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Statistical modelling of lip movement in the clinical context

H. Popat
A. I. Zhurov
A. M. Toma
S. Richmond
D. Marshall
P. L. Rosin

Authors' affiliations:
H. Popat, A. I. Zhurov, A. M. Toma, S. Richmond, Applied Clinical Research and Public Health, School of Dentistry, Cardiff University, Cardiff, UK
D. Marshall, P. L. Rosin, School of Computer Science & Informatics, Cardiff University, Cardiff, UK

Correspondence to:
Hashmat Popat
Applied Clinical Research
and Public Health
School of Dentistry
Cardiff University
Cardiff, CF14 4XY, UK
E-mail: popath@cardiff.ac.uk

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Structured Abstract

Objective – To establish three-dimensional (3D) reference data on average lip movement in normal healthy subjects using statistical shape analysis techniques.

Setting and Sample Population – School of Dentistry and Cardiff School of Computer Science, Cardiff University, United Kingdom. One hundred and fifteen white subjects.

Material and Methods – Subjects performed four reproducible verbal gestures (*puppy*, *rope*, *baby* and *bob*) in a normal relaxed manner, which were captured using a non-invasive, 3D motion scanner (3dMDFace™ Dynamic System). Six landmarks were manually placed around the lips of the 3D facial shells showing maximum lip displacement. Generalized procrustes analysis followed by principal component analysis was applied to the landmark coordinates to characterize lip movement for each word.

Results – The first four principal components (PCs) describe the majority of variation in lip movement for the four words involving a complex interaction of lip movements in three dimensions. Bilateral landmarks were paired within PCs showing that movement was largely symmetrical. Female resting lip shape was narrower and shorter in height than males. During motion, females preferred a more protrusive articulation than males.

Conclusion – Statistical shape analysis techniques can be used to characterize lip movement during articulation. Data from this study can act as a reference for average lip movement to compare similar population groups.

Key words: articulation; lip movement; motion analysis; three-dimensional

Introduction

Evaluation of lip movement can form an important consideration in many dental applications. These include the analysis of smile dynamics (1), in the treatment of patients with cleft lip (2) and those with facial nerve impairments (3). Despite its relevance in

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the dental context, objective assessments of lip function are rarely performed in clinical practice. Although the simplest methods of assessing lip function are to use subjective grading scales (4), they provide limited information on the subtle nuances of facial movement (5). Medical imaging techniques are more appropriate when detailed, objective information is required but, in the past, have been complex and time-consuming to operate, and therefore inappropriate for routine clinical use (6). Current advances in three-dimensional (3D) imaging and computer-assisted analyses have now made the capture of facial movement more accessible. This has allowed research groups to carry out preliminary investigations of lip movement in cleft and orthognathic patients (7, 8). Investigations of lip movement have also been made in individuals with facial weakness and facial palsy (9).

Prior to analysing facial movement in target groups, it is important to establish normative reference data. This approach has been used widely in orthodontics and craniofacial research by age- and/or sex-matching lateral cephalograms, (10) and more recently, 3D laser scans from population groups to enable comparisons to be made between an individual and their respective template (11). The aims of this study are therefore to:

- Present a statistical method of characterizing lip movements and explore its ability to distinguish various lip movements
- Establish 3D normative data on lip movements in an ordinary population

Materials and method

This was a cross-sectional observational study based on one participant group that the authors plan to use as a control group for future studies. Ethical approval was obtained from South East Wales Research Ethics Committee (no. 09/41) prior to the commencement of the study.

Inclusion criteria were the following: participants to be aged between 21 and 40 years, no relevant medical history, no history of facial surgery or paralysis, a full dentition with a normal maxillary–mandibular skeletal relationship and British English as their first language. One hundred and fifteen white subjects (62 male, 53 female) with a mean age of 33.4 years were included.

Image capture

The following notation is used throughout the paper: visemes (visual) are underlined and phonemes (audio) are written within slashes.

Subjects were orientated into Natural Head Posture and asked to say four words (*puppy*, *rope*, *baby* and *bob*) in a normal relaxed manner. All subjects were scanned using the 3dMDFace™ Dynamic System (3Q Technologies, Atlanta, GA, USA) at 48 frames/s under standardized conditions. The detailed specifications of the imaging system have been described in a previous publication (12).

Image processing

The video sequences were analysed according to the different visemes or mouth shapes for each word. The corresponding phonetic (audio) descriptions based on British English (13) are shown in Fig. 1. For the four words used in this study, there are nine phonemes (including silence). Note that there is not always one-to-one mapping between phonemes and visemes – sometimes, several phonemes will have the same viseme (14). Therefore, for the nine phonemes, seven visemes (rest, **p**uppy, pupp**y**, **r**ope, **b**aby, bab**y** and b**o**b) were analysed as part of the study.

Six landmarks were manually placed by one examiner (HP) around the lips for each 3D facial shell (Fig. 2). The landmarks used in the study are defined in anthropometric studies as labiale superius (ls) – the midpoint of the upper vermilion line, labiale inferius (li) – the midpoint of the lower vermilion line, crista philtri (cph L/R) – the point on the left and right elevated margins of the philtrum above the vermilion line and cheilion (ch L/R) – the point located at the left and right labial commissure (15). Only the maximum displacement vectors (x, y, z coordinates for each landmark, giving 18 landmark clusters for each lip shape) equivalent to the maximum lip movement for each viseme were analysed.

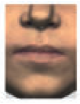
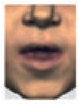
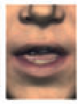
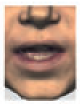
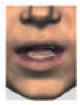
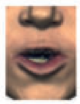
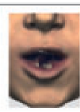
Phoneme	Description	Example	Viseme analysed
Silence	At rest		
/p/ /b/	Plosive consonant	Puppy Baby	 
/ʌ/	Short vowel	Puppy	
/eɪ/	Short vowel	Baby	
/i/	Long vowel	Puppy Baby	 
/r/	Approximant consonant	Rope	
/əʊ/	Diphthong vowel	Rope	
/ɒ/	Short vowel	Bob	

Fig. 1. Phoneme-to-viseme mapping of the four study words based on British English.

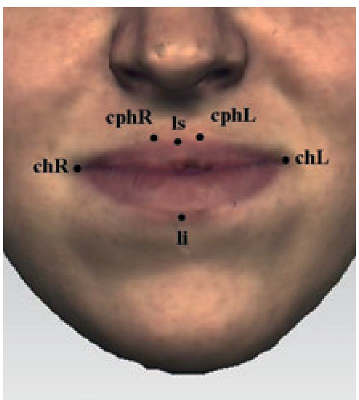


Fig. 2. Lip landmarks used in the study.

Error of the method

Accuracy of landmark placement was crucial to ensure that valid data were to be obtained on lip movement. Therefore, intra- and inter-examiner reproducibility of landmark placement was assessed by HP and a separate examiner by repeating landmark placement for 80 facial shells within the data set (chosen by a random number generator) 2 weeks later. This represented a 10% proportion of the whole data set. Mean distance error calculations were used to consider the reproducibility of the six lip landmarks in the x, y and z planes (16).

Statistical analysis

Generalized Procrustes Analysis (GPA) was used to align the coordinates for all landmarks in the data set. GPA is a well-known technique in statistical shape analysis, which involves superimposition of coordinates in optimal positions by means of their translation, rotation and scaling so as to minimize the sum of squared Euclidean distances (17). For the purposes of this study, which was to investigate variation in lip size and shape, scaling was removed from the analysis leaving only translation and rotation (18).

Following registration, a centroid representing the mean position for each of the 18 clusters of landmarks was derived. Two standard deviations (SD) around each centroid (representing 95% of the variability in x, y and z from the mean) were calculated for all individuals and plotted as ellipsoids.

Principal component analysis (PCA) was then applied to the registered coordinates to isolate patterns and relationships between the lip landmarks for each viseme. This was carried out using the software package SPSS 16.0 (SPSS Inc., Chicago, IL, USA). The model defines the first principal component (PC1) as those coordinates that account for the highest variation in the data set. Subsequent components account for the next highest variation (PC2, PC3, PC4 and so on) and are independent of the previous components. Linear combinations of the variables that account for 90% of the total variation in the data were extracted for this study. The PCA data are presented in tabular format with coordinates ranked in terms of their eigenvector, which represents the contribution of each coordinate to its respective component. Higher eigenvectors indicate a greater contribution of a particular coordinate to a PC. In addition, the sign of the coordinate (i.e. positive or negative) gives an indication of the direction of movement. For example, a positive

Table 1. **Ranked landmark reproducibility in three planes of space as expressed by mean distance error**

	Intraexaminer			Interexaminer		
Rank	Landmark	Mean distance error (mm)	SD	Landmark	Mean distance error (mm)	SD
1	ls	0.62	0.21	ls	0.60	0.32
2	li	0.87	0.31	cphL	0.77	0.27
3	cphL	0.96	0.37	li	0.87	0.27
4	cphR	1.04	0.46	cphR	0.99	0.58
5	chL	1.01	0.59	chR	1.26	0.42
6	chR	1.35	0.46	chL	1.42	0.35

value for ls_y and negative value for li_y would imply that these landmarks are moving in opposite directions.

Results

Landmark reproducibility

Landmarks ls and li tended to be most reproducible in all planes, whereas both chL and chR were least reproducible particularly in the *x* and *y* plane. The reproducibility of landmark placement between intra- and inter-examiner assessments was largely similar. Table 1 shows the landmarks ranked in the order of most reproducible with respect to the mean distance error in three planes of space between assessments. The range in total landmark distance error for both intra- and inter-examiner assessments was 0.6–1.42 mm.

Table 2. **Principal component analysis table for the viseme rope**

PC (% variance)	*x-y-z* coordinates	PC with associated eigenvector of landmark 1	2	3	4	5
PC1 (48)	chR_y	−0.948				
	chL_y	−0.942				
	ls_z	0.897				
	cphL_z	0.894				
	cphR_z	0.873				
	chR_z	−0.748				
	chL_z	−0.734				
	ls_y	0.711		0.599		
PC2 (17)	li_z		0.948			
	chR_x		−0.660			
	chL_x		0.657			
PC3 (10)	li_y			−0.980		
	cphL_y			0.715		
	cphR_y			0.694		
PC4 (8)	cphL_x				0.953	
	cphR_x				−0.873	
PC5 (7)	ls_x					0.876
	li_x					0.622

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

This compares favourably with other studies, which showed a range of 0.32–1.11 mm for the same landmarks on laser scanned surface images (16).

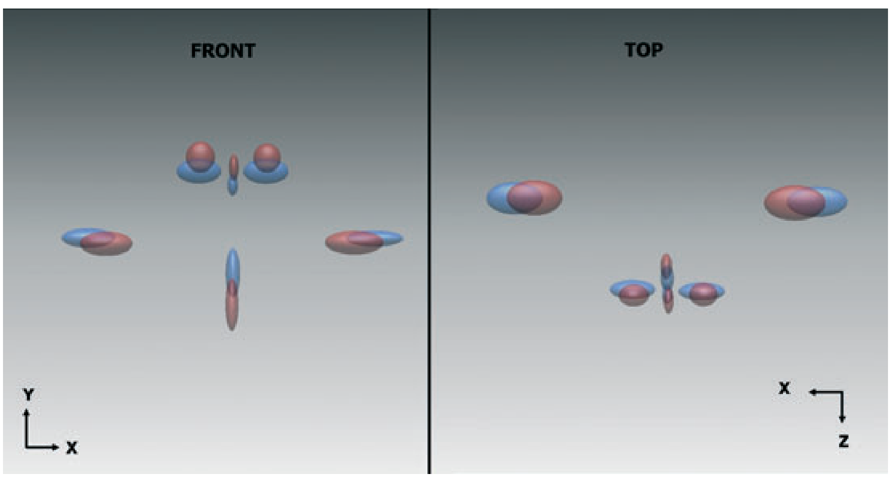


Fig. 3. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to articulation of the viseme rope (red).

Table 3. **Principal component analysis table for the viseme puppy**

PC (% variance)	x-y-z coordinates	PC with associated eigenvector of landmark 1	2	3	4	5	6
PC1 (42)	chL_y	−0.922					
	chR_y	−0.868					
	cphL_z	0.809					
	cphR_z	0.742	0.508				
	ls_z	0.640					
PC2 (16)	li_z		0.917				
	chL_z		−0.781				
	chR_x		−0.742				
	chL_x		0.740				
	chRZ	−0.531	−0.716				
PC3 (11)	li_y			−0.985			
	cphL_y			0.869			
	cphR_y			0.853			
	ls_y			0.615			
PC4 (8)	cphR_x				0.960		
	cphL_x				−0.955		
PC5 (8)	ls_x					0.944	
PC6 (5)	li_x						0.979

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

Principal component analysis

Table 2 shows the PCA eigenvectors for the viseme rope. PC1 for the viseme rope controls upper lip movement in the *y* and *z* planes accounting for 48% of the total variation in lip movement with the midpoint of the upper lip moving up and out, and the corners of the mouth moving down and inwards. PC2 controls mouth width as the corners of the mouth move towards each other narrowing the mouth aperture (17%). Following this in PC3 (10%), the lower lip moves downwards and is correlated with the upper elevated vermilions moving upwards. PC4 (8%) then shows that the upper elevated vermilions narrow. Finally, there is a slight tendency for right sided movement as shown by the factor loadings for ls_x and li_x in PC5, although this accounts only for 7% of the total variation. A standard deviation envelope of lip movement for the viseme rope can be visualized as an ellipsoid plot in Fig. 3.

The viseme puppy can be described to follow a primarily downward movement of the corners of the mouth and outward movement of the upper lip (Table 3 and Fig. 4). This is controlled by PC1 and accounts for 45% of the total variation in movement. In PC2 (15%), the corners of the mouth and lower lip move outwards in conjunction with the mouth narrowing in width. PC3 explains mouth height as both the upper and lower lips move away from each other opening the mouth aperture (11%). The elevated margins of the upper vermilion narrow in PC4 (8%). Both PC5 and PC6 show small changes in horizontal movement of the midpoint of the upper and lower lips, respectively.

As the viseme changes to puppy, PC1 (47%) shows that the upper lip moves upwards and

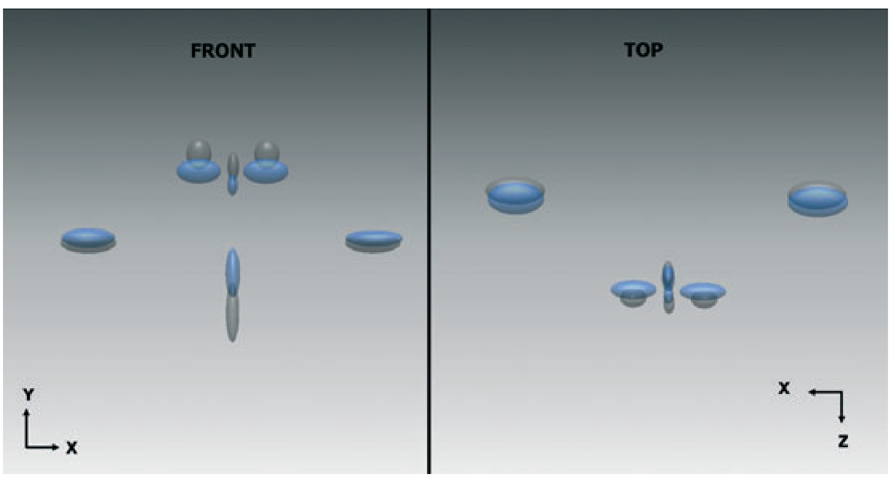


Fig. 4. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to articulation of puppy (grey).

Table 4. **Principal component analysis table for the viseme puppy**

PC (% variance)	*x-y-z* coordinates	PC with associated eigenvector of landmark 1	2	3	4	5
PC1 (48)	chL_y	−0.927				
	chR_y	−0.913				
	cphL_z	0.873				
	ls_z	0.862				
	cphR_z	0.857				
	cphL_y	0.714		0.632		
	cphR_y	0.682		0.661		
	chR_z	−0.641	−0.637			
PC2 (15)	li_z		0.952			
	chL_z	−0.645	−0.673			
	chR_x		−0.604			
	chL_x		0.584			
PC3 (10)	li_y			−0.957		
	ls_y	0.610		0.657		
PC4 (8)	cphR_x				−0.921	
	cphL_x				0.818	
	li_x				0.767	
PC5 (7)	ls_x					0.936

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

outwards, along with the corners of the mouth moving downwards and inwards (Table 4 and Fig. 5). PC2, as in **p**uppy, controls for mouth width as the corners of the mouth move towards each other narrowing the mouth aperture (15%). PC3 isolates vertical mouth opening with both the upper elevated vermilions moving upwards and lower vermillion downwards (10%).

The variation in movement between the visemes b**o**b (Table 5 and Fig. 6) and **r**ope is largely similar with PC1 explaining over half of the total variation for bob (51%). This was entirely in the *y* and *z* planes with the elevated upper vermilion and midpoint of the upper lip moving upwards and outwards together with the corners of mouth moving downwards.

The PC table for **b**aby (Table 6 and Fig. 7) showed that several landmarks including cphL, cphR, ls_y, chL_z and chR_z had crossover between the first three components. Therefore, movement of these six landmarks in the *y* and *z* planes accounted for 71% of the total variation of this viseme. Landmark movement in *x* plane, which made up PC4, 5 and 6, explained only 19% of the variation in lip movement. This configuration changes as bab**y** is articulated forming the second half of the word (Table 7 and Fig. 8). Here, PC1 (42%) controls mouth height as the upper and lower lip moves upwards and downwards, respectively. PC2 (17%) is a complex movement as the corners of the mouth move inwards and narrow slightly, and the upper elevated vermilions move outwards. In PC3 (10%), the elevated upper vermilion widens.

Prior to comparing male lip movement with that of females, note first the variation in resting lip shape between the genders (Fig. 9). Females had a narrower lip width both between the corners of the mouth and also between the elevated upper vermilion borders. In addition, females had

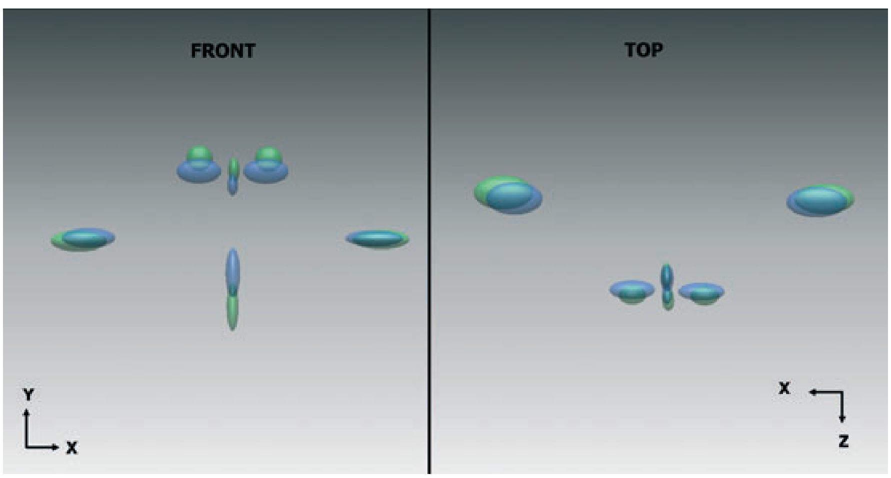


Fig. 5. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to articulation of pupp**y** (green).

Table 5. **Principal component analysis table for the viseme bob**

PC (% variance)	*x-y-z* coordinates	PC with associated eigenvector of landmark 1	2	3	4	5
PC1 (51)	cphL_z	0.935				
	ls_z	0.928				
	cphR_z	0.923				
	cphL_y	0.917				
	cphR_y	0.917				
	chL_y	−0.871				
	chR_y	−0.866				
	ls_y	0.847				
	chL_z	−0.816				
	chR_z	−0.812				
PC2 (17)	cphR_x		−0.935			
	cphL_x		0.909			
	chR_x		−0.533			
	chL_x		0.528			
PC3 (9)	li_z			0.937		
PC4 (7)	li_y	−0.636			−0.719	
PC5 (6)	li_x					0.876
	ls_x					0.977

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

Table 6. **Principal component analysis table for the viseme baby**

PC (% variance)	*x-y-z* coordinates	PC with associated eigenvector of landmark 1	2	3	4	5	6
PC1 (47)	chLY	−0.880					
	chR_y	−0.877					
	cphL_z	0.842					
	cphR_z	0.829					
	ls_z	0.812					
PC2 (16)	li_y		−0.990				
	cphRY	0.506	0.813				
	cphLY	0.533	0.803				
	ls_y	0.555	0.711				
PC3 (11)	li_z			0.950			
	chRZ	−0.643		−0.661			
	chL_z	−0.605		−0.618			
PC4 (9)	cphR_x				−0.900		
	cphL_x				0.805	0.521	
	chR_x				−0.563		
	chL_x				0.509		
PC5 (6)	ls_x					0.963	
PC6 (6)	li_x						0.988

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

a shorter overall lip height when compared with males. For lip movement between the genders, differences were seen for some visemes more than others. For the viseme baby, males preferred a combined movement of the upper lip outwards and corners of mouth downwards as shown by *y* and *z* characteristics in PC1. Females, however, were dominated by movement in the *z* plane for PC1 with both the upper and lower lips protrusive and the corners of the mouth intrusive. PC2

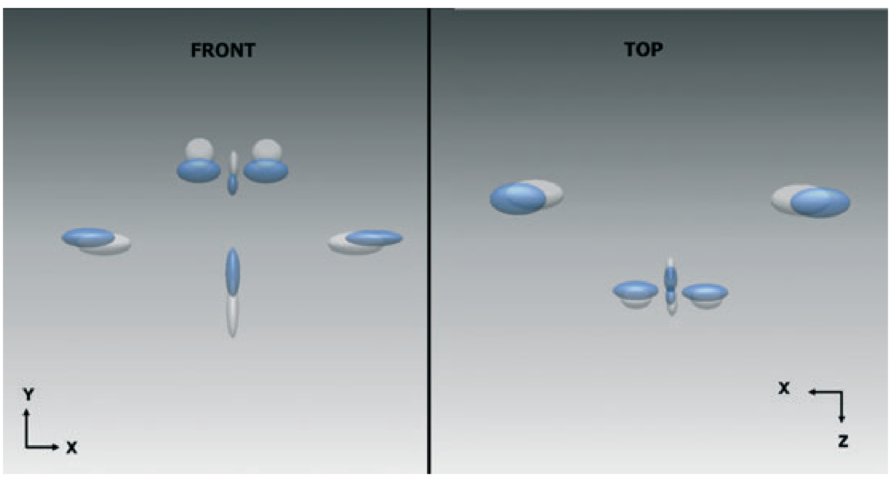


Fig. 6. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to bob (white).

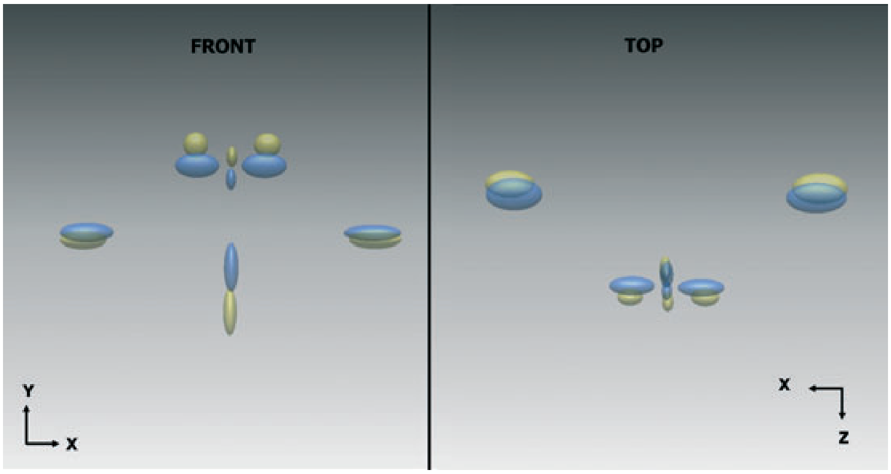


Fig. 7. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to baby (gold).

controlled mouth width in males but vertical opening for females. Vertical opening for males was not seen until PC3.

For the viseme **p**uppy, males showed a greater tendency for vertical mouth opening as shown by high-factor loadings for li_y and ls_y in PC1, whereas females preferred to articulate with a smaller horizontal and vertical aperture. This was shown by the presence of chL_x and chR_x in PC1 for females with ls_y not triggered until PC2 and li_y not evident until PC5. Both genders showed similar amounts of protrusion and symmetrical movement. The most similarly articulated visemes between the genders were **r**ope and pupp**y**, which were in their majority controlled by PC1. This explained an increase in lip opening, a retrusion of the corners of the mouth and an increase in mouth width for puppy and for rope, a largely protrusive movement of the upper and a narrowing of the mouth width.

Male articulation for b**o**b and bab**y** was particularly compartmentalized as PC1 explained mouth width and mouth protrusion/intrusion, and PC2 mouth height. Females on the other hand combined mouth height and protrusion/intrusion entirely within PC1. For the viseme bob, males preferred to adopt a narrower mouth, whereas females preferred a wider, more open and protrusive movement.

Discussion

The most widely used measures of facial movement used in clinical practice are subjective grading scales (19). They form easily applied regional systems for the description of facial movement but lack precise quantitative analysis and can suffer from inter-observer error (20). The quantitative approach began with marker-based video tracking systems that track 2–6 mm retro-reflective balls placed on the subject's face allowing 3D analysis of trajectory and displacement of specific points (21). There is a burden on the patient using this method, and as in some studies, the markers can be up to 10 mm, error is likely to be introduced into the analysis (22). More recently, marker-free 3D imaging systems have evolved that eliminate the time required to prepare the patient and therefore appear to be more suitable for use in the clinical context (23).

Facial expressions form the bulk of the research carried out on facial movement (8, 24–26), and they are often used in the computer science industry for animation and in psychological evaluations to discern emotive behaviour. This has important implications in assessing facial movement after a clinical intervention, as the facial expression could vary depending on whether the intervention was successful or not. In this study, the authors used words that form part of a validated cleft speech assessment (27). Being bilabial speech postures, they involve articulation of both upper and lower lips and give good representation of lip movement. In addition, these words have been shown to be more reproducible than some maximal facial expressions (28).

In this study, a sample of 115 normal subjects was used to statistically model ordinary lip

Table 7. **Principal component analysis table for the viseme baby**

PC (% variance)	*x-y-z* coordinates	PC with associated eigenvector of landmark 1	2	3	4	5
PC1 (43)	cphL_y	0.911				
	cphR_y	0.908				
	ls_y	0.852				
	li_y	−0.830				
	ls_z	0.681	0.563			
	chL_y	−0.556				
PC2 (17)	chL_z		−0.909			
	chRZ		−0.843			
	cphL_z		0.756			
	cphR_z	0.517	0.734			
	chL_x		0.729	−0.515		
	chR_x		−0.716			
	li_z		0.691			
PC3 (10)	cphR_x			0.852		
	cphL_x			−0.791		
PC4 (10)	ls_x				0.956	
PC5 (7)	li_x					0.627
	chR_y	−0.528				0.615

Principal components are colour coded with the first five components explaining 90% of the total variation in lip movement for this viseme. Landmarks with their associated direction of movement (*x*, *y* and *z*) are grouped and ordered according to eigenvector or their contribution to the respective component.

movement for different visemes. The sample size is comparable to previous studies that have created average 3D static facial templates (11, 29). To account for temporal variations in different subjects articulating the words, only the maximum displacement vectors for each word were used to create the average templates. The subjects performed the words only once, and in this respect, intra-individual variability could not be studied. As previous work has shown that these words show high levels of repeatability over time (and hence their use in the study), the intra-individual variability can assumed to be low (28).

Integration of GPA and PCA was used to analyse lip movement. GPA ensures that all coordinates were aligned in the same 3D space, which compensated for head movements during articulation. Other studies have used head frames to introduce immobile reference points to compensate for head movements, but using GPA eliminates this requirement (30). The other advantage of our methodology is that the coordinates of the landmarks are statistically analysed rather than inter-landmark distances. This has the advantage that the results of the statistical analyses can be visualized as deformations of landmark configurations, thereby increasing the sensitivity as more shape information is analysed (31).

In addition, as the method adopts established statistical techniques, it is transferable to apply in clinical practice although investment in a 3D motion scanner would clearly need to be a prerequisite. The appropriate commercial companies should be approached for a customized quote. Manual landmarking forms the basis of the data analysis, and this is labour intensive. Integration of

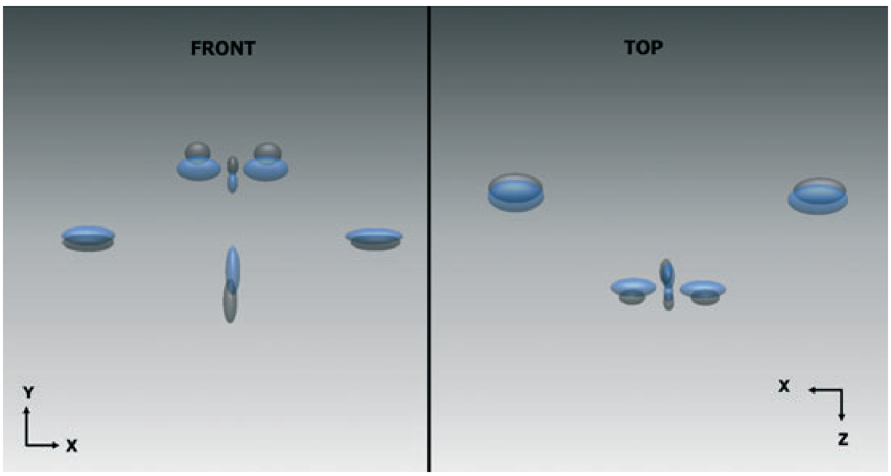


Fig. 8. Ellipsoid plot showing the standard deviation envelope of lip movement from rest (blue) to baby (black).

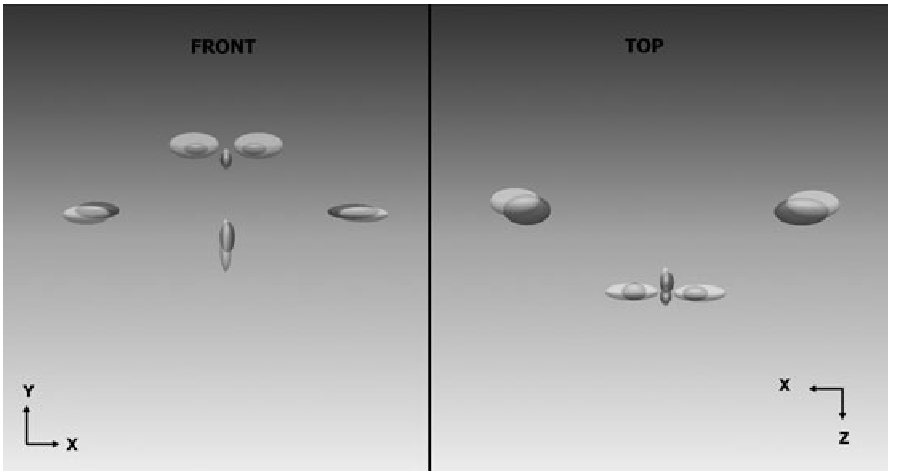


Fig. 9. Ellipsoid plot showing 95% of the standard deviation envelope of resting lip shape between males (white) and females (black).

automated registration and landmarking tools that have recently emerged (32) could provide further robustness to the methods described in this study.

We have shown that PCA can characterize ordinary lip movements. Between 4 and 6 PCs will describe 90% of the total variation in movement for the words used in our study. Symmetry of articulation was found as bilateral landmarks were grouped together throughout the analysis. In addition, coordinates ls_x and li_x were consistently in the last component for all visemes implying midline symmetry. Therefore, not only can symmetry be assessed in terms of lip shape using PCA, when cross-referenced to the equivalent standard deviation envelope plot, lip position/placement can also be quantified, for example to see whether the lips are drawn to the stronger side of the face in patients with unilateral facial nerve palsy. This is an important finding when using our data as a control group for comparison with patient groups. Other studies, which have used facial expressions as their measure of movement, have shown that the effect of age and sex on asymmetric movements is limited within a normal sample which concurs with our findings (33, 34). However, the authors acknowledge that the data generated in the study are specific to the geographical area and language.

Conclusion

Lip movement can be characterized and normative reference data constructed using the statistical modelling techniques described in this study. Although lip movement was seen to be largely symmetrical, there were differences in lip movement between males and females, with females preferring a more protrusive articulation of words than males. The data can act as a template for comparison of similar population groups with facial nerve/muscle impairments thereby aiding treatment planning and outcomes.

Clinical relevance

An objective evaluation of lip movement can be beneficial in many settings including lip–tooth relationships during smiling or function, for surgical outcome assessment in patients with cleft lip and for the rehabilitation of patients with facial nerve impairments. It is important to establish a reference for comparison with these patient groups to ascertain what level of lip movement is considered to be normal or acceptable. This study assesses lip movement in a sample of normal adults during four spoken words using statistical shape analysis techniques. The methodology and findings can be used as a reference to compare lip movement in similar population groups.

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