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**Towards movement-based outcome measures for apraxia of speech:  
a systematic review**

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**Abstract**

**Background:** Apraxia of speech (AOS) is defined as a disorder of articulatory movements, yet a cohesive account of the movement deficit in AOS appears to be lacking. Kinematic evaluation yields precise and objective information regarding the movement deficit in AOS; however, it is an underutilized technique in AOS assessment and in the planning and delivery of treatment. Clearly defined kinematic features of AOS can potentially play a central role in the identification of treatment targets and in measuring treatment outcomes in AOS.

**Aims:** The overall goal of this systematic review was to characterise the state of the science pertaining to kinematic features of acquired AOS. Specifically, we aimed to (1) characterise kinematic features that distinguish speech in AOS from healthy controls, and (2) determine how these features may vary as a function of task complexity and speaking condition. Five electronic databases were searched from their start-date up to July 2017 using the key terms *AOS* and *speech kinematics*. Two raters independently screened abstracts and full texts for inclusion based on pre-determined criteria. Data regarding participant demographics, study design, methods, and results were extracted and analysed descriptively. Two independent raters used a modified version of the Critical Appraisal Tool for Cross-Sectional Studies (AXIS) to assess the methodological quality of included studies.

**Main Contribution:** The review yielded a total of 11 studies, including 10 case-control studies and one case study. The results revealed a lack of high-quality literature reporting on the kinematic features of AOS. In broad terms, the small body of existing literature reported increased movement range and duration of the lips, jaw, and tongue, increased movement variability, the presence of silent articulatory attempts, and the influence of increasing stimulus complexity on articulatory precision/execution. While initial studies have been helpful in

demonstrating the potential of kinematic evaluation in AOS, future studies with higher-quality methodology and larger sample sizes are needed to better characterise movement-based impairments related to AOS and to facilitate potential clinical applications.

**Conclusions:** Movement-based evaluation provides a promising avenue for the assessment and treatment of AOS, including potential target-selection and measurement of treatment outcomes.

**Keywords:** apraxia of speech, speech movements, stroke, systematic review

## Introduction

Apraxia of speech (AOS) is defined as “a neurologic speech disorder reflecting an impaired capacity to plan or program sensorimotor commands necessary for directing movements that result in phonetically and prosodically normal speech” (Duffy, 2013, p. 4). While AOS is generally accepted as a phonetic-motoric impairment, the precise underlying nature of acquired AOS remains unclear (Ballard, Granier, & Robin, 2000; Maas, Robin, Wright, & Ballard, 2008). Given that AOS frequently co-exists with aphasia – a language disorder – challenges arise when trying to delineate between its motoric and linguistic impairments (Ballard et al., 2000). The study of kinematic features of AOS aims to characterise the underlying nature of AOS as a motor/articulatory speech disorder. A more precise understanding of AOS as a movement disorder can have powerful implications for the assessment of AOS, including the identification of treatment targets and determining treatment outcomes.

Acquired AOS typically occurs after a neurological event, such as a stroke or brain injury, or as a result of a neurodegenerative disease, such as primary progressive aphasia (PPA) (Duffy, 2013). Although specific and reliable data regarding the incidence and prevalence of AOS is not readily available (American Speech-Language-Hearing Association, 2018), approximately 25% of all stroke survivors exhibit a communication disorder; nearly a half of these individuals are affected by motor speech disorders - dysarthria and AOS (Knollman-Porter, 2008). AOS has also been identified as one of the two core features of the nonfluent/agrammatic variant of primary progressive aphasia (nfPPA) (Gorno-Tempini et al., 2011). AOS is the most common impairment in nfPPA that can present as the initial sign of the disease and is an important feature in the differential diagnosis of this debilitating condition (Gorno-Tempini et al., 2011; Josephs et al., 2006). Difficulty communicating through speech, regardless of aetiology, is associated with worse

social health, depression, and an overall decreased quality of life (Cruice, Worrall, Hickson, & Murison, 2003; Medina & Weintraub, 2007).

AOS is typically assessed using auditory-perceptual methods. The perceptual characteristics associated with AOS, although not exclusive to the disorder, are divided into four categories: articulation, rate and prosody, fluency, and influential task variables (Duffy, 2013). The articulatory characteristics associated with AOS are sound distortions and distorted sound substitutions (Duffy, 2013; McNeil, Pratt, & Fossett, 2004; Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006). Rate and prosodic abnormalities include characteristics such as slow rate of speech, syllable segregation, equal stress, and prolonged and variable sound durations (Duffy, 2013; McNeil et al., 2004; Wambaugh et al., 2006). Characteristics of impaired fluency include sound and syllable repetitions, effortful groping behaviours, false starts/re-starts and variable attempts to self-correct (Duffy, 2013; McNeil et al., 2004). Finally, task or condition effects include increased error rates with longer or more complex sounds (e.g., consonant clusters), syllables, and words, and in spontaneous/volitional speech as compared to automatic speech (Duffy, 2013; McNeil et al., 2004; Wambaugh et al., 2006).

Auditory-perceptual evaluation is a valuable tool in the assessment of AOS; however, challenges exist with this type of assessment. Its pitfalls include perceptual illusions, multisensory interference, and misperceptions due to categorical perception strategies (Bond & Garnes, 1980), all leading to reduced reliability of this type of assessment (Kent, 1996). These aspects can substantially hinder its diagnostic sensitivity. Instrumental techniques based on acoustic and kinematic speech analyses are used to overcome these limitations (e.g., Hagedorn et al., 2017; Jacks, Mathes, & Marquardt, 2010). Recent exciting research demonstrated high diagnostic utility of acoustic measures (e.g., absolute and relative segment durations, reduced

rate, amplitude envelope modulation spectrum) in distinguishing speakers with aphasia who have AOS from those without AOS and from neurologically-intact controls (Basilakos et al., 2017; Cordella et al., 2017; Duffy et al., 2017; Vergis et al., 2014).

While acoustic methods allow us to infer information about articulatory movements, kinematic evaluations offer a direct means of assessment of articulatory deficits. Speech articulation involves the movement of the jaw, lips, tongue, and velum in shaping the vocal tract to produce various sounds, and kinematic analyses can directly measure the aspects of their movements such as size, speed, and coordination (Gracco, 1992). As such, kinematic studies have great potential to improve our understanding of the underlying nature of the perceptual and acoustic abnormalities in AOS. Identification of the kinematic features of AOS may also have direct implications for treatment of the disorder. As stated by Rosenbek, Lemme, Ahern, Harris, and Wertz (1973), AOS is a “nonlinguistic sensorimotor disorder of articulation... [and therefore] therapy should concentrate on the disordered articulation... [and] emphasize the relearning of adequate points of articulation and the sequencing of articulatory gestures” (p. 192). Although the goal of AOS treatment is to improve the spatial and temporal aspects of speech (Wambaugh et al., 2006), kinematic targets – defined in this paper as the spatio-temporal features of movements required for accurate speech sound production (e.g., range of movement or positional accuracy) – have not been systematically defined in the AOS literature. The establishment of such targets may be clinically significant for therapy planning in AOS (see Mauszycki, et al., 2007). In order to accurately determine treatment targets and define treatment outcome measures, the precise kinematic features of AOS must be clearly delineated using direct kinematic methods.

The present systematic review aims to characterise the state of the science pertaining to

kinematic features of acquired AOS. Since kinematic data are relatively difficult to obtain in clinical populations and sample sizes of the existing studies are typically small, it is important to integrate the existing data to identify a common set of features of AOS. In the future, these features may then be assessed for sensitivity to the disorder, in order to determine their diagnostic value, or be used as treatment outcomes. In this systematic review, we addressed the following questions: (1) How do kinematic features differ between individuals with AOS and neurologically-intact controls, and (2) what is the effect of task complexity and speaking conditions (e.g., speaking rate, bite block) on speech kinematics in AOS?

## **Method**

### ***Operational definitions***

Operational definitions that guided the search were determined a priori and included (1) *Acquired AOS*, defined as a nonhereditary speech disorder with neurologic origin characterised by impairment in the ability to plan and/or program movements required for speech production (Duffy, 2013), and determined by clinical examination; and (2) *Speech (articulatory) kinematics*, defined as spatial and temporal aspects of movement of the articulators (i.e., the lips, jaw, tongue, velum, larynx) as they relate to speech production.

### ***Search strategy***

Five electronic databases were searched and included Allied and Complimentary Medicine Database, Cumulative Index to Nursing and Allied Health Literature, Embase, MEDLINE, and PsycINFO. Each database was searched from their inception to March 16, 2016. An updated search, following the same protocol, was conducted on July 18<sup>th</sup>, 2017 to include recently published studies. The key search terms were *AOS* and *speech kinematics* and their associated terms (e.g., AOS: *dyspraxia*, *Broca's aphasia*, *aphemia*, *pure motor aphasia*, *afferent motor*



*aphasia*; speech kinematics: *kinematics*, *speech production measurement*, *speech analysis*, *movement (physiology)*). Variations in key search terms were used depending on each database (e.g., MeSH headings in Embase and Subject Headings in the Cumulative Index to Nursing and Allied Health Literature). Additional search terms that were suggested by a database were accepted if deemed relevant (e.g., *biomechanics*). Where possible, searches were limited to the human population and all searches were limited to adult populations. See the Appendix for an example search from the Embase database. To ensure inclusion of all relevant articles, reference lists of the accepted articles were manually checked for additional reports.

### ***Inclusion and exclusion criteria***

The review was limited to articles that reported objective measures of articulatory kinematics in patients with AOS. Studies that simply described kinematic traces or patterns of tongue-palate contact were excluded. Additional exclusion criteria were articles: unrelated to speech or articulation, with childhood or developmental AOS, and those using acoustic/electromyography measures only. Tutorials, education reports, bibliographies, study proposals, and commentary or conference abstracts were also excluded.

### ***Screening***

Titles and abstracts were independently screened by two authors (KB, EK) and either accepted or rejected as per exclusion criteria with the reason specified. Any conflicts were resolved via discussion, and a consensus was reached. For all accepted abstracts, the full-texts were screened following the same process.

### ***Data extraction***

Data were extracted from full texts of all accepted articles and included: participant data from speakers with AOS and neurologically-intact controls (i.e., sample size, age, sex, type of stroke

or disease, time since onset of stroke or disease diagnosis, diagnosis and lesion site, severity of AOS, and concomitant communication impairments), instrumentation, articulators, details of tasks and stimuli, and kinematic measures and associated findings. Data from participants with other communication disorders, such as dysarthria or aphasia, were not extracted as these data were considered beyond the scope of the review.

During data extraction, accepted articles were also assessed for duplication, i.e., the publication of an article that overlaps substantially with one already published in print or electronic media (Choi et al., 2014). For the purposes of this review, articles republishing data (with no new data added) were excluded. Articles reporting new data from the same participants were included; however, reports were merged under a single study when the participants, tasks, and measures overlapped.

### ***Critical appraisal***

Methodological quality of the articles was assessed using a modified version of the Critical Appraisal Tool for Cross-Sectional Studies (AXIS; Downes, Brennan, Williams, & Dean, 2016). The AXIS tool, composed of 20 items, was developed to specifically evaluate study design quality and risk of bias in cross-sectional studies (Downes et al., 2016). Some of the items on the AXIS tool were not applicable to studies in the current review and were omitted (e.g., item 13: ‘does the response rate raise concerns about non-responders described?’). A total of 16 items were assessed: (1) clear study aims/objectives; (2) appropriate study design; (3) justified sample; (4) clearly defined target/reference population; (5) representative sample frame; (6) random selection process; (7) appropriate outcome variables relative to study aims; (8) correctly measured outcome variables using trialed, piloted, or published previously instruments/measurements; (9) clear methods to determine statistical significance and/or

precision estimates (e.g.,  $p$  values, confidence intervals, effect sizes); (10) sufficiently described methods to enable them to be repeated; (11) adequately described basic data; (12) presented results for all analyses described in methods; (13) authors' discussions and conclusions justified by the results; (14) discussion of limitations of the study; (15) reporting of funding sources or conflicts of interest; (16) attainment of ethical approval or consent of participants. All items were independently rated as 'yes', 'no' or 'not reported' by two authors (KB, ER), corresponding to a high, low, or unclear methodological quality. Differences in ratings were discussed and resolved by consensus.

## **Results**

### ***Study identification***

The initial search identified 801 articles from five databases, and an additional 23 articles were identified by manually checking reference lists (see Figure 1). After removing duplicates ( $n = 193$ ), a total of 631 titles and abstracts were screened for inclusion. One hundred and one relevant articles were included for full-text review through this process, with a 96.98% agreement between raters. Any conflicts were resolved via consultation and consensus. The same two authors then completed full-text reviews with 91.23% agreement. A total of 14 articles were identified as meeting the inclusion criteria for the systematic review.

Of the accepted articles, six presented highly overlapping data and were considered as a total of three studies. The data from these studies were recorded from the same participants performing the same tasks (with some minor variation in stimuli) using the same instrumentation and with overlapping measures. Specifically, McNeil, Caligiuri, and Rosenbek (1989) and McNeil and Adams (1991) were considered as a single study; Bartle, Goozée, and Murdoch (2007a) and Bartle, Goozée, and Murdoch (2007b); and Bartle, Goozée, and Murdoch (2009a).

and Bartle-Meyer, Goozée, and Murdoch (2009b). The final number of studies reviewed was 11 and included 10 case-control studies and one case study.

### *Participant characteristics*

Table 1 summarises the participant characteristics in the 11 included studies, presented chronologically. The total number of individuals with AOS across all studies was 19. All participants were diagnosed with AOS by a speech-language pathologist based on a clinical assessment using (a) a standardised clinical tool meant to diagnose AOS such as the Apraxia Battery for Adults (ABA; Dabul, 2000), (b) other standardised communication assessments (e.g., the Boston Diagnostic Aphasia Examination; Goodglass, Kaplan, & Barresi, 2000), (c) by comparing participant's clinical presentation to a pre-determined specific criterion or checklist, such as the proposed mandatory characteristics of AOS as outlined in McNeil et al. (2004), or (d) a combination of the above. AOS severity was difficult to compare across studies due to the inconsistencies in how severity was measured. For example, some studies used a standardised assessment (e.g., ABA) to inform severity ratings (e.g., van Lieshout, Bose, Square, & Steele, 2007), while others relied on observation of performance on informal speech tasks but did not specifically describe which features were used to assign a severity rating (e.g., Mauszycki, Dromey, & Wambaugh, 2007). The majority of studies ( $n = 10$ ) compared kinematic measures in AOS to those of healthy controls, while one study (Katz, Bharadwaj, & Carstens, 1999) reported an intervention with a single participant and used kinematic data to set a treatment target and as a dependent variable (outcome) to assess change during/following treatment.

[Table 1 near here]

### *Study characteristics*

Table 2 provides methodological details of each study (e.g., instrumentation, tasks, measures). As a brief summary, six studies used electromagnetic articulography (EMA), three studies employed strain-gauge systems, two studies used electropalatography (EPG), and a single study used an optoelectronic system. Most studies ( $n = 9$ ) did not decouple movements of the jaw from the tongue or lips, with the exception of Robin et al. (1989), who compared lip movements with and without a bite-block, and van Lieshout et al. (2007), who examined independent lower lip movement by using a mathematical decoupling method. The measures were organised into the following categories (1) range of motion, which included measures of movement displacement and distance; (2) speed of motion, which broadly included measurements of velocity, acceleration, and deceleration; (3) movement durations; (4) intra-articulator control; (5) inter-articulator coordination; (6) repetition variability; (7) positional accuracy; and (8) measures of tongue-palate contact (place, amount, pattern) for the EPG method only. The list of specific measures and their definitions are outlined in Table 3.

[Table 2 near here]

[Table 3 near here]

### ***Methodological quality***

Two independent raters (KB and ER) showed good agreement in appraising the methodological quality of the included studies (70.36% agreement). All differences in ratings were discussed and resolved by consensus. Table 4 provides a summary of the critical appraisal of each study. All studies were rated as having a target/reference population that was clearly defined, having a sample representative of the population of interest, and using appropriate measurement tools and outcome variables. Most studies ( $n = 10$  of 11) stated clear aims and objectives, had a study design that was appropriate for the stated aim(s) ( $n = 10$  of 11), and described all results ( $n = 10$

of 11). Eight of the 11 studies were deemed to provide justified conclusions based on results. The methodological quality of some articles included in this systematic review was compromised, however, by certain factors. For example, none of the studies had a justified sample size or an unbiased selection process. Several studies did not adequately conduct (or report) information regarding methods, analysis, results, and limitations. Three studies did not provide clear information regarding criteria used to determine statistical significance, did not have repeatable methods, or described the data adequately. Discussion of limitations was missing in four studies. The presence of funding sources or conflicts of interest that may impact results was inconsistently reported and information regarding ethical approval and/or consent was not reported in any of the studies.

[Table 4 near here]

### ***Summary of findings***

#### *Differences between speakers with AOS and neurologically-intact controls*

Ten of the 11 studies reported findings comparing articulatory kinematics of speakers with AOS to neurologically-intact controls (Figure 2). The summary was obtained by combining both perceptually accurate and inaccurate productions. The most prevalent articulators assessed across studies were the lower lip/jaw ( $n = 5$ ) and the tongue (tip, body, dorsum) ( $n = 6$ ), and as a result, are the primary focus of the analysis. Across all measures, findings were often speaker- or stimulus-dependent.

Range of motion of the lip/jaw and tongue were consistently larger for participants with AOS during opening and closing gestures, as compared to neurologically-intact control speakers (Bartle-Meyer, Goozée, & Murdoch, 2009a, 2009b; Bartle-Meyer & Murdoch, 2010; Bartle et al., 2007a, 2007b; Mauszycki et al., 2007; McNeil & Adams, 1991; McNeil et al., 1989; Robin et

al., 1989; van Lieshout et al., 2007). Speed of motion (i.e., peak velocity, acceleration, and deceleration) during opening and closing gestures, on the other hand, varied by articulator: lip/jaw movements were characterised by faster (van Lieshout et al., 2007), slower (Mauszycki et al., 2007), or comparable speeds (McNeil & Adams, 1991; McNeil et al., 1989; Robin et al., 1989) relative to controls, whereas the tongue moved slower (Bartle et al., 2007a, 2007b) or within normal limits (Bartle-Meyer, Goozée, & Murdoch, 2009a, 2009b). Measures of movement durations during both opening/closing gestures and words were longer than normal for the jaw/lip and tongue (Ackermann, Scharf, Hertrich, & Daum, 1997; Bartle-Meyer, Goozée, & Murdoch, 2009a, 2009b; Bartle-Meyer & Murdoch, 2010; Mauszycki et al., 2007; McNeil & Adams, 1991; McNeil et al., 1989; van Lieshout et al., 2007). Tongue movement durations during words were also more variable for speakers with AOS (Bartle-Meyer & Murdoch, 2010). Only one study captured measures of upper lip movements (van Lieshout et al., 2007) and, similarly to the lower lip, these movements were characterised by larger ranges of motion, longer movement durations, and faster speeds.

Intra-articulator control of the lower lip in speakers with AOS was characterised by longer times to peak velocity during opening and closing gestures (McNeil & Adams, 1991), and an increased number of velocity peaks and changes in velocity direction during syllables and words (Mauszycki et al., 2007; McNeil et al., 1989). Lip kinematic stiffness in AOS, however, was comparable to neurologically-intact controls during opening and closing gestures (McNeil & Adams, 1991; Robin et al., 1989). Tongue control in AOS was characterised by an increased velocity profile parameter and either an increased or comparable to controls velocity profile symmetry index (Bartle-Meyer, Goozée, & Murdoch, 2009a, 2009b; van Lieshout et al., 2007). Kinematic stiffness of the tongue was within a normal range (van Lieshout et al., 2007).

Upper-lower lip inter-articulator coordination was reduced in speakers with AOS in two studies relative to neurologically-intact control speakers when measured by the correlation or covariance between articulators (Mauszycki et al., 2007; van Lieshout et al., 2007), and within a normal range in another study when measured by the asynchrony between articulator movement onset (Robin et al., 1989). Additionally, one study reported increased coupling between multiple articulators during syllable repetition (e.g., tongue tip & jaw, tongue dorsum & jaw, tongue tip & dorsum) (Bartle-Meyer, Goozée, Murdoch, & Green, 2009), and another study showed relatively stable coordination between multiple articulators in a similar task (bilabial closure & tongue tip, tongue tip & body) (van Lieshout et al., 2007). Compared to healthy control speakers, those with AOS showed larger lip and tongue movement variability during perceptually correct syllables (van Lieshout et al., 2007).

One additional measure type concerned only the tongue – measures of tongue-palate contact – and none of the corresponding measures were impaired in speakers with AOS, relative to controls (Bartle-Meyer & Murdoch, 2010; Bartle-Meyer, Murdoch, & Goozée, 2009).

#### *Performance of speakers with AOS in various speaking conditions*

Seven studies examined effects of various tasks and conditions on articulatory kinematics within speakers with AOS (Bartle et al., 2007a, 2007b; Bartle-Meyer, Goozée, & Murdoch, 2009b; Bartle-Meyer, Goozée, Murdoch, et al., 2009; Katz et al., 1999; Mauszycki et al., 2007; Robin et al., 1989; Van Lieshout et al., 2007). Specifically, the studies compared differences in perceptual accuracy (i.e., correct versus incorrect productions), variations in stimulus complexity, changes in speaking rate, performance over time, the use of augmented visual feedback, and the presence of a bite-block. Figure 3 summarises the measures and indicates their sensitivity to variation in task or condition.



Three studies included a within-speaker comparison of accurate versus inaccurate verbal productions and showed an effect of perceptual accuracy on speech movements (Bartle et al., 2007b; Robin et al., 1989; van Lieshout et al., 2007). Specifically, inaccurate productions of syllables were found to be associated with a smaller range of tongue motion, slower peak speeds of the tongue, longer tongue movement durations, and relatively comparable inter-articulator coordination between upper and lower lips, bilabial closure and tongue tip, and tongue tip and tongue body (Robin et al., 1989; van Lieshout et al., 2007). When the inaccurate productions were characterised by silent attempts, however, the tongue movements were characterised by larger ranges of motion and longer movement durations (Bartle et al., 2007b).

The effect of stimulus complexity was examined by comparing consonants and consonant-clusters in one study (Robin et al., 1989) and mono-syllabic and multi-syllabic words in another two studies (Bartle-Meyer, Goozée, & Murdoch, 2009b; Bartle et al., 2007a). The results revealed similar lip velocities between consonants and consonant-clusters for speakers with AOS and a control speaker in Robin et al. (1989), but several differences between the mono- and multi-syllabic words in Bartle et al. (2007a) and Bartle-Meyer et al. (2009b). Specifically, the release phase (but not approach or closure phases) of consonants was more impaired in the multi-syllabic words for the speakers with AOS relative to control speakers. There were a lot of inconsistencies, however, in the way complexity affected movement measures. Specifically, more complex stimuli were associated with both larger and smaller ranges of tongue motion, faster and slower tongue motion, longer and shorter tongue movement durations, and impaired intra-articulator control.

When compared between different speaking rates (normal vs fast rates), peak velocities of the lower lip were similar in one study (Robin et al., 1989), and inter-articulator coordination

was comparable in a second study (Bartle-Meyer, Goozée, Murdoch, et al., 2009). The lack of rate effect for these measures was also noted for the control speakers.

A single study examined the consistency of movements over time by comparing articulatory performance in one speaker across three sampling sessions conducted over eight days (Mauszycki et al., 2007). Data revealed consistent findings over time with regards to range and speed of motion, movement durations, and intra- and inter-articulator control and coordination of the lips during words. Repetition variability varied across recording sessions for words beginning with the alveolar consonant ‘d’ but not for other stimuli.

The effect of augmented visual feedback was examined in the context of practice in a single session (Robin et al., 1989) and as part of a movement-based treatment conducted over five sessions (Katz et al., 1999). In a single session, the results suggested improved control of lower lip velocities during syllables for some speakers when practicing with visual feedback than with verbal cues (Robin et al., 1989). Treatment with visual feedback led to a reduction in tongue tip distance travelled and an increase in positional accuracy during words from session one to session five (Katz et al., 1999).

A final study compared lip movement during syllables recorded with and without a bite-block and showed comparable peak velocities for both conditions (Robin et al., 1989). A similar pattern was found for a single control speaker.

## **Discussion**

### ***Summary of findings***

The goal of this review was to examine the literature on articulatory kinematics in AOS in order to summarise the state of knowledge in the field and its readiness for potential movement-based outcome measures and, by extension, treatment targets relevant to this motor speech disorder.

McNeil and colleagues stated that the importance of physiological measures is in their “potential to reveal the nature of the movement disruptions that give rise to various perceptually realised features of speech in AOS, which, in turn, can inform development of new interventions targeting the disruption or compensatory maneuvers” (McNeil, Ballard, Duffy, & Wambaugh, 2016, p. 207). The review revealed a very small body of kinematic literature characterised by discrepancies in findings based on the speaker, stimulus, context, and a variety of other production and methodological factors (e.g., instrumentation). Below, we summarise the results by measures, articulators, and conditions, list limitations of the current literature, and propose some possible solutions to tackle standardisation of kinematic studies in AOS.

### ***Movement-based assessment in AOS***

Kinematic studies, however limited, offer general support for the understanding of AOS as a motor speech disorder. The analysis of current literature seems to demonstrate that a deficit in movement scaling is at the core of AOS, with measures of movement range and duration, but not speed, showing the most consistent differences across phonetic contexts and articulators. These changes in movement scaling are also able to explain the majority of differences detected in measures of intra-articulatory control detected in AOS, such as longer times to velocity peaks, changes to the velocity profile parameter, and multiple velocity peaks within a single movement (Adams, Weismer, & Kent, 1993).

Changes in the extent and duration of articulatory movements do not by themselves, however, shed light on positional characteristics of the articulators, particularly of the tongue, during vowels and consonants. The dearth of quantitative studies reporting on tongue positions is surprising, considering that “the relearning of adequate points of articulation” is central to articulatory-kinematic therapy in AOS (Rosenbek et al., 1973, p. 192), and kinematic methods

offer a unique advantage in the evaluation of this articulatory parameter. A single EPG study quantified the tongue position relative to an artificial palate and reported similarity between patterns of three speakers with AOS relative to five neurologically-intact controls during perceptually accurate and inaccurate productions. This study, however, examined only monosyllabic stimuli; more complex stimuli, as well as a focus on perceptually incorrect productions, may have elicited different results. In contrast, inappropriate and “distorted” tongue-palate contact patterns during syllable and word production have been reported in a number of qualitative EPG studies (Bartle-Meyer, Murdoch, et al., 2009; Edwards & Miller, 1989; Hardcastle, Barry, & Clark, 1985; Southwood, Dagenais, Sutphin, & Garcia, 1997) in addition to treatment studies (Howard & Varley, 1995; Katz et al., 1999), and requires further investigation.

Movement variability has been identified as another hallmark movement feature of AOS in a number of acoustic reports – particularly in the temporal domain (see summary in Ballard et al., 2000) – but the understanding of its extent remains limited. Increased articulatory variability has been formally assessed using the spatiotemporal index in two studies, which showed higher than normal values even for perceptually correct productions of syllables and phrases (Mauszycki et al., 2007; van Lieshout et al., 2007). A less formal comparison of standard deviations obtained across repetitions and studies revealed an inconsistent effect of AOS on movement measure variability (McNeil et al., 1989; see Robin et al., 1989), and this feature of AOS needs a further and more carefully controlled kinematic examination.

Tracking multiple articulators is essential from the point of view of understanding whether or not AOS is a coordination disorder, which has been suggested based on existing perceptual and acoustic studies (see Ballard et al., 2000). Only four studies measured more than one articulator at a time (tongue and lip,  $n = 2$ ; upper and lower lips,  $n = 3$ ), and showed

inconsistent results from study to study (Bartle-Meyer, Goozée, Murdoch, et al., 2009; Mauszycki et al., 2007; Robin et al., 1989; van Lieshout et al., 2007). For example, Robin et al. (1989) showed normal coordination between the upper and lower lips, whereas another study showed tighter articulatory coupling between the tongue and jaw (Bartle-Meyer, Goozée, Murdoch, et al., 2009), possibly indicating simplification of a control strategy (Kelso, 1995). The existing literature warrants further investigation of the control of multiple articulators in speakers with AOS as it may offer new insights into the manifestation of AOS in speech movements and directions for therapy that possibly capitalise on movement-based compensatory strategies.

Monitoring movements during perceptually silent intervals, which are below the level of clinical observation, is yet another clear advantage of kinematic methods. Silent intervals that are of interest in AOS occur when individuals have difficulty initiating movement towards a speech target and display articulatory groping behaviour, or have difficulty coordinating the initiation of articulation and phonation for a specific segment, which then is perceived as silence. Bartle et al. (2007b) showed that silent articulatory attempts clearly existed and often preceded word-initial consonants, revealing movements that differed from those expected for the consonants. Additionally, a descriptive study captured multiple initiation attempts prior to correct or incorrect spoken productions – in both repeated and spontaneous speech contexts - indicative of silent groping or false starts (Hagedorn et al., 2017). Difficulty coordinating articulation and phonation onsets may be even more hidden from auditory and visual perception than groping behaviours; errors that were perceived as segment omissions were not always true omissions and often showed evidence of tongue-palate contact with both correct or incorrect placements observed (Sugshita et al., 1987).

A number of studies that linked perceptual evaluation to kinematic findings reported, perhaps unsurprisingly, that instrumental assessment was more sensitive than auditory perception to articulatory information (Edwards & Miller, 1989) and “aspects of motor control” (Mauszycki et al., 2007, p. 240). Yet, the kinematic literature has not delivered on the promise to improve our understanding of AOS. Observing the articulatory patterns that are not always visible to the naked eye (e.g., those of the tongue) or movements during perceptually silent intervals might offer unique data to inform the assessment and diagnosis of AOS. Furthermore, this information would be extremely beneficial to clinicians in both initial assessment and ongoing evaluation of the effects of treatment on AOS.

### ***Relevance to treatment in AOS***

Movement-based methods are emerging as beneficial in the design and implementation of individualised treatments for AOS (Bartle-Meyer, Goozée, Murdoch, et al., 2009; van Lieshout et al., 2007). Considering that very little is known about normal expectations regarding treatment targets (see Yunusova, Rosenthal, Rudy, Baljko, & Daskalogiannakis, 2012), and the extensive variability of speech movements in AOS, the feasibility of movement-based targets might be questioned. Encouragingly, Mauszycki et al. (2007) examined the consistency of speech kinematics across three recording sessions over eight days and showed that findings regarding range and speed of motion, movement duration, and coordination were generally consistent from session to session. This report is clinically important and supports the establishment of kinematic targets for therapy.

There have been a number of reports on the effect of augmented visual feedback method on speech motor learning in AOS. The studies typically used either EPG (Howard & Varley, 1995; Mauszycki, Wright, Dingus, & Wambaugh, 2016) or EMA (Katz et al., 1999; Katz,

McNeil, & Garst, 2010; McNeil et al., 2010) for treatment purposes. Only one study, however, was included in this review based on our pre-determined inclusion criteria (Katz et al., 1999). This study demonstrated that regaining correct points of articulation is possible with EMA-based therapy, showing changes in the positional accuracy of the tongue during consonants from 23-30% to 54-90%, depending on a sound target and stimulus. These findings were reported for a single participant; augmented visual feedback-based treatment effects have, nevertheless, been reported for at least eight more individuals with AOS in the treatment studies that were not included in this review. The reason for excluding this important work was that, even though treatments have used instrumentation during therapy (i.e., EMA or EPG), the outcomes have been solely perceptually-based (e.g., percent correct of target sounds). Therefore, our understanding of what kinematic changes were required in therapy to elicit changes in perceptual accuracy remained limited. As a comment, perceptual measures might be limited in their ability to identify participants who would respond to treatment, because these measures may not be sensitive enough to subtle changes in the control of speech movements.

Other common “articulatory kinematic” treatment approaches and strategies that have been evaluated in the literature include integral stimulation, drill/repeated practice, articulatory placement cueing, and clinician modelling (Ballard et al., 2015). In the aforementioned approaches, articulatory goals, such as positional accuracy and range of motion, have not been defined kinematically. Rather, they are based on setting a perceptual goal and are only indirectly focused on movement. Tracking kinematic outcomes as in a pre-/post-treatment evaluation of changes in movement characteristics are therefore lacking. Further studies examining how the use of articulatory approaches may affect speech movements and impact functional (perceptually accurate) performance during speech are warranted.

*Limitations of the existing studies*

While the findings from this systematic review reveal some general patterns of articulation impairment in speakers with AOS, the literature is fundamentally very sparse, and the overall quality of the studies and their reporting is relatively low. Specifically, studies had small sample sizes – a total of 19 participants were studied across all studies. Moreover, a number of studies reported findings related to the same participants, making existing findings less generalizable. The clinical presentation and, presumably, the kinematic data may vary depending on the severity of AOS and the presence of concomitant communication disorders (e.g., dysarthria or aphasia). The severity of AOS and co-existing disorders was, however, not documented systematically across all studies. An agreement on using one (or more) established measures (e.g., ABA or Apraxia of Speech Rating Scale (ASRS); Strand, Duffy, Clark, & Josephs, 2014) is necessary in future research.

In addition to a small and highly heterogeneous sample, the stimuli highly varied across studies. Stimulus complexity, particularly in the context of words of increasing length, has an effect on speech kinematics in AOS (Bartle-Meyer, Goozée, & Murdoch, 2009b; Bartle et al., 2007a). Often, the complexity of the stimuli was not considered in studies unless experimentally manipulated. The inclusion of consistent stimuli across studies that control for complexity would improve comparisons across studies and broaden the interpretation of results.

The kinematic results are further muddled by the inclusion (and averaging) in many studies of both perceptually correct and incorrect productions (Bartle-Meyer, Goozée, & Murdoch, 2009a, 2009b; Bartle-Meyer & Murdoch, 2010; Bartle et al., 2007a, 2007b; Katz et al., 1999). Correct and incorrect productions are likely to exist on a continuum of articulatory accuracy. It is possible, therefore, that different or stronger group and condition effects may have



been observed if the perceptual accuracy of productions were taken into account more systematically. More careful assessment of motor variability may also shed light on the nature of the planning/programming deficit in AOS and identify the specific components of movement (e.g., closing versus opening gestures) that are vulnerable to this type of impairment.

### ***Conclusions and recommendations***

Given the ability of instrumental evaluation to accurately and repeatedly identify movement patterns that may be misidentified or below the level of detection through perceptual or acoustic means, kinematic evaluation of speech may be highly useful in defining treatment targets and outcome measures for AOS. Critical appraisal of studies included in the systematic review demonstrated, however, the limited nature of published works and the need for more and better-quality research in the kinematic domain. Additionally, a better understanding of the link between speech kinematics and their perceptual consequences is warranted in this population, in order to identify movement targets and outcomes that are associated with perceptually meaningful change in speech production. Kinematic methods are well suited and are much needed for examining aspects of speech motor control that are not easily detected through perceptual or acoustic methods, such as (1) positional characteristics of the tongue, (2) inter-articulator coordination, and (3) behaviours during perceptually silent intervals. None of these issues have been studied in detail to date in the existing literature.

For kinematic evaluations to become a clinical reality, technologies that can be accessible by clinicians must be developed. Unfortunately, technologies remain out of reach for most speech-language pathologists, as user-friendly and inexpensive solutions are lacking. EMA is prohibitively expensive and difficult to use in a clinic setting, and EPG is cumbersome, requiring an orthodontic intervention to create an artificial palate for each client. Further, the EPG palate

may substantially alter tactile/proprioceptive feedback, which, as is, can be impaired in neurological populations, particularly in those post-stroke (Sullivan & Hedman, 2008).

Positively, a number of devices, which may offer these accessible and affordable tracking capabilities, are currently under development; they include the Multimodal Speech Capture System (MSCS; Sebkhi et al., 2017) and video-based facial tracking (Bandini, Janik-Jones, Taati, Green, & Yunusova, 2018).

With such technologies on the immediate horizon, it is pertinent that kinematic studies continue to collect data on movement characteristics of AOS and their relevance to the perceptual consequences of the disorder. Because the patient pool able to participate in these studies is relatively limited and recruitment is challenging, standardisation of data collection protocols (e.g., clinical assessment, speech and non-speech tasks and conditions) is essential. At the minimum, the severity of AOS must be assessed and concomitant aphasia, dysarthria, and their type clearly documented. A hierarchy of tasks from non-speech (e.g., maximum opening of jaw/elevation of tongue, palate trace – to identify movement limits) to speech-like (e.g., alternative motion rates) to speech (e.g., syllable, minimal pairs, multisyllabic words, phrases) should be agreed upon, not unlike clinical tests (e.g., ABA or ASRS). A standard set of measures would be useful as well, prioritising perhaps those that are most in need of kinematic methods, such as lingual positional targets, inter-articulatory coordination, and movement during silent intervals. A collective effort across many laboratories would be necessary to create a comprehensive body of knowledge, revealing the nature of AOS as a movement disorder.

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### Appendix

#### *Sample Embase Search*

#	Search
1	exp speech/
2	exp speech disorder/
3	speech articulation/
4	exp "speech and language"/
5	(speech or articulat\$ or buccofacial or non-speech or oral or verbal or mouth).tw,mp,kw.
6	exp apraxia/
7	apraxia.tw,mp,kw.
8	(speech adj5 aprax\$).tw,mp,kw.
9	exp "apraxia of speech"/ or exp speech apraxia/
10	aphemia.tw,mp,kw.
11	(aphas* and phonologic impairment).tw,mp,kw.
12	afferent motor aphasia.tw,mp,kw.
13	pure motor aphasia.tw,mp,kw.
14	Broca's Aphasia.tw,mp,kw.
15	dyspraxia.tw,mp,kw.
16	exp kinematics/
17	kinematic\$.mp,kw.
18	exp "movement (physiology)"/
19	"movement (physiology)".mp,kw.
20	speech analysis/
21	speech analysis.mp,kw.
22	speech production measurement.tw,mp.
23	or/1-5
24	6 or 7

25	or/8-15
26	23 and 24
27	or/16-22
28	25 or 26
29	27 and 28
30	limit 29 to (human and (adult <18 to 64 years> or aged <65+ years>))

Table 1.  
*Participant Characteristics.*

Study No.	Article Title(s)	Reference(s)	N	Sex (M/F)	Age (years, mean $\pm$ SD)	AOS			
						Time post onset/ diagnosis (mean years $\pm$ SD)	Diagnosis, lesion site	AOS severity	Concomitant speech/ language disorders
1	Lip movement in apraxia of speech	Robin, Bean, & Folkins (1989)	AOS: 5 Control: 1	AOS: 1/4 Control: 0/1	AOS: 52.4 $\pm$ 18.4 Control: 30	NR	CVA ( $n = 5$ ); Left areas 44, 6, 22, 37, 39, 41, 42, 1, 2, 3 ( $n = 5$ )	NR	No
2	A comparison of labiomandibular kinematic durations, displacements, velocities, and dysmetrias in apraxic and normal adults; A comparison of speech kinematics among apraxic, conduction aphasic, ataxic dysarthric, and normal geriatric speakers	McNeil, Caligiuri, & Rosenbek (1989); McNeil & Adams (1991)	AOS: 4 Control: 5	AOS: 4/0 Control: 5/0	AOS: 61.8 $\pm$ 6.6 Control: 64.0 $\pm$ 4.1	53.3 $\pm$ 10.3	Diagnosis NR; Cortical + subcortical structures ( $n = \text{NR}$ ), inferior portion post-central gyrus ( $n = 4$ )	NR	No
3	Articulatory disorders in primary progressive aphasia: An acoustic and kinematic analysis	Ackermann, Scharf, Hertrich, & Daum (1997)	AOS: 1 Control: 1 6	AOS: 1/0 Control: 8/8	AOS: 69 Control: Range = 30-78	4	nfPPA ( $n = 1$ ); Hypometabolism of left inferior frontal region ( $n = 1$ )	NR	Dysarthria

4	Electromagnetic articulography treatment for an adult with Broca's aphasia and apraxia of speech	Katz, Bharadwaj, & Carstens (1999)	AOS: 1	AOS: 0/1	AOS: 63	8+	CVA ( $n = 1$ ); Left MCA, subinsular region, genu of corpus callosum ( $n = 1$ )	Moderate-severe ( $n = 1$ )	Broca's aphasia
5	An EMA analysis of the effect of increasing word length on consonant production in apraxia of speech: A case study; Preliminary evidence of silent articulatory attempts and starters in acquired apraxia of speech: A case study	Bartle, Goozée, & Murdoch (2007a); Bartle, Goozée, & Murdoch (2007b)	AOS: 1 Control: 3	AOS: 0/1 Control: 0/3	AOS: 52 Control: 51.3 $\pm 2.5$	11	CVA ( $n = 1$ ); Left hemisphere frontal to parietal region ( $n = 1$ )	Mild-moderate ( $n = 1$ )	Broca's aphasia, oral apraxia
6	Variability in apraxia of speech: A perceptual, acoustic, and kinematic analysis of stop consonants	Mauszycki, Dromey, & Wambaugh (2007)	AOS: 1 Control: 1	AOS: 1/0 Control: 1/0	AOS: 38 Control: 37	2.92	Focal head injury ( $n = 1$ ); Left (reported right hemiparesis) ( $n = 1$ )	Moderate ( $n = 1$ )	Agrammatic aphasia, Broca's aphasia
7	Speech motor control in fluent and dysfluent speech production of an individual with apraxia of speech and Broca's aphasia	van Lieshout, Bose, Square, & Steele (2007)	AOS: 1 Control: 6	AOS: 0/1 Control: 2/4	AOS: 30 Control: 27.7 $\pm 4.3$	1.08	Haemorrhagic CVA ( $n = 1$ ); Left frontoparietal occipital region ( $n = 1$ )	Moderate ( $n = 1$ )	Severe non-fluent Broca's aphasia

<b>8</b>	Kinematic investigation of lingual movement in words of increasing length in acquired apraxia of speech; Kinematic analysis of consonant production in acquired apraxia of speech	Bartle-Meyer, Goozée, & Murdoch (2009a); Bartle-Meyer, Goozée, & Murdoch (2009b)	AOS: 5 Control: 12	AOS: 2/3 Control: 8/4	AOS: 53.6 ± 11.3 Control: 52.1 ± 12.5	1.66 ± 0.65	Ischemic CVA (n=3), left MCA parietal (n = 1), left MCA (n=1), and bilateral left fronto parietal & right postero-parietal (n=1); Hemorrhagic CVA (n=1); left frontal (n = 1); Clinical CVA (not visualized on CT) (n = 1)	Mild (n = 1) Mild-moderate (n = 1) Moderate (n = 2) Moderate-severe (n = 1)	Non-fluent aphasia
<b>9</b>	Kinematic analysis of articulatory coupling in acquired apraxia of speech post-stroke	Bartle-Meyer, Goozée, Murdoch, & Green (2009)	AOS: 5 Control: 12 (Same as 2009a/2009b)	AOS: 2/3 Control: 8/4	AOS: 53.6 ± 11.3 Control: 52.1 ± 12.5	1.66 ± 0.65	Ischemic CVA (n=3), left MCA parietal (n = 1), left MCA (n=1), and bilateral left fronto parietal & right postero-parietal (n=1); Hemorrhagic CVA (n=1); left frontal (n = 1); Clinical CVA (not visualized on CT) (n = 1)	Mild (n = 1) Mild-moderate (n = 1) Moderate (n = 2) Moderate-severe (n = 1)	Non-fluent aphasia
<b>10</b>	An electropalatographic investigation of linguopalatal contact in participants with acquired apraxia of speech: A quantitative and qualitative analysis	Bartle-Meyer, Murdoch, & Goozée (2009)	AOS: 3 Control: 5 (Subset of 2009a/2009b)	AOS: 1/2 Control: 3/2	AOS: 51 ± 11.2 Control: 51.4 ± 13.5	2.75 ± 0.89	Ischemic CVA (n=2); Left MCA (n = 1) and bilateral left fronto parietal & right postero-parietal (n=1); Clinical CVA (not visualized on CT) (n = 1)	Moderate-severe (n = 1) Moderate (n = 1) Mild-moderate (n = 1)	Non-fluent aphasia

<b>11</b>	A kinematic investigation of anticipatory lingual movement in acquired apraxia of speech	Bartle-Meyer & Murdoch (2010)	AOS: 3 Control: 5 (Subset of 2009a/ 2009b)	AOS: 1/2 Control: 3/2	AOS: $50.7 \pm 11$ . Control: $52.6 \pm 14.5$	$1.86 \pm 0.71$	Ischemic CVA ( $n=2$ ); Left MCA ( $n = 1$ ) and bilateral left fronto parietal & right postero-parietal ( $n=1$ ); Clinical CVA (not visualized on CT) ( $n = 1$ )	Moderate- severe ( $n = 1$ ) Moderate ( $n = 1$ ) Mild- moderate ( $n = 1$ )	Non-fluent aphasia
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*Note.* AOS: Apraxia of speech; CVA: Cerebrovascular accident; MCA: Middle cerebral artery; nfPPA: Nonfluent primary progressive aphasia; NR: Not reported



Table 2.  
*Study Characteristics*

Study No.	Article Title(s)	Instrument	Articulators	Task (elicitation method, stimuli, speaking rate, # repetitions, # sessions)	Movement Analysed (signal selection, accuracy of productions, # repetitions analysed)	Kinematic measures
1	Lip movement in apraxia of speech	Strain-gauge (Barlow, Cole, & Abbs, 1983)	UL LL (+/- J; bite block)	<u>Syllable (Repetition task)</u> : /pæ/; 4 rates (normal, fast, a little faster, faster still); 5 repetitions <u>Syllable (Visual feedback task)</u> : /pæ/; 4 different velocity targets (big, bigger, bigger yet, as big as you can); 5 repetitions <u>Words (Repetition task)</u> : 7 CV, CVC, CCV, or CCVC words; no carrier phrase; x 5 repetitions <u>Phrase (Repetition task)</u> : “me and my big mouth”; 3 rates (normal, fast, fastest); 3 repetitions	Vertical displacement during opening gestures; accurate and inaccurate productions analysed separately; all syllable/word repetitions, 1 phrase repetition	LL max displacement LL peak velocity LL kinematic stiffness UL-LL onset asynchrony
2	A comparison of labiomandibular kinematic durations, displacements, velocities, and dysmetrias in apraxic and normal adults; A comparison of speech kinematics among apraxic, conduction aphasic, ataxic dysarthric, and normal geriatric speakers	Strain-gauge (Barlow et al., 1983)	LL	<u>Phrases (Repetition task)</u> : “stop fast”, 5 repetitions; “buy Bobby a poppy”, repetitions NR	Vertical displacement during opening and closing gestures; perceptual accuracy NR for “stop fast”, accurate productions of “buy bobby a poppy”	Duration Max displacement Peak velocity # of changes in velocity direction Time to peak velocity Kinematic stiffness

3	Articulatory disorders in primary progressive aphasia: An acoustic and kinematic analysis	Optoelectronic system (BTS ELITE)	LL	<u>Words (Reading task):</u> 2 German “gepVpe” words, where V = /a, a:/; embedded in “ich habe ____ gelesen”; 8 repetitions	3D distance of LL to nasion during opening and closing gestures; accurate and inaccurate productions; all repetitions	Max displacement Peak velocity Duration
4	Electromagnetic articulography treatment for an adult with Broca’s aphasia and apraxia of speech	EMA (Carstens AG100)	TT	<u>Words (Repetition task):</u> 2 non-words, “asa”, “asha”, and 2 words, “a sip”, “a ship” in an alternating fashion; minimum of 80 on-target repetitions; 5 treatment sessions with visual feedback over 1 month approx.	Midsagittal x/y position; perceptual accuracy NR; all repetitions	Distance Positional accuracy
5	An EMA analysis of the effect of increasing word length on consonant production in apraxia of speech: A case study; Preliminary evidence of silent articulatory attempts and starters in acquired apraxia of speech: A case study	EMA (Carstens AG200)	TT TD	<u>Words (Repetition task):</u> 8 monosyllabic, disyllabic, or trisyllabic words with C = /t, s, k/ in word-initial position; embedded in “a ____” (e.g., a target,); 12 repetitions	<u>Words</u> Vertical movements during (1) approach, (2) closure, and (3) release phases of initial C; accurate and inaccurate productions; 5 “most typical” productions <u>Silent attempts</u> Vertical movements before the initial syllable	Distance Max velocity Max acceleration Max deceleration Duration
6	Variability in apraxia of speech: A perceptual, acoustic, and kinematic analysis of stop consonants	Strain- gauge (Barlow et. al., 1983)	UL LL	<u>Words (Repetition task):</u> 24 CVC words where C <sub>1</sub> = /b,p,t,d/, C <sub>2</sub> = /b, m, t, l, r/ (e.g., a bill); 25 repetitions; 3 sessions over 8 days	Vertical displacement during word (first to last velocity peak) and closing gesture for C <sub>2</sub> ; accurate and inaccurate productions (“grossly inaccurate” productions excluded); 10 repetitions	<u>Word-level:</u> LL duration # LL velocity peaks UL-LL displacement correlation <u>Closing gesture:</u> LL max displacement LL peak velocity LL spatiotemporal index

7	Speech motor control in fluent and dysfluent speech production of an individual with apraxia of speech and Broca's aphasia	EMA (Carstens AG100)	TT TB UL LL (-J) J	<u>Syllables (Repetition task):</u> "api", "ipa", and "pataka" repetitions with stress on first syllable; repeated for 12 seconds	2D Euclidian distances between nose sensor and TT and TB, and between UL and LL; vertical displacement of UL, LL, J; accurate and inaccurate productions analysed separately, + 1 second interval before inaccurate production; all repetitions	<u>Closing gestures:</u> Duration Max displacement Peak velocity Kinematic stiffness Velocity profile parameter Velocity profile symmetry index <u>Whole trajectory:</u> Cyclic spatio-temporal index Relative phase
8	Kinematic investigation of lingual movement in words of increasing length in acquired apraxia of speech; Kinematic analysis of consonant production in acquired apraxia of speech	EMA (Carstens AG200)	TT TD	<u>Words (Reading task):</u> 6 monosyllabic, 5 disyllabic words with C = /t, s, l, k/ or C-cluster = /kl, sk/ in word initial position; embedded in "a ____" (e.g., a tar); 12 repetitions	Vertical movements during (1) approach, (2) closure, (3) release phases of initial C; accurate and inaccurate productions (perceptually "most accurate" when multiple attempts made); 8 repetitions	Distance Max velocity Max acceleration Max deceleration Duration Velocity profile symmetry
9	Kinematic analysis of articulatory coupling in acquired apraxia of speech post-stroke	EMA (Carstens AG200)	TT x J TD x J TT x TD	<u>Syllables (Repetition task):</u> Repeated syllables 'Ca', where C = /t, s, l, k/; 2 rates (typical (3 syl/sec), fast (5 syl/sec)); 12 repetitions	Vertical movements during consecutive 8-syllable sequence identified for each repetition; perceptual accuracy NR; 8 repetitions	Inter-articulatory coupling
10	An electropalatographic investigation of linguopalatal contact in participants with acquired apraxia of speech: A quantitative and qualitative analysis	EPG (Reading EPG3)	Linguopalatal contact	<u>Words (Repetition task):</u> 6 monosyllabic words with C = /t, s, l, k/ or C-cluster = /kl, sk/ in word initial position; embedded in "a ____" (e.g., a tar); 12 repetitions	Frame of maximum contact; accurate and inaccurate productions (perceptually "most accurate" when multiple attempts made); 8 middle repetitions	Centre of gravity Amount of contact Aspects of closure Aspects of constriction Relative variability index

<b>11</b>	A kinematic investigation of anticipatory lingual movement in acquired apraxia of speech	EMA (Carstens AG200); EPG (Reading EPG3)	TT Linguo-palatal contact	<u>Words (Reading task):</u> 2 disyllabic words with C <sub>1</sub> VC <sub>2</sub> or C <sub>1</sub> VC <sub>2</sub> C in second syllable position; embedded in “a ____” (e.g., a sergeant, a scarlet); 12 repetitions	Vertical movements during release phase of C <sub>1</sub> (EMA); point of max contact C <sub>1</sub> to max contact C <sub>2</sub> (EPG); accurate and inaccurate productions; 8 middle repetitions	TT max displacement Duration Coefficient of variation of duration Relative timing Coefficient of variation of relative timing
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*Note.* C: Consonant; V: Vowel; J: Jaw; +J: Coupled to jaw; -J: Decoupled from jaw; LL: Lower lip; UL: Upper lip; TB: Tongue body; TD: Tongue dorsum/ tongue back; TT: Tongue tip/ tongue blade; NR: Not reported.

Table 3.  
*Measure definitions.*

Measure Type	Definition (Study No.)
Range of motion	<b>Displacement/ amplitude (mm):</b> Range of movement between two movement extrema (1, 2, 7, 11) <b>Distance (mm):</b> Distance traveled by articulator between two time points (4, 5, 8)
Speed of motion	<b>Maximum/peak velocity (mm/s):</b> The maximum value of the first derivative of position between two time points (1, 2, 5, 7, 8) <b>Maximum acceleration/deceleration (m/s<sup>2</sup>):</b> The maximum and minimum values of the second derivative of position between two time points (5, 8)
Movement durations	<b>Absolute duration (s):</b> Time between two kinematic landmarks (2, 3, 6, 7, 8, 11) <b>Coefficient of variation of duration:</b> Normalized index of standard deviation of duration (11)
Intra-articulator control	<b>Time to peak velocity</b> (2) <b>Number of velocity peaks</b> (6) <b>Number of changes in velocity direction:</b> Number of zero crossings in velocity signal (2) <b>Kinematic stiffness:</b> Peak velocity as a function of amplitude (1, 2, 7) <b>Velocity profile parameter:</b> Index of the shape of the velocity profile, calculated as kinematic stiffness multiplied by duration (7) <b>Velocity profile symmetry index:</b> Index of the relative time spent on acceleration vs. deceleration during opening and closing movements (7)
Inter-articulator coordination	<b>Upper lip – lower lip onset asynchrony:</b> Difference in time between upper and lower lip movement onsets (1) <b>Upper lip – lower lip displacement correlation:</b> A running correlation function between upper and lower-lip displacement signals (6) <b>Inter-articulator coupling:</b> Covariance values computed between articulator pairs (9) <b>Relative phase:</b> Time- and amplitude-normalized index of relative timing between two articulators or gestures (7)
Repetition variability	<b>Cyclic spatio-temporal index:</b> Measure of stability of speech motor execution, calculated as the sum of standard deviations within a plane of movement (vertical or horizontal) (7)
Positional accuracy	<b>Accuracy:</b> Number of correct articulatory positions as a function of total number of attempts (4)
Tongue-palate contact	<b>Centre of gravity:</b> The main concentration of electrode contact anteriorly to posteriorly at point of max contact (10) <b>Amount of contact:</b> Number of activated electrodes within the anterior or posterior zone of the palate at point of max contact (10) <b>Aspects of closure:</b> Most anterior row contacted, number of rows with complete closure, length of closure in the mid-line (10) <b>Aspects of constriction:</b> Location of the point of max constriction, groove width (10) <b>Relative variability index:</b> Sum of representative contact-pattern values expressed as a function of total number of activated electrodes (10) <b>Relative timing:</b> Absolute duration between maximum tongue-palate contact of two consonants expressed as a function of total syllable duration (11) <b>Coefficient of variation of relative timing:</b> Normalized index of standard deviation of relative timing (11)

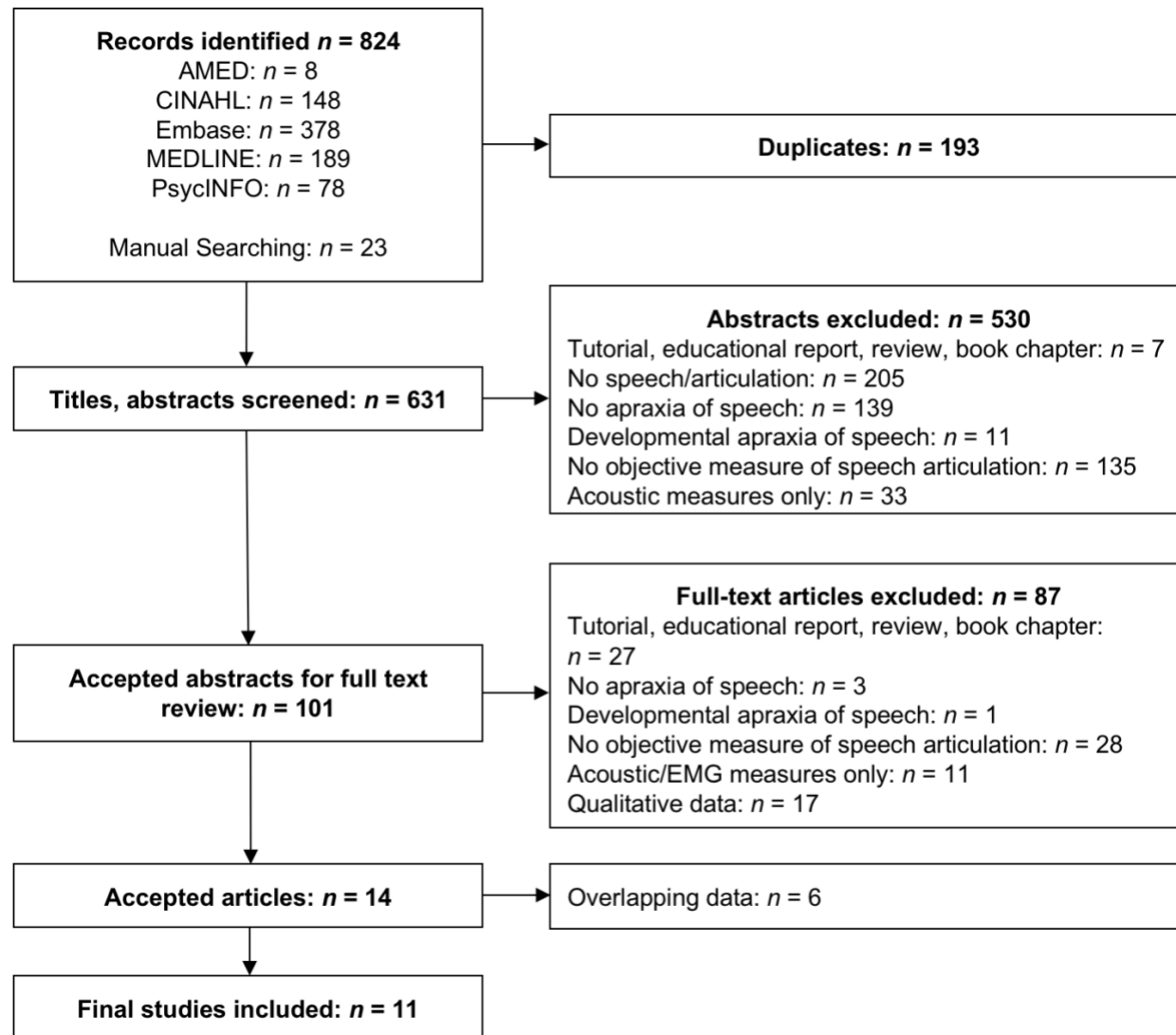
Table 4.

*Critical appraisal of methodological quality*

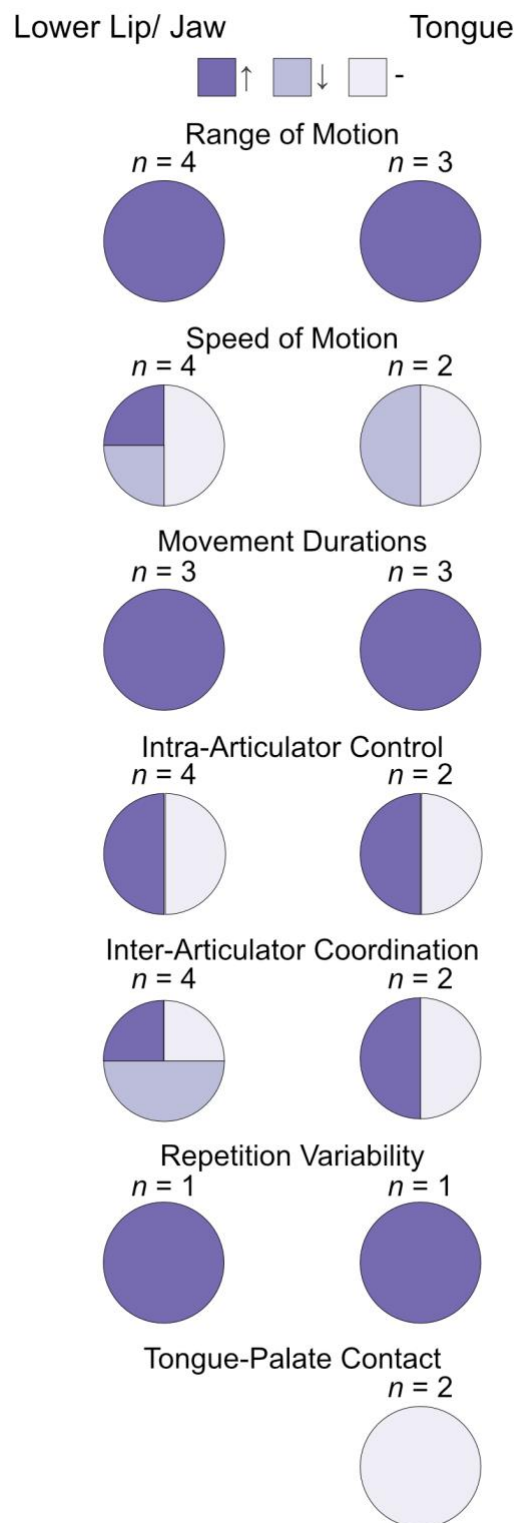
Study No.	Clear aims	Appropriate study design	Justified sample size	Population defined	Sample representative of population	Unbiased selection process	Appropriate variables	Appropriate measurement of variables	Clear statistical significance criteria	Repeatable methods	Basic data adequately described	All results described	Conclusions justified by results	Limitations discussed	Funding sources/ conflicts affecting interpretation	Ethical approval and consent obtained
<b>1</b>	+	+	-	+	+	-	+	+	-	-	-	+	+	-	NR	NR
<b>2</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	-	NR	NR
<b>3</b>	-	+	-	+	+	-	-	+	-	-	-	-	+	-	NR	NR
<b>4</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	+	NR	NR
<b>5</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	+/-	NR	NR
<b>6</b>	+	+	-	+	+	-	+	+	-	-	-	+	-	+	NR	NR
<b>7</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	+	NR	NR
<b>8</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	+	NR	NR
<b>9</b>	+	+	-	+	+	-	+	+	+	+	+	+	-	+	-	NR
<b>10</b>	+	+	-	+	+	-	+	+	+	+	+	+	+	+	-	NR
<b>11</b>	+	-	-	+	+	-	+	+	+	+	+	+	-	+	NR	NR

*Note.* +: Yes; -: No; NR: Not Reported; +/-: indicates the respective ratings of two articles from one study, where the ratings varied by article.

## Figures and Captions



**Figure 1.** A flowchart showing the search strategy and screening process.






**Figure 2.** Summary of results depicting differences in kinematic measures obtained from speakers with AOS and healthy controls. The number of studies that captured each type of



measure is shown above each pie chart. '↑' indicates an increase and '↓' a decrease in a measure for speakers with AOS as compared to healthy controls; '-' indicates no difference between the groups.

Effect	Range of Motion	Speed of Motion	Movement Durations	Intra-Articulator Control	Inter-Articulator Coordination	Repetition Variability	Positional Accuracy	Tongue-Palate Contact
Perceptual Accuracy	Effect	Effect	Effect	Not examined	No effect	Effect	Not examined	Not examined
Stimulus Complexity	Effect	Effect	Effect	Effect	Not examined	Not examined	Not examined	Not examined
Speaking Rate	Not examined	No effect	Not examined	Not examined	No effect	Not examined	Not examined	Not examined
Performance Over Time	No effect	No effect	No effect	No effect	No effect	Effect	Not examined	Not examined
Augmented Visual Feedback	Effect	Effect	Not examined	Not examined	Not examined	Not examined	Effect	Not examined
Presence of Bite-Block	Not examined	No effect	Not examined	Not examined	Not examined	Not examined	Not examined	Not examined

 Effect  
 No effect  
 Not examined

**Figure 3.** Summary of results by task/condition effects examined within speakers with AOS.

Measures that were sensitive to these effects are shown in green, whereas measures that were not sensitive are shown in blue. The white dashed boxes indicate measures that were not examined in the review studies.