

# Lip and tongue movements during phonetic sequences: analysis and definition of normal values

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**SUMMARY** Precise knowledge of lip and tongue movements is limited. Conventional investigative methods do not allow for their precise representation and analysis. In the present study, electromagnetic articulography (EMA) was used to define normal values for lip movements based on consonant–vowel–consonant (CVC) sequences and for tongue movements based on vowel–consonant–vowel (VCV) sequences. The study population included 25 volunteers (11 males and 14 females) with a median age of 26 (23 to 29) years. An EMA unit was used to conduct the measurements. For this purpose, the volunteers repeated a number of VCV and CVC text sequences 10 times each during two different body positions (upright and relaxed). Statistical analysis (including Bland and Altman’s measurement error, non-parametric Wilcoxon rank score testing, and analysis of variance) of distance and time variables resulted in a small measurement error.

There was no effect of different body positions on measurement error. Gender was found to have a significant effect on the values measured (67 versus 17 per cent of variables related to distances in CVC versus VCV sequences and 38 versus 75 per cent of variables related to intervals in CVC versus VCV sequences). This finding did not, however, hold true for any of the other parameters investigated as potential influencing factors. EMA is capable of providing valuable information about lip and tongue movements and any pathological dysfunctions involved.

## Introduction

Orofacial dysfunctions are a common finding in orthodontics, and this applies particularly to dysfunctions of the lip and tongue (Stahl *et al.*, 2007). Limited data are available on their precise movements and how they interact during phonetic sound formation. The general requirement for evidence-based procedures calls for scientific evaluation of methods of diagnosis and therapy. Dyskinesia of the lips and tongue will promote developmental abnormalities, and any findings of pathological malocclusion will influence orthodontic therapy and the stability of treatment (Schopf, 1972, 2000a,b; Fränkel and Fränkel, 1982; Rakosi, 1982; Steegmayer *et al.*, 1991; Thiele *et al.*, 1992; Diedrich, 2000; Ehmer, 2000; Fischer-Voosholz and Spenthof, 2002; Patti and Perrier d’Arc, 2007). Electromagnetic articulography (EMA) is the most suitable technique for analysing these movements (Engelke *et al.*, 1989, 1996; Schwestka-Polly *et al.*, 1992; Horn *et al.*, 1997a; Koos *et al.*, 2009). Less ideal options include video analysis, optoelectric systems (Ackermann *et al.*, 1995; Hertrich and Ackermann, 1997), techniques to measure lip and tongue pressure (Schopf, 1971; Horn *et al.*, 1995; Schuster *et al.*, 2009; Stöhr *et al.*, 2009), recordings made with strain gauges (Connor *et al.*, 1989; Forrest *et al.*, 1989),

radiographic microbeam technology (Kiritani *et al.*, 1975; Itoh *et al.*, 1980; Stone, 1990; Ishii, 1999; Green and Wang, 2003; Steele and Van Lieshout, 2004), and magnetic resonance tomography (MRT) (Mehnert *et al.*, 2009). Sonography is also an option, although its usefulness is limited to tongue movements (Peng *et al.*, 2007). EMA is, however, the only technique that allows both tongue and lip movements to be precisely recorded in time and space.

The objectives of the present study were to analyse the accuracy of EMA measurements, evaluate any effect of gender/body position on the values measured and the measurement error, and to define normal values for lip and tongue movements during phonetic sequences.

## Subjects and methods

Approval for this investigation was obtained from the Ethics Commission of the Faculty of Medicine, University of Tübingen (project no. 109/97).

The study population included 25 volunteers (11 males and 14 females) with a median age of 26 (23–29) years at an interquartile range of 1. All volunteers were healthy (no signs of sore throat, snuffles, hoarseness, underlying motor, central nervous system, or psychological disorders) and

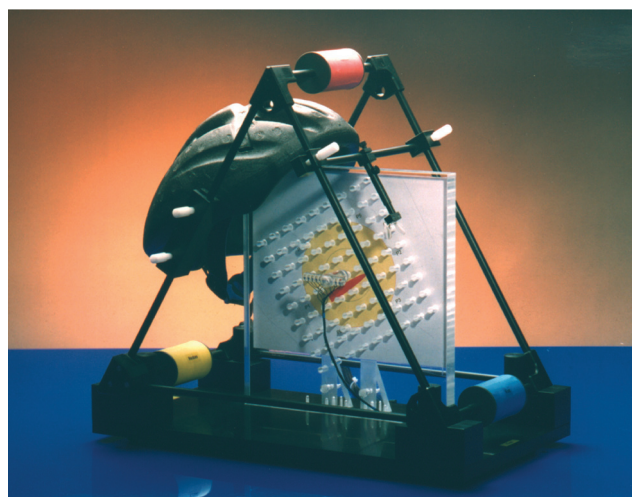
did not exhibit any orthopaedic, functional, orthodontic, or dental abnormalities (such as prosthetic restorations, crossbites, open bites, orofacial dysfunctions, or craniofacial disorders). None of the volunteers showed functional abnormalities (especially a somatic swallowing pattern or sigmatism). A neutroclussion was bilaterally present in all cases. In 21 subjects, the overjet was within the normal range of  $2 \pm 2$  mm (Drescher, 2000). Deviations from normal by +0.5 and +1 mm were observed in two subjects. An important inclusion criterion was the correct pronunciation of certain phonetic sequences; the pronunciation of all participants was accent free.

Measurements were performed with the EMA unit available at the Department of Orthodontics, Center of Dentistry, Oral Medicine and Maxillofacial Surgery, University Hospital Tübingen, Germany; (Figure 1) (Horn *et al.*, 1997a,b; Horn and Scholl, 1998). This advanced version of the EMA unit (Carstens Medizinelektronik, Lengler, Germany) (Carstens 1989; Engelke *et al.*, 1989; Schwestka-Polly *et al.*, 1992, 1995) includes a helmet with transmitter and receiver coils, an amplifier, and a computer (Figures 1 and 2). The advantages of this newly developed EMA unit over the previously used Carstens EMA unit include increased precision of measurements, an increased number of useable coils, automatic correction of coil twisting, and a more comfortably seated element.

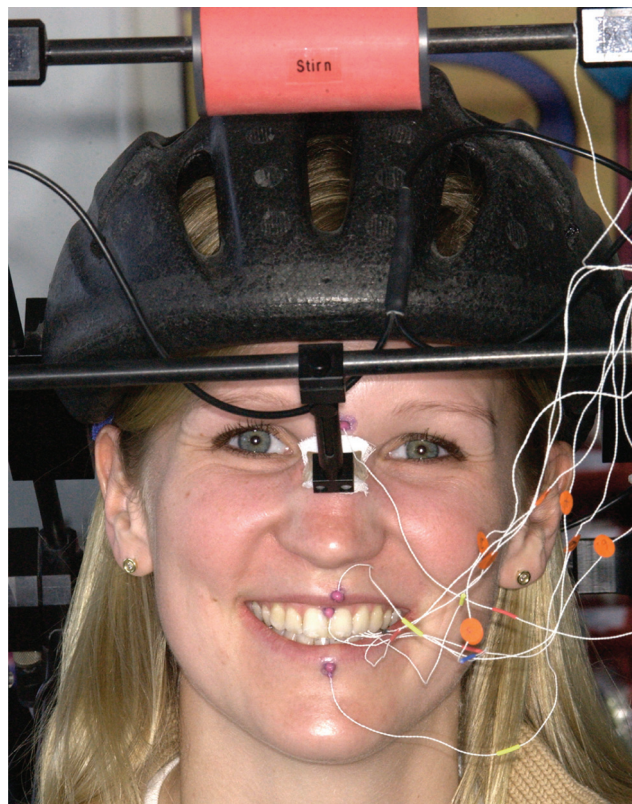
EMA is based on the principle of electromagnetic induction. Three transmitter coils arranged in an equilateral triangle whose sides (chin, forehead, neck), which are approximately 40 cm long, are connected to a light polystyrene helmet with carbon rods, producing a non-homogeneous, radially symmetric magnetic field. Within this magnetic field, receiver coils (Table 1), 2 mm in size, are connected to the receiver units at the positions to be examined with a thin connecting wire (diameter: 0.3 mm). The voltage induced in the sensor is characteristic of the respective position within the magnetic field and is reported to the connected personal computer by way of an A/D converter. The AGMDE software (Scholl T, Department of Orthodontics, University Hospital of Tübingen) allows the movement to be depicted in the median sagittal plane using the XY coordinate system. The origin of the coordinate system is located at the antero-caudal border of the measurement area. The spoken text can be recorded synchronously with the movement via two attached microphones.

The measurement error of the system is 0.12 mm within the ideal measurement zone and regardless of direction or speed (Horn *et al.*, 1997a). The ideal measurement zone is located within the measurement centres of the helmet (diameter: 80 mm). After being switched on, the system will start by calibrating the coils (Figure 1). Therefore, the helmet must be positioned carefully so that the centre of measurement coincides with the range of motion of the tongue and lips.

Histoacryl tissue adhesive (Braun, Melsungen, Germany) was used for intra- and extraoral mounting of 10 receiver



**Figure 1** Electromagnetic articulography unit and helmet configuration with calibration device.



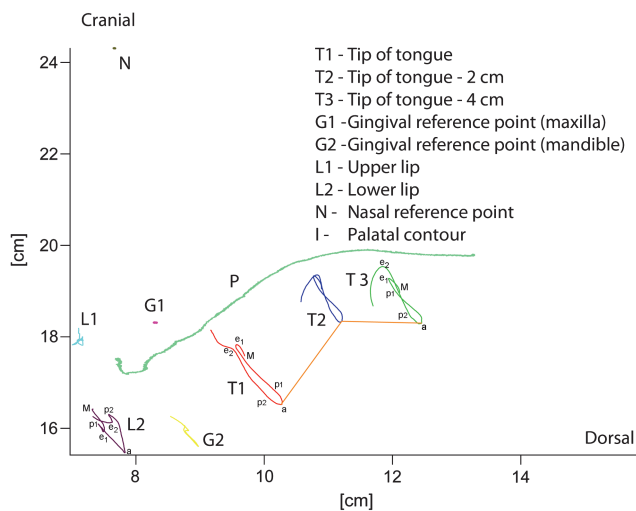
**Figure 2** Volunteer with helmet configuration and coils glued in place.

coils (Figures 2 and 3) (Koos, 2008). Coils 1 to 8 were used for the primary measurements as the phonetic sequences were recorded. The purpose of coils 9 and 10 is to capture reference structures (occlusal plane and palatal contour) before conducting the primary measurements. The palatal contour was recorded by tracing it with coil 10 attached temporarily to an index finger. The incisal plane was

**Table 1** Description of the positioning of the coils.

| Coil no. | Coil name                             | Description   |
|----------|---------------------------------------|---|
| 1        | Tip of the tongue                     |   |
| 2        | Tip of the tongue—2 cm                | 2 cm dorsal from the tip of the tongue                                  |
| 3        | Tip of the tongue—4 cm                | 4 cm dorsal from the tip of the tongue                                  |
| 4        | Gingival reference point (maxilla)    | Beginning of the fixed gingiva between the central incisors             |
| 5        | Gingival reference point (mandible)   | Beginning of the fixed gingiva between the central incisors             |
| 6        | Upper lip                             | Cupid bow of the lip vermillion   |
| 7        | Lower lip                             | Edge of the lip vermillion  |
| 8        | Nasal reference point                 | (soft-tissue nasion) middle point of the soft-tissue frontonasal suture |
| 9        | Anterior point of the occlusal plane  | Preliminary recorded anterior point of the occlusal plane               |
| 10*      | Posterior point of the occlusal plane | Preliminary recorded posterior point of the occlusal plane              |
| 10*      | Palatal contour                       | Preliminary recorded palatal contour                                    |

\*Coil 10 was used during the preliminary recording in two separate records, first to depict the palatal contour and then to register the anterior point of the occlusal plane (as part of the bite fork).



**Figure 3** X/Y graph of lip movement (left lateral view) during consonant-vowel-consonant sequences (*me-PAP-e*). The course of the movement is depicted by M – e<sub>1</sub> – p<sub>1</sub> – a – p<sub>2</sub> – e<sub>2</sub>.

registered with a custom bite fork that had coil 9 attached to its anterior aspect and coil 10 attached to its posterior aspect. The bite fork was adapted to the mandibular central incisors and first molars using occlusal Futar-D impressions (Kettenbach, Eschenburg, Germany) in order to determine a customised occlusal plane.

A number of German consonant-vowel-consonant (CVC) sequences (Table 2) were recorded and analysed. The sequences were *me-PAP-e*, *me-PEP-e*, *me-PIP-e*, *me-POP-e*, *me-PUP-e*. The variant part represents the five clear vowels as present in many European and other languages. Approximations in standard English would be A = AH; E = EY; I = EE; O = OA; U = OO. Each sequence was embedded in a short German sentence (*Ich habe . . . gesagt*, meaning “I said . . .”) and repeated 10 times. Next, the vowel-consonant-vowel (VCV) sequences (Table 2) were recorded. The sequences were *met-AFA-te*, *met-AKA-te*, *met-ALA-te*,

*met-ANA-te*, *met-ASHA-te*, *met-ATA-te*. (Note the earlier comment concerning vowel values.) The VCV sequences had been established by Engelke *et al.* (1989) in their study of speech sequences. Choosing the sequences facilitates comparability of the results with those of earlier studies (Engelke *et al.*, 1989; Horn *et al.*, 1997b). The particular spoken CVC sequences were selected to promote highly precise lip movements for the choice of the sequences themselves and in order to recognize potential deficiencies in lip motility and subsequent studies. Between sequences, the volunteers alternated between an upright and relaxed body position. The upright position was defined by a tense posture of the back and head with the volunteers sitting with the knees bent. For the relaxed position, they were asked to take a comfortable habitual sitting position. In contrast to previous studies, this variation in body posture had been predefined, and the number of distances measured was approximately four times as large. In addition, the corresponding time intervals were also calculated.

Articulograph functionality within the Igor-Pro CAD software (release 5.01M; Wavemetrics, Lake Oswego, Oregon, USA) was used for graphical representation and analysis of the data. The corresponding statistics module was used to convert the data to a format readable by the software. As can be seen from Figures 3–6, the audio track is used as a reference to read out the corresponding values of the kinematic track at the manually defined points of measurement. To ensure mutual comparability, all recordings were level with their respective occlusal planes parallel to the X-axis.

A total of 540 variables were analysed, including 45 for each of the 12 phonetic sequences; 14 variables were used to describe the marked reproducible positions along the x- and y-axes and five to describe the points of time assigned to the positions. The marked reproducible positions were defined, in VCV sequences as the tongue coil (tip of the tongue, coil 1) and in CVC sequences as the minimum and maximum values in the y-direction of movement and maximum values in the y-direction of lip movement (lower lip, coil 7).



**Table 2** Description of variables.

Evaluated variables, electromagnetic articulography (speech movements, consonant–vowel–consonant (CVC) and vowel–consonant–vowel (VCV))  
The a-VCV-a sequence is analogous to the e-CVC-e sequence

## 1. Baseline variables

a. Positions (each consisting of an  $x$  and  $y$  variable/coordinate)

- p1:  $x + y$  Position: start of first 'e' of the e-CVC-e sequence (first marker position)  
 p2:  $x + y$  Position: extreme position, first 'p' of the e-CVC-e sequence  
 p3:  $x + y$  Position: extreme position, consonant of the e-CVC-e sequence  
 p4:  $x + y$  Position: extreme position, second 'p' of the e-CVC-e sequence  
 p5:  $x + y$  Position: start of second 'e' der e-CVC-e sequence (second marker position)  
 b1:  $x + y$  Nasal reference point  
 b2:  $x + y$  Maxillary reference point

## b. Time

- t1: Time: start of first 'e' of the e-CVC-e sequence  
 t2: Time: extreme position, first 'p' of the e-CVC-e sequence  
 t3: Time: extreme position, consonant of the e-CVC-e sequence  
 t4: Time: extreme position, second 'p' of the e-CVC-e sequence  
 t5: Time: start of second 'e' der e-CVC-e sequence

## 2. Calculated variables

## a. Distances

- D1: Line p1p2 ('e1'-C1)  
 D2: Line p2p3 (C1-V)  
 D3: Line p3p4 (V-C2)  
 D4: Line p4p5 (C2-'e2')  
 D5: Line p1p5 ('e1'-'e2')  
 D6: Line p2p4 (C1-C2)  
 D7: Line p1p3 ('e1'-V)  
 D8: Line p3p5 (V-'e2')  
 D9: Line p1-b2 (x direction)  
 D10: Line p1-b2 (y direction)  
 D11: Line p2-b2 (x direction)  
 D12: Line p2-b2 (y direction)  
 D13: Line p3-b2 (x direction)  
 D14: Line p3-b2 (y direction)  
 D15: Line p4-b2 (x direction)  
 D16: Line p4-b2 (y direction)  
 D17: Line p5-b2 (x direction)  
 D18: Line p5-b2 (y direction)

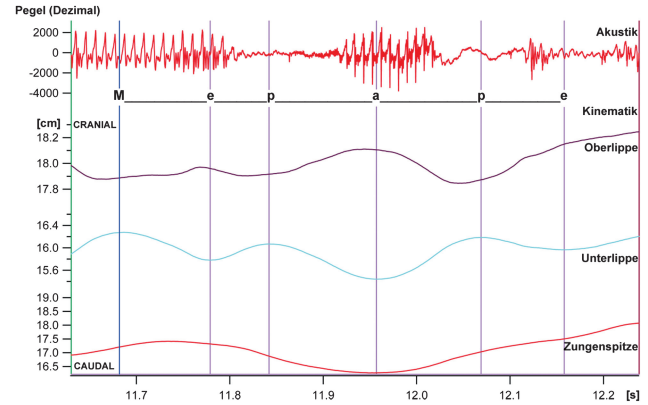
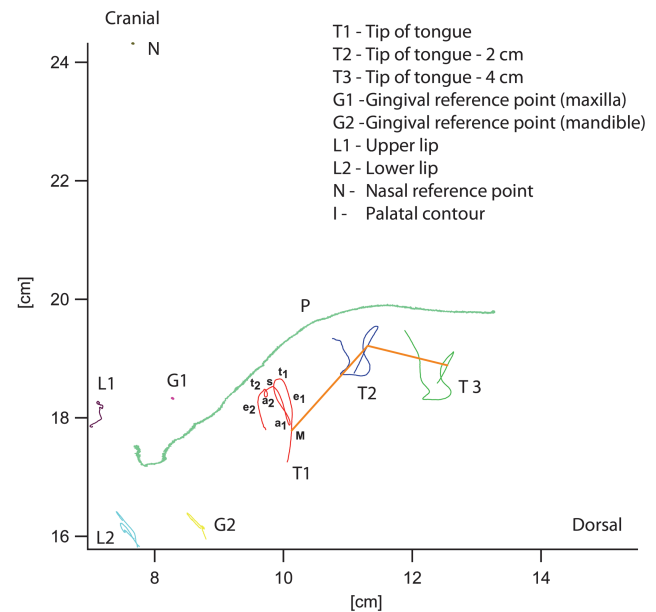
## b. Time intervals

- T1: Time interval t1t2 ('e1'-C1)  
 T2: Time interval t2t3 (C1-V)  
 T3: Time interval t3t4 (V-C2)  
 T4: Time interval t4t5 (C2-'e2')  
 T5: Time interval t1t5 ('e1'-'e2')  
 T6: Time interval t2t4 (C1-C2)  
 T7: Time interval t1t3 ('e1'-V)  
 T8: Time interval t3t5 (V-'e2')

## Total number of variables

- Positions (7  $x$  variables plus 7  $y$  variables) 14  
 Times 5  
 Distances 18  
 Time intervals 8  
 Total 45

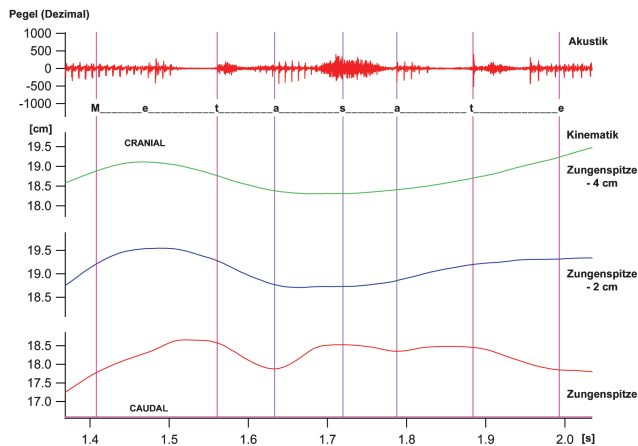
A total of 18 variables were used to calculate the distances between the positions and eight the time intervals between the points of time (Figures 4 and 6) (Koos, 2008). These 26 variables provided the basis for evaluating the statistical effects of body position and gender. Statistical analysis with JMP IN, Release 5.1 (SAS Institute Inc., Cary, North

**Figure 4** Representation of lip movement during consonant–vowel–consonant sequences (*me-PAP-e*).**Figure 5** X/Y graph of tongue movement (left lateral view) during vowel–consonant–vowel sequences (*met-ASA-te*). The course of the movement is depicted by M – e<sub>1</sub> – t<sub>1</sub> – a<sub>1</sub> – s – a<sub>2</sub> – t<sub>2</sub> – e<sub>2</sub>.

Carolina, USA) yielded the measurement errors involved in measuring phonetic sequences and the 1.96/2.77 factor errors during repeated measurements as described by Bland and Altman (1996). Measurement errors were classified along a scale ranging from 1 (ideal quality range) to 4 (unacceptable quality range). The assessment quotients ( $Q^*$ ) were defined over a range from 0 to 3 (Koos, 2008).

$$Q^* = \text{Round} \left[ \frac{(N(*) * 1 + N(**) * 2 + N(***) * 3)}{N(\text{Rows})}, 2\text{nd decimal place} \right]$$

The definition of  $Q^* = 3$  implied that the measurement errors for all variables fell into category 1, whereas  $Q^* = 0$  indicated that all measurements errors fell into category 4.



**Figure 6** Representation of tongue movement during vowel-consonant-vowel sequences (*met-ASA-te*).

Analysis of variance (ANOVA) (Sall, 1990) was used to assess the effects of body position, phonetic sequences, measured variables, and gender on measurement error. Unifactorial analysis by non-parametric Wilcoxon rank score testing (Campbell and Gardner, 1988; Whitley and Ball, 2002a,b; Bewick *et al.*, 2004; Rosner *et al.*, 2006) was used to estimate the effect of the key factors (upright and relaxed position) on the measurement error at a significance level of 0.05 (Altman, 1991). Further unifactorial analyses were conducted to verify any statistical effects of key factors (upright versus relaxed, male versus female) on the values obtained. Other points of verification concerned the requirements for using ANOVA, homogeneity of variance, and normal distribution of values. The tests employed to verify the homogeneity of variance included O'Brien's (Campbell and Gardner, 1988), Brown-Forsythe, Bartlett's, and two-sided *F*-tests. The presence of normal distribution was verified by Shapiro-Wilk *W* testing.

## Results

Based on CVC sequences, the quotient  $Q^*$  used to classify measurement errors was 3 for spatial distances and 2.25 for time intervals. This finding was true both for sorting by variables (distances D01 through to D18 and intervals T01 through to T08) and for sorting by phonetic sequences (*me-PAP-e*, *me-PEP-e*, *me-PIP-e*, *me-POP-e*, *me-PUP-e*). By comparison, the  $Q^*$  values were less favourable for VCV sequences. When sorted by variables, they were 1.89 (distances D01 through to D18) and 2.16 (intervals T01 through to T18).  $Q^*$  values sorted by text sequences were 1.88 for distances and 2.2 for intervals.

O'Brien's (Campbell and Gardner, 1988), Brown-Forsythe's, Bartlett's and two-sided *F*-tests conducted with JMP IN software did not reject the presence of homogeneity of variance. The assumption that the data were based on a normal distribution was rejected for 77 per cent of the

variables tested for VCV sequences and for 86 per cent of the variables tested for CVC sequences.

ANOVA of the overall model (total effect of phonetic sequence, variable, body position, and gender on the measurement error) yielded  $R^2$  values of 0.56 (CVC) and 0.65 (VCV) for distances. For intervals, a difference of  $R^2$  of 0.8 in CVC versus 0.45 in VCV was noted.

No statistically significant effects of body position on measurement error were demonstrated.

Based on the values obtained, formal statistical effects of body position were only obtained with VCV sequences for 17 per cent of variables based on distances. No statistically significant effects were observed in the separate unifactorial analysis of differences in sound formation between *met-AFA-te* and *met-AKA-te*. Body positions had no effect on time intervals. Gender revealed significant effects for 67 per cent of variables for distances in CVC sequences compared with 17 per cent in VCV sequences. For time intervals, effects of gender were found for 38 per cent of variables in CVC sequences and for 75 per cent of variables in VCV sequences.

These results defined the normal values. An exhaustive representation cannot be given due to the high number of values involved. Examples of values measured are given in Table 3 (lip movement obtained during CVC sequences, *me-PAP-e*) and Table 4 (tongue movement obtained during VCV sequences, *met-ASA-te*).

## Discussion

Statistical analysis yielded the validity of all measured values. As shown above, excellent or good levels of measurement error were obtained for most of the values measured. Most notably, the distances involved in CVC sequences were measured more reliably and accurately than those in the VCV sequences. All variables of CVC sequence fell into category 1 of measurement error quality. One factor accounting for this result was extraoral placement of the reference coils, which prevented the wires used for measurement from binding in the corner of the mouth, thus ensuring unrestricted movements of the tongue.

Parts of the formal requirements for ANOVA testing were met. While homogeneity of variance could not be rejected, normal distribution of the data was predominantly rejected. With this consideration in mind, one should remain critical about the  $R^2$  values obtained by ANOVA testing. Reservations of this type are not necessary for unifactorial analysis based on Wilcoxon rank scores, as this non-parametric procedure is sufficiently robust against external factors, thus offering good validity (Altman, 1991).

None of the variables revealed a statistically significant effect of body position on measurement error.

The results of unifactorial analysis showed that the values obtained differed by gender. While positron emission

**Table 3** Exemplary normal values of lip movement obtained during consonant–vowel–consonant sequences (*me-PAP-e*)—shown in Figure 3.

| Variable  | Value (mm) male | Value (mm) female | Description  |
|---|-----------------|-------------------|--|
| Spatial distances involved in lip movement (values measured at the lower lip) |                 |                   |  |
| D2  | 1.4             | 1.2               | Distance: first lip closure to maximum lip opening (»p <sub>1</sub> « to »a«)      |
| D3  | 1.4             | 1.2               | Distance: maximum lip opening to second lip closure (»a« to »p <sub>2</sub> «)     |
| D5  | 0.3             | 0.3               | Distance: start to end of entire sequence (»e <sub>1</sub> « to »e <sub>1</sub> «) |
| D6  | 0.2             | 0.1               | Distance: start to end of core sequence (»p <sub>1</sub> « to »p <sub>2</sub> «)   |
| Time intervals involved in lip movement (values measured at the lower lip)    |                 |                   |  |
| T2  | 0.13            | 0.14              | Interval: first lip closure to maximum lip opening (»p <sub>1</sub> « to »a«)      |
| T3  | 0.10            | 0.11              | Interval: maximum lip opening to second lip closure (»a« to »p <sub>2</sub> «)     |
| T5  | 0.42            | 0.45              | Interval: start to end of entire sequence (»e <sub>1</sub> « to »e <sub>2</sub> «) |
| T6  | 0.23            | 0.25              | Distance: start to end of core sequence (»p <sub>1</sub> « to »p <sub>2</sub> «)   |

**Table 4** Exemplary normal values of tongue movement obtained during vowel-consonant-vowel sequences (*met-ASA-te*)—illustrated in Figure 5.

| Variable   | Value (mm) male | Value (mm) female | Description   |
|--|-----------------|-------------------|---|
| Spatial distances involved in tongue movement (values measured at tip of tongue) |                 |                   |   |
| D2   | 8.0             | 8.2               | Distance: vowel (off palate) to consonant (near palate) (»a <sub>1</sub> « to »s«)                            |
| D3   | 3.1             | 3.3               | Distance: consonant (near palate) to vowel (off palate) (»s« to »a <sub>2</sub> «)                            |
| D5   | 2.1             | 2.2               | Distance: plosive (contact with palate) to plosive (contact with palate) based on entire sequence (T1 to T2). |
| D6   | 5.1             | 5.2               | Distance: vowel to vowel based on core sequence (»a <sub>1</sub> « to »a <sub>2</sub> «)                      |
| Time intervals involved in tongue movement (values measured at tip of tongue)    |                 |                   |   |
| T2   | 0.09            | 0.1               | Interval: vowel (off palate) to consonant (near palate) (»a <sub>1</sub> « to »s«)                            |
| T3   | 0.07            | 0.07              | Interval: consonant (near palate) to vowel (off palate) (»s« to »a <sub>2</sub> «)                            |
| T5   | 0.33            | 0.37              | Interval: plosive (contact with palate) to plosive (contact with palate) based on entire sequence (T1 to T2). |
| T6   | 0.16            | 0.17              | Interval: vowel to vowel based on core sequence (»a <sub>1</sub> « to »a <sub>2</sub> «)                      |

tomography and functional MRT did not reveal any differences in speech control between the genders (Schlösser *et al.*, 1998); differences that might explain the finding exist between underlying anatomical situations and between the physiological mechanisms involved (Huber *et al.*, 1999; Ferrario *et al.*, 2000; Hou *et al.*, 2002).

The issue of body position is a different matter. Unlike gender, the different postures used did not influence the values obtained. The *met-AFA-te* and *met-AKA-te* sequences were evaluated on a separate basis due to their special nature of sound formation. The fricative *f* is primarily formed by the lower lip and upper incisors, whereas the plosive *k* is formed at the back of the tongue. As a result, the most pertinent reference coils were coil 7 (lower lip) for the fricative and coil 3 (back of tongue) for the plosive. To simplify the experimental set-up, body position should be disregarded in future investigations.

The study is the first to define normal values for tongue and lip movements. The EMA unit offered several advantages over similar articulography units (Carstens, 1989; Schweska-Polly *et al.*, 1992, 1995; Engelke *et al.*, 1996; Kretschmer, 1996; Müllauer, 1996; Horn *et al.*, 1997b). Its accuracy within the measurement zone was 0.1 mm. The helmet consisted of a light carbon structure that could be individually

adjusted and did not significantly impede the volunteer's range of motion. This helmet is also available in a lighter and smaller version specifically designed for use with children, taking into consideration a number of anatomical differences. Due to its mobile design, the measurement system can be readily transferred from one site to another.

Other systems of measurement such as video analysis, optoelectric systems (Ackermann *et al.*, 1995; Hertrich and Ackermann, 1997), techniques to measure lip and tongue pressure (Schopf, 1971; Horn *et al.*, 1995), and recordings made with strain gauges (Connor *et al.*, 1989; Forrest *et al.*, 1989) are inferior and cannot be readily compared. These methods represent intraoral processes either insufficiently or not at all. Extraorally they cannot match the EMA unit in terms of measurement accuracy. X-ray microbeam technology (Kiritani *et al.*, 1975; Stone, 1990; Itoh *et al.*, 1980; Ishii, 1999; Green and Wang, 2003; Steele and van Lieshout, 2004) is known to offer good spatial visualization during intraoral recording of tongue movements, but its usefulness is limited by radiation exposure, high operative cost, and interference of metal structures (restorations or implants). A novel technology that would suggest itself for use is three-dimensional (3D) optical facial scanning (Hönn and Göz, 2007). Up to now, however, these systems are confined to individual static

images. Whether they are capable of reaching the precision of EMA will become known once extended intervals of time can be covered by dynamic recordings and accompanied by parallel audio recordings. A clear limitation of this method is the purely extraoral nature of 3D facial scans; intraoral movements cannot be represented with this method.

## Conclusions

The present study revealed statistically significant differences between VCV and CVC sequences. This was demonstrated by the evaluation coefficient,  $Q^*$ . Comparisons indicated that for CVC sequences,  $Q^*$  was 3 for distances and 2.3 for time intervals. VCV sequences scored lower at a  $Q^*$  of 1.9 for distances and 2.2 for time intervals. The analysis of CVC sequences with reference coils at the upper and lower lips proved more reliable in terms of measurement and interpretation than analysis of the VCV sequences with reference coils on the tongue. Gender had an effect on the values measured resulting in a differentiated approach.

EMA is a precise technology for the examination of lip and tongue movements based on the compared CVC and VCV sequences. Apart from minor limitations, the phonetic sequences and variables selected can be considered reliable and, for the most part, ideally serve the intended purpose.

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