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Dynamic Evaluation of Skin Displacement by the Frontalis Muscle Contraction Using Three-Dimensional Skin Displacement Vector Analysis

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Purpose: Understanding the muscle actions and resultant skin movement can enable more safe and effective botulinum toxin injection for the treatment of forehead wrinkles. We aimed to investigate skin displacement patterns of the forehead and adjacent skin due to frontalis muscle contraction using three-dimensional skin vector displacement analysis.

Materials and Methods: Thirty healthy individuals were enrolled. Photographs of the face were taken at rest and during maximal contraction of the frontalis muscle. Each expression image was aligned to its respective static image to compute the differences in the skin position.

Results: When frontalis muscle contracts, forehead skin displacement vectors were mostly vertical (63.4%), followed by lateral oblique (33.3%) and medial oblique (3.3%). In 53.3%, only the lower part of the forehead moved upward, while 40.0% showed bidirectional skin movement with transition line at a mean distance of 59.4 mm above the pupil. Moreover, 86.7% showed asymmetric skin displacement, and 83.3% showed both glabellar and eyebrow skin displacement. Frontalis muscle contraction also induced medial 2/3 (50.0%) or entire (33.3%) skin movement of the temple.

Conclusion: Botulinum toxin injection into the forehead can be individualized by considering the vector and asymmetry of skin displacement. Vertical or medial vector requires more centrally located injections, while laterial vector requires more laterally located injections. The presence and location of the vertical transition line are important for preventing ptosis when treating forehead lines with botulinum toxin. Glabellar movement during frontalis contraction suggests the need for a concomitant injection into the glabella to prevent glabella wrinkle accentuation.

Key Words: Botulinum toxin, dynamic anatomy, three-dimensional skin vector

INTRODUCTION

Botulinum toxin injection is one of the most commonly performed aesthetic procedures to treat facial wrinkles.[1-3] Botulinum toxin treatment can lead to unwanted results due to unintended effects on nearby muscles through local diffusion of up to 3 cm in diameter from the injection point.[4,5] Thus, a complete understanding of facial anatomy is essential for effective and safe treatment.[6-8] While cadaveric anatomy training has improved our knowledge of facial anatomy for aesthetic practitioners, it still has some limitations as facial expression muscles are dynamic structures.[9,10] Based on the information of static facial wrinkle lines alone, we cannot predict the shapes of muscles, degree and range of muscle actions, degree of resultant movement of the skin, and connection or interaction of one muscle with other nearby muscles. Therefore, the analysis of facial dynamic anatomy is required for the individualized treat-

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ment of botulinum toxin for facial wrinkles.[11]

Three-dimensional (3D) skin vector displacement analysis has been shown to provide objective quantification of skin movement.[12,13] It can provide information on strength, direction, and area of muscle contraction by quantification of skin displacement.[14] Forehead wrinkles are a popular target for botulinum toxin injections.[15] There have been two studies on dynamic anatomy of forehead, however they were conducted in mostly Caucasian and African American population and focused only on the movements of the forehead skin.[12,13] Comprehensive data on adjacent muscle and skin movements during frontalis muscle contraction are not yet available.

Therefore, in this study, we included an Asian cohort, considering the possible difference in skin type and muscle strength by race, and objectively quantified movement patterns of the forehead and adjacent skin on frontalis muscle contraction using 3D skin vector displacement analysis to characterize the dynamic anatomy of the frontalis muscle.

MATERIALS AND METHODS

This prospective study was conducted from September 2021 to November 2021 in accordance with the ethical principles of the Declaration of Helsinki. The study protocol and informed consent form were reviewed and approved by the Institutional Review Board of Gangnam Severance Hospital (IRB No. 3-2021-0156).

Written informed consent was obtained from each participant before the start of the study. All participants consented to the use of their blurred images for research and education. Participants with a previous history of botulinum toxin injection, surgical, or filler treatments in the regions of interest within 6 months and those with diseases that impair the movement of facial muscles were excluded from the analysis. Ultimately, 30 eligible participants were selected. The participants were trained until they fully understood how to create facial expressions of the forehead related to frontal wrinkles. Photographs

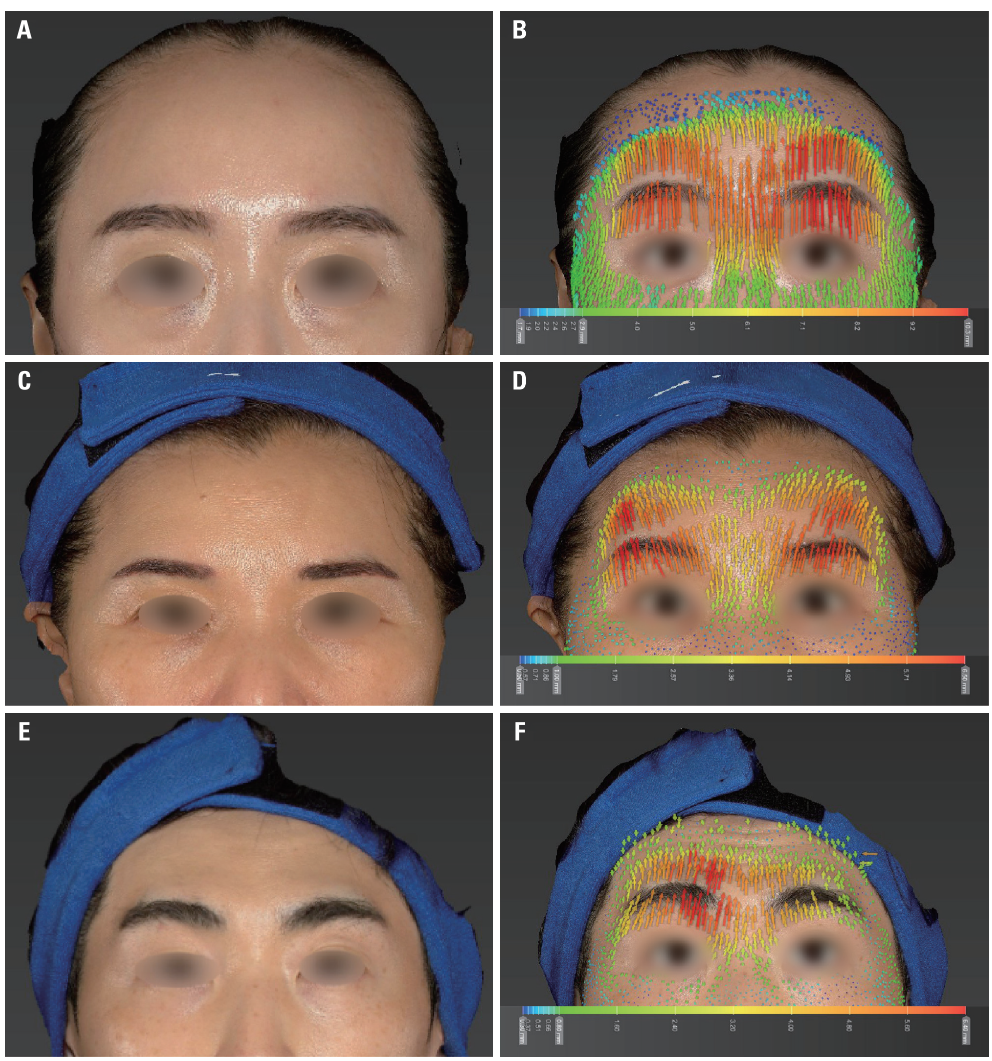

Fig. 1. Vector of skin displacement by frontalis muscle contraction is vertical (A: at rest; B: at maximal contratcion), lateral oblique (C: at rest; D: at maximal contratcion), and medial oblique (E: at rest; F: at maximal contraction).

of the faces were taken at rest (static image) and during hyperkinetic frontalis contraction (on request) on the same day, keeping the camera, lighting, and distance constant. All images were captured using a Vectra H1 camera system (Canfield Scientific Inc., Fairfield, NJ, USA). Each expression image was aligned to its respective static image to compute the differences in skin position and calculate skin displacement vectors. By applying the automated algorithms of the Vectra Software Mirror Suite (Canfield Scientific Inc.), values for local changes in skin displacement were calculated and visualized using the color and size of the arrow. As the degree of skin displacement gradually increases, the color of the arrow changes to blue, green, yellow, orange, and red, and the degree displacement is proportional to the length of the arrow. Using these values, we evaluated the movement vector, strength, and range of the frontalis muscle and the resultant skin displacement patterns.

Table 1. Skin Displacement Vector and Vertical Movement Patterns of Forehead Skin during Frontalis Muscle Contraction (n=30)

	Value
Vector of forehead skin displacement	
Vertical	19 (63.4)
Lateral oblique	10 (33.3)
Medial oblique	1 (3.3)
Vertical movement patterns of forehead skin displacement	
Whole skin is displaced upward	2 (6.7)
Lower part of skin is displaced upward	16 (53.3)
Bidirectional displacement of skin	12 (40.0)

Data are presented as n (%).

RESULTS

Thirty healthy participants aged 30–62 years (median age: 40.5 years) were included in this study. The male-to-female ratio was 1:6.5.

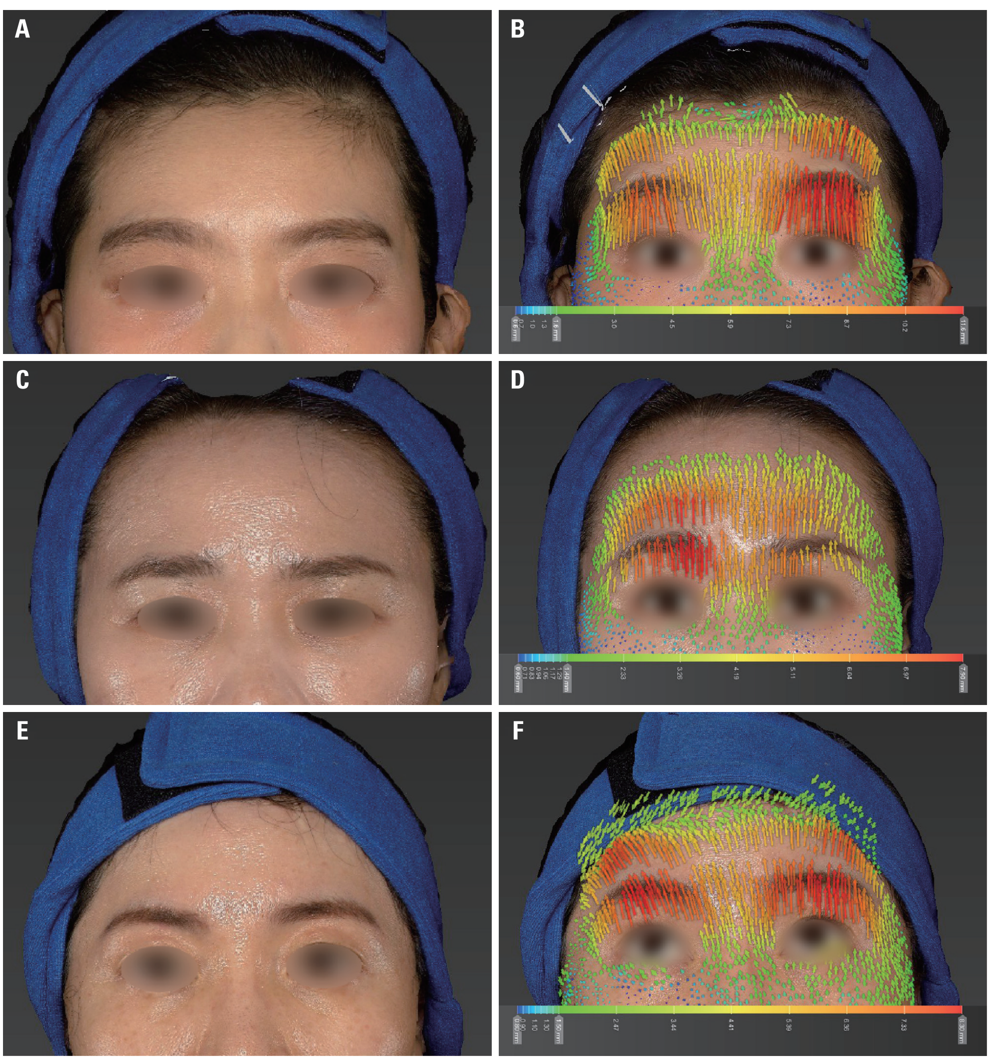

Fig. 2. Direction and vertical range of movement of forehead skin during frontalis contracture. (A and B) Whole forehead skin is displaced upward (A: at rest; B: at maximal contraction). (C and D) Only lower part is displaced upward (C: at rest; D: at maximal contraction). (E and F) The lower part is displaced upward, and the upper part is displaced downward (E: at rest; F: at maximal contraction).

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Forehead skin displacement vector during frontalis muscle contraction

Through the analysis of 3D skin vector displacement and face painting using the photographs of 30 participants, we observed three kinds of vectors of forehead skin displacement. A vector was considered vertical if the average angle of all vectors was 90±5 degrees from the x-axis (0-degree). Lateral oblique was defined as the average angle of 95 degrees or greater with respect to the x-axis. Medial oblique was defined as the average angle less than or equal to 85 degrees with respect to the X axis. When the frontalis muscle contracted to raise the eyebrows, 19 participants (63.4%) showed forehead skin movement mostly along the vertical direction [mean angle; 90.6±1.193 (range, 89.02–94.39)], while 10 participants (33.3%) showed skin movement with a lateral oblique vector [mean angle; 107.1±6.258 (range, 98.86–119.0)], and 1 participant (3.3%) showed skin movement with a medial oblique vector (angle; 76.23) (Fig. 1, Table 1).

Direction and range of movement of forehead skin during frontalis muscle contraction

Next, we identified three patterns regarding the direction of movement and range of skin displacement during frontalis muscle contraction. In 16 (53.3%) participants, only the lower part of the forehead was displaced upward. In 12 (40.0%) participants, forehead skin displacement showed bidirectional movement. In these participants, the lower part was displaced upward, and the upper part was displaced downward (Fig. 2, Table 1). The transitional point of the bidirectional movement was 59.4 mm above the pupil (Fig. 3). In 2 (6.7%) participants, the whole forehead skin was displaced upward during frontalis muscle contraction (Fig. 2, Table 1).

Horizontal extent of forehead skin displacement during frontalis muscle contraction

The frontalis interdigitates inferomedially with the fibers of the procerus muscle, and it has inferolateral attachments to the orbicularis oculi and corrugator muscles. Considering the anatomical variations, we next assessed the horizontal extent of forehead skin displacement during frontalis muscle contraction. In 25 (83.3%) participants, both the glabella and whole or part of the eyebrows moved upward during frontalis muscle contraction. Among these individuals, 20 (66.6%) showed the upward movement of glabellar and whole eyebrows, while 5 (16.7%) showed the upward movement of glabellar and medial 2/3 of eyebrows. In 5 (16.7%) participants, only the whole or part of the eyebrows moved upward during frontalis muscle contraction. Among these individuals, 2 (6.7%) showed the movement of the whole eyebrows, 1 (3.3%) showed the movement of medial two-thirds of the eyebrows, and 1 (3.3%) showed the movement of lateral two-thirds of the eyebrows. The areas that moved with the maximum range were in the order of medial two-thirds (30%), lateral two-thirds (23.3%), and lateral one-third (16.7%) of the eyebrows (Table 2). The average width of eyebrow displacement was 5.6 mm (range, 1–11.2 mm).

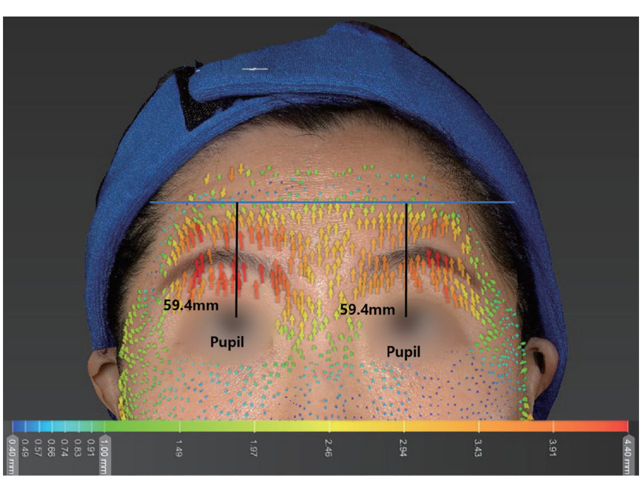

Fig. 3. Transitional line of the bidirectional movement (blue line).

Asymmetry

A total of 26 (86.7%) participants showed asymmetric skin displacement; 16 (53.4%) showed more movement on the right side, whereas 10 (33.3%) showed more movement on the left side (Fig. 4, Table 2).

Pattern of temple skin displacement during frontalis muscle contraction

All participants showed temple skin displacement during fron-

Table 2. Asymmetry and Horizontal Extent of Skin Displacement during Frontalis Contraction (n=30)

	Value
Dominant moving side	
Right dominance	16 (53.4)
Left dominance	10 (33.3)
No dominance on either side	4 (13.3)
Horizontal extent of skin displacement	
Glabella and whole eyebrow	20 (66.6)
Glabella and medial 2/3 of eyebrow	5 (16.7)
Medial 2/3 of eyebrow	1 (3.3)
Whole eyebrow	2 (6.7)
Lateral 2/3 of eyebrow	2 (6.7)
Maximal skin displacement	
Glabella	1 (3.3)
Glabella and medial 1/3 of eyebrow	1 (3.3)
Glabella and medial 2/3 of eyebrow	2 (6.7)
Medial 2/3 of eyebrow	9 (30.0)
Medial 1/3 of eyebrow	2 (6.7)
Middle 1/3 of eyebrow	2 (6.7)
Lateral 1/3 of eyebrow	5 (16.7)
Lateral 2/3 of eyebrow	7 (23.3)
Whole eyebrow	1 (3.3)

Data are presented as n (%).

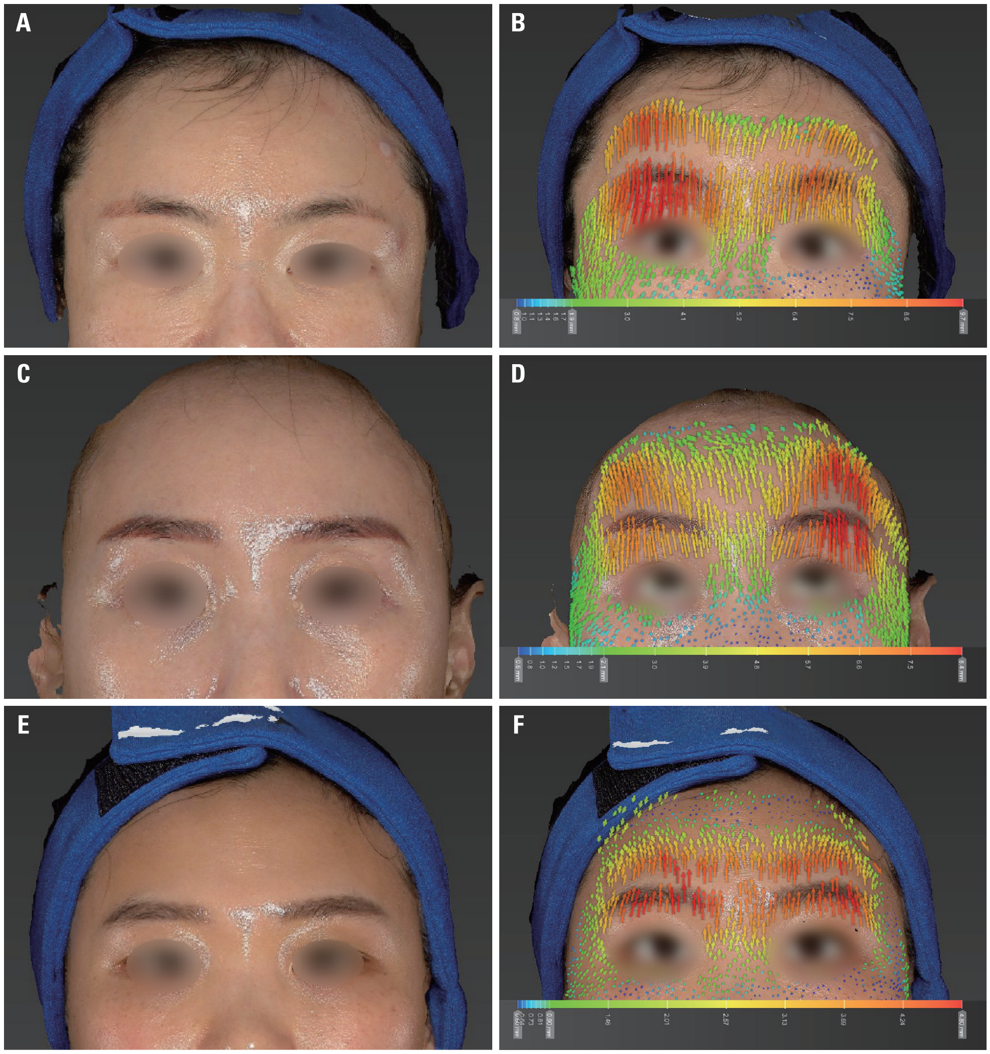

Fig. 4. Asymmetry in skin displacement during frontalis muscle contraction. The degree of skin displacement was dominant on the right side (A: at rest; B: at maximal contraction) or on the left side (C: at rest; D: at maximal contraction) or the same on both sides (E: at rest; F: at maximal contraction).

talis muscle contraction. When the temple area was divided into three parts, skin displacement in the medial two-third area of the temple was the most common (50.0%). In 10 participants (33.3%), skin displacement over the entire temporal region was observed during frontalis muscle contraction. Skin displacement in the medial one-third area of the temple was observed in 5 participants (16.7%) (Fig. 5, Table 3).

DISCUSSION

Using 3D vector skin displacement analysis in 30 Asian individuals, we were able to analyze the direction, strength, as well as vertical and horizontal range of movement of the forehead and adjacent skin during frontalis muscle contraction.

First, we identified three patterns of skin movement vectors. The fibers of the frontalis muscle are known to diverge upward and outward from the glabella.[16] Therefore, we predicted that the vector of skin displacement would be oblique. A previous study by Frank, et al.[13] showed that in individuals of diverse ethnicities, the mean overall forehead motion angle was 13.19°±8.6° on frontalis muscle contraction and a greater laterial motion angle of forehead was associated with wavy horizontal forehead lines rather than straight horizontal lines. However, in this study, >60% of the participants showed vertical skin displacement, resulting in straight forehead wrinkle lines, and only 36.6% presented oblique skin displacement. This discrepancy between the findings of the present and previous studies can be attributed to several factors. 1) The static anatomy of the frontalis muscle may be different between races, as most participants (34/36) in the previous study by Frank, et al.[13] were Caucasians or African Americans. 2) The previous study enrolled 8 male (38%) and 13 female (62%) participants (male-to-female ratio 1:1.63) and found that straight horizontal forehead lines, indicative of vertical skin movement, were observed more frequently in female participants than in male participants. The

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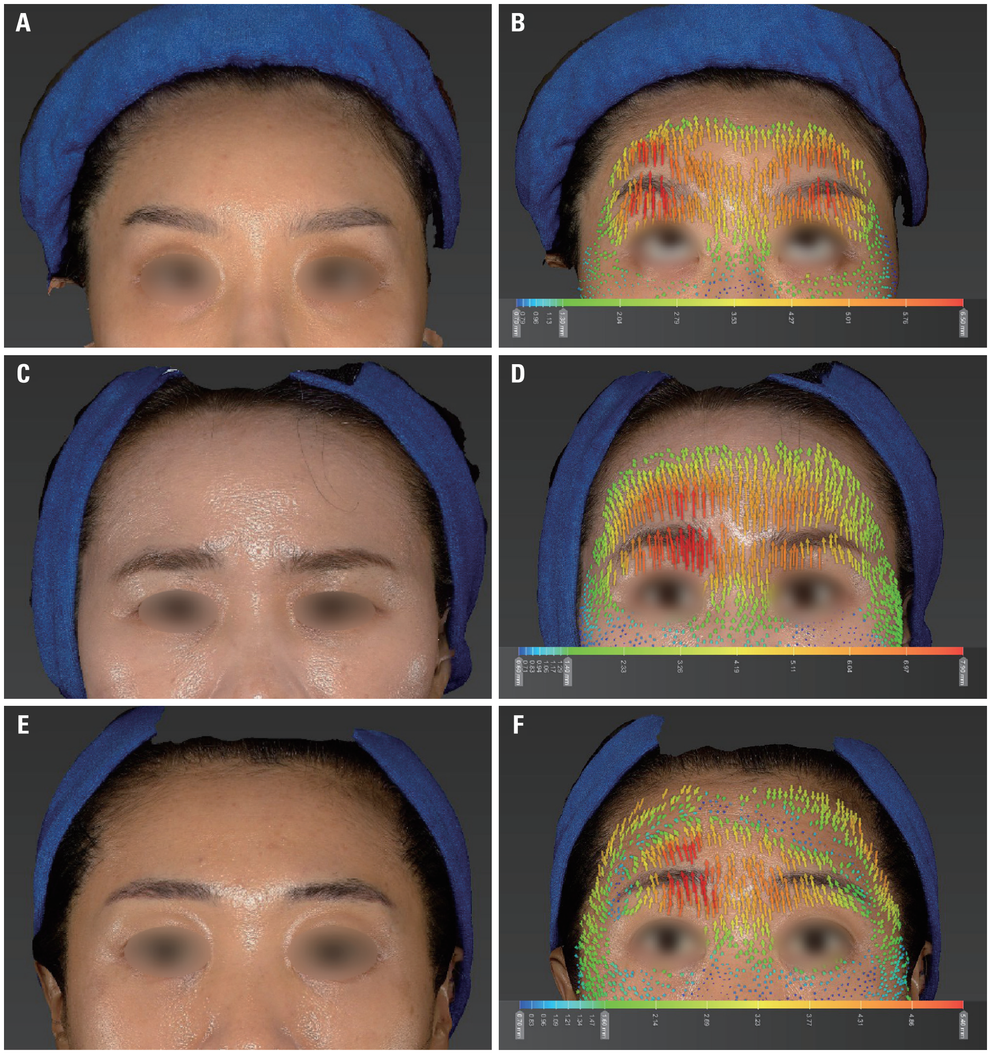

Fig. 5. Patterns of temple skin displacement by frontalis muscle contraction. Skin displacement was noticed at the medial 1/3 of temple (A: at rest; B: at maximal contraction), at the medial 2/3 of temple (C: at rest; D: at maximal contraction), or at the whole of temple (E: at rest; F: at maximal contraction).

Table 3. Pattern of Temple Skin Displacement during Frontalis Muscle Contraction (n=30)

	Value
Medial 1/3 of temple	5 (16.7)
Medial 2/3 of temple	15 (50.0)
Whole of temple	10 (33.3)

Data are presented as n (%).

proportion of female participants in our study (male-to-female ratio 1:6.5) was significantly higher than that in the previous study. Based on these findings, we can hypothesize that the predominance of a vertical skin movement pattern in our study may be related to the high proportion of female participants. 3) Cadaveric studies have suggested that the frontalis muscle appears to be fan-shaped; however, the strength, thickness, and depth of the frontalis muscle, as well as the thickness of the overlying skin, may differ between medial and lateral fibers of frontalis muscle, and these differences may vary depending on race and sex. The predominance of a vertical skin movement pattern in our study may suggest that the thickness or contractility of the medial part of the frontalis muscle is stronger in Asian women compared to other races or males. Our data suggest that botulinum toxin injection should be individualized depending on the skin displacement vector; vertical or medial vectors require more central injections, whereas lateral oblique vectors require more lateral or medial injections.

Second, similar to the findings of a previous study[12] that showed bidirectional movement of the skin in subjects when the forehead was maximally contracted, we observed bidirectional movement of the forehead skin during maximal frontalis muscle contraction in 40.0% of participants in this study. In these individuals, the skin of the lower forehead moved upward, whereas that of the upper forehead moved downward on raising the eyebrows and eyelids. The transitional line was located approximately 59.4 mm above the pupil. A unique finding of our study is that in over half of the participants (53%), only the lower part of the forehead moved upward while the upper part of the forehead remained fixed and immobile during frontalis muscle contraction, whereas in a previous study,[12] all subjects exhibited bidirectional skin movement. Further research is required to ascertain whether these differences are attributable to racial variations. Our data prove that the main eyebrow-lifting muscle is the lower part of the frontalis muscle. Thus, eyebrow ptosis can occur when botulinum toxin is injected into the lower part of the forehead, particularly below the transitional line. The current consensus is that botulinum toxin injection within 2 cm from the eyebrow increases the risk of ptosis.[12,17-19] Our data showing that the transition line is located 59.4 mm above the pupil support this consensus.[19] In addition, Asians tend to prefer a round forehead line that forms a gentle arch from an aesthetic perspective. Our results suggest that botulinum toxin injection into the upper part of the forehead can result in rounding of the forehead line by preventing hairline depression in individuals showing bidirectional forehead skin movement.

Third, frontalis muscle contraction induced movement of the temple skin and lateral eyebrows. In this study, all participants showed skin displacement of the temple area on raising their eyebrows and eyelids. In 33.3% of participants, the entire temporal skin was displaced upward and outward. In addition, 96.7% of participants showed the movement of the outer eyebrows during frontalis muscles contraction. These findings suggest that the lateral fibers of the frontalis muscle control the movement of the temple and outer eyebrows. Therefore, during botulinum toxin injection therapy for the treatment of forehead wrinkles, if the lateral fibers of the frontalis muscles are not sufficiently paralyzed compared to the medial fibers, excessive lateral brow elevation ("Mephisto's sign") may occur. To prevent this, an additional botulinum toxin injection into the distal end of the frontalis muscle may be necessary for persons showing skin movement of the temple and outer eyebrows on frontalis muscle contraction.

Fourth, asymmetry of forehead skin displacement during frontalis muscle contraction was noted in 86.7% of participants. The contraction intensity and width of the left and right frontalis muscles may differ, possibly due to differences in muscle mass. These findings suggest that the dominant side requires a higher dose of botulinum toxin to correct forehead wrinkles.[20,21]

Fifth, in most of the participants (83.3%) in this study, the glabella moved upward when the eyebrows and eyelids were raised as the frontal muscle contracted. These results showed that during the frontalis muscle contracture, the skin overlying both eyebrows move upward, and this movement also lifts the adjacent glabella skin. Functionally, frontalis muscle antagonizes the corrugator muscle which acts on glabella skin, draws the eyebrow down, and wrinkles the glabella vertically. Thus, when the frontalis muscle acts strongly, the corrugator muscle is less active. This results in a smaller downward vector and a larger upward vector of the eyebrows and glabella, resulting in a net upward motion. Conversely, hyperfunction of the corrugator and procerus muscles may occur during frontalis muscle weakness. Therefore, it is recommended to concomitantly inject botulinum toxin into the corrugator and procerus muscles when treating forehead wrinkles in individuals showing glabellar skin displacement on frontalis muscle contraction.

In conclusion, our study provides comprehensive data on the dynamic anatomy of the frontalis muscle by analyzing the displacement pattern of the skin adjacent to the forehead, such as the glabella, eyebrows, and temple, during frontalis muscle contraction. This information can enable us to establish guidelines for individualized injection of botulinum toxin for forehead wrinkle treatment.

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AUTHOR CONTRIBUTIONS

Conceptualization: Hyoung-Jin Moon and Sang Eun Lee. Data curation: Il Joo Kwon. Formal analysis: Won Lee. Funding acquisition: Hyoung-Jin Moon. Investigation: Il Joo Kwon and Hyoung-Jin Moon. Methodology: Il Joo Kwon and Hyoung-Jin Moon. Project administration: Hyoung-Jin Moon and Sang Eun Lee. Resources: Hyoung-Jin Moon and Won Lee. Software: Il Joo Kwon. Supervision: Sang Eun Lee. Validation: Hyoung-Jin Moon and Won Lee. Visualization: Il Joo Kwon and Won Lee. Writing—original draft: Il Joo Kwon and Sang Eun Lee. Writing—review & editing: Il Joo Kwon and Sang Eun Lee. Approval of final manuscript: all authors.

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