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Research article

Atlas of 3D face models of facial muscle activation during standardized mimic exercises and basic emotional expressions in healthy adults

Tim Büchner [a], Gerd Fabian Volk [b,c,d], Christian Dobel [b,c], Christoph Anders [e], Joachim Denzler [a,1], Orlando Guntinas-Lichius [b,c,d,*,1]

[a] Computer Vision Group, Friedrich Schiller University Jena, Jena, Germany
[b] Department of Otorhinolaryngology, Jena University Hospital, Friedrich-Schiller-University Jena, Jena, Germany
[c] Facial-Nerve-Center Jena, Jena University Hospital, Jena, Germany
[d] Center for Rare Diseases, Jena University Hospital, Jena, Germany
[e] Division Motor Research, Pathophysiology and Biomechanics, Department of Trauma, Hand and Reconstructive Surgery, Jena University Hospital, Friedrich-Schiller-University Jena, Jena, Germany

ABSTRACT

The face is three-dimensional (3D). Hence, also functional and emotional mimic muscle activation happens in 3D. Nevertheless, this is neglected in many studies as such activation is mostly presented visually in photos or videos and by intensity maps using electromyography (EMG) recordings in two dimensions (2D). Here, bilateral high-resolution facial surface electromyography (HR-sEMG) and 3D videos were recorded synchronously from 36 healthy participants (53% female, 18-67 years). Two different HR-sEMG recording schemes were used synchronously on the face, i.e., a muscle-position oriented electrode application scheme (Fridlund scheme) and a landmark-oriented, muscle unrelated symmetrical electrode arrangement scheme (Kuramoto scheme).The participants performed a standard set of different mimic movements and expressed the six basic emotions. For each participant, 3D face models were generated showing the EMG activity during each mimic movement and emotional expression. Hyperlinks to a 3D platform were provided allowing to freely rotate the 3D models for each facial functional and emotional expression. The 3D facial visualizations of the facial muscle activity during each facial expression task are presented on the 3D platform separately for the Fridlund scheme and the Kuramoto scheme. To generalize the results, the HR-sEMG data of all participants were averaged. 3D-morphable models and holographic views were generated to represent general models of this standard set of facial expressions in 3D. These holograms can be downloaded from an online repository. The presented atlas of holographic 3D models may help to understand the real facial expressions in 3D and the underlying facial muscle's activation as it is important for medical and psychosocial diagnostics and clinical studies.

1. Introduction

The human facial muscles have multiple functions. They form a complex interdependent system to produce three-dimensional (3D) changes in the superficial geometry of the face by interacting with the facial skin [1]. The facial motor system allows important physiological functions (for instance, eye closure), and especially emotional expressions as a cornerstone of non-verbal communication [2]. Hence, analyses of facial movements and facial muscle activation play a major role in psychophysical studies on human non-verbal communication [3]. These studies mostly rely on subjective or automated two-dimensional (2D) photo or video analyses and surface electromyography (sEMG) recordings of facial muscles, which interpret facial muscle activity in a 2D plane [4]. The presentation in 2D

* Corresponding author. Department of Otorhinolaryngology, Jena University Hospital, Am Klinikum 1, D-07747, Jena, Germany.
E-mail address: orlando.guntinas@med.uni-jena.de (O. Guntinas-Lichius).

[1] Shared last authorship.

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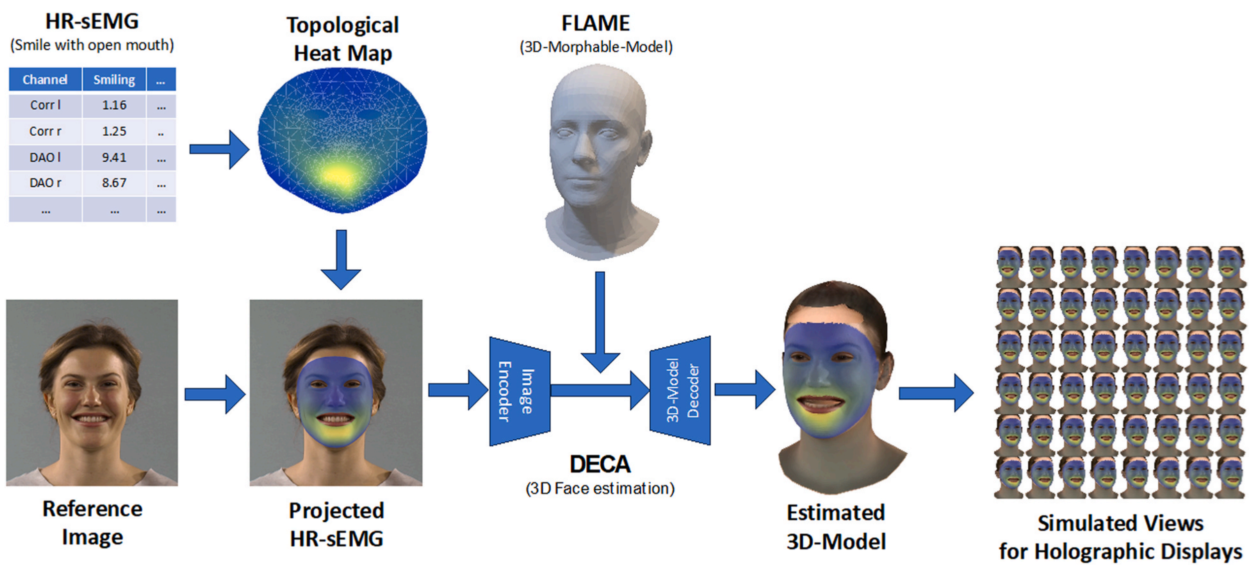

Fig. 1. Processing pipeline for artificial 3D models. High-resolution surface electromyography (HR-sEMG) activation heat maps are projected on 2D facial images. The Morphable-Model (3DMM) and the DECA model were used to fit the EMG activation onto generated FLAME 3DMM 3D facial models. Finally, holographic displays were applied to facilitate a realistic visualization of the 3D models.

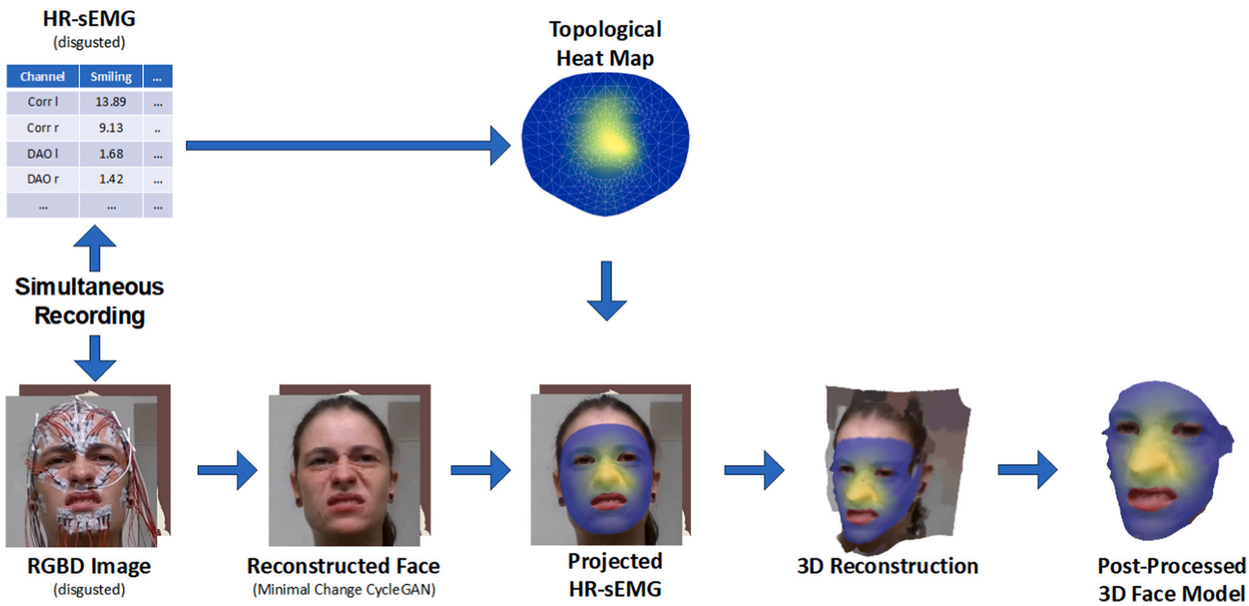

Fig. 2. Processing pipeline for real and individual 3D models. The recorded 3D video data and the simultaneously recorded high-resolution surface electromyography (HR-sEMG) data were used in combination with a Minimal Change CycleGANs approach to restore these critical facial features without inducing hallucinations. The original RGB frame of the 3D video was enriched by the projected topological individual heat map. A mesh representation of the point cloud using Poisson surface reconstruction was used for the 3D reconstructions. Finally, the same process to generate the 3D holograms was used as described in Fig. 1.

is of course a simplification or even a falsification of natural facial muscle activation. We hypothesize that the neglect of the third dimension oversimplifies the complex facial expressions and therefore may miss important parameters of functional facial movements and mimic expressions. The current standard in facial research to think in 2D may simplify the interpretation of emotional facial expressions too much and prevent the recognition of emotional subtleties that are only visible in 3D. Furthermore, facial reanimation surgery using muscle transfers in the face of patients with permanent facial paralysis has so far thought too much in terms of 2D instead of in 3D, which could explain the at best satisfactory functional results of facial muscle transfer so far.

Recently, we showed that bilateral high-resolution facial surface electromyography (HR-sEMG) allows a specific and

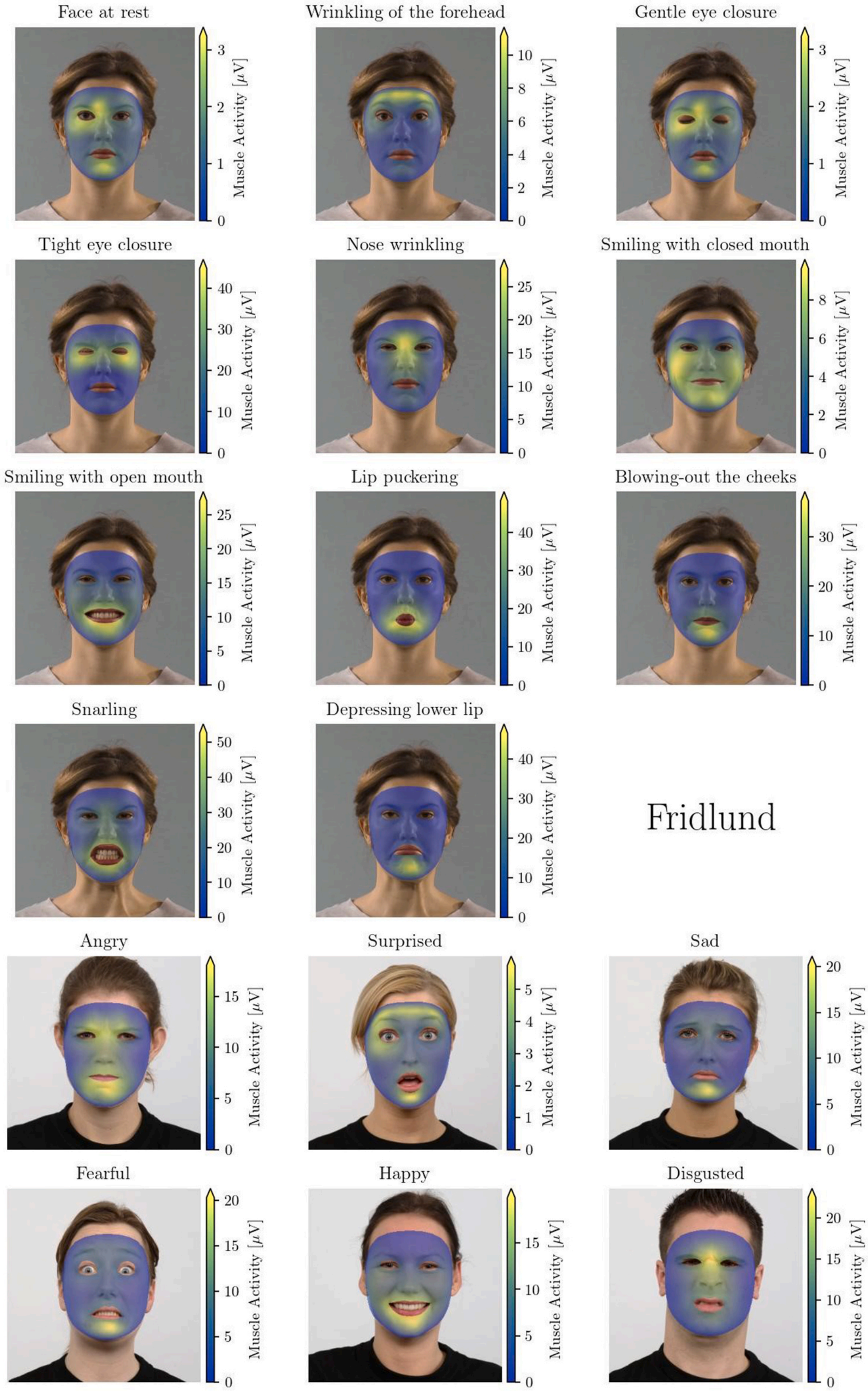

Fig. 3. 2D-visualization of the average facial surface EMG activity of all healthy participants with intensity maps using the Fridlund EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the average EMG amplitudes (muscle activity) in μV.

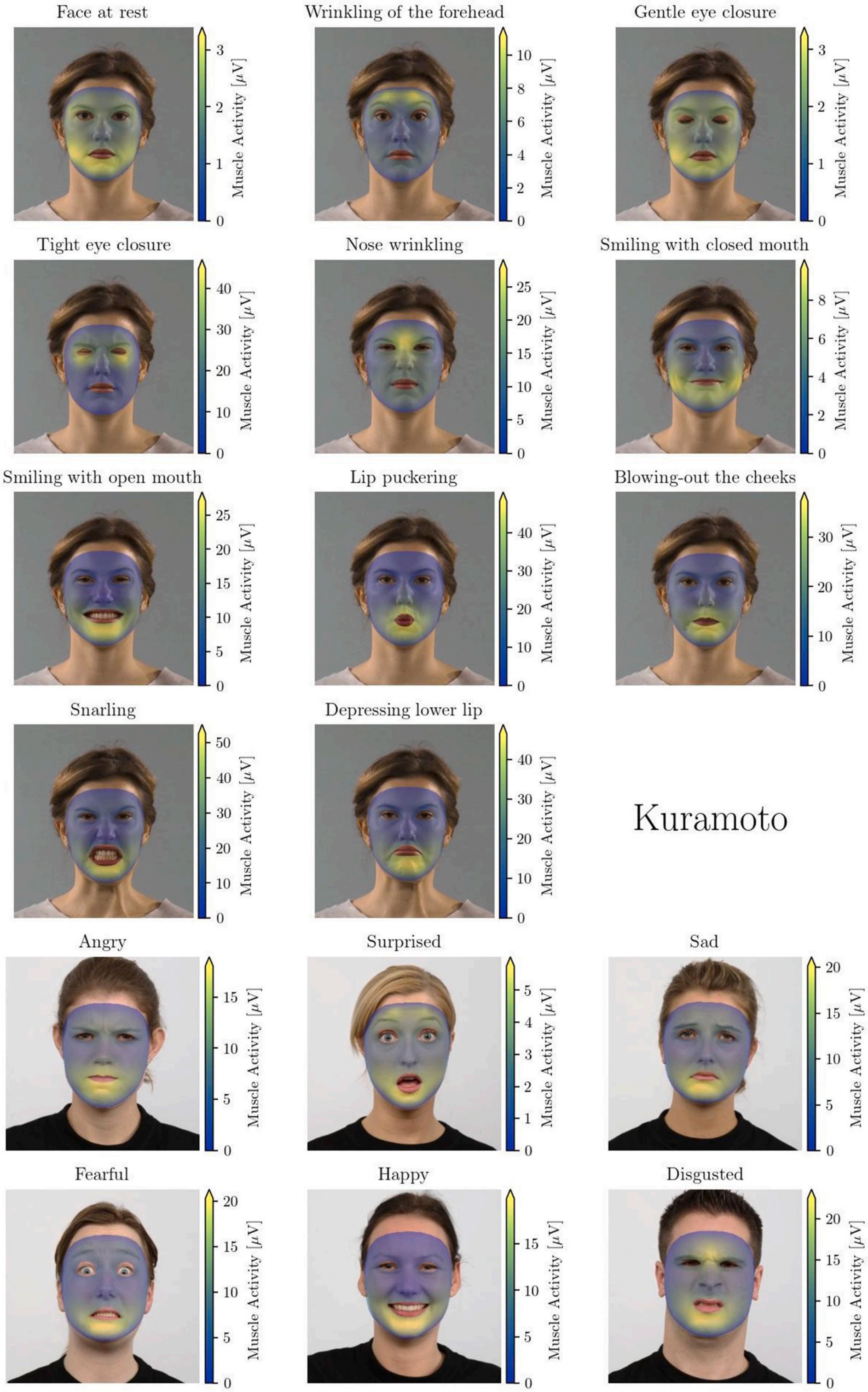

Fig. 4. 2D-visualization of the average facial surface EMG activity of all healthy participants with intensity maps using the Kuramoto EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the average EMG amplitudes (muscle activity) in μV.

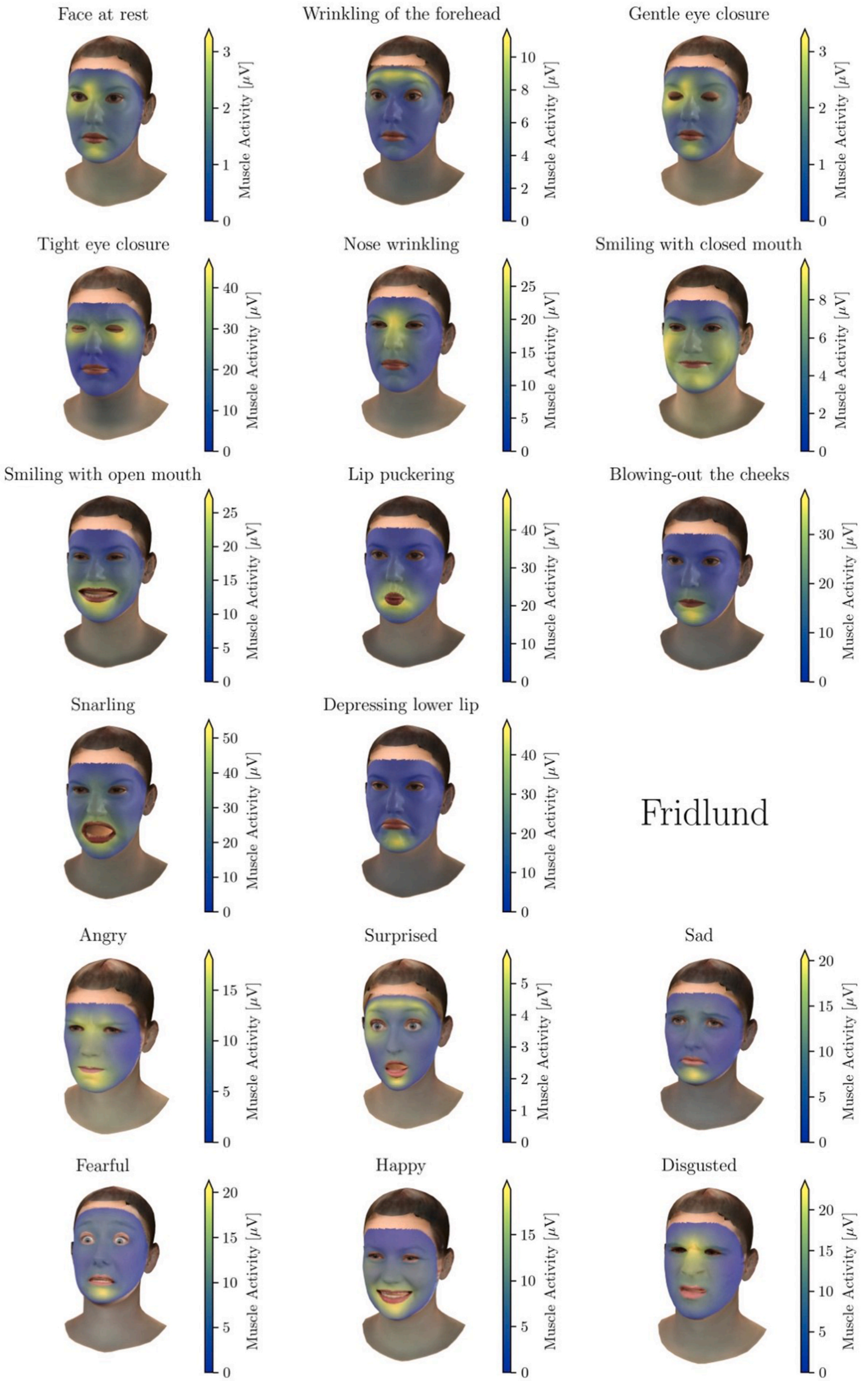

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Fig. 5. General 3D models of the average facial surface EMG activity of all healthy participants with intensity maps using the Fridlund EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the average EMG amplitudes (muscle activity) in μV.

discriminatory detection of facial muscle activity patterns during facial movement tasks as well as during the six basic emotions [5,6]. As a next step, we wanted to integrate these HR-sEMG data into 3D models of the face using 3D video synchronously captured during the HR-sEMG recordings. This, for the first time will allow a 3D visualization of the most important functional facial movements and also of the six basic emotions. The presented 3D atlas lays the foundation for future research into emotional expression in psychophysical experiments in 3D as well as the basis for future reconstructive facial surgery, which can reconstruct functional facial movements more naturally, namely in 3D.

2. Materials and methods

2.1. Healthy participants and performance of facial expressions

Data was used from previous studies. Nineteen (19) women and 17 men (age range: 18-67 years) were included. The participants were healthy, had no history of any neurological disease, or an active neurological disease as well as a history of facial surgery. Results of the functional mimic movements and emotional expressions were published recently [5,6].

The instructions for functional mimic movements and the emotional expressions presented by a video tutorial were explained. Details are presented elsewhere [6]. The participants performed a face at rest as baseline, and then 10 standardized mimic movements (frowning, gentle eye closure, forced eye closure, nose wrinkling, smiling with closed mouth, smiling with open mouth, lip puckering, blowing cheeks, snarling, depressing the lips). Each movement was performed three times. Subsequently, the participants imitated the six basic emotions (fear, surprise, joy, sadness, anger, disgust). Each emotion was presented four times.

2.2. High-resolution facial surface electromyography (HR-sEMG) registration

Bilateral high-resolution facial surface electromyography (HR-sEMG) was performed during all exercises. Details are presented in recent publications [5,6]. Briefly, two electrode arrangements were applied simultaneously: The classical scheme developed by Fridlund and Cacioppo (shortly named “Fridlund” in the following) [7] was used as well as the recently published scheme by Kuramoto et al. (shortly “Kuramoto”) [8]. To ensure reliable electrode positioning, the application of the two schemes was done by two well experienced examiners (NM and VT), adhering to a strictly defined application mode and with the additional use of template foils. EMG amplitudes were quantified as mean root mean square (RMS) values during the steady state contraction phases of every facial expression and EMG channel. The analysis therefore always started 1 s after the respective emotion appeared and was carried out for 1.5 s. To illustrate the topographic distribution of the EMG activity over the face for both schemes, topographical heat maps were calculated as in the previous study [5]. For a more detailed statistical analysis, including an examination of variability among the 36 participants, we refer to a previous study, where these results are presented in full [6].

2.3. Artificial 3D models and holograms based on 2D data

The workflow is summarized in Fig. 1. Recently we published a Python package tool (open-source Python package ‘electromyogram’; https://github.com/cvjena/electromyogram) to provide a convenient way to create EMG intensity plots designed for facial muscles. With this tool it is possible to visualize and analyze the intensity of EMG data collected from various facial muscles [9]. Using this tool, the topographical heat maps were projected onto 2D facial images, considering anatomical structures. This allowed an alignment of facial expressions with muscle activation patterns. The canonical face model presented by Kartynnik et al. was used to position the EMG electrodes at the corresponding anatomical muscle sites [10]. To reproduce the capturing capabilities of the EMG electrodes, radial basis function (RBF) interpolation was employed to fill in the spatial relationships of the detected muscle activity. All processing parameters can be found in Supplementary Table 1. Using this methodology, the generated topographical heat maps could then be projected onto any face. The transformed images are the basis for generating the estimated 3D models.

Since most 2D facial images lack depth information, monocular facial reconstruction techniques are used to generate a plausible 3D representation of the provided faces. By employing a 3D-Morphable-Model (3DMM) as a basis [11], the face could be decomposed the face into shape and expression parameters. The shape describes the person's individual characteristics, while the expressions are independent of the person. To approximate these parameters, we deployed the Detailed Expression Capture and Animation (DECA) model to use the FLAME 3DMM as the form of representation [12,13]. Additionally, the projected EMG topographical heat maps were mapped onto the facial regions of the generated 3D model.

Given recent advancements in holographic displays, the LookingGlass Portrait (Looking Glass Factory Inc., New York, U.S.) was applied to facilitate a realistic visualization of the 3D models. To generate the necessary viewing angles, the Visualization Toolkit (VTK; [14]) library was employed to load the models and compute 48 camera positions in front of the face, simulating an invariant viewing experience regardless of the viewing angle. Hyperlinks to the 3D platform Sketchfab (New York, United States) were used to allow a visualization of the 3D models. The 3D models can be freely rotated in space on the platform.

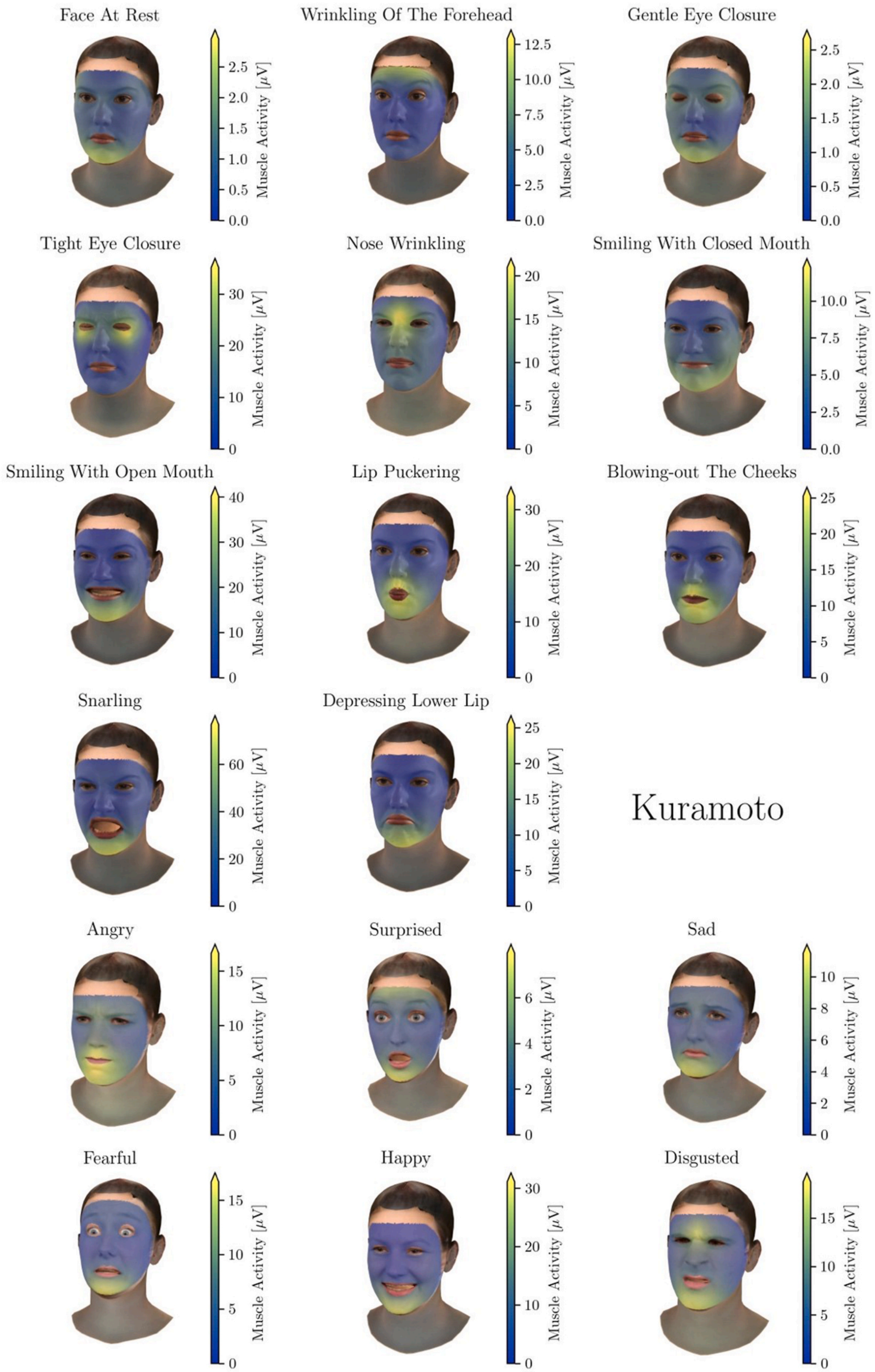

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Fig. 6. General 3D models of the average facial surface EMG activity of all healthy participants with intensity maps using the Kuramoto EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the average EMG amplitudes (muscle activity) in μV.

2.4. *Individual 3D models based on 3D videos*

All 36 participants were simultaneously recorded using both bilateral HR-sEMG and a stereo depth camera (Intel RealSense D435, Intel, California, U.S.). To integrate the topographical heat map into the 2D images, the facial features were obstructed by the surface EMG electrodes required restoration. The previously published Minimal Change CycleGANs approach was used to restore these critical facial features without inducing hallucinations [15]. In addition, the original red green blue (RGB) frame of the 3D video was substituted with a new frame containing the projected topological heat map. Recorded depth information and built-in camera parameters were used to compute the corresponding point cloud. This method accurately captured the 3D facial structure when comparing it to the 3D-Morphable-Model technique. Finally, we acquired a mesh representation of the point cloud using Poisson surface reconstruction [16]. All generated triangular faces with a greater distance between nose and chin were discarded [9]. Finally, the same process as described above was used to generate the 3D holograms. The complete workflow is shown in Fig. 2.

2.5. *Ethical approval*

All procedures involving the human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The ethics committee of the Jena University Hospital approved the study (No. 2019-1539). All participants gave written informed consent to participate in the study. Informed consent has also been obtained to publish the facial images in an online open-access publication.

Table 1
Overview about all 3D models and holograms for each facial functional and emotional expression with hyperlinks to the 3D platform and to the archive with the hologram data.

HR-sEMG Scheme	Task (Functional and Emotion)	Online View (Sketchfab)	Model Download	Hologram Download
Fridlund	Face at rest	View	figshare Download	figshare Download
	Wrinkling of the forehead	View		
	Gentle eye closure	View		
	Tight eye closure	View		
	Nose wrinkling	View		
	Smiling with closed mouth	View		
	Smiling with open mouth	View		
	Lip puckering	View		
	Blowing-out the cheeks	View		
	Snarling	View		
	Depressing lower lips	View		
	Angry	View		
	Surprised	View		
	Sad	View		
	Fearful	View		
	Happy	View		
	Disgusted	View		
Kuramoto	Face at rest	View	figshare Download	figshare Download
	Wrinkling of the forehead	View		
	Gentle eye closure	View		
	Tight eye closure	View		
	Nose wrinkling	View		
	Smiling with closed mouth	View		
	Smiling with open mouth	View		
	Lip puckering	View		
	Blowing-out the cheeks	View		
	Snarling	View		
	Depressing lower lips	View		
	Angry	View		
	Surprised	View		
	Sad	View		
	Fearful	View		
	Happy	View		
	Disgusted	View		

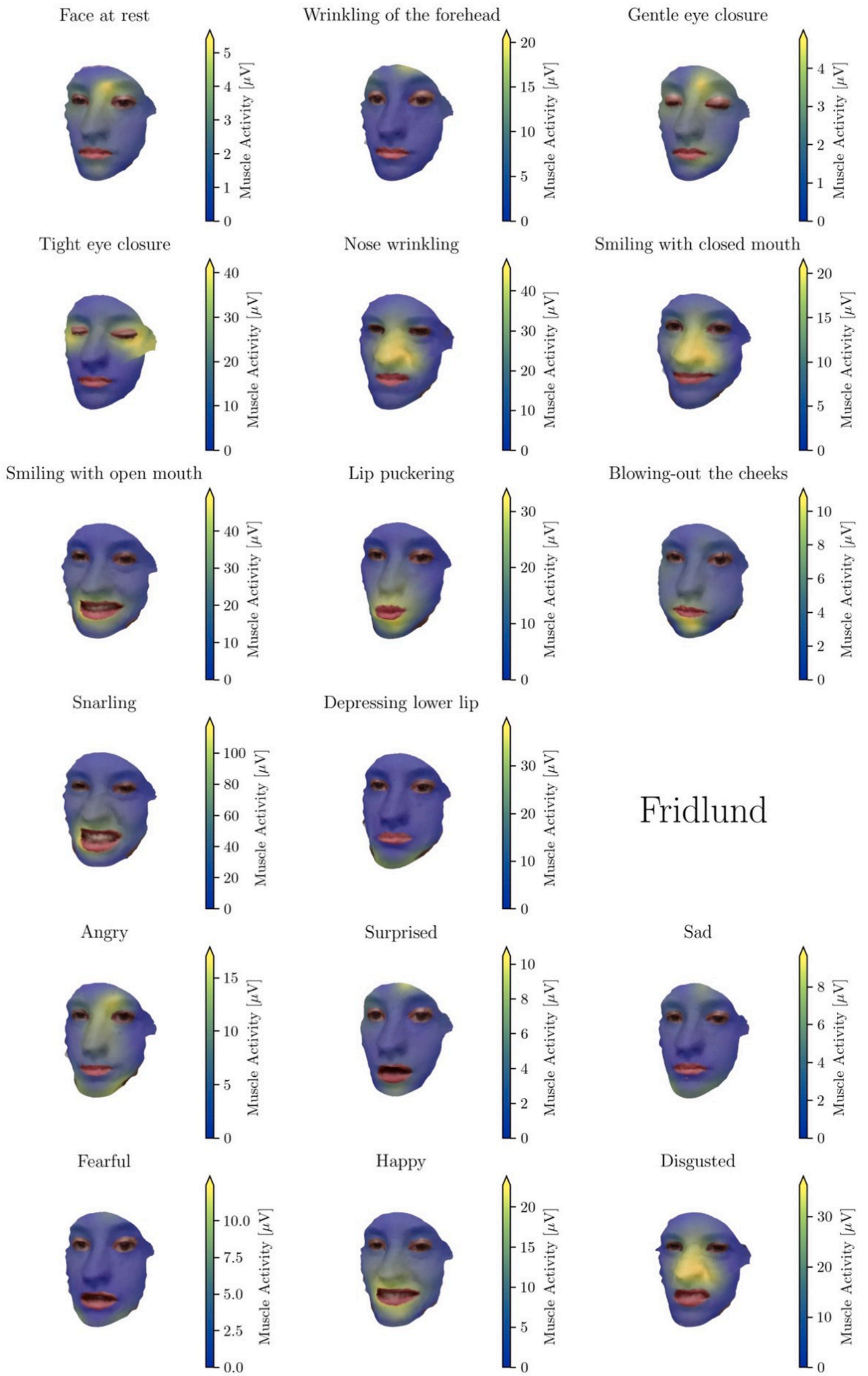

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Fig. 7. Example of an individual 3D model of one study participant based on the individual facial surface EMG activity of this participants with intensity maps using the Fridlund EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the individual EMG amplitudes (muscle activity) in μV of this participant.

3. Results

Artificial 3D models and holograms of the high-resolution facial surface electromyography (HR-sEMG) activation during functional and emotional expressions based on 2D data.

The average and distinct facial EMG activity in the different facial regions at rest, during 10 functional mimic expressions, and the six basic emotions projected onto 2D facial images are shown for the Fridlund EMG recording scheme in Fig. 3 and for the Kuramoto recording scheme in Fig. 4. The 3D-models of the average facial EMG activity during the different tasks are presented for the Fridlund EMG recording scheme in Fig. 5 and for the Kuramoto recording scheme in Fig. 6. Table 1 includes hyperlinks to a 3D platform. On the platform, the 3D models for each facial functional and emotional expression can be freely rotated in space. Furthermore, Supplementary Fig. S1 and Supplement Fig. S2 provide a comparison with conventional heatmaps showing that the new topological version allows for a more intuitive understanding of the relationship between muscle activity and face region.

Individual 3D models of high-resolution facial surface electromyography (HR-sEMG) activation during functional and emotional expressions based on 3D videos of individual persons.

The 3D videos were used to generate 3D model for each individual study participant. An example is shown for the Fridlund EMG recording scheme in Fig. 7 and for the Kuramoto recording scheme in Fig. 8.

4. Discussion

The face and mimic expressions have three dimensions. The facial muscles producing the expressions have three dimensions as well and hence also the facial muscle activity measured by EMG during specific functional and emotional expressions is three dimensional. Nevertheless, facial muscle expression is currently presented in psychosocial research and medical diagnostics mainly only in two dimensions [17] or in pseudo-3D projecting 2D data on 3D drawings [4]. Hence, mimic expression is not visualized correctly and neglects effects that can only be recognized by three dimensions.

Recently, we have shown that HR-sEMG is able to differentiate with high accuracy and reliability between the most important functional facial expressions and between the six basic emotions [5,6]. Furthermore, we could show that 3D video scans are able to quantify volumetric changes in the face during facial expressions [18]. Here, we brought both methods together to provide, with the help of machine learning tools, a first comprehensive 3D atlas. Furthermore, the holograms allow the viewer to observe the face from all spatial directions. The atlas included facial muscle activation recorded by the Fridlund scheme, as it is the best known EMG scheme for psychosocial experiments [7], but also for the newer Kuramoto scheme [8], which seems to be more reliable in settings with repeated measurements [5].

3D modelling of facial muscle function was so far restricted to 3D morphometric analysis in human cadavers for some the zygomatic muscles [19], or HR-sEMG projections of the lower face on a biomechanical face model [20]. Furthermore, 3D facial scans were used for analysis of morphometric changes of the facial skin surface during smiling [21,22], in patients with facial paralysis [23], before and after botulinum toxin treatment in the periorbital area [24], but always without the inclusion of muscle activation data. Mostly, facial markers were needed to characterize the facial surface in 3D videos [25]. Like in the present study, Özsoy et al. combined EMG measurements with 3D video scans, but not simultaneously, with the need of facial markers, and restricted to the zygomatic muscle [26].

The present study has some limitations. For the averaged results among the 36 participants, where no depth information was available, we relied on monocular 3D face reconstruction algorithms for visualization purposes only. However, we acknowledge that this approach may introduce inaccuracies, as the reconstruction is an ill-posed problem [11]. Furthermore, the disentanglement of shape and expression components relied on the underlying 3D morphable model, which can lead to ambiguous predictions [28]. Nevertheless, for our visualization purposes, these limitations should not significantly impact the results. Furthermore, the number of cases as basis for the 3D modeling was currently small and needs to be increased in order to be able to investigate the effects of gender, age and cultural diversity on muscle activation.

This first 3D atlas should help to design more realistic facial EMG experiments for teaching, clinical trials, psychological experiments, speech therapy and planning of facial reconstruction surgery for improved rehabilitation of specific facial functions. Compared to the previous heatmap visualization, the new 3D approach enables a more intuitive understanding of electrode positions representing muscle activity and facial regions. For the next step, we would like to expand the approach to 4D, i.e. to visualize specific 3D facial muscle activation over time (as fourth dimension) from the onset to the end of the mimic expression. Such an approach would highlight the complexity of the dynamic interwoven network of facial muscles during dynamic movements. Furthermore, the approach will be used in patients with facial palsy for a first 3D classification of the severity of the palsy.

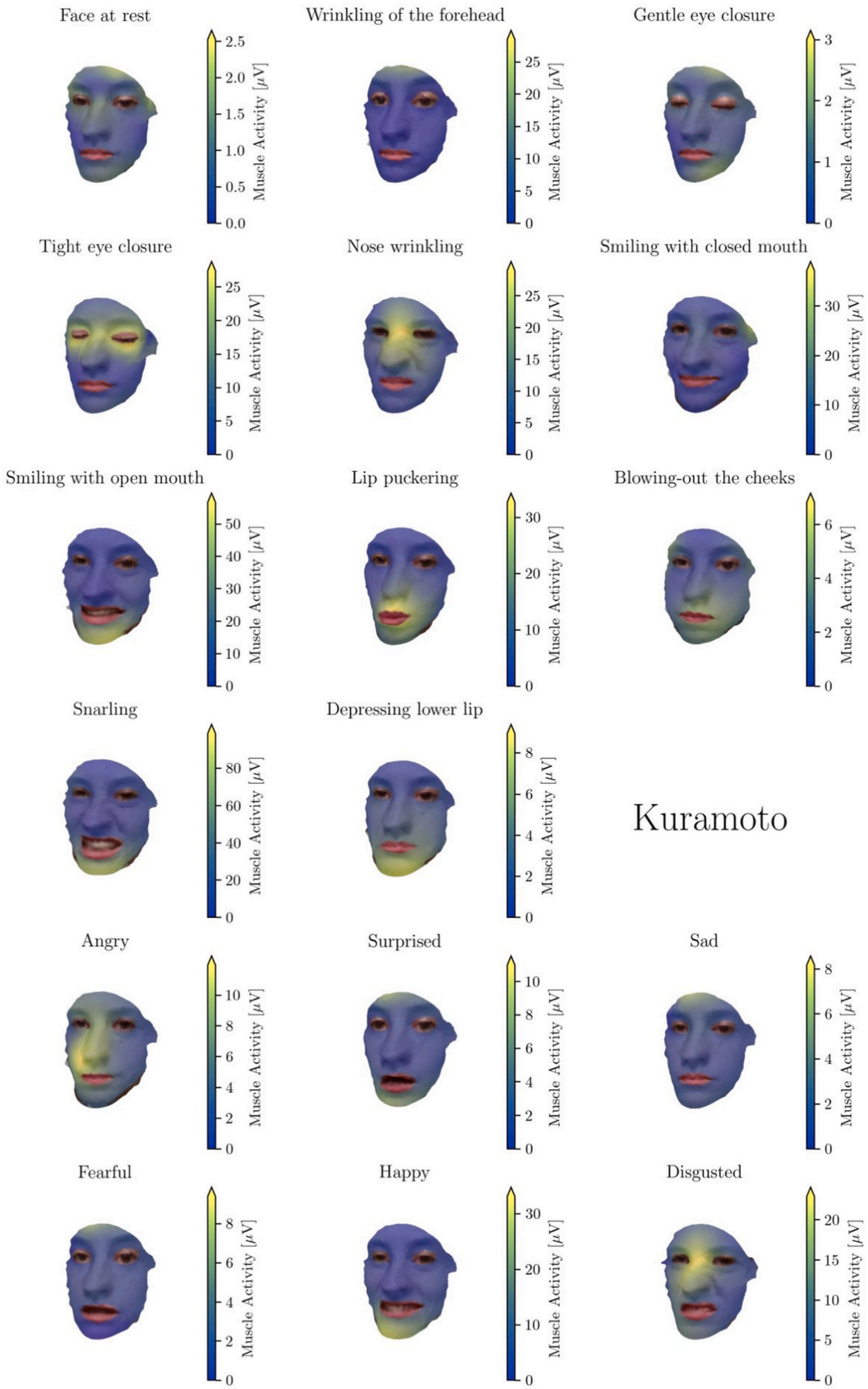

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Fig. 8. Example of an individual 3D model of same individual as in Fig. 5 based on the individual facial surface EMG activity of this participants with intensity maps but now using the Kuramoto EMG recording scheme during standardized mimic exercises and six basic emotional expressions. The heat maps reflect the individual EMG amplitudes (muscle activity) in μV of this participant.

5. Conclusions

This first 3D atlas of facial EMG activity during the most important functional tasks and during the six basic emotions gives a 3D impression of the complex but task-specific facial muscle activation. In addition, the approach can be used to visualize facial EMG activation in 3D for individual cases. This will be of future interest of individual disease classification, conservative or surgical therapy planning, and realistic therapy monitoring for diseases affecting facial muscle function. Via the hyperlinks interested researchers in the field of facial expression and emotion research as well as in the field of facial reconstructive surgery can use the 3D atlas for their own research planning to make the step from 2D to 3D facial research. The 3d atlas should be expanded in the future to include more participants in order to be able to better investigate age and gender effects.

CRediT authorship contribution statement

Tim Büchner: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Gerd Fabian Volk:** Writing – review & editing, Supervision, Methodology, Investigation. **Christian Dobel:** Writing – review & editing, Supervision, Conceptualization. **Christoph Anders:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation. **Joachim Denzler:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Orlando Guntinas-Lichius:** Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Data availability statement

The original contributions presented in the study are included in the article. Furthermore, hyperlinks in Table 1 are leading to the 3D platform and the hologram archive. Further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from all participants. The ethics committee of the Jena University Hospital approved the study (No. 2019-1539).

Additional information

Correspondence and requests for materials should be addressed to OGL.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2026.e45408.

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