.45 $\pm$ 14.11 s). Kays et al. [15] reported endurance values measured with the tongue in the anterior position for both males and females, but observed that lower endurance values were obtained from posterior position.

Hand Strength

Few studies have reported hand strength measured by the IOPI. In general, males tended to have higher values than females, and younger adults had higher values than older adults. Populations with a disorder also had lower hand strength values than healthy controls. There is a clear need for further studies to determine representative values for healthy gender-based age groups.

Hand Endurance

Duration of hand endurance at 50 % of maximum hand strength is not well established. Only one study investigated isometric hand endurance in only healthy individuals [10]. No significant gender or age effects were observed. Data from this study and the control group data in Table 5 indicate a large variation in hand endurance values.

Studies in Populations with a Disorder

Most of the studies to date have been conducted in participants with PD, OPMD, or HNC. Within each of these populations there are still too few data to gain a clear quantitative indication of the types of values that would be typical of these conditions. Most surprisingly, there have been few studies in which the IOPI was used with stroke patients or with patients with other neurological conditions. Thus, there is a wide scope in which to establish IOPI values for tongue and hand strength and endurance in clinical populations.

Intervention Studies

Five studies [41–45] used the IOPI as an evaluation tool in intervention research. Four of these studies [42–45] examined the effects of using the IOPI as a tongue exercise training device, but no studies have used it as a training device for the hand. These studies clearly indicate that the IOPI can be an effective device for improving tongue strength, and possibly tongue endurance. There is now substantial information to develop training protocols to address particular tongue strength or endurance deficits. The IOPI is also an effective tool to quantify the impact of tongue-training interventions on tongue strength and endurance. Clearly, there is also the potential for the IOPI to track recovery after interventions or to provide better monitoring of loss of strength or endurance in progressive diseases.

The IOPI appears to be an effective tool for quantifying the impact of tongue-training interventions on tongue strength and endurance. Randomizing participants to groups, including control groups, blinding the assessors, and performing and reporting sample size calculations could clearly improve the quality of reporting of these intervention studies. There is also room to improve measurement precision by providing confidence intervals or, at a minimum, standard deviations. Also, the reporting of effects sizes would be beneficial to provide clear objective indications of the magnitude of any effects. Future studies should address these problems to prevent potential reporting bias.

Strengths and Limitations

There are several strengths to this review: the conduct and reporting of this review were aligned with the PRISMA statement for reporting of systematic reviews and meta-analyses. There was a comprehensive search strategy across multiple databases with no date restrictions, high agreement levels for quality assessments, and detailed data extraction to allow for comparisons between studies. However, the review also has some limitations. Unpublished literature was not located. This may have resulted in an overrepresentation of positive treatment effects (i.e., publication bias) in this review. Additionally, due to limited translation resources, only articles published in English were included. Therefore, it is possible that some studies addressing the use of the IOPI were not found. The studies investigating tongue and hand strength and endurance differed across many of the variables examined, including age groups, medical conditions, gender imbalance, study duration, group sizes, evaluation periods, exercise programs, IOPI bulb position, and training specificity. This inconsistency makes it difficult to determine the effect of these variables on outcomes and to compare effects across studies.

As an Application for Clinical Research and Routine Clinical Practice

Based on the findings from this review, there is some evidence supporting the use of the IOPI as an effective tool for research. The IOPI has been used primarily as an evaluation device, and more investigation is needed to determine its effectiveness as an intervention tool to improve strength or endurance for both adults and children with swallowing problems. There is enormous potential to improve patient outcomes in clinical practice by using a standardized assessment instrument such as the IOPI, which is relatively inexpensive and capable of providing objective measures of tongue strength and endurance rather than relying on the speech-language pathologist's clinical assessment, especially when multiple staff are making assessments. The IOPI has recently been approved by the Australian Therapeutic Goods Administration for use in both research and clinical practice, which may increase the number of studies conducted outside the US. There is a need to clearly establish relationships between tongue strength and endurance measures and swallowing function and performance in a range of populations. Also, the reliability of these strength and endurance measures has not yet been reported.

Conclusion

There is clear evidence indicating the effectiveness of the IOPI for the measurement of tongue and hand strength and endurance. This evidence is strongest for strength measurements and is best established for measurements of tongue strength. There is a clear need to establish population-specific representative values to gain maximum benefit from the use of these measures with this device.

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Valerie Adams BSpPath (Hons)

Bernice Mathisen PhD, MSc, BSpThy

Surinder Baines BSc (Hons), PhD, Grad Dip Nutr, Grad Dip Diet, APD

Cathy Lazarus PhD, CCC-SLP, BRS-S

Robin Callister BPharm, MSc, PhD