Original Article

Three-dimensional analysis of lip changes in response to simulated maxillary incisor advancement

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ABSTRACT

Objective: To assess the immediate response of lips in three dimensions (3D) resulting from simulated maxillary incisor advancement.

Materials and Methods: Incremental maxillary incisor advancement was simulated by placing wax of increasing thickness (+2 mm, +4 mm, +6 mm) on the incisors of 20 participants, and the induced lip changes were recorded using 3D stereophotogrammetry. The induced displacement of lip landmarks was quantified using 3D image analysis software. Data were analyzed using a repeated-measures analysis of variance (ANOVA) after adjusting for age and sex of the study participants.

Results: A large interindividual variation in lip response to simulated incisor advancement was observed. A significant overall effect on 3D lip changes was found for increasing values of simulated incisor advancement ($F = 13.2$; $P < .001$) as well as significant differences between anatomical landmarks of the lip ($F = 7.4$; $P < .01$). Most points moved outward and anterosuperiorly, except the midpoint and corners of the lip. Greatest movement was observed in the sagittal plane, followed by the vertical and transverse planes.

Conclusions: Maxillary incisor advancement significantly affects upper lip change in three planes of space: particularly the anteroposterior plane, in which the response to simulated advancement appears to be nonlinear. (*Angle Orthod.* 2020;90:118–124.)

KEY WORDS: Lips; Perioral muscles; Stereophotogrammetry; 3D; Incisor position

INTRODUCTION

Contemporary orthodontics emphasizes the role of soft tissue relationships[1] in the establishment of optimal facial esthetics. Treatment-induced changes in the lip area are most readily noted by the public,[2] with extreme lip movement often considered unattractive.[3]

Lip contours and lip protrusion are affected by orthodontic procedures that alter the position of the incisors.[4] Horizontal incisor movement and horizontal lip movement have long been thought to have a linear relationship, but this appears to be true only within a limited range of movement.[5] Significant correlations have been found between maxillary incisor retraction and lower lip retraction[6,7] as well as lip elongation.[7] Upper lip response to orthodontic movement of the incisors has found to be less predictable than lower lip response,[6] with large interindividual variability.[5–7] This variability has been attributed to a complex interplay between skeletal, dental, and intrinsic soft tissue factors.[4]

Due to superimposition of a three-dimensional (3D) object to a two-dimensional (2D) image, lateral cephalograms limit our understanding of the relationship between lip changes and incisor movement and provide limited information on the soft-tissue structures lateral to the midline.[8] This is an important limitation, because incisor movement can also induce lip changes lateral to the midline.[9]

Stereophotogrammetry is a 3D surface imaging technique that compares multiple photographs from various angles to construct a 3D model of the surface.[10] It is quick, non-invasive,[10] accurate, and reliable.[11] The

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use of cameras with high frame rates makes image acquisition relatively insensitive to movement of the subject being imaged.[12]

The aim of this study was to investigate the relationship between incisor advancement and the resulting lip changes in three dimensions. The ability to more accurately predict soft tissue response to incisor movement is crucial in orthodontic treatment planning.

METHODS AND MATERIALS

Ethical approval for the study was obtained from the University of Otago Ethics Committee (H16/151). All study participants provided written informed consent prior to the investigation.

Subjects

A convenience sample of 20 participants (average age 17.6 ± 7.8 years) was recruited from the orthodontic patients of the University of Otago, Faculty of Dentistry.

The inclusion criteria were as follows: patient in retention phase (<6 months posttreatment) or not yet in active treatment phase, availability of a good quality pre- or post- treatment maxillary study model not older than 6 months, and an age range of 12 to 30 years. Exclusion criteria were: craniofacial syndromes, lip incompetence, soft tissue asymmetry (lip cant/ chin deviation >3 mm), overjet >6 mm, moderate to severe crowding of upper incisors, missing/ ectopic canines, and/or lateral incisors. None of the selected participants had any relevant sagittal or vertical skeletal malocclusion, as revealed by an ANB angle comprised between 1° and 5°, and by the SN-MP angle comprised between 30° and 40°.

Incisor Advancement

Wax buildups were used to simulate maxillary incisor advancements. Three wax pieces of increasing standardized thicknesses (+2 mm, +4 mm, +6 mm) covering the four upper incisors were constructed using a putty index.[13]

Labial Landmarks

The following labial landmarks were identified: right and left Christa Philtri (RCHP, LCHP), defined as points at the intersection of the vermillion border and the elevated margin of the right and left philtrum;[14] Labrale Superius (LS), defined as midpoint of the vermilion border of the upper lip;[14] and Labrale Inferius (LI), defined as midpoint of the vermilion border of the lower lip. This landmark was identified at the intersection of a vertical plane passing through LS and the vermillion border of the lower lip; right and left Cheilion (RCHL & LCHL), defined as points at the most lateral aspect of the vermilion border of the right and left corner of the subject's mouth[15] (Figure 1).

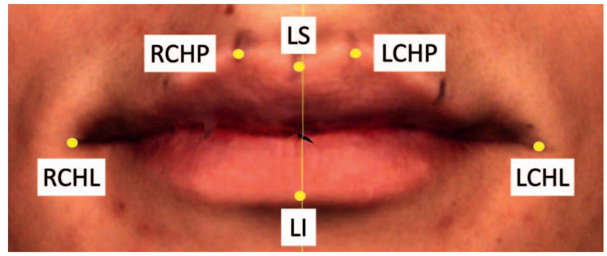

Figure 1. Labial landmarks used in the study: RCHL, Right Cheilion; RCHP, Right Christa philtri; LS, Labrale Superius; LI, Labrale Inferius; LCHP, Left Christa Philtri; LCHL, Left Cheilion.

Stereophotogrammetry

Scanning method. Prior to 3D surface image acquisition, preparatory measures were used to minimize image artifacts or errors.[16] Patients were advised to remove reflective objects (eg, jewelry, glasses) and blot their face with gauze to remove any excess sebum. A headband was used to retract hair and expose the forehead. A surface electromyographic electrode (T3402M, Thought Technology Ltd., Montreal, Canada) was attached to the forehead, serving as a fiducial marker for subsequent image registration. Markings were placed on participants' lips using hypoallergenic pencil makeup[17] to facilitate identification of anatomical landmarks during image analysis (Figure 1). Participants were then asked to look straight at a screen positioned at their eye height in natural head position, maintain a neutral facial expression, and keep posterior teeth in slight contact with lips relaxed.

If the lips became incompetent after placement of the wax buildup, the participants were asked to keep lips separated, thus avoiding unwanted perioral muscle strain.

Device and Acquisition

A 3dMDtrio System (3dMD LLC, Atlanta, GA, USA) was used. For each 3D image acquisition, a short video (10 to 20 seconds) of the participants was taken and the best still frame chosen. Individual frames were captured every 1.5 ms. The 3D surface mesh was constructed by the software provided (3dMDpatient; 3dMD) using the still frames acquired. Each surface mesh was visually inspected; if unsatisfactory, a new surface image was acquired.[18] The system was calibrated prior to each research session to avoid distortion of images captured.

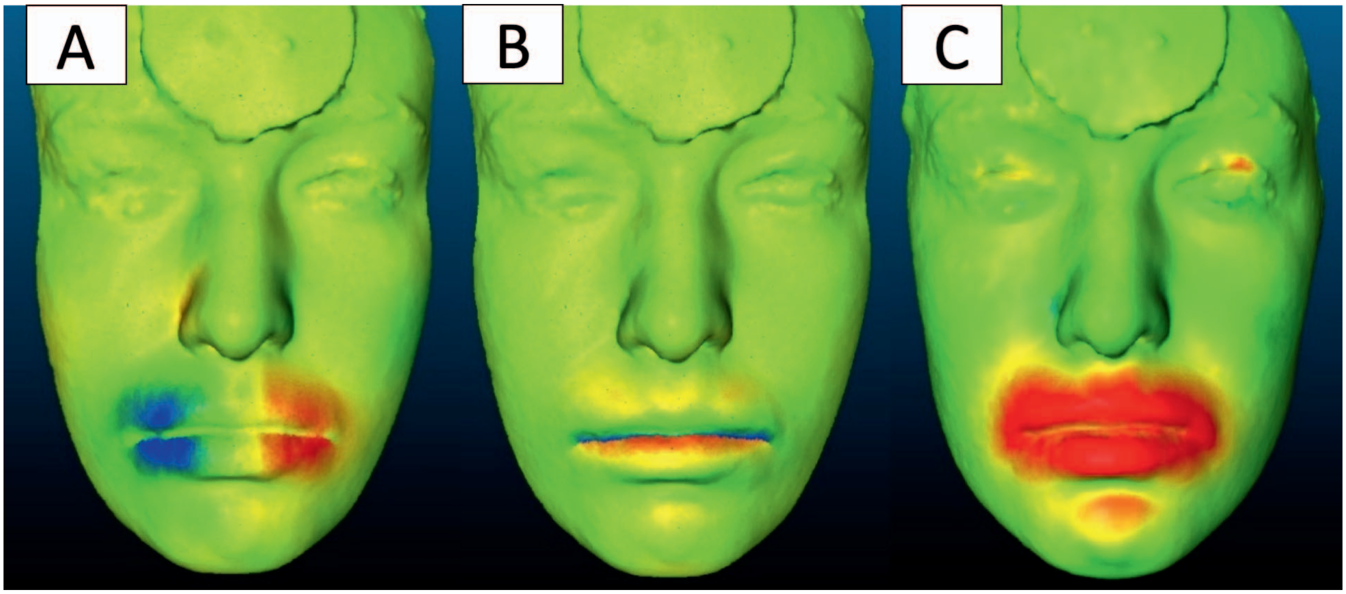

Figure 2. Color-coded scalar fields generated on the basis of surface distances on a blue-green-red scale. (A) Induced lip displacement in the transverse plane. (B) Induced displacement in the vertical plane. (C) Induced displacement in the anteroposterior (sagittal) plane.

The 3D surface image acquired of the participant's face at rest was termed the "baseline" image. Each acquisition of the baseline image was repeated twice to estimate method error.

Next, a wax buildup was placed on the maxillary incisors and a 3D surface image of the patient was captured immediately after to record the lip displacement induced. This image was termed the "displacement" image and labeled according to the amount of simulated maxillary incisor displacement (+2 mm, +4 mm, or +6 mm). In total, five 3D surface images were captured on the same day during a 20- to 30-minute session: two "baseline images" and three "displacement images."

Image Analysis

Reference coordinate axes were established for the 3D surface images using soft tissue landmarks[19] to define the *x* (coronal), *y* (axial), and *z* (sagittal) planes. The origin (point 0, 0, 0) was set at soft tissue nasion.[9] The *x*-axis (left-right/transverse) was defined as the plane connecting right and left pupil points.[19] The *y*-axis (up-down/vertical) was defined as the plane formed by the perpendicular bisector of the segment connecting right and left pupil points.[19] The *z*-axis (anteroposterior/sagittal) was defined as the plane rotated 7.5° above the ala-tragus line (Camper's plane).[14,19]

The "displacement" images were superimposed on the "baseline" images using the nose bridge and the forehead (with the electromyography electrode attached) as reference structures;[20] these regions were unaltered by the induced lip displacement[21] and showed the least variation at rest relative to other facial structures.[22]

Open-source 3D imaging software was used to visualize and assess lip changes in the 3D images acquired, and included MeshLab (MeshLab v.1.3.4, Visual Computing Lab, ISTI-CNR) and CloudCompare (version 2.7.0, GPL software). The distance between each set of coordinates was calculated to evaluate positional changes of the labial landmarks (Figure 2).

Statistical Analysis

To test reliability of the measurements, method errors were calculated for image registration, image acquisition, and buildup manufacture using Hausdorff distances and RMS error.[23]

Registration error was estimated in the area of the forehead and nose bridge. If the mean Hausdorff distance or RMS value calculated was more than 0.5 mm,[20] the alignment was repeated.

For the acquisition error, the two "baseline" 3D images were superimposed, and the related error estimated at the lip and perioral area.

To estimate manufacturing error, a second set of wax build-ups was prepared for five randomly selected participants.[13] Additional 3D images were acquired using the second set of wax buildups and superimposed on the first set of 3D images.

Conventional descriptive statistics and repeated-measures ANOVA were used for data analysis after adjusting for age and sex of study participants. Data were analyzed using SPSS Statistics version 25 (IBM Corporation, New York, USA) with two-sided $P < .05$, considered statistically significant in all cases.

Table 1. Mean Values and Standard Deviations (SD) of Hausdorff Distances and RMS Errors for Different Study Measurements

	Hausdorff Distance (mm)		RMS Error (mm)	
	Mean	*SD*	Mean	*SD*
Registration error	0.14	0.07	0.19	0.09
Acquisition error	0.37	0.11	0.43	0.12
Manufacturing error (for each thickness of wax)				
+2 mm wax buildup	0.48	0.13	0.61	0.13
+4 mm wax buildup	0.58	0.19	0.75	0.22
+6 mm wax buildup	0.66	0.20	0.79	0.23

RESULTS

No value of method error exceeded 1.0 mm mean Hausdorff distance or RMS error (Table 1).

A repeated-measures ANOVA determined that increasing values of simulated maxillary incisor advancement had a statistically significant overall effect on mean 3D lip response ($F = 13.2$; $P < .001$). Increasing values of simulated maxillary incisor advancement produced statistically significant changes in anteroposterior and vertical lip displacement ($F = 14.5$; $P < .001$, and $F = 5.2$; $P < .05$, respectively), but not transverse displacement ($F = 1.2$; $P > .05$). Trend analysis indicated that mean anteroposterior lip change in response to simulated maxillary incisor advancement had a statistically significant linear ($F = 30.1$; $P < .001$) and quadratic ($F = 6.2$; $P < .05$) component.

The lip response to simulated maxillary incisor advancement differed between anatomical landmarks ($F = 16.8$; $P < .001$; Figure 3). Significant differences were found in induced transverse lip change at different points along the lip ($F = 8.5$; $P < .001$). Although landmarks away from the midline were displaced laterally, midline landmarks (Labrale Superius, Labrale Inferius) displayed <0.2 mm of mean transverse displacement for all three increments (+2 mm, +4 mm, +6 mm) of simulated maxillary incisor advancement. Mean induced transverse displacement was no greater than 1.0 mm in either direction (Figure 3A). Induced vertical lip change also varied significantly at different points along the lip ($F = 6.7$; $P < .01$). Both Cheilions and Labrale Inferius displayed negative (downward) displacement, whereas landmarks in the middle of the upper lip were displaced upward (Figure 3B). Mean induced vertical displacement in either direction did not exceed 2.0 mm.

All landmarks exhibited the same pattern of positive displacement in the anteroposterior plane, with no significant differences between points along the lip ($F = 1.6$; $P > .05$; Figure 3C).

Overall a large interindividual variability in response to lip displacement was observed (Figure 4). This

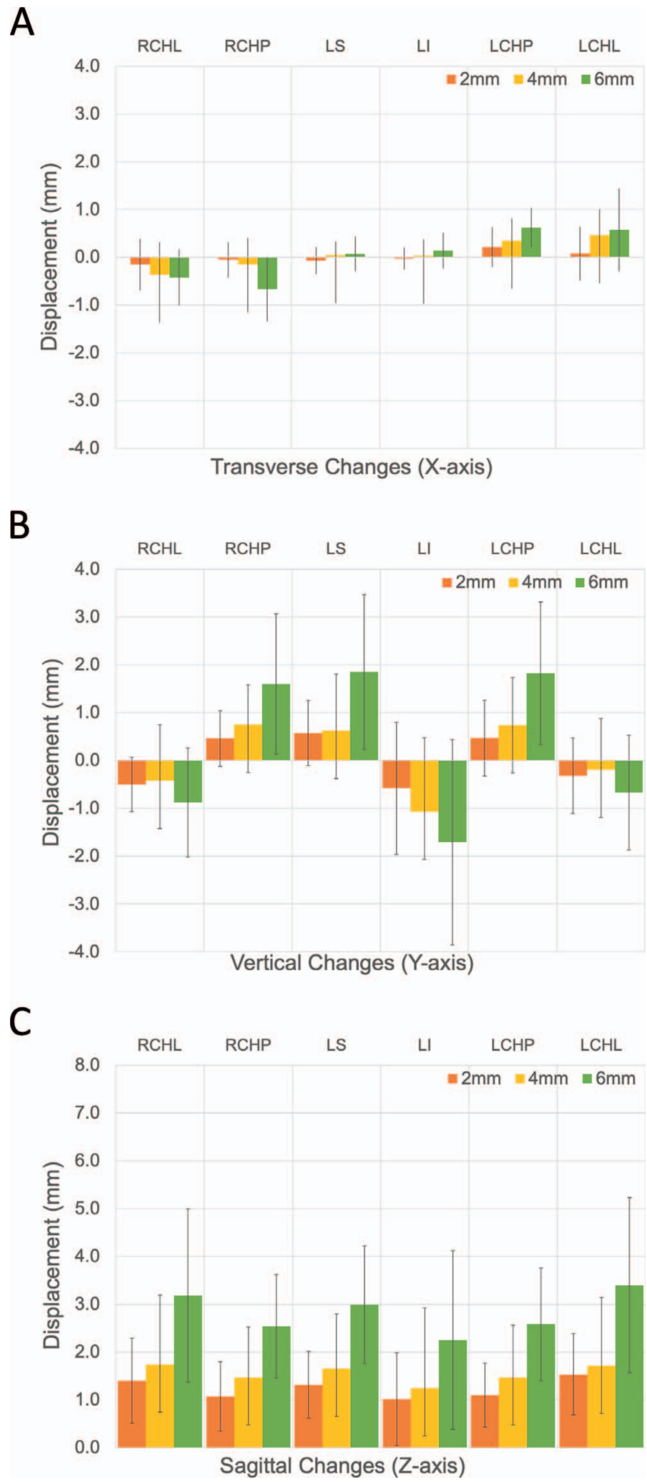

Figure 3. Induced displacement of labial landmarks in the transverse (A), vertical (B), and sagittal (C) planes, in response to simulated maxillary incisor advancement of +2 mm, +4 mm, and +6 mm. Bar heights represent mean values and error bars represent standard deviations.

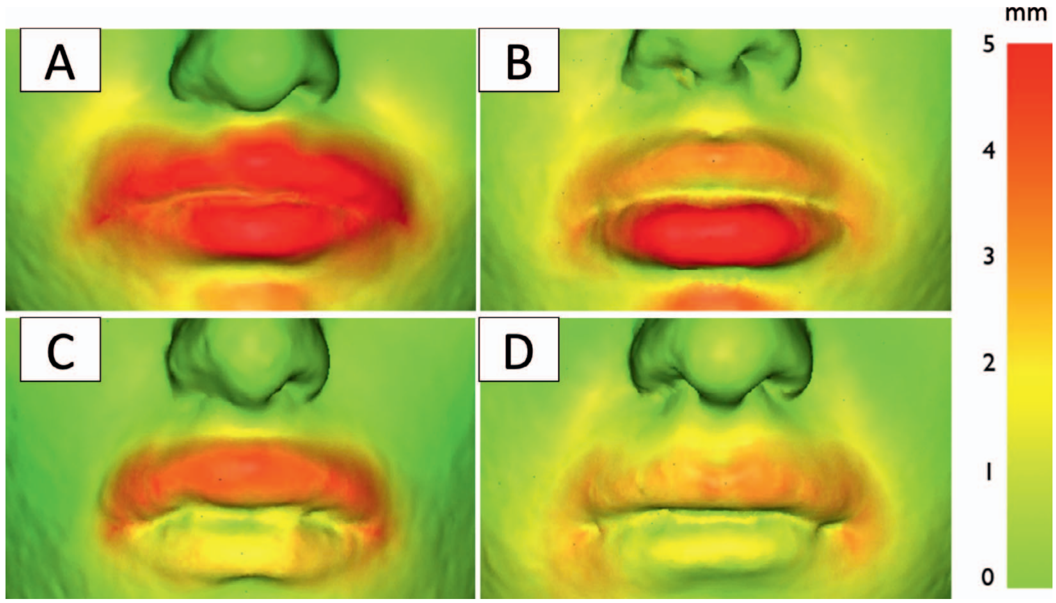

Figure 4. Examples of color-coded scalar fields from four different female participants (A,B,C,D) with + 6 mm of incisor advancement. Green areas correspond to areas of little to no change (–0.5 mm to 0.5 mm); yellow and red correspond to increasingly positive values of displacement. Note the large interindividual difference in soft tissue response.

variability was pronounced for changes in the transverse and vertical planes, in which standard deviations were equal to or greater than the relevant mean (Figures 3A, 3B). Age and sex did not influence 3D displacements of the labial landmarks investigated ($F = 0.8$, $P = .57$; and $F = 0.4$, $P = .56$, respectively).

Values of induced 3D displacement of labial landmarks were also expressed as a percentage of the simulated maxillary incisor advancement (Table 2). The greatest relative amount of induced lip displacement occurred in the antero-posterior plane, followed by the vertical and transverse planes. Lip displacement in the anteroposterior plane ranged from 31.0% (LI, 4 mm advancement) to 76.5% (LCHL, 2 mm advancement) of the simulated maxillary incisor advancement, whereas vertical lip displacement ranged from 4.8% (LCHL, 4 mm advancement) to 30.8% (LS, 6 mm advancement) of simulated incisor advancement. Excluding Labrale Superius and Labrale Inferius, transverse lip displacement ranged from 2.5% (RCHP, 2 mm advancement) to 11.5% (LCHL, 4 mm) of the simulated maxillary incisor advancement. A decreasing trend was noted in both vertical and anteroposterior lip change as a percentage of simulated maxillary incisor advancement between +2 mm and +4 mm simulated maxillary incisor advancement.

An increase in the mean amount of induced anteroposterior lip response was noted for landmarks away from the midline. Both Cheilions consistently displayed greater values of anteroposterior displacement relative to landmarks closer to the midline. Landmarks within the lip corners showed similar values of vertical displacement for each increment of simulated maxillary incisor advancement. No consistent pattern could be found for mean induced transverse displacement apart from little to no movement occurring for landmarks at the midline.

No participants' lips were found to become incompetent at +2 mm or +4 mm maxillary incisor advancement; at +6 mm maxillary incisor advancement eight out of 20 participants' lips became incompetent. When considering values of positional change of Labrale

Table 2. Mean Values of Induced 3D Displacement of Labial Landmarks in the Transverse (X-Axis), Vertical (Y-Axis), and Sagittal (Z-Axis) Planes Expressed as Percentage of Simulated Advancement of Maxillary Incisors (%)

	Transverse Plane			Vertical Plane			Sagittal Plane		
Landmark	+2 mm	+4 mm	+6 mm	+2 m	+4 mm	+6 mm	+2 mm	+4 mm	+6 mm
RCHL	7.5	9.3	7.0	25.0	10.5	14.7	70.0	43.5	53.0
RCHP	2.5	3.8	11.2	23.0	18.8	26.7	53.5	36.8	42.3
LS	3.5	1.3	1.2	28.5	15.5	30.8	65.5	41.3	49.8
LI	1.5	0.8	2.3	29.0	26.8	28.5	50.5	31.0	37.5
LCHP	10.5	8.8	10.3	23.5	18.5	30.3	55.0	36.8	43.0
LCHL	4.0	11.5	9.5	16.0	4.8	11.2	76.5	42.8	56.7

Superius at +6 mm incisor advancement compared to +4 mm incisor advancement, values of vertical change were consistently larger than values of anteroposterior change for each of these eight participants.

DISCUSSION

Based on the values of displacement observed, most labial landmarks moved outward and forward in response to simulated maxillary incisor advancement. Consistent with findings of previous studies,[5] anteroposterior lip response to maxillary incisor advancement appeared to be nonlinear, suggesting that, for smaller increments of maxillary incisor advancement, soft tissue thickness change occurs to a greater degree than positional change.[14] The pattern of anteroposterior lip change observed was coincident with that observed in the literature,[9] particularly bracket debonding studies,[21,23] which described significant retraction of the Cheilions.

Although the aim of the study was not to assess the influence of the upper incisor changes on the lower lip, a relationship between movement of the lower lip and the maxillary incisors was observed, consistent with the findings of multiple studies.[6,7]

The large interindividual variability in response observed was also in accordance with previous studies. This may be due to interindividual variation in intrinsic soft tissue factors[5,6] (unaccounted for in this study). Lip changes were less pronounced[5,24] in individuals with thick lips, and were more pronounced[25] for individuals with greater lip muscle tonicity. Gender and age also appeared to contribute to the variance observed in upper lip response to orthodontic treatment in the literature. Gender differences may be attributed to sexual dimorphism in lip growth, which ceases around age 15 in females but continues beyond age 18 in males.[26] In the current study, however, a significant effect of age and sex could not be identified, most likely because of the small sample size investigated.

This study had several limitations. First, the sample size was small and the selection criteria restrictive. Therefore the sample may not have been sufficiently representative of the general population. Secondly, the wax buildups fabricated simulated incisor displacement in the anteroposterior plane only; changes in angulation or vertical displacement of the incisor were unaccounted for. Although maxillary incisor angulation was found previously to be only weakly correlated to upper lip movement,[7] maxillary incisor vertical movement has been found to have an influence on horizontal movement of the upper lip.[27] Furthermore, the wax buildups fabricated simulated advancement of the crown of the maxillary incisors only; this is anatomically impossible in a clinical scenario and movement of the root and alveolar process was unaccounted for.

Another limitation is represented by the fact that the values of displacement recorded may be affected by capture accuracy and error introduced by superimposition of surface meshes. A mean difference of 0.21 mm has been previously found between measurements taken using 3D stereophotogrammetry and direct anthropometric measurements.[11] It was estimated that surface registration of the baseline and displacement surface meshes introduced an additional error no greater than 0.5 mm (as the superimposition was accepted for analysis only if the mean Hausdorff distance calculated was $<$0.5 mm), which is a relatively small error. Finally, it must be acknowledged that the lip changes induced by simulated displacement were immediate, and did not take into account soft tissue adaptation or remodeling over time, which occurs at different rates for different individuals.[21]

Nonetheless, the findings provide new insight into lip changes observed in response to orthodontic movement of the maxillary incisors, which is an important parameter in the decision to extract teeth. This research also supports the use of 3D stereophotogrammetry in clinical research to investigate soft tissue changes induced by orthodontic tooth movement.

CONCLUSIONS

- Simulated maxillary incisor advancement had a statistically significant overall effect on 3D lip response.
- Anteroposterior lip response to simulated maxillary incisor advancement appears to be nonlinear.
- Significant differences were observed in 3D lip response to simulated maxillary incisor advancement at different points along the lip, indicating that maxillary incisor advancement causes well-defined patterns of lip change.
- Soft tissue response to maxillary incisor advancement remains difficult to predict on an individual level, as lip response to simulated maxillary incisor advancement was found to exhibit a large interindividual variability. Further investigation is needed to correlate findings with soft tissue characteristics to better understand the large interindividual variability observed in this study.

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