Digital Image Correlation: A Novel Dynamic Three-Dimensional Imaging Technique for Precise Quantification of the Dynamic Rhytid and Botulinum Toxin Type A Efficacy

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Background: Quantification of facial dynamic motion is paramount for improving cosmetic and reconstructive surgical outcomes. The authors introduce digital image correlation using speckle tracking photogrammetry and ARAMIS software (GOM mbH, Braunschweig, Germany) to study facial dynamics and demonstrate its application in quantifying botulinum toxin efficacy.
Methods: Fourteen subjects were evaluated using a dual camera system and three-dimensional optical analysis. Using ARAMIS software, the anatomic regions of the glabella, forehead, and total face were identified and highlighted. Tissue strain, defined as either compression or stretch, was measured within these regions over 36 frames during brow furrowing. Each patient was measured before and 2 weeks after injection of 20 units of onabotulinumtoxinA in the glabella. Average stretch and compression in treated areas were analyzed across all available frames. Results were compared using a Wilcoxon signed rank test.
Results: After neurotoxin injection, average vertical stretch of the glabella during brow furrowing decreased from 2.51 percent to 1.15 percent ($p < 0.05$), and average vertical stretch in the forehead decreased from 6.73 percent to 1.67 percent ($p < 0.05$). Horizontal compression in the glabella decreased from 9.11 percent to 2.60 percent ($p < 0.05$) and from 4.83 percent to 0.83 percent ($p < 0.05$) in the forehead. Total facial major strain decreased from 4.41 percent to 3.05 percent ($p < 0.05$), and total facial minor strain decreased from 5.01 percent to 3.51 percent ($p < 0.05$).
Conclusions: The authors introduce digital image correlation as a novel technology for measuring dynamic rhytid and neurotoxin efficacy. This technique allows for advancements in the study of dynamic aging and neuromuscular disorders. (*Plast. Reconstr. Surg.* 135: 869e, 2015.)
CLINICAL QUESTION/LEVEL OF EVIDENCE: Diagnostic, II.

There is a clear need for an objective and reproducible means of measuring the dynamic rhytid in aesthetic and reconstructive surgery. Currently, attempts at measuring the dynamic rhytid have relied largely upon static photographs and degree of permanent etching.[1–4] This study introduces a novel technology of dynamic speckle tracking three-dimensional

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digital image correlation with the ARAMIS analysis system (GOM mbH, Braunschweig, Germany) for precisely measuring and quantifying the dynamic rhytid during facial animation.

Three-dimensional speckle tracking photogrammetry has been described previously in basic research settings. Although validated, previous applications failed to gain widespread use in clinical research and therapeutic applications.[5–8] These technologies have been burdensome, often requiring user-driven data calculation and subjective interpretation of speckle placement and subsequent relative displacement during animation. Here, the authors use an innovative form of speckle tracking photogrammetry with ARAMIS software to quantify the compression and stretch of the skin and subcutaneous tissue secondary to mimetic muscles. This technology is user-friendly and reproducible. Unlike previous technologies, ARAMIS software is capable of running a sensor and controller of a three-dimensional camera system and subsequently processes and computes all postimaging data on a user-friendly interface with a heat map color reference.[9] This obviates any user measurement of speckle displacement and subsequent tedious calculations of strain. Before the authors' work on facial dynamics, digital image correlation with ARAMIS had been used to investigate the mechanical properties of a variety of biologic materials, including in vivo deformational measurements in frog hearts, local strain behavior in artificial muscle, and bone surface strain secondary to loading in mouse tibias.[10–12] Digital image correlation is widely accepted in the study of synthetic materials for commercial applications.[11] However, this is the first published application of this technology in the study of the quantification and attenuation of the facial dynamic rhytid.

To accurately interpret this application of digital image correlation, several fundamental principles applied in the analysis must be defined: namely strain, stretch, and compression. Strain refers to the percent change in distance between two points. Strain can be simplified as either compression (negative strain) or stretch (positive strain) of any material. With respect to facial motion, the dynamic rhytid is the compression of skin and subcutaneous tissues secondary to mimetic muscle contracture. The distance between two points selected on either side of the forming rhytid decreases as the rhytid strengthens. This decreased distance is calculated as negative strain or compression. This compression can be quantified precisely, and the rhytid is thus defined objectively.

Speckle tracking photogrammetry and the corresponding technology of digital image correlation calculate the displacement of multiple points on any surface with respect to one another. For human subjects, points are painted on the subject in a random pattern, with sufficient density and quantity for camera appreciation and calculation. Initially, white foundation makeup is placed on all subjects. Black face paint on a large makeup brush is then applied in a dabbing fashion to the subject in the region of interest. The result is a random speckled pattern on the subject's face (Fig. 1). White foundation and black makeup are necessary for sufficient contrast and accurate calculation. The three-dimensional camera and associated ARAMIS software automatically calculate the displacement between all points on a subject's face during animation compared with the patient's reference static (adynamic) face.

Digital image correlation allows for measurement of strain in a vertical or cranial-caudal direction, defined as major strain, and in the horizontal or transverse dimension, defined as minor strain. The authors hypothesize that through neuromodulation of the brow muscles, botulinum toxin type A should cause a distinct and quantifiable change in strain as either a decrease in compression or a decrease in stretch of the skin in the cranial-caudal (vertical) or transverse (horizontal) direction. Digital image correlation technology will accurately calculate this change in strain, thereby objectively defining the attenuated dynamic rhytid and efficacy of the botulinum toxin.

PATIENTS AND METHODS

After institutional review board approval at the University of Pennsylvania, 14 female subjects with Fitzpatrick skin types I through III between

Fig. 1. A subject prepared for imaging. White foundation and black speckle makeup are applied to each patient. The speckles are tracked by the digital camera, and their displacement is quantified with ARAMIS.

the ages of 29 and 67 years (mean age, 44 years) were recruited. Patients who had undergone previous surgery or filler injections of the face were excluded, as were patients who had undergone neuromodulator injections less than 12 months before participating in this study. Also excluded were patients who had a history of facial trauma or patients with facial paralysis.

At time of initial imaging and before toxin injection, a single individual applied white foundation and black speckled makeup to the entire face of each patient according to the aforementioned technique. To prevent interference, hair was held back with a surgical bouffant or hair band. After speckles were applied, subjects were placed 5 feet from a high-resolution, digital dual-camera system. Consistent positioning was maintained by precise measurement of patient position from the camera and accurate camera calibration. Each subject was then recorded following the instruction to make an angry face (i.e., to furrow her brow). A single reference static (adynamic) frame was taken before initiation of motion, serving as the position for painted reference points. After this initial still frame, the active expression was started and then maintained for 7 seconds. The dual digital camera captured images at a rate of five frames per second. Thirty-five dynamic frames were captured per patient in addition to the solitary reference frame for a total of 36 frames per patient, per visit. After acquisition, images were directly imported into ARAMIS for further data capture and analysis.

Within the ARAMIS application, measured regions were defined and outlined anatomically on each image by a single measuring physician. Glabellar strain was calculated within a reference box defined by the soft-tissue nasion, caudally, to one-third of the brow height cranially and between the medial canthi laterally. Forehead strain was defined within a reference box from the height of the brow to the hairline and between temporal ridges (Fig. 2). In addition, given injections beyond the glabella and forehead and potential effects of neuromodulation in other regions of the face, total facial strain was also calculated. The total face was defined as the region located within the vertical boundaries of the hairline to the chin and transversely from the angle of the mandible to the contralateral angle of the mandible. The average stretch and compression (positive and negative strain, respectively) of dynamic brow action, per frame, was then calculated within the user-defined reference boxes. To eliminate miscalculation secondary to aberrant movements, any value that was greater than three standard deviations from the mean was removed from analysis. The

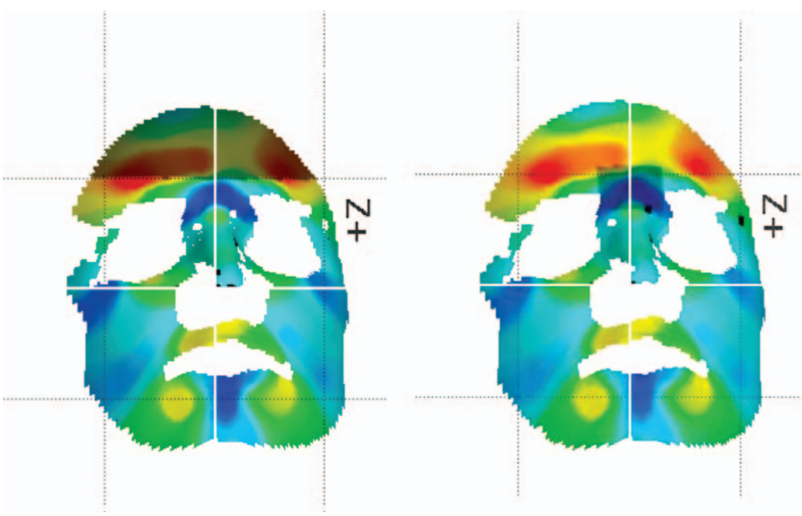


Fig. 2. Measurements. Forehead and glabellar regions were measured separately by an investigator. Pictured are the glabellar and forehead regions defined by the user in the ARAMIS interface. The software then tabulates and displays the strain values within those boxes. Variability in measurement of strain results from variation in user-defined region size and shape. The forehead is defined as the area between the temporal ridges bilaterally from hairline to above brow. This is a representative box designated by a physician observer. Glabella is defined as the area from the medial canthus to contralateral medial canthus and from nasion to one-third above brow. These areas are defined by the observer and not by the program.

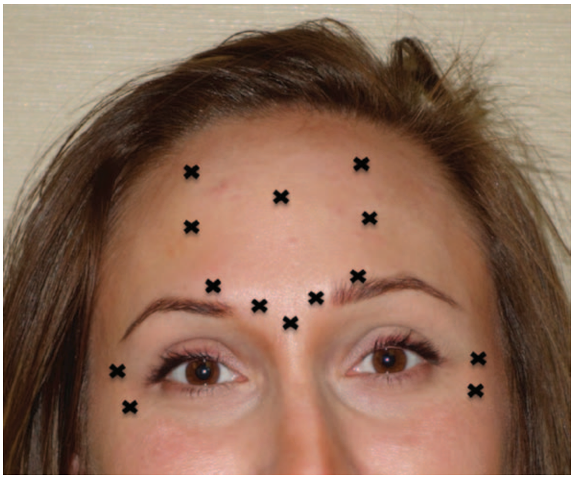


Fig. 3. Injection points. Twenty units of onabotulinumtoxinA injected into the frontalis at five injection points, 20 units of onabotulinumtoxinA injected into the glabella at five injection points, and five units of onabotulinumtoxinA injected into the orbicularis oculi at two injection points.

physician role in calculation was limited to defining the anatomic region of interest. ARAMIS software calculated speckle displacement and strain within the physician-defined region.

After baseline imaging, one experienced clinician injected each patient with 20 units of onabotulinumtoxinA (Allergan, Irvine, Calif.) into the glabella (five injection points), 20 units into the forehead (five injection points), and 5 units in each lateral orbicularis oculi (two injection points) (Fig. 3). For injection, 100 units of toxin were diluted in 2.2 ml of normal saline. The injection points and doses were consistent among patients despite variations in anatomy and muscle strength. After a 2-week interval, patients were reimaged. Imaging and data processing were done in an identical manner to the previous session. Before and after average vertical and horizontal strain in the glabella, forehead, and total face were calculated. Differences between baseline and postinjection strain were analyzed using a Wilcoxon signed rank test. A p value less than 0.05 was considered significant.

In addition, interobserver reliability for glabellar, forehead, and total facial major strain was determined. For this specific portion, two separate physicians defined the regions of the glabella, forehead, and total face per the above-mentioned parameters. To perform this, each physician outlined these areas according to the study definition of glabella, forehead, and total face. Average major strain was calculated within these defined regions. Variability was assessed using the Spearman ranked order correlation.

RESULTS

Digital image correlation with Aramis software successfully identified and quantified upper facial strain during brow furrowing and a change in this strain in subjects after botulinum toxin type A therapy. Furthermore, it identified an overall decrease in total facial strain after neuromodulation. During brow furrowing, we observed primarily horizontal glabellar compression (negative strain) associated with clinically apparent rhytids and compensatory vertical stretch (positive strain) in the lateral forehead (Figs. 4 and 5). After injection, the degree of glabellar compression decreased in both the horizontal and vertical direction. This change in glabellar strain with botulinum toxin type A therapy was statistically significant (Table 1). After neurotoxin injection, average vertical stretch of the glabella during brow furrowing decreased from 2.51 percent to 1.15 percent ($p < 0.05$), and average vertical stretch in the forehead decreased from 6.73 percent to 1.67 percent ($p < 0.05$). Horizontal compression in the glabella decreased from 9.11 percent to 2.60 percent ($p < 0.05$) and from 4.83 percent to 0.83 percent ($p < 0.05$) in the forehead. Total facial major strain decreased from 4.41 percent to 3.05 percent ($p < 0.05$), and total facial minor strain decreased from 5.01 percent to 3.51 percent ($p < 0.05$).

Both the individual patients and a cohort as a whole were assessed. Figure 6 demonstrates a graphical depiction of the furrowing movement in a single patient. The onset, maintenance, and termination of facial action are depicted before and after injection of toxin. The difference in both the vertical stretch of the forehead and horizontal compression of the glabella is clear (**see Video, Supplemental Digital Content 1**, which demonstrates dynamic rhytid calculation before neurotoxin injection for this same patient, ***http://links.lww.com/PRS/B279***; and **see Video, Supplemental Digital Content 2**, which demonstrates dynamic rhytid calculation after neurotoxin injection for this same patient, ***http://links.lww.com/PRS/B280***). Figure 7 illustrates the before and after minor strain across the entire cohort. The reduction in strain is seen in every patient. The difference among patients likely reflects the relative potency/dosing per patient given each patient's individual muscle strength and mass as observed in clinical practice.

When two separate trained physicians independently defined the anatomic total face, glabella, and forehead in all patients, excellent reliability was found. The Spearman rank order coefficient was used to determine correlation. The coefficient

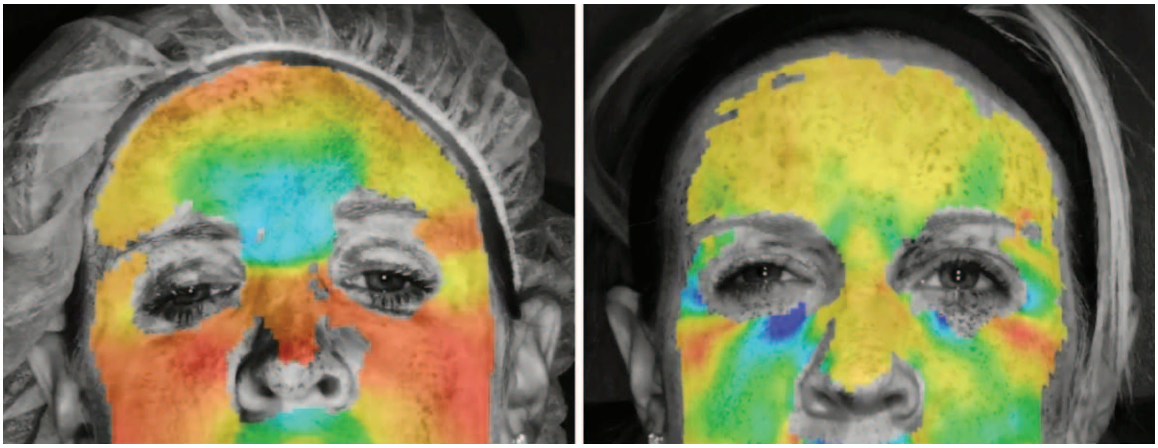


Fig. 4. The decrease in horizontal compression of the glabella after neuromodulation. Illustrated here is the decreased horizontal compression of the glabella and decreased vertical stretch of the forehead (see Fig. 5); these are the parameters most affected by neuromodulation. Program-defined heat map reference ranges from dark blue to red, where *dark blue* is the greatest compression and *red* is the greatest stretch. In these images, the software is visually mapping horizontal movement of the face. (*Left*) The image is taken during maximal furrow before any neurotoxin injection. The *light blue* in the center indicates glabellar compression. (*Right*) The image is taken during maximal furrow 2 weeks after injection with neurotoxin. Notably, the central *light blue* has been replaced with *light green* and *yellow*. These new colors are representative of decreased compression.

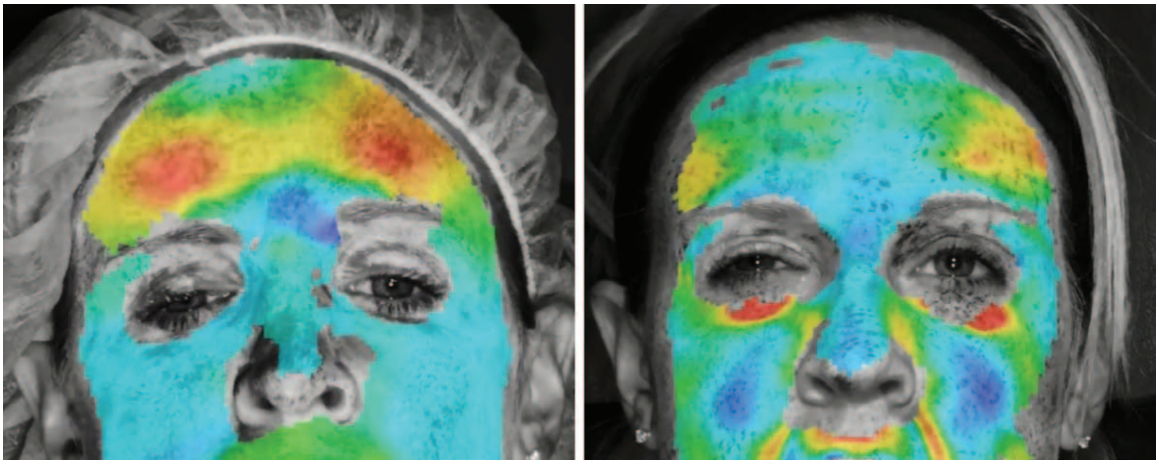


Fig. 5. The decrease in vertical stretch of the forehead after neuromodulation. Again, program-defined heat map reference ranges from dark blue to red, where *dark blue* is the greatest compression and *red* is the greatest stretch. In these images, the software is highlighting vertical motion. (*Left*) The lateral forehead shows increased stretch during maximal furrow, suggesting that as the glabellar rhytid is formed, forehead tissue is recruited from a vertical vector. (*Right*) Stretch of the lateral forehead is decreased but not completely eliminated. Notably, the decrease is more prominent on the patient's right side than the left. Why such differences exist could vary from injection technique, to anatomical variability, to toxin spread.

Table 1. Major Strain (Vertical Stretch) before and after Injection and Minor Strain (Horizontal Compression) before and after Neurotoxin

	Major Strain (Vertical)			Minor Strain (Horizontal)		
	Before Neurotoxin	After Neurotoxin	p	Before Neurotoxin	After Neurotoxin	p
Total face average	4.41%	3.05%	0.004	5.01%	3.53%	0.002
Glabella average	2.51%	1.15%	0.005	9.11%	2.60%	0.001
Forehead average	6.73%	1.67%	0.001	4.83%	0.87%	0.001

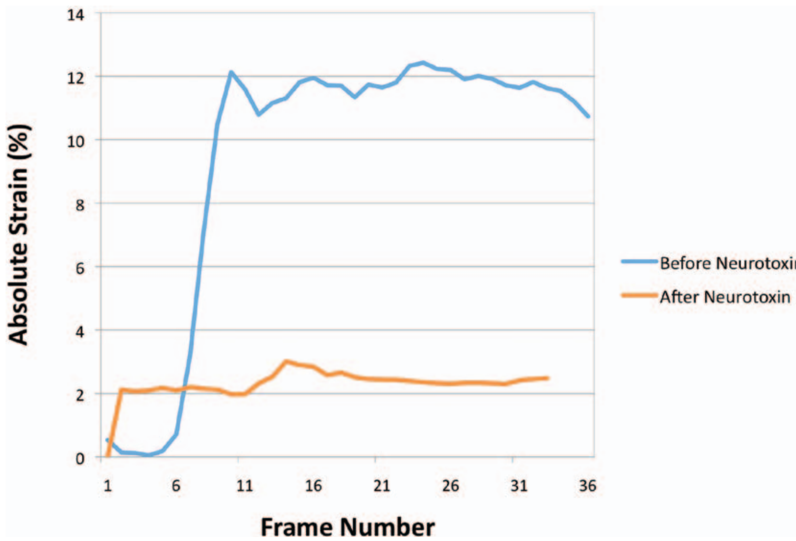
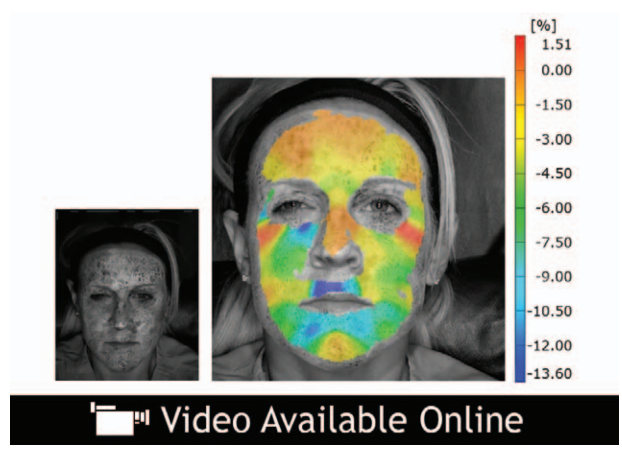


Fig. 6. Individual patient. Minor strain (horizontal compression) of the glabella before and after botulinum toxin type A treatment.

Video 1. Supplemental Digital Content 1 demonstrates dynamic rhytid calculation before neurotoxin injection for this same patient, ***http://links.lww.com/PRS/B279***.



Video 2. Supplemental Digital Content 2 demonstrates dynamic rhytid calculation after neurotoxin injection for this same patient, ***http://links.lww.com/PRS/B280***.

was determined to be 1.0 for the total face, 0.91 for the forehead, and 0.80 for the glabella alone.

DISCUSSION

In the current investigational climate, there is a clear need and demand for objective analysis of aesthetic results, including the characterization and quantification of dynamic rhytid reduction. This study serves two primary goals: (1) to demonstrate a user-friendly clinical research platform using digital image correlation for the evaluation of specific dynamic facial rhytids; and (2) to establish the application of this technology for the precise quantification of botulinum toxin type A effect on dynamic rhytids. In our cohort, horizontal compression in the glabella, consistent with rhytid formation caused by contraction of corrugator and procerus muscles, was significantly decreased by neuromodulation. Compensatory vertical stretch in the lateral forehead also decreased correspondingly. Intriguingly, the significant decrease in total facial stretch and compression suggests localized botulinum toxin type A therapy may result in changes at sites distant to the treatment areas. This observation requires significant further exploration before any conclusions.

With respect to interobserver reliability, we performed a limited evaluation of major strain. Two separate physicians were asked to define the total face, the glabella, and the forehead based on the previously described landmarks. The software then

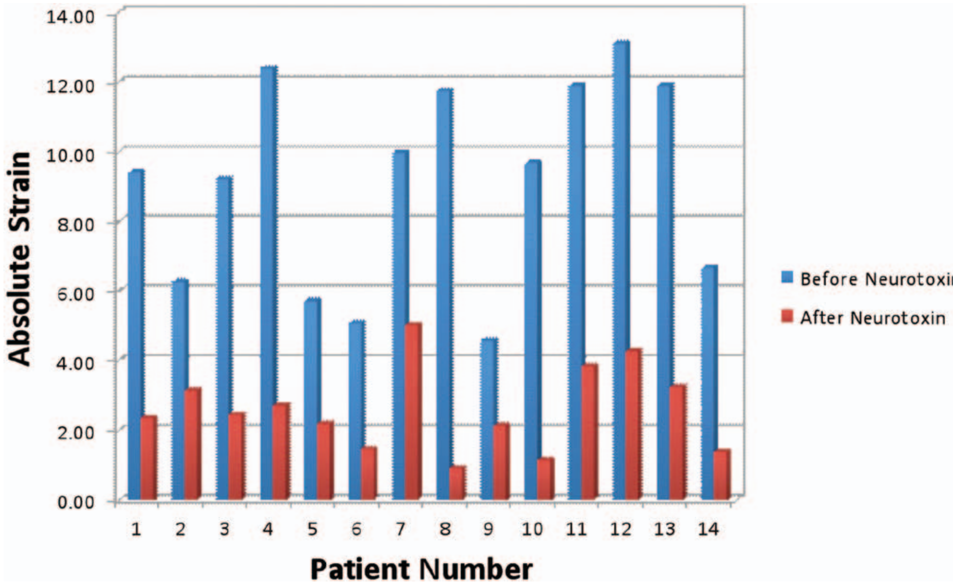


Fig. 7. Entire cohort. Graph demonstrating minor strain reduction (horizontal compression) in all patients.

calculated the strain within those regions. There is a potential for strong interobserver reliability provided that observers select precisely the same anatomic regions. If there are inconsistencies in the anatomically defined regions among observers, there will be inconsistent results. As expected, as the anatomic region of interest becomes more defined, and the respective surface area becomes smaller, there is an increased likelihood that individual observers will vary in the placement of the measurement boxes. In this study, because the regions are incrementally defined from the largest (the total face) to the smallest (the glabella), variability increases, although correlation remains strong.

Medical and surgical techniques that focus on the dynamic rhytid, including neuromodulation, can be investigated further and improved using digital image correlation with ARAMIS. In aesthetic medicine, formulations of botulinum toxin type A are commonly used for the prevention and treatment of dynamic rhytids. In the United States, there are currently three approved formulations for treatment of glabellar rhytids: onabotulinumtoxinA (Botox;, Allergan), incobotulinumtoxinA (Xeomin; Merz Pharmaceuticals), and abobotulinumtoxinA (Dysport; Galderma). Although all formulations have proven clinical benefit, defining the precise treatment parameters has been limited by a lack of objective characterization of clinical response. Controversy persists regarding preparation, dilution, onset, duration, spread, and dosing efficacy of a given toxin. Previous investigations have largely used static photography with subjective, although validated, scoring scales (Merz, Wrinkle Severity Scale, and so on) or anhidrosis as a proxy for muscle paralysis.[2,4,13–17] These methods do not assess the direct effect of neuromodulation on dynamic rhytid formation. The result is a subjective clinical practice of toxin selection, dilution, and application based largely on anecdotal experience. Digital image correlation can clarify much of the current controversy, providing objective interpretation of outcomes.

As an extension of this project, digital image correlation can objectively measure clinical efficacy of individual toxins. This current study specifically quantified the effect of neuromodulation 2 weeks after injection; however, the imaging can be extended to subjects at various intervals, permitting evaluation of the onset of effect as well as its duration. Given the precise quantification of change in compression and stretch, digital image correlation may provide an effective manner of determining different dose efficacy in various populations (i.e., male versus female patients from various age groups). As new toxins and expanded applications become available, their clinical efficacy can be quantified to establish precise therapeutic regimens.

Speckle tracking and digital image correlation with ARAMIS require specialized technology and dedicated staff to appropriately perform a study such as this. The three-dimensional camera with software can be purchased outright at a cost of approximately $80,000 or rented daily for approximately $3000. In this study, one staff member applied white foundation and speckled makeup in a consistent and reproducible manner, and a second staff member instructed patients and calibrated the camera according to protocol. Training for camera calibration is based on a camera-specific instructional manual. This study employed a trained software engineer whose fee was incorporated into the camera rental. Patient preparation required less than 5 minutes, and an entire session from patient arrival to departure was 15 minutes. Given the short duration of this study and the limited number of patients recruited, the total cost of the camera was approximately $8000. After imaging, an observer or observers must define measurable regions on separate images and then export computer-tabulated strain values. For each patient at each individual session and for each expression, this took approximately 5 minutes.

Given the fixed cost of the camera and software, digital image correlation may not be feasible in all research settings. However, digital image correlation as described in this project can have future application in the validation of currently existing or future facial wrinkle scores. Further validation by correlating precise strain at maximal furrow and corresponding static wrinkle score would provide quantitative value to these commonly used, simple, and low-cost assessment tools. Validation of assessment tools requires further dedicated investigation with a larger cohort.

CONCLUSIONS

Digital image correlation with ARAMIS software is a three-dimensional imaging technology that precisely measures dynamic facial rhytids and detects statistically significant changes in rhytid formation after onabotulinumtoxinA injection. As an objective and reproducible research platform, digital image correlation can be applied further to study a spectrum of clinical challenges in plastic surgery, including the aging and paralyzed face and respective rejuvenation, reinnervation, and reconstruction therapies.

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PATIENT CONSENT

Patients provided written consent for the use of their images.

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