Functional Outcomes of Cleft Lip Surgery. Part III: Measurement of Lip Forces

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Objective: **To investigate lip force dynamics among participants with a repaired cleft of the lip and noncleft control participants.**

Design: **A parallel, three-group, nonrandomized clinical trial.**

Subjects: **Forty-eight participants with cleft lip and 36 noncleft participants.**

Analysis: **Participants attended two separate visits. At each visit, they were instructed to produce fine motor control and maximum compression forces with each upper and lower lip in response to visual force targets. Measures of force were extracted, and the data were fit using regression techniques.**

Results: **The upper and lower lips of the participants with a cleft lip demonstrated less time on target, while the lower lips had shorter rise time but higher peak forces, a higher rate of force recruitment, and increased maxima of the first derivative of force compared with the noncleft participants. For all participants, there was a learning effect for certain force variables between the two visits and with increasing age.**

Conclusion: **For participants with a cleft lip, force regulation of the circumoral region within the operating range presumed important for speech and facial animation is compromised because of impairments in force recruitment, gradation, fractionation, and stability. In the presence of a change in upper lip tissue mechanics due to scarring or neuromotor impairment, such as a cleft, the lower lip typically exhibits compensatory motor actions.**

KEY WORDS: *lip forces, lip form, lip function*

Abnormalities in lip function may be attributed to impaired muscle-force regulation (i.e., abnormal force dynamics) and/or mechanical limitations in the perioral tissues secondary to scarring. These abnormalities may result in disorders of (1) facial movement, (2) oral continence, (3) eating, (4) communication, and (5) oral access (Stranc and Fogel, 1984; Trotman et al., 2000, 2005). For example, when studying patients with oral incontinence, Stranc and Fogel (1984) discovered that normal lip strength/force and sensation were necessary for a satisfactory lip seal. Trotman et al. (1998, 2000, 2005) found isolated and quantifiable areas of impaired circumoral movements in patients with repaired cleft lip and palate that were related to the effects of the original cleft defect and the scarring as a result of the primary surgical repair. Barlow (Barlow, 1984; Barlow and Abbs, 1984; Barlow and Burton, 1990) found that patients with neurological conditions such as Parkinson disease, cerebral palsy, and traumatic brain injury that affect the functioning of the circumoral region produced inaccurate lip compression forces compared with unaffected subjects (Barlow, 1984; Barlow and Burton, 1990; Barlow et al., 1998). These inaccuracies were based on several well-defined force parameters obtained from methods developed to assess fine motor control and maximum force capacity of the upper and lower lips (Barlow and Abbs, 1983, 1984; Barlow and Rath, 1985; Barlow and Abbs, 1986; Barlow and Netsell, 1986) and the biomechanics of the perioral sphincter (Barlow and Muller, 1991).

Initial pilot studies using these methods to assess fine motor control and maximum force capacity (D'Antonio et al., 1994, 1995) suggested that several of the lip force parameters could be used to characterize facial impairment in children with a repaired cleft lip. These children showed impairment in a number of measures of upper lip force regulation and strength when compared with similar measures from noncleft control subjects. Studies on facial movement (Trotman et al., 2000, 2005) supported the possibility that in a child with a cleft lip, abnormalities in the upper lip may involve and extend to the lower lip, and pilot studies on lip coordination during movement in a small sample of patients with repaired cleft lip con-

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TABLE 1 Inclusion and Exclusion Criteria for Study Participants

Criteria	Description
Inclusion	1. Subject interest and parent willingness to participate in the study 2. An ability to comprehend verbal instructions 3. Specifically for the participants, a previously repaired complete unilateral or bilateral cleft lip with or without a cleft of the palate
Exclusion	1. Previous orthognathic or facial soft tissue surgery 2. A medical history of diabetes, collagen vascular disease, and/or systemic neurologic impairment 3. Mental or hearing impairment to the extent that comprehension or ability to perform tests is hampered 4. Specifically for the participants, a lip revision surgery within the past 2 years

ducted by Rutjens et al. (2001) and van Lieshout et al. (2002) demonstrated that young subjects who had recent lip surgery were most likely to show asynchronies in lip movements. Thus, measures of lip force and movement have been shown to be of value for the assessment of lip impairment in patients with cleft lip; however, to date, such measures have not been employed in formal studies and have not been used to monitor surgical treatment outcomes in these patients. This study was designed to investigate the differences in lip force dynamics between a group of participants with a repaired cleft of the lip (with or without cleft palate) and a group of noncleft participants. The hypothesis to be tested was whether the perioral musculature of the participants with a cleft lip exhibits impaired fine motor control (force regulation) and lower maximum force capacity (lip strength) compared with that of the noncleft participants.

Method

Participants were recruited from those attending the University of North Carolina School of Dentistry Orthodontic and Craniofacial Clinics and were part of a larger clinical trial funded by the National Institutes for Dental and Craniofacial Research (Trotman et al., 2007a). The inclusion and exclusion criteria for all participants are described in Table 1. Participants who met the selection criteria were recruited and screened in the Craniofacial Center, the Graduate Orthodontics Clinic, the Pediatric Dentistry Clinic, and the Orthodontics Faculty Practice at the University of North Carolina. No subject was excluded from participation on the basis of sex, race, or ethnic background. The purpose and protocol of the study was explained to the participant(s) and parent(s), and informed consent and assent were obtained. Consent and HIPAA documents have been approved by the School of Dentistry Human Subjects Institutional Review Board.

The participants in this study represented a subset of the recruited individuals because a few were not able to comply with the lip force–testing requirements from which the data for this study were obtained. In addition, both because of the exploratory nature of the study and because this analysis deals with the presurgery data, the participants were grouped into

TABLE 2 Age and Gender Distribution of Study Participants

		Age, y		Gender	
Group	n	Mean	SD	Male	Female
Noncleft	31	13.4	3.7	14	17
Cleft lip	42	13.3	3.3	12	30

those with a cleft lip and those without a cleft lip instead of the revision, nonrevision, and noncleft groupings described in the companion articles (Trotman et al., 2007a, 2007b). The two participant groups considered in the present report included 48 participants with a cleft lip (with or without a cleft palate) and 36 noncleft participants. The age and gender distributions of the participants in each group are provided in Table 2. Of the participants with a cleft lip, 10 had a repaired bilateral cleft of the lip, 36 had a repaired cleft palate, 34 had received an alveolar bone graft, and 22 had received orthodontic maxillary expansion. Approval for the study was obtained from the Institutional Review Board at the University of North Carolina. Informed consent was obtained from a parent or legal guardian and assent was obtained from each participant prior to any data collection. The data collection occurred at two time points ranging from 1 week to 3 months apart.

Instrumentation

Each participant was seated comfortably in an upright posture so that the screen of an oscilloscope was visible. A load-sensitive cantilever with an integrated lip saddle mounted to an interdental yoke sized for the participant was used to sample midline compression forces generated by the upper and lower lips (Fig. 1). To reliably reposition the yolk in the participant's mouth between measurements, the U-shaped portion of the yoke was encapsulated in a moldable dental impression material (Regisil 2x; Dentsply International, Milford, DE) and placed between the participant's teeth to record an impression of the upper and lower dentition. The yoke was attached to the cantilever, which was adjusted so that the saddle contacted the upper lip in the resting position (Fig. 1).

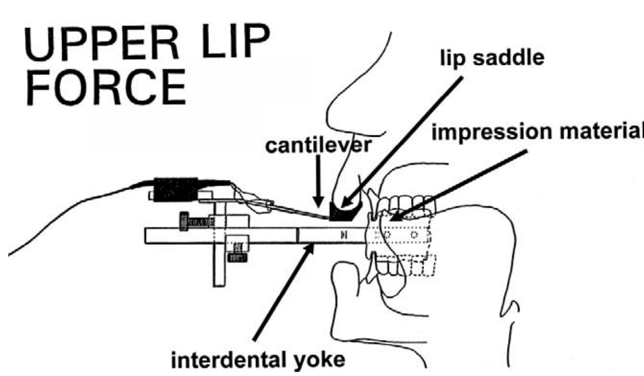

FIGURE 1 Schematic showing placement of interdental yoke with the impression material. The load-sensitive cantilever with lip saddle is attached to the yoke and is positioned to measure forces from the upper lip and then the lower lip.

Each participant then was instructed to produce a series of low-level ramp-and-hold contractions followed by a series of maximum compression forces. The participants were instructed to produce the ramp-and-hold forces with their upper lip as rapidly and as accurately as possible in response to computer-generated visual targets at 0.25, 0.5, 1.0, and 2.0 N (Fig. 2). The target force was to be maintained for 3 seconds (the hold phase). At the end of each series, the target force was reset to zero prior to the signal for the next trial. Each target was presented five times. This frequency of target presentation provided a reliable estimate of the within-participant variability (Barlow, 1984; Barlow and Abbs, 1986). For the maximum compression forces, each participant was instructed to exert as much force as possible with the upper lip. Lip strength was measured five times. Sufficient time was allowed between successive trials to prevent muscle fatigue. In addition, the forces used were of a low level, below the level that induces tetany and fatigue. Following the completion of the set of target forces, the yoke was removed and the cantilever was inverted on the yoke and adjusted in the mouth so that the saddle contacted the lower lip comfortably, and the entire process was repeated for the lower lip.

Measures

Fine Motor Control

For each replication (5 replications) of each target force (4 forces) and for each lip (2 lips), a series of two-dimensional vectors defined by (F, t), where F is the sampled force and t is time, were analyzed and plotted automatically using specially designed application software. For each series of target forces and for each lip, eight salient measures of force ramp-and-hold were extracted. The measures of interest were reaction time, rise time, peak force, mean force during the hold phase, standard deviation (SD) of the mean force during the hold phase, average rate of force change (during recruitment), maxima of the first derivative of force during recruitment, and criterion percentage. An explanation of these measures is provided in Table 3 and Figure 2.

Maximum Force Capacity

For each trial (5 trials) and for each lip (2 lips), the maximum force exerted by the lip under study was automatically extracted using a maximum discrimination algorithm (Table 3).

For seven of the eight measures of fine motor control that were extracted from the data, the following transformations were made to aid the statistical analysis and interpretation:

Reaction time (seconds): Transformed as $\log_e$Time. This log transformation normalized the response and made the predictor effects multiplicative.

Rise time (seconds): Transformed as $\log_e$Time. This log transformation normalized the response and made the predictor effects multiplicative.

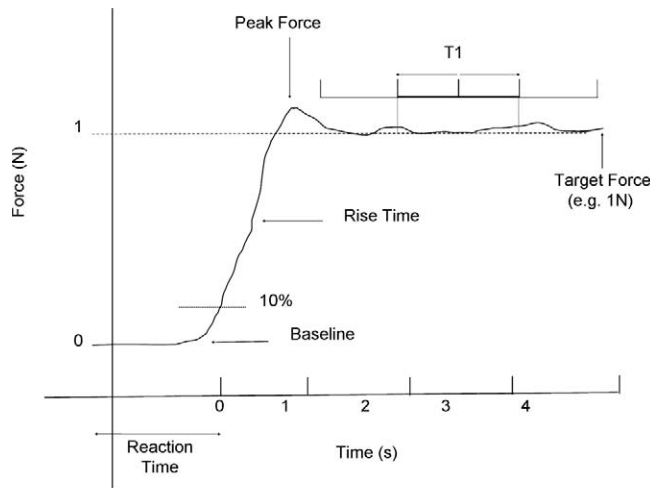

FIGURE 2 Schematic showing the trace of a ramp-and-hold task in response to a computer-generated visual target of 1 N.

Peak force: Transformed as (Peak Force − Target Force)/Target Force. This transformation produced the relative overshoot of the target force.

Mean force: Transformed as (Mean Force − Target Force)/Target Force. This transformation produced the relative difference from the target force.

Standard deviation of mean force (N): Transformed as log SD to normalize the response.

Rate (seconds^{-1}): Transformed as $\log_e$(Rate/Target Force). This transformation normalized the response and made the predictor effects multiplicative. Also, division by the target force adjusted for the slope's tending to be larger than the target force.

Maximum of the first derivative: Transformed as $\log_e$Derivative. This transformation normalized the response and made the predictor effects multiplicative.

Criterion percentage: Not transformed.

TABLE 3 Description of Lip Force Measures (see Fig. 2)

Measure	*Description*
Reaction time	The time (seconds) once the target signal is seen on the screen until the force has reached 10% of the peak force
Rise time	The time (seconds) during the recruitment ramp phase between 10% and 90% of peak force
Peak force	Highest force level (N) during recruitment and occurring in the 1-second period immediately after 0.1 N
Mean force	Mean force level (N) during the middle 1 second of the 3-second hold phase
Standard deviation (SD) mean force	Standard deviation of the mean force (N) level during the middle 1 second (T1) of the 3-second hold phase
Rate	Average rate of force change (N/s) during the recruitment from 10% to 90% of peak force
Derivative	Maxima of the first derivative of force during the recruitment ramp expressed as the instantaneous rate of force change (N/s)
Criterion percentage	Criterion level window discrimination based on user-defined limits, in this case, 95%
Maximum force capacity	Maximum voluntary force contraction level (N)

TABLE 4 †

	Noncleft Response at Baseline	*Estimated SD Within an Individual*	*Cleft Difference (Presenceof a Cleft Lip Effect)*
Upper lip			
Reaction time	0.54 s	19%	1.8% less
Rise time	0.62 s	22%	2.7% less
Peak force	64% overshoot	28%	8% more
Mean force	7% above target	11%	1% more
SD of mean force	4.6%	32%	13% more
(Force normed) rate	2.6	42%	7.5% more
Derivative	3.00 N/s	25%	11% more
Criterion	12%	7%	4% less*
Maximum force	3.7 N	1.7 N	3% more
Lower lip			
Reaction time	0.54 s	22%	7% less
Rise time	0.55 s	26%	15% less**
Peak force	82% overshoot	37%	15% more****
Mean force	13% above target	12%	1% more
SD of mean force	4.8%	36%	21% more ****
(Force normed) rate	3.6	46%	32% more**
Derivative	3.1 N/s	28%	24% more***
Criterion	14%	8%	4% less*
Maximum force	7.5N	2.8 N	11% more

† Control response at baseline is the predicted response using the first model for a noncleft participant on the first visit at the lowest force level who is Caucasian, female, and 13 years old. The logged responses (reaction time, rise time, SD of mean force, rate, and derivative) have been unlogged for easier interpretation. The estimated SD is derived from the model and represents the residual variation within individuals. For the logged variables, the SD has been expressed in a relative sense. The model-predicted difference due to the cleft effect is expressed in a relative sense for the logged variables.

* $p < 5\%$.

** $p < 1\%$.

*** $p < 0.1\%$.

**** Marginally significant, $p \geq 4.5\%$ to $p \leq 6\%$.

Statistics

For each transformed fine motor control variable and for the maximum force variable, two different mixed-effect linear regression models were fit with participant and visit as nested random effects. The first regression model was designed to determine differences between the two groups of participants (those with a repaired cleft lip and those without) and included possible confounders that were identified for the larger clinical trial and thus included in the analysis here (Trotman et al., 2007a). Model 1 took the following form:

Model 1:

$$\text{Response} = \text{presence of a cleft lip} + \text{visit} + \text{target force} + \text{age} + \text{race} + \text{gender},$$

where visit is a factor with two levels (first and second) and target force is a factor with four levels. As an example, the response is one of the measures described above, such as peak force.

The second model used only the data for the participants with a cleft lip and assessed the effects of those cleft-related predictors that were present in this group of participants with a cleft lip and identified for the clinical trial (Trotman et al., 2007a). Model 2 took the following form:

TABLE 5 Visit and Age Effects†

	Second Visit Effect	*Age Effect*
Upper lip		
Reaction time	1% more	1% more
Rise time	3% less	0%
Peak force	13% less**	3% less**
Mean force	2% less	0%
SD of mean force	27% less***	8% less***
(Force normed) rate	7% less	2% less
Derivative	19% less***	3% less**
Criterion	6% more***	2% more***
Maximum force	0.4 N	0.2 N*
Lower lip		
Reaction time	8% more****	1% more
Rise time	5% more	1% less
Peak force	2% less	4% less***
Mean force	1% less	1% less****
SD of mean force	16% less**	9% less***
(Force normed) rate	5% less	1% less
Derivative	9% less*	5% less***
Criterion	3% more**	2% more***
Maximum force	1.0 N	0.3 N*

† Differences for logged responses: reaction time, rise time, SD of mean force, rate, and derivative have been expressed in a relative sense. The differences for the other variables are in an absolute sense. Age effect is the estimated effect of 1 additional year.

* $p < 5\%$.

** $p < 1\%$.

*** $p < 0.1\%$.

**** Marginally significant, $p \geq 4.5\%$ to $p \leq 6\%$.

Model 2:

$$\text{Response} = \text{presence of a cleft palate} + \text{presence of an alveolar bone graft} + \text{presence of a bilateral cleft lip} + \text{maxillary expansion} + \text{visit} + \text{target force} + \text{age} + \text{race} + \text{gender}.$$

For both models, the possibility of interaction effects was investigated, but none were found.

Results

Table 4 shows a comparison of the response variables be- ?2
tween the noncleft participants and the participants with a cleft lip. Model 1 was used to predict the baseline responses for a 13-year-old, noncleft, Caucasian, female participant on the first visit and at the lowest force level. The effects of the other predictors relative to the baseline described above are given in Tables 4 and 5. Neither race nor gender was statistically significant for any of the fine motor control responses, and these two factors/predictors were not reported. Also, because some variables were transformed using log transformations, these variables then were transformed back to the original scale for the purposes of the tables. The model also provided an estimate of the SD of the response for an individual on a given visit. These SDs are presented in a relative sense for the logged variables and in the chosen scale for the other variables (Table 4). Also, Table 4 gives the differences between the noncleft participants and the participants with cleft lip as well as the

SDs for the noncleft participants only: the SDs for the participants with cleft lip were quite similar to the noncleft participants. The size of the differences between the two groups of participants is substantially smaller than the individual SDs, meaning that a noncleft participant can exhibit variation that is generally larger than the mean difference between the groups.

Table 5 shows the effect of visit and age of the participant. The gender and race effects are not shown because those predictors were not statistically significant, except in one instance described below. Model 2 yielded no significant effects due to the cleft-related predictors.

Fine Motor Control

Reaction Time

The reaction time is the difference between the time of the onset of the target signal and the time at which the force generated has reached 10% of the peak force. There were marginally significant effects ($p = .045$) on the lower lip reaction time due to the predictor visit. For all participants in both groups, the lower lip reaction time increased by 8% from visit 1 to visit 2 (Table 5).

Rise Time

The rise time is calculated as the time interval between 10% and 90% of the peak force during the recruitment phase. The rise time of the lower lip of the participants with a cleft lip was 15% lower than that of the noncleft participants.

Peak Force

The peak force is the highest force level during recruitment that occurs in the 1-second period immediately after attaining 0.1 N of force. It is measured as the relative overshoot of the target force. There were significant effects on the upper lip peak force due to the predictor visit and on both the upper and lower peak lip forces due to the predictor age (Table 5). For all participants, the overshoot of the upper lip peak force relative to the target force decreased by 13% from visit 1 to visit 2, and the relative overshoot of the upper and lower lip peak forces decreased by 3% and 4% for each year increase in age, respectively. Also, there were marginally significant effects ($p = .059$) on the lower lip peak force for the participants with a cleft lip: the overshoot of the lower lip peak force relative to the target force was 15% greater compared with the noncleft participants (Table 4).

Mean Force

The mean force is the force generated during the middle 1-second (T1) of the hold phase. It is measured as the relative difference from the target force. There were marginally significant effects ($p = .046$) on the lower lip mean force due to the predictor age. For all participants, the relative differences in the lower lip mean force (from the target force) decreased by 1% for each year increase in age (Table 5).

SD Mean Force

The SD mean force is the standard deviation of the force generated during the middle 1-second (T1) of the hold phase. There were significant effects on the upper and lower lip SD mean force due to the predictors visit and age. For all participants, the upper lip SD decreased by 27% from visit 1 to visit 2 and decreased by 8% for each year increase in age, while the lower lip SD decreased by 16% from visit 1 to visit 2 and by 9% for every year increase in age (Table 5). The SD mean force of the lower lip of participants with a cleft lip was marginally significant ($p = .049$) and increased by 21% compared with the noncleft participants (Table 4).

Rate

The average rate of force recruitment is the change in force divided by time calculated between the 10% and 90% force intercepts occurring between the baseline and peak forces. The rate was measured relative to the target force. There were significant effects on the lower lip rate of force recruitment for the participants with a cleft lip: this lower lip rate was greater by 32% in the participants with a cleft lip compared with the noncleft participants (Table 5).

Maxima of First Derivative

The recruitment phase of the ramp-and-hold force trajectory is differentiated to yield a measure of the first derivative of lip force. The maxima of this function is identified and regressed as a function of target force. There were significant effects on the upper lip maxima of the first derivative due to the predictors visit and age and on the lower lip due to the predictors presence of a cleft lip, visit, and age. For all participants, the upper lip maxima decreased by 19% from visit 1 to visit 2 and by 3% for each year increase in age, while the lower lip maxima decreased by 9% from visit 1 to visit 2 and by 5% for each year increase in age (Table 5). The lower lip maxima was 24% greater for the participants with a cleft lip compared with the noncleft participants (Table 4).

Criterion Percentage

The criterion percentage represents the amount of time during the ramp-and-hold behavior that the subject was on target. There were significant effects on the upper and lower lip criterion percentages due to the predictors presence of a cleft, visit, and age. Both the upper and lower lip criterion percentages decreased by 4% due to the presence of a cleft lip (Table 4). For all participants, the upper lip criterion percentage increased by 6% from visit 1 to visit 2 and by 2% for each year increase in age, while the lower lip criterion percentage increased by 3% from visit 1 to visit 2 and by 2% for each year increase in age (Table 5).

Maximum Force Capacity

The maximum force capacity is the maximum voluntary force contraction level. There were significant effects on the upper and lower lip maximum force capacity due to the predictors age and gender. The upper and lower lip maximum forces were increased by 0.19 N and 0.34 N for each year increase in age, respectively (Table 5). Men had 2.24 N greater upper lip and 2.69 N greater lower lip maximum forces than women did. There also was a significant effect on the lower lip maximum force capacity due to the predictor visit; the lower lip maximum force increased by 1 N from visit 1 to 2 (Table 5).

Discussion

This study compared the muscle force dynamics between a group of participants with repaired cleft lip and a noncleft control group. Compression forces were sampled at the midline of both the upper and lower lips separately. This approach was used because electrophysiological and biomechanical studies of the perioral system in noncleft normal adults have demonstrated quasi-independent function and activation of the orbicularis oris superior (upper lip) and the orbicularis oris inferior (lower lip) muscle segments (Barlow and Muller, 1991). Given that the expected functional anatomy of the orbicularis oris muscle in participants with a repaired cleft of the upper lip is expected to resemble the muscle function in noncleft participants, this approach of sampling the midline lip forces was the most conservative and realistic. The target forces for muscle force assessment were selected to represent realistic functional forces within the range characteristic of normal orofacial functions, that is, those forces needed for the movements of facial animation/expression, chewing, and speech (Muller et al., 1984, 1997).

The hypothesis tested in this study was that the perioral musculature of the participants with a cleft lip exhibits impaired fine motor control (force regulation) and lower maximum force capacity (lip strength) compared with that of the noncleft participants. For fine motor control or force regulation, this hypothesis was supported by the results, and surprisingly, the effects were seen mainly in the lower lip. The lower lip of the participants with a cleft lip demonstrated less rise time and had greater instability by demonstrating the least amount of time on target and slightly increased variation in force during the ramp-and-hold phase compared with the noncleft participants. The upper lip of the participants with a cleft lip also demonstrated instability with less time on target than the noncleft participants, but this was the only measure that differentiated the upper lip forces between the groups. As described previously, the lower lip has the ability to function quasi-independently from the upper lip; however, in the presence of a mechanical perturbation or neuromotor impairment to the upper lip, the lower lip typically exhibits compensatory motor actions (Barlow et al., 2004; Estep and Barlow, 2004).

Such compensatory motor actions were evident in the lower lip peak force and the rate of force recruitment for the participants with a cleft lip, which was greater than the same respective forces for the noncleft participants. The excessive peak force was accompanied by higher first derivatives in the lower lip, indicating that the neural drive to the orbicularis oris inferior and mentalis muscles was increased, quite possibly to accommodate for hypofunction of the upper lip in the participants with a cleft lip. In previous studies on facial animation or movement in cleft patients (Trotman et al., 2000, 2005), obvious compensatory movements were found in the lower lip, which mirror the findings in this study. These compensations may imply one of three possibilities either independently or collectively. The first is that scarring of the upper lip could induce limitations in movement and constrictions of the circumoral region that affect motor control of the lower lip. Such limitations may be just as evident during lip opening as during lip closing (compression maneuvers). The second is that altered central nervous system mechanisms due to plasticity and neural reorganization may be active to compensate for altered tissue properties associated with scarring of the upper lip. The third is that, based on an analysis of the facial soft tissues, the participants with a repaired cleft lip tended on average to have flatter faces, a finding that also may increase the lower lip compensatory behavior for certain participants.

Another finding of this study was that there were no differences in lip strength (maximum force capacity) between the two groups of participants. This finding supported the interpretation that in the participants with a repaired cleft lip, fine motor control and animation are compromised because of impairments in force recruitment, gradation, fractionation, and decruitment. Fine motor control and orofacial kinematics for facial animation use vastly different sets of motor units than those required for maximum lip strength and tetany (Barlow and Muller, 1991). Tetanic forces and associated motor unit activation patterns are typically on a greater order of magnitude compared with the fine motor control tasks of speech and facial animation. Barlow and Rath (1985) have shown that measurements of maximum lip force are reliable and highly sensitive to differences in the lip strength between men and women and between the upper and lower lips in normal individuals. Our findings show that for both groups of participants, the lower lip strength was twice that of the upper lip and is consistent with previous observations in the human face (Barlow and Rath, 1985). The findings also supported a learning effect for the participants from the first to the second visit in that for many of the upper and lower lip force variables, the performance of the participants improved at the second test session or visit. For example, the rise time, overshoot of the peak forces, and SD during the ramp-and-hold phase decreased from visit 1 to visit 2, indicating improved fine motor control, and similar improvements were noted with increasing age, although not necessarily for the same variables. These improvements were coupled with a generalized longer reaction time from the first to the second visit, a finding that suggested that the participants probably also took the time to do the task well on the second visit, thus enhancing performance. Only the reaction time worsened in both groups of participants between visits and with increasing age. Possible explanations for this observation may hinge on changes in the perioral force plant that occur with modifications and growth of the body plan, tissue scarring, and adaptations among sensorimotor representations in the nervous system.

In summary, participants with a cleft of the upper lip exhibited increased contraction instability and elevated force recruitment rates of the lower lip. These impairments contributed to a reduction in on-target force behavior and degradation in force control, which is considered central to facial kinematics and animation. As seen in movement disorders of the lower face (i.e., dysarthrias), the lower lip exhibited compensation manifested as excessive peak force during recruitment and higher rates of force recruitment, possibly to make up for decreased upper lip function. The changes in the circumoral muscle function were consistent with the biomechanical challenges facing an individual with a defect in upper lip formation during embryogenesis. These changes, combined with the dramatic anterior-inferior growth, expansion of the facial skeleton, and functional performance anatomy from birth through adolescence, compound the ever-changing compensatory mechanisms for sensorimotor control of the lower face that must adapt for speech, animation, and mastication.

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