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Facial Muscle Activity: High-Sensitivity Noncontact Measurement Using Laser Doppler Vibrometry

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Abstract— Facial expression is regulated by facial muscles and it is an important communication modality, generally held to convey signs of emotion, stress, pain and social engagement. The assessment of facial expression has a role in a variety of scientific areas, as well as applied situations including affective computing, marketing, and clinical evaluation, and is now an area of intensive development using computerized image processing approaches. Assessment has conventionally involved the analysis of facial images by trained coders, relying on the parsing of facial movements into standardized elemental actions. Direct measurement of the electromyographic (EMG) activity from the engaged muscles offers theoretical advantages, especially in terms of sensitivity, but involves burdensome procedures including application of electrodes. Here we describe an alternative measurement method for the direct assessment from facial muscles using the non-contact technique of Laser Doppler Vibrometry (LDV). The application of LDV to measuring muscle activity relies on detection of the small lateral muscle vibration signals that accompany contraction along the longitudinal axis. The sensitivity of the LDV method was demonstrated in a study involving a posed facial expression that is generally associated with the emotion of disgust. Ascending sequences of expression strength were anchored by a condition entailing imagery of a disgusting odor, while avoiding visible facial expression. LDV signals were shown to compare favorably with the simultaneous EMG, in disclosing signs of activation even at levels that were not sufficient to produce visible facial actions.

Index Terms— Laser Doppler Vibrometry, facial expression, muscle activity, remote monitoring;

I. INTRODUCTION

THE study of facial expression has a long and distinguished history, and remains the subject of intense research and development [1]. Facial expression is an important communication channel, generally held to convey emotion, pain, stress and social processes. Evaluation of facial expression continues to expand and extend to multiple issues--in scientific research involving the study of expression and coding of affect, and in widely diverse applications including

marketing, credibility assessment, affective computing, facial animation and characterization of psychiatric and neurological disorders [2]–[4].

The data presented in this report demonstrate the feasibility of measuring activity directly from the responsible muscles during facial expression, on a non-contact basis using the method of Laser Doppler Vibrometry (LDV). The focus is on the sensitivity of the LDV measures, within context of the companion electromyogram (EMG) signal and coding of the video records by trained coders. The critical finding is that LDV facial muscle activity can be directly sensed, even at levels of facial action that are too low to be detected by human coders. The LDV measures are competitive with the EMG in terms of sensitivity.

Conventionally, there have been two general approaches to the study of facial expression, one image-based [5], and the second involving direct measurement of the EMG signals from the involved facial musculature [6]. The most detailed and widely accepted approach to coding facial expressions based on the visual appearance is the Facial Action Coding System (FACS)[7]. FACS coding involves the careful analysis by trained human coders, for identifying elemental facial action units (AUs) and their associated laterality, strength, temporal properties and co-occurrence with other AUs. Conventionally coded AUs include 9 from the upper face and 18 from the lower face. These AUs have a well-defined anatomical basis. Also coded are AUs related to head positions and movements, eye positions and movements, and several related to gross behaviors and actions. Visibility codes are used to describe the strength of the AU. The relationship of these AUs in terms of their relationship with basic emotions continues as a controversial topic which has attracted considerable research attention.

Because of the labor intensiveness, impracticality of real-time access, and rigorous training involved in conventional FACS coding, there are now extensive efforts at automating the coding using computerized image processing and machine learning methods, e.g. [8-12]. Such methods typically use

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manually coded images for training purposes, and to guide the dimensionality of the computerized coding. Recent developments include the incorporation of 3D [13] and thermographic [3] information, with increasing emphasis on fluid temporal properties as well as making the methods robust in the face of variations in face shape, pose, and lighting [2], [14]. Automated coding has been the subject of a series of “Grand Challenges” utilizing standardized databases of facial videos under various expression induction conditions [15]. The competence of these automated systems is evident, for example, in situations involving hybrid affective response and compound simultaneous AUs [16], and in the detection of activity that escapes conventional FACs coding [17].

The second general approach to studying facial expression involves the direct measurement of the activity of the underlying muscles, using the EMG technique [18]. As considered in greater detail below, EMG measurement offers in principle a number of distinct advantages in terms of such factors as sensitivity, temporal course, objectivity and spatial discreteness. In practice, however, there are well-recognized limitations to the EMG method. These involve the encumbrance associated with the attachment and wearing of the EMG electrodes and leads, which produces an inescapable awareness that would, in turn, almost certainly interfere with the natural expression of facial expression. The cosmetic disfiguration would also be generally unacceptable outside of the laboratory environment.

A. Laser Doppler Vibrometry (LDV): Principles and application to physiological recording

LDV is a mature method that is used extensively in industrial and manufacturing settings, for non-destructive testing of mechanical vibrations. It is based on detection of the Doppler shift in scattered light from the moving test surface, with respect to an internally-maintained reference standard. Inclusion of a Bragg cell allows for directional coding of the velocity signal. Noteworthy aspects of the method include its extreme sensitivity, capable of detecting displacements in the picometer range, broad bandwidth which typically extends from DC to at least 20-50 kHz, and working distances that can extend to hundreds of meters using long range systems [19]. Commercial, off the shelf instruments are available that use eye safe lasers, including newer systems using infrared lasers that are classified as completely eye and skin safe (Type I by accepted standards [20], wavelength 1550 nm, power < 10 mW) [21]. Various configured systems include a fixed spot laser, as well as scanning systems in which the beam position is controlled by dual galvanometer mirrors, are automatically focused using feed-back and feed-forward approaches, as well as optics ranging from confocal microscopy to long range. The spot size is a function of a number of factors including offset distance as well as the laser and optics used in the system, but for typical interior working distances is well under 1 mm. For the Polytec PSV-300 instrument used in the experiment described here, the nominal specifications (provided by the manufacturer) for spot size is < 40 μm , the velocity resolution is 0.3 $\mu\text{m/s}$, and signal bandwidth is DC to 50 kHz. See [22] for a review of the general principles and applications of the LDV technology.

The application to human physiology is based on the fact that most physiological activity, particularly at a system level, includes a mechanical component. The energy from the internal vibrations, sounds, pulsations and movements is transmitted to the surface of the skin where it can be sensed using a variety of techniques. In research and clinical applications these techniques often include the stethoscope, microphones, accelerometers, piezo-electric sensors and other transducers as well as palpation. The application of LDV for this purpose has a number of advantages, insofar as it entails no mass loading on the surface of the skin, and is free from resonance, bandwidth limitations, electrical interference and other common sources of error. A principal advantage is that the LDV method is noncontact and can be applied at extended distances, thus completely avoiding the need for application of conventional sensors.

We and others have demonstrated the effectiveness of the LDV method for measuring a range of mechanophysiological activity, especially cardiorespiratory activity in which case a number of advanced measures related to cardiac and vascular function are supported [23-27].

B. LDV measurement of muscle activity

Here we describe a general method for measuring directly from the underlying facial musculature, based on the LDV technique. This application does not involve contact with the skin, or, necessarily, any obtrusiveness associated with the awareness of the measurement method.

The basis for LDV measurement of muscle activity lies in the inherent vibratory nature of muscle contraction. There is a detailed scientific and clinical literature relating to muscle vibrations, which we have reviewed elsewhere with specific reference to LDV-based studies [28]. Several candidate contributions to the muscle vibrational signal have been identified, but a major one appears to lie in the lateral expansion that is complementary to the longitudinal shortening during contraction. This expansion is an inherently vibratory process, associated with repetitive contractions of the engaged motor units, and can be detected at the level of the skin overlying the active muscle. We adopt here the nomenclature Mechanical Myogram (MMG) for the vibration signal. Conventionally the MMG is typically recorded with a range of mechanical transducers including accelerometers and microphones.

The LDV method utilized in the present study offers significant advantages. In comparison to conventional methods, it overcomes some of the inherent problems such as mass loading and resonance of conventional devices used to measure the MMG. Additional advantages, cited above, include the extreme sensitivity and the ability to obtain the measures on a non-contact basis, at distances up to at least several meters.

We have previously demonstrated in a series of studies that LDV-MMG signals can be reliably recorded in a range of muscles. A detailed study of a small hand muscle (first dorsal interosseous) demonstrated a close relationship with the strength of contraction [28], and this result has been confirmed in leg and arm muscles [29]-[31].

Of more direct relevance to the present report, we have also confirmed in a prior report that robust LDV-MMG signals can

be recorded from a range of facial muscles, from both upper (AU1: frontalis pars medialis; AU4: corrugator supercilii) and lower face (AU10: levator labii superioris; AU20: risorius; AU31: masseter) [32].

The conditions on which that prior report was based entailed only a single level of activation strength for each AU; there was no attempt to address the key questions on which the present report focuses, i.e., the sensitivity of the LDV-MMG measures in comparison to the contemporaneous video images and EMG signals, or the relationship between the LDV-MMG measures and strength of facial expression. The data described in our earlier report showed that the signals were present during contraction for each of the muscles studied but also disclosed substantial differences in amplitude among muscles—with the activity from the frontalis muscle (measured in terms of spectral power in the range of 30–50 Hz) about only 15%–20% that seen in the levator labii and risorius muscles. Detailed assessment of the onset and offset characteristics indicated that the LDV-MMG measures would be particularly useful in the study of brief “micro-expressions” and other temporal properties of facial actions.

The present experiment was focused specifically on the issue of the relationship between the LDV-MMG and strength of the facial muscle contraction. For this purpose, we selected AU10 for detailed analysis. AU10 is produced by contraction of the levator labii superioris muscle, and when expressed strongly involves lifting the upper lip. Recent findings confirm earlier evidence in showing that AU10 is associated with emotions involving disgust [16] (or, in combination with other AUs especially those involving the upper face, pain [33]). After a period of training, research participants were led through a graded induction procedure, in several steps from resting to full expression of AU10. This sequence included a low-level condition involving only the imagery of a disgusting odor, with admonishment to avoid observable facial deformation. The LDV-MMG signals were compared to the simultaneous EMG signals, and to the gold standard measures of facial expression provided by trained FACS coders of both video and static images.

II. METHODS

A. Participants

Data used in this analysis were obtained from 11 adult participants within the age range of 20–28 years (6 female). Exclusionary criteria included body mass index > 25; facial hair, piercing or severe acne that would interfere with any of the measurement procedures; history of psychiatric illness; and any illness, use of medication or cosmetic procedure that would interfere with normal neuromuscular function. The experimental condition described here was part of a larger experiment involving the study of multiple upper and lower facial muscles, as described above [32]. All participants provided informed consent (including specific consent to reproduce images containing the face) using a protocol approved by the Washington University School of Medicine.

B. Facial posing

AU10 was selected for detailed study, under conditions of graded induction. AU10 involves contracting the levator labii superioris muscle, immediately lateral to the nose, producing a lifting and angular bend in the upper lip. The action widens and raises the nostril wings, and when strongly expressed parts the lips to expose the teeth [1].

Participants received 15 to 20 min of training in producing AU10 (and other AUs involved in the separate conditions). Training followed the methods and guidelines described in the Facial Action Coding System (FACS) manuals [1]. Training included detailed instruction and supervised production, assisted by videos and still photos drawn from the FACS manuals, and with an opportunity to practice in front of a mirror. Participants were encouraged to produce the facial actions symmetrically with an emphasis on avoiding co-contraction of other muscles—especially the common linkages cited in the FACS manuals, including AU9 (nose wrinkle) and AU17 (chin lift).

During the graded AU10 sequence, participants responded to a series of verbal instructions, consisting of the pre-recorded spoken digits, “0” through “5”. The actions cued by these digits were as follows:

“0” = neutral (resting, no tension).

“1” = think of a disgusting odor, but be careful to avoid any tension in facial muscles.

“2” = induce low level of tension, not sufficient to produce visible deformation of face.

“3” = minimal level of tension, sufficient to produce barely visible expression of AU10.

“4” = sufficient tension to produce readily identifiable expression of AU10.

“5” = maximal expression of AU10, with upper teeth exposed.

The spoken digits were presented in ascending order. Participants were instructed to hold the gesture at the indicated level, then increment as signaled. The cadence was established on the basis of pilot testing; the “0” and “1” levels were held for 3 s, “2” for 2.5 s, and “3,” “4,” and “5” for 2 s each, after which the prerecorded instruction “relax” was given. The series was repeated twice (separated by a 3 s rest period), and was preceded by two full productions of AU10 at level “5” (for two s each, with a 3 s rest period before start of the ascending series). These full production expressions were cued by the digit “5” and “relax.” A continuous video record of the posing sequence was obtained at a rate of 30 fps, from a vantage immediately in front of the participant. All data analyses described below are based on the final 1.5 s segments of the individual posing stages.

C. Physiological measurement methods

Physiological data were acquired using a Biopac MP150 system, with the EMG and LDV data integrated into a common file with a 1 kHz sampling rate. Data were obtained from the left side of the face. Figure 1 shows the signal acquisition and processing methods, as described in the following paragraphs.

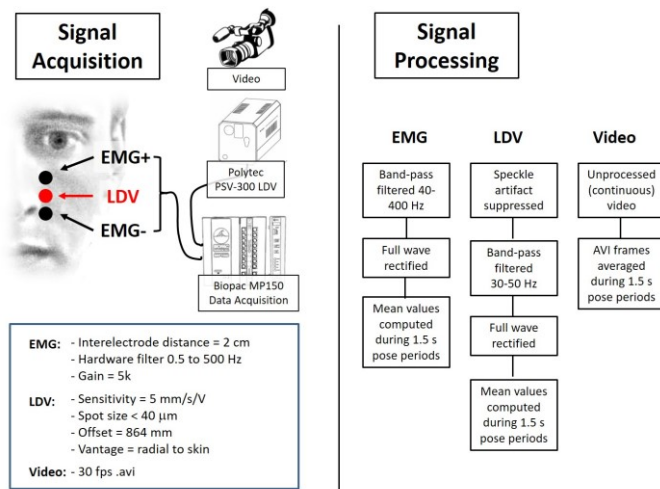


Fig. 1. Signal acquisition and processing methods.

D. EMG measurement

EMG was recorded using shielded 4 mm Ag/AgCl electrodes affixed with double-sided tape collars, from a bipolar pair with inter-electrode spacing of 2 cm. Sites were prepared by cleaning with alcohol and abrading with a sterile lancet. Signals were amplified with a gain of 5k, with a hardware high pass filter of 0.5 Hz and a low pass filter of 500 Hz. The electrode pair was oriented vertically, approximately 1 cm lateral to the wing of the nose, over the course of the levator labii superioris muscle. A ground electrode was affixed to the mid-forehead.

E. Laser Doppler Vibrometry (LDV) measurement

LDV data were obtained using a Polytec PSV-300 scanning vibrometer system (OFV-505 sensor head and OFV 3001 controller). This instrument utilizes a 633 nm laser beam, which at an output power < 1 mW classifies it as an “eye safe” laser (Class 2 by international standards). Data were obtained with the beam direction approximately radial to the target skin site, from an offset of 826 mm (corresponding with a laser beam coherence node), with a sensitivity of 5 mm/s/V and an anti-aliasing filter at 500 Hz. Prior to measuring, the reflectivity of the skin was enhanced by treating it with a compound of 80 μm glass retroreflective beads mixed in suspension with mineral oil, with additional beads applied to the surface using a cosmetics brush. The retroreflective bead treatment was applied with the aim of decreasing the incidence of speckle-related artifact, while avoiding any appreciable surface loading or areal summation of the signal that might be associated with use of retroreflective tape. The beam was targeted at a site midway between the EMG electrodes overlying the principally engaged muscle. Although we used retroreflective treatment in this study, we have since found it not necessary to pretreat, and can refer to empirical findings confirming that high quality LDV signals can be obtained from untreated skin [34]. To the extent that there is an appreciable loss of signal quality, it is manifest in the increase of speckle dropout artifact—an artifact that can

be successfully controlled using the nonlinear suppression methods we have developed for that purpose (see below).

F. Preprocessing of LDV signal

Prior to specific analyses described below, the LDV signal was processed to suppress speckle dropout artifacts [35], [36], which are present especially when measuring from non-cooperative surfaces such as the skin that have high micro-roughness, as well as a relatively low reflectivity and lack of translational stability. Even with treatment of the skin with the retroreflective glass beads, speckle dropout artifacts were not completely eliminated. The speckle artifact is manifest in the LDV signal in the form of aperiodic large amplitude high frequency events in the waveform, typically affecting single sample points. The artifact was suppressed using a non-linear method that was designed to minimize the suppression of genuine higher frequency aspects of the signal. Speckle-affected data points were defined in terms of the abrupt (and aphysiological) transition points in the waveform, as identified in the thresholded second derivative of the original velocity signal. These points were then removed from the waveform, and the missing points were resampled using linear interpolation. In general, the speckle artifact affected less than 1% of all points after skin treatment with glass beads.

G. LDV-MMG, EMG and video data analyses

The physiological signal processing methods, and the underlying rationales, are described in detail in a prior report [32]. In brief, the LDV myographic data were band pass filtered (using a filter of finite impulse design) within the pass band of 30-50 Hz. This filter was empirically selected, to suppress a variety of activities included in the raw signal that were considered artefactual for this purpose, insofar as their origins were not intramuscular. These included gross surface deformation during contraction, physiological tremor [37], [38] a readily visible ballistocardiac signal, and nonspecific, adventitious movement of the body and face. The filtered signal was full-wave rectified, the mean values were computed over each 1.5 s epoch, and the values for the two repetitions were averaged. EMG data were similarly processed, over a band of 40 to 400 Hz.

H. FACS coding of facial images

The video records of the facial images were scored using two methods, both performed by trained FACS coders (co-author MGF and a trained staff member in his laboratory). One method involved review of the video records, accompanied by the audio record of the spoken pose instructions (with options for pausing, reversing, and slow motion playback). In accord with prior evidence that the inter-coder reliability for AU10 is high [39], there were only a few instances in which the two scorers were required to form a consensus judgment.

Still images during the posing sequence were derived from the video record, in terms of averaged .avi frames over the identical 1.5 s segments (also averaged over replicate poses) that were used to analyze the LDV MMG and EMG data. The averaging process produced some discernible blur in the images from several participants, but they were judged nevertheless to

be of sufficient quality to support formal coding of the AUs using the criteria described in the FACS manuals.

III. RESULTS

A. Facial Images

An example of the facial poses (based on the averaged .avi frames, combining the two 1.5 s periods) from a single participant is shown in Figure 2. The position of the illuminated laser target is clearly seen, as are the EMG electrodes. As is true in the majority of participants, little if any evidence of AU10 production is evident under the low-level response conditions (“0” though “2” or “3”).

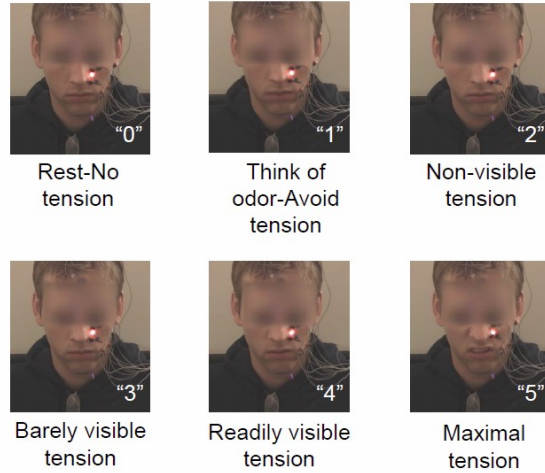


Fig. 2. Facial images from a representative participant under the six instructed tension poses (averaged over video .avi frames during last 1.5 s of each pose, and averaged over the two replications).

Scoring of the original unedited video records found no evidence for AU10 production for any participant during the “0” (resting) or “1” (disgusting thought) levels, and inconsistent appearance for five participants during level 2—with AU10 visible in only one of the two sequences. Eight of the participants showed evidence of AU10 for at least one sequence during level “3” (“produce minimally visible expression”) and the AU10 was detected in all participants and sequences for levels “4” and “5”. The video scoring results are summarized in Figure 3, and Figure 4.

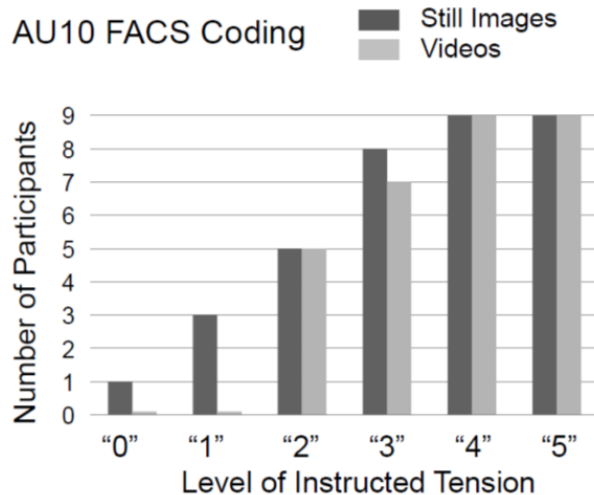


Fig. 3. Summary of FACS coding of AU10 under the graded induction conditions, based on both video and still image sequences, showing the number of participants (out of 9) who showed evidence of AU10 in at least one of the two posing segments.

		Instructed AU10 Production Level					
		“0”	“1”	“2”	“3”	“4”	“5”
Participant	05	Sequence 1				10C 12A	10D 12B
	05	Sequence 2				10B 12B	10C 12C
	06	Sequence 1		10A	10A	10C	10D
	06	Sequence 2			10A 38A	10B	10C
	07	Sequence 1				10B	10D
	07	Sequence 2				10B	10D
	08	Sequence 1		38A		10B	10C
	08	Sequence 2			10A	10B	10C
	09	Sequence 1			10B 38A	10B 38A	10C 38A
	09	Sequence 2		38A	10B 38A	10B 38A	10C 38A
	10	Sequence 1			10A	10B	10C 26A
	10	Sequence 2		10A	10B	10B 26A	10C
	11	Sequence 1		10A	10B	10B 26A	10C
	11	Sequence 2			10B	10B	10C
	12	Sequence 1				10A 23B, 38B	10B 23B, 38B
	12	Sequence 2			23A, 38A	10B 23B, 38B	10C 23B, 38B

Fig. 4. FACS coding of the unedited video sequences associated with the graded production of AU10. Instances of AU10 are highlighted in Bold (large font), and co-occurring extraneous AUs are indicated in the smaller italicized font.

The second scoring method used the static images associated with the graded AU10 production, based on averaged .avi frames during the associated terminal 1.5 s periods of each posing segment. A summary is shown in Figure 3, and detailed findings in Figure 5. In agreement with the video-based scoring, all of the participants succeeding in producing scorable AU10s, with intensities of at least 10C under the maximal contraction condition (“5”). This analysis detected a higher co-occurrence of other AUs, particularly under the more forceful expressions. The most commonly occurring included AU38 (nostril dilator), and actions reflecting non-AU10 associated movements of the lip (AU25, AU23, AU15). The important aspect in this coding, as in that based on the videos, was the relatively low incidence of observable AU10 activity at the instructed low levels of force production. Only two participants showed an increase in AU10 from level “0” (resting) to level “1” (disgusting thought), and only four showed a detectable increase from level “1” to level “2” (minimal tension but no observable deformation of face). The incidence and/or strength of AU10 progressively increased, with six participants showing an increase from level “2” to “3,” eight an increase from “3” to “4,” and nine from “4” to “5.”

		Instructed AU10 Production Level					
		"0"	"1"	"2"	"3"	"4"	"5"
Participant	05	10A 38A	10A 7A, 38A	10B 7B, 25A, 38B	10B 7A, 25A, 38B	10C 7A, 12B, 25B, 38C	10C 7A, 12C, 25C, 38C
	06	15A, 64	15A, 64	15A, 64	10A 25A, 38A, 64	10B 15A, 25B, 64	10D 25C, 38B, 64
	07	15A	10A 15A	10A 15A, 38A	10A 38B	10B 7A, 25A, 38B	10C , 4A, 7B, 18A, 25C, 38C
	08	25A	25A	25A	10A 25A, 38A	10B 25B, 38B	10C 9A, 25C, 38B
	09	38A	38A	10A 38B	10B 25A, 38B	10B 25A, 38B	10C 4A, 9A, 25C, 38B
	10	12A	(none)	(none)	10B	10C 7A, 25A	10C 7B, 25B
	11	(none)	(none)	10B 15A, 38A	10C 7B, 15A, 38B	10C 7B, 15A, 25B, 38B	10D 4A, 7C, 16B, 25C, 38B
	12	14A	14A, 23A	14A, 23A, 38A	14A, 23B, 38A	10B 14B, 23B, 25A, 38C	10C 12A, 14B, 23B, 25B, 38D
	13	(none)	10A 38B	10B 38B	10B 25A, 38B	10B 25A, 38B	10C 25B, 38B
	14	(none)	(none)	(none)	10B 7A, 38A	10B 7B, 9B, 25A	10C 4B, 7C, 9B, 25B
	15	26A	(none)	4B, 7D	10A 4B, 7D,	10B 7C, 9A, 25A	10C 4B, 7D, 9B, 25B

Fig. 5. Facial Action coding of the averaged .avi frame sequences (static images) associated with the graded production of AU10. Instances of AU10 are highlighted in Bold (large font), and co-occurring extraneous AUs are indicated in the smaller italicized font.

B. LDV-MMG and EMG

Shown in Figure 6 are illustrative waveforms, for the participant whose facial images are shown in Figure 2.

The moments marking the instructions to contract at the various levels are indicated in the shaded rectangles along the bottom. The top trace is the original LDV waveform, in which the speckle artifacts are suppressed as described above but which is otherwise unprocessed. As noted above, the waveform is complex, arising from multiple sources including surface displacement during contraction, adventitious movement, tremor and ballistocardiac impulses. A clearer depiction of the intramuscular contribution is apparent in the LDV-MMG waveform shown in the center trace, in which the original LDV signal has been digitally filtered with a pass-band of 30-50 Hz. The corresponding filtered EMG signal is shown in the bottom trace. The broad general agreement between the LDV-MMG

and EMG signals is evident.

The critical test in this condition involved the sensitivity of the corresponding LDV-MMG data, in comparison to the image-based scoring methods and the simultaneous EMG. These data are presented in Figure 7, which shows the mean (and standard errors) of the LDV-MMG and EMG data obtained during the graded AU10 induction procedure (and following relaxation period). Both functions show highly-significant increases in amplitude—even at the very lowest non-resting level (“1”—“disgusting thought”) for which 10 of 11 participants showed an increase in LDV-MMG amplitude with respect to the “0” (resting) level. This can be compared with an increase in 9 of 11 participants for the EMG amplitude, 0 participants for the video-based scoring, and 2 of 11 participants for the static image-based scoring. The amplitude of both LDV-MMG and EMG signal increases progressively at higher levels, with the mean LDV values rising from 0.2 mm/s while resting (force level “0”) to 17 mm/s at the highest force level (“5”). However, the LDV-MMG and EMG functions differ, with the LDV-MMG approaching an asymptote at level “4” in contrast to the EMG amplitude which rises sharply between levels “4” and “5”.

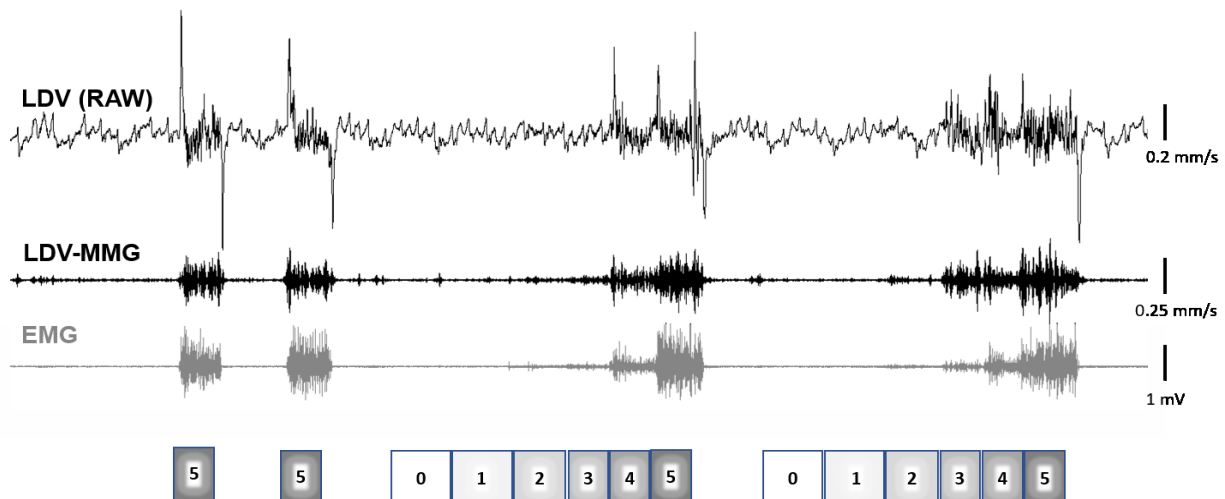


Fig. 6. Unprocessed LDV signal, LDV-MMG signal, and EMG signals for a representative participant (7) over the full 54 s course of the measurement period. The times of instructed contraction, and associated strength, are indicated along the bottom.

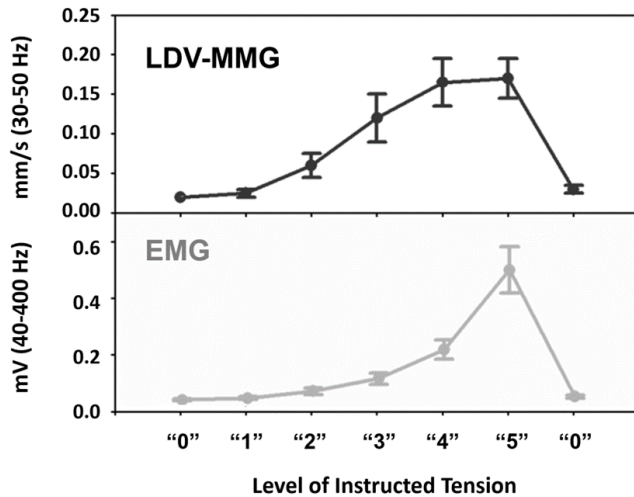


Fig. 7. LDV-MMG and EMG amplitudes (means and standard errors) as a function of instructed level of AU10 production.

IV. DISCUSSION

These data demonstrate the sensitivity of the LDV-MMG signal recorded from a facial muscle during the graded production of the AU10 facial action. The LDV-MMG signal compared favorably with the EMG signal, and was detected even when participants were instructed simply to image a situation (disgusting odor) in which AU10 might be activated. The LDV-MMG activation could be detected in the absence of consistent or reliable visible movement of the facial surface, as coded using formal FACS criteria by trained coders. It can be noted that the target gesture and activation sequence were known in advance to the coders, so they were unlikely to have overlooked any evidence of visible movement and if anything were likely biased toward detecting AU10 movement.

In general, AU10 is a robust movement that is readily identified in conventional FACS coding. A detailed study of FACS reliability determined that AU10 showed excellent inter-coder agreement in terms of detection as well as coding of trace movement and action strength [39]. That study was based on spontaneous movements; it can be anticipated that even higher sensitivity and reliability would be observed with posed facial action as was the case in this experiment [8].

Although the LDV-MMG and EMG signals performed about equally well with respect to the ability to detect small levels of tension, the forms of the function relating to gesture strength were different at high levels. Whereas the EMG continued to increase progressively at high levels, the LDV-MMG signal approached an asymptote at an intermediate level of force production. Contraction force is gained over low to moderate levels by recruitment of additional motor units, which increases the magnitude of the associated vibration signal. At some intermediate level, the available units have been recruited, and the strategy changes to increased firing rates of individual units, leading to a mechanical fusion of the vibration signal and accompanying asymptote or downturn in MMG signal strength. The level at which this inflection point appears is a function of the muscle fiber composition [40], [41]. Even though there may

be some ambiguity between LDV-MMG signal strength and contractile force at high levels, this would not compromise the sensitivity of the LDV method for detecting and quantifying facial muscle actions at lower and more subtle levels of expression.

Although the performance of computerized image processing-based systems continues dramatically to improve, the direct measurement of intramuscular activity likely will continue to be of complementary value. There is now a sizeable literature relating to facial EMG in the study of facial expressions as well as neuromuscular disease. EMG methods have proven useful not only in study of affective valence, but also the measurement of specific facial muscle actions that are involved in the expression and appreciation of affect (e.g. [42-45]). Multiple advantages of the EMG method have been cited, including sensitivity, ability to identify focal sources, objectivity, high-resolution quantitative nature, resistance to such factors as pose and lighting conditions, and precision of timing measures. Tassinari and Cacioppo [46], for example, note that "Although muscle activation must occur if these facial actions are to be achieved, muscle action potentials in the face can occur in the absence of any overt facial activation if the activation of the muscles is weak or very transient or if the overt response is aborted sufficiently early in the facial action." (p 28). To the extent to which the LDV-MMG can be considered a functional equivalent of the EMG, the EMG literature can be called upon to underscore the possible importance of the present findings.

The inherently non-contact nature of the LDV-MMG method would appear to confer significant benefits. As noted in the introduction, conventional EMG methods, while useful in the laboratory, are generally incompatible with the natural expression of emotion, and with the demands of field measurement situations. The precise timing measures provided by the LDV-MMG signal, as apparent in our earlier report [32], may be particularly advantageous in terms of the possible ability to expose brief microexpression-related responses, and the special character of dynamic expressions in terms of potency and recognizability [47]. It is also important to consider the fundamental differences in the biophysical bases of the EMG and LDV-MMG signals. Surface EMG intrinsically aggregates activity over some volume, defined not only by the diameter of the recording electrodes, but also the tissue intervening between bipolar pairs. The attempt to localize with greater focus the electromotive sources is an active area of research, based on high-density multi-electrode recording arrays and methods for analyzing the spatial distributions of the signals [48]. In contrast, the LDV method is intrinsically highly focal. The spot size in our recording conditions was $< 40 \mu\text{m}$. The illustrations in Figure 2 appear to show a larger spot size; however, this results from diffusion of the light in dermal layers and subdermal tissue, with local patterns of interference. The effective recording locus, from which the vibrations are recorded, is the $< 40 \mu\text{m}$ spot of initial laser contact. This is, of course, not to deny that there may well be in-plane conduction by volume of the vibration signal itself, aggregated over multiple underlying muscle zones.

It will be important to extend these findings, to multiple facial muscles and their associated AUs, using multiple induction procedures. The evocation procedure here was limited to a specific reference to the emotion of disgust. It is worth noting, however, that disgust itself is an important emotion in its own right, with the associated AUs signifying an orofacial aversion response [49], perhaps with an important disease avoidance communication component [50] and perhaps extending more broadly to moral issues [51]. The inclusion here of a condition entailing imagined exposure to a disgusting odor was consistent with evidence that imagery of a disgusting odor produces brain hemodynamic [52] and orofacial [53] responses that mirror those seen during actual exposure to an offending odor. The facial signs of disgust, as disclosed in the EMG, may be unique sources of information insofar as they can appear independently of autonomic signs or self-appraised strength of disgust reaction [43].

Several additional limitations can be identified in this research. One important limitation lies in the homogeneous sample of participants, in terms of such factors as age, health and body mass index. Prior studies in our laboratories involving large samples drawn representatively from the general community (ages across the adult life span) indicate that high quality LDV signals--focusing in those cases on cardiopulsatile activity in the neck--can be recorded from obese individuals [26, 27]. These observations would suggest that the subcutaneous fat tissue communicates the underlying mechanical vibrations with minimum effect on amplitude at the skin surface, although one might anticipate some loss of surface focalization. This is an important issue for additional research. Another issue is the confinement to a single AU and simplified induction procedures as noted above. A technical limitation lies in the use of the Class 2 laser which, although nominally "eye safe" by regulatory standards would nevertheless be inappropriate for measuring from peri-orbital muscles. Fortunately this is no longer an issue in future studies, given the recent availability of commercial Class 1 vibrometers (i.e., no concerns with eye or skin exposure) based on infrared lasers [54]. These infrared systems have the additional advantage of utilizing an invisible laser beam and thus being completely nonobtrusive. Also, we chose to pretreat the target facial skin sites with a retroreflective preparation, to increase the LDV signal quality. As noted earlier, our experience with recent advances in signal analysis and LDV systems including Class 1 systems confirm that this precaution is no longer required. With the introduction of multi-point and full-field techniques, it would be possible to sample more broadly and more densely from multiple facial regions, providing a much more comprehensive depiction of facial muscle activity.

In a broader context, we note that the focus here on non-contact measurement is in keeping with growing pressure for more flexible and broadly applicable measurement methods. The demands for non-contact measurement methods are amplified within the current pandemic crisis, which exposes the critical need for remote, long-term recoding methods that minimize the burden on the patient, as well as limiting exposure of medical personnel to infectious patients (see [55]). The

emphasis in this report on facial muscle activity is but one aspect of the extensive suite of clinically-relevant physiological signals, particularly cardio-respiratory activities, that can be recorded using the LDV method (as reviewed above). As such, the LDV method may well be poised for development as a useful clinical assessment method.

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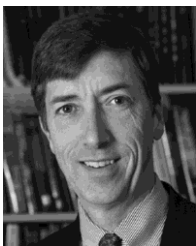
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