Title:

Hand and face somatotopy shown using MRI-safe vibrotactile stimulation with a novel Soft Pneumatic Actuator (SPA)-Skin interface

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Abstract:

The exact somatotopy of the human facial representation in the primary somatosensory cortex (S1) remains debated. One reason that progress has been hampered is due to the methodological challenge of how to apply automated vibrotactile stimuli to face areas in a manner that is: 1) reliable despite differences in the curvatures of face locations; and 2) MR-compatible and free of MR-interference artefacts when applied in the MR head-coil. Here we overcome this challenge by using soft pneumatic actuator (SPA) technology. SPAs are made of a soft silicon material and can be in- or deflated by means of airflow, have a small diameter, and are flexible in structure, enabling good skin contact even on curved body surfaces (as on the face). To

validate our approach, we first mapped the well-characterised S1 finger layout using this novel device and confirmed that tactile stimulation of the fingers elicited characteristic somatotopic finger activations in S1. We then used the device to automatically and systematically deliver somatosensory stimulation to different face locations. We found that the forehead representation was least distant from the representation of the hand. Within the face representation, we found that the lip representation is most distant from the forehead representation, with the chin represented in between. Together, our results demonstrate that this novel MR compatible device produces robust and clear somatotopic representational patterns using vibrotactile stimulation through SPA-technology.

Keywords:

Somatosensory, vibrotactile technology, fMRI, face, hand, soft pneumatic actuators

Introduction

Over the past decades, somatotopic mapping provided us with an increasingly better understanding of how the body is represented in the brain. However, providing tactile stimulation in an MR environment remains challenging. Experimenters commonly use an active movement paradigm (Kolasinski et al., 2016; Root et al., 2021; Schellekens et al., 2018; Zeharia et al., 2015) or manual stroking of body parts (Martuzzi et al., 2014; Sanders et al., 2019; Van Der Zwaag et al., 2015) to probe somatotopic representations. However, both paradigms are limited: movement execution does not allow to study the representation of tactile stimuli in isolation and distinguishing between body parts that are not able to move independently (e.g., certain parts of the face or toes) is impossible. Manual stroking induces experimenter dependent spatiotemporal variance since the intensity, timing, and body part coverage of manual stimulations may not be consistent and precise. Furthermore, there are practical challenges when multiple body parts need to be stroked simultaneously, or if space is limited (e.g. when using a narrow head- or body coil). The usage of mechanical vibrotactile devices provides an opportunity to overcome these limitations. However, common vibrotactile elements contain metals or electrical circuits that are mostly not compatible with the MR environment (Yu and Riener, 2006). Stimulating body parts in (or close to) the MR head coil is especially technically demanding given the narrow geometry of the head coil and the safety constraints and imaging artefacts induced by metal components even if they are small.

Commercially available piezoelectric and piezoceramic devices are able to deliver vibrotactile stimulation at high-frequency ranges at a fixed amplitude. However, these devices mostly still contain some metal components and lead electrical wires inside the scanner (Puckett et al., 2017; Sanchez-Panchuelo et al., 2010). While active RF shielding is sufficient to prevent heating by RF pulses when such stimulators are placed far from the head coil such as on the fingers, they could still induce unwanted signal interference when placed closer to,

63 or inside, the MR head coil. Pneumatically driven or air puff devices circumvent these issues
64 and can be made of non-metallic MR compatible materials.

65 The pneumatic devices that have been developed for safe delivery of tactile stimulation
66 to multiple stimulation sites inside the MR head coil are however limited. The Dodecapus was
67 amongst the first pneumatically driven devices build to apply automated tactile stimulation via
68 air puffs to a range of face locations (Huang and Sereno, 2007). The device was extended
69 to deliver punctate tactile stimuli to the face using Von Frey filaments with a high
70 spatiotemporal accuracy (Dresel et al., 2008). However, in these setups stimulation could only
71 be applied to parts of the face that are exposed (i.e., that are not covered by the head coil).
72 Later, flexible plastic tubes were attached to a facial mask (custom moulded for each subject)
73 to deliver air puffs to locations of the face that are covered by the head coil, allowing for a
74 more complete picture of face somatotopy (Chen et al., 2017; Huang et al., 2017). However,
75 this face mask may not fit in head coils with more narrow geometry and when using participants
76 with larger head sizes. Furthermore, providing air puffs close to the mouth, nose, or eyes may
77 not be comfortable for participants. More recently, the GALILEO Somatosensory™ was
78 developed. This device can provide tactile stimulation through pressure dynamics in individual
79 stimulators with high spatiotemporal control (Custead et al., 2017). While this device is very
80 promising and allows the study of stimulation velocity, the stimulators are 6mm in height and
81 may not fit in head coils with very narrow geometry. Furthermore, it may not be easy to attach
82 the stimulators to highly curved body surfaces and the device is rather expensive.

83 An optimal vibrotactile device for MRI usage comprehensively consists of MR-safe
84 materials, is safe to place on the skin, and does not induce any MR interference artefacts even
85 inside the MR head coil. Furthermore, it should allow a controllability over vibration frequency
86 and amplitude, enabling both sub- and suprathreshold vibrotactile stimulations. The stimulators
87 themselves should be flexible in nature, such that they can be placed on skin surfaces with

88 different curvatures, and small and narrow to provide focal stimulation in narrow head coils
89 that are typical for ultra-high field imaging. Lastly, the device should be portable and cost-
90 efficient.

91 Here we present a newly developed tactile stimulation device that delivers all the
92 characteristics of the aforementioned "optimal vibrotactile" device. This novel platform
93 provides focal, suprathreshold vibrotactile stimulation to the face (even inside a narrow head
94 coil) or to other parts of the body inside an MRI scanner. The soft pneumatic actuator (SPA)-
95 skin does not contain any metals at the contact point and still provides thorough control over
96 actuation frequencies (Sonar et al., 2019; Sonar and Paik, 2016). SPAs are made of a soft MR-
97 safe silicone (Dragon Skin 30®, Smooth On Inc., USA) and can be inflated or deflated by
98 varying internal pressure. SPA-skins are extremely versatile in their geometric dimensions and
99 material choices: the presented prototype measures under 1 mm thin, with a 1.4 cm diameter
100 actuation point. It is soft and flexible in structure, enabling compliant skin contact even on
101 curved body surfaces (as on the face). Furthermore, the low profile design of the SPA-skin
102 allows for usage in the narrow geometry of the MR head coil and in narrow bores that are
103 typical for ultra-high field MRI environments. The choice of materials with matching
104 mechanical compliance with human skin improves the optimal transfer of tactile feedback
105 while maintaining mechanical transparency when worn.

106 We demonstrated the feasibility of using the SPA-skin setup for somatotopic mapping in
107 an fMRI study. By doing so we not only provide a methodological but also a scientific advance
108 as our device allowed us to detail the somatotopic layout of the face via an automated face
109 stimulation paradigm. While the gross representation of body parts and fingers in S1 is largely
110 agreeable across studies, results on the exact somatotopic mapping of the face have been mixed.
111 Indeed, contrasting work reports both an inverted (Servos et al., 1999; Yang et al., 1993) and
112 upright somatotopic face representation (Huang and Sereno, 2007; Penfield and Rasmussen,

113 1950; Root et al., 2021; Roux et al., 2018; Sato et al., 2005; Schwartz et al., 2004). Yet other
114 studies reported more mixed face representations following an 'onion skin model' where the
115 nose was represented more inferior in S1 than stimulations on the lower jaw or above the eye
116 (DaSilva et al., 2002; Moulton et al., 2009). To detail the full somatotopic layout of the face an
117 automated face stimulation paradigm and both univariate analysis and multivariate analysis
118 methods that are sensitive to representational overlaps (i.e., representational similarity
119 analysis) are needed.

120 We hypothesized that tactile SPA stimulation would yield robust localised activations in
121 somatosensory areas. We further hypothesized that tactile finger stimulation would elicit
122 characteristic somatotopic finger activations in the primary somatosensory cortex. Lastly, we
123 investigated the somatotopic layout of the face, using the device to automatically and
124 systematically deliver somatosensory stimulation inside the head coil.

Material and methods

Participants

Seventeen healthy participants (mean age ± s.e.m. = 37.1 ± 4.3; 7 females; 2 left-handers) participated in this study. Ethical approval was granted by the Kantonale Ethikkommission Zürich (EK-2018-00937) and written informed consent was obtained prior to study onset. This study is registered on clinicaltrials.gov under the number NCT03772548. As our fingers stimulation experiment was meant as a mere validation of the device and was expected to reveal convincing data in a limited number of participants, we only tested 8 participants for this feasibility aspect of the study. Face somatotopy was tested in all participants.

SPA-skin stimulator design

We developed a novel soft skin like interface (Figure 1): i.e., a SPA-skin that can be driven using modulated pneumatic pressure and is capable of generating a plethora of actuation < 100 Hz and can be complemented by integrated sensors (Sonar et al., 2019; Sonar et al., 2019; Sonar and Paik, 2016). The SPA-skin is fabricated using silicone (Dragon Skin 30, Smooth-On Inc., USA) that has similar stiffness as the human skin and provides optimal comfort, as is necessary for long-duration fMRI studies (Figure 2). The actuator layer, i.e., the SPA, consists of an elastomeric membrane that can be pneumatically inflated with a pressure input (Sonar and Paik, 2016; see Figure 2B). This actuator is fabricated with three thin layers with a total thickness of < 1mm: a middle flexible mask layer (50μm) to define the actuator's shape that is sandwiched between two silicone layers. The masking layer is laser machined to obtain the desired shape and is then laminated onto the bottom silicone layer to be encapsulated by a thin top silicone layer. The polypropylene mask adheres to the bottom silicone layer and ensures that, upon inflation, the top membrane deforms. It is important to ensure a proper grounding

with the skin and attaching the SPA-skin properly at a given location without obstructing the inlet pneumatic flow lines.

For any robotic system, a sensor feedback plays an important role to ensure accurate control and understanding of the surrounding environment. The traditionally available pressure or force sensors, needed for providing coherent tactile feedback, work well but like rigid tactile stimulators, these are also limited in their application when they need to be worn by humans, as they often lack the mechanical compliance with the human body. This mismatch obliterates the accurate control of any wearable devices because it is impossible to predict how effective the signal, force, and location of the stimulation is when there is inconsistent and arbitrary grounding. We have hence developed and integrated possibilities of sensing layers in the SPA-skin that provide a localised measurement of interactive forces by virtue of different sensing technologies including an active piezo charge sensing (Sonar and Paik, 2016) or passive methods like resistive strain sensor (Sonar et al., 2019) and soft capacitive skin (Sonar et al., 2018). The sensing layer and the SPA-skin design process tackle this challenge using a finite element based simulation (Agarwal et al., 2017; Moseley et al., 2016) and closed-loop feedback control through the sensing layer. This ensures an accurate tactile stimulation even under variable loading conditions or manufacturing variabilities (Sonar and Paik, 2016).

For the fMRI compliant tactile stimulator application, we designed and prototyped a ring-shaped SPA-skin actuation point (with a 1.4cm diameter and 2mm inlet tube channel) to maximize the application area on the skin while minimizing the volume of air being transferred through the long tubing that helps improve the maximum actuation frequency or bandwidth. This state-of-the-art setup independently controls 8 channels that extended to different SPA-skins. The need for a long tubing (< 6m) limited the volume flow of the air to the actuators during inflation and then back during the deflation cycle. A careful system design was therefore carried out for each component of the pneumatic supply system (PSS) to achieve maximum

bandwidth at 6m tube length and maintain the expected functionality of SPAs at less than 80kPa, as discussed in detail in (Joshi et al., 2021; Joshi and Paik, 2021). This allowed us to stretch the actuation bandwidth up to 15Hz in the current setup. When attempting to reach a bandwidth of 30Hz, we were still able to measure 0.5N of force at 30Hz, which is largely above the perception threshold for the face and fingers.

The SPA-skin was pneumatically controlled through a customized control circuit that was interfaced through serial communication to the stimulus computer (see Figure 1). The pneumatic controller was composed of the following components: a stimulus computer, a portable air compressor, a portable pneumatic control circuit module, and corresponding pneumatic tubes. An air compressor (Implotex, Germany) produced the airflow to a pressure regulator (ITV1050, SMC Corp., USA) that was controlled by the microcontroller in the control circuit. The stimulation intensity could be adjusted using a single pressure regulator and an array of high-speed solenoid valves which were driven through high-power MOSFET switches and stimulus from the micro-controller.

A portable pneumatic supply line, AC power supply and USB cable for serial communication enabled the primary extension of the controller setup to be placed just outside the RF shielding walls of the fMRI scanner. A 50mm diameter hole in the wall then carried the 5-6m long and 4mm thick tubes to the SPAs that were places on the face or the fingers. Once connected in this fashion, the system acted as a plug-n-play device that can be easily controlled via the stimulus computer using simple serial commands to turn a given channel on or off at a given frequency. The pressure regulator could be manipulated through the stimulus computer and the working pressure of the pneumatic system could be read in real time. The build-in limitation of 100kPa operational pressure ensures a delamination free operation of the SPA-skin.

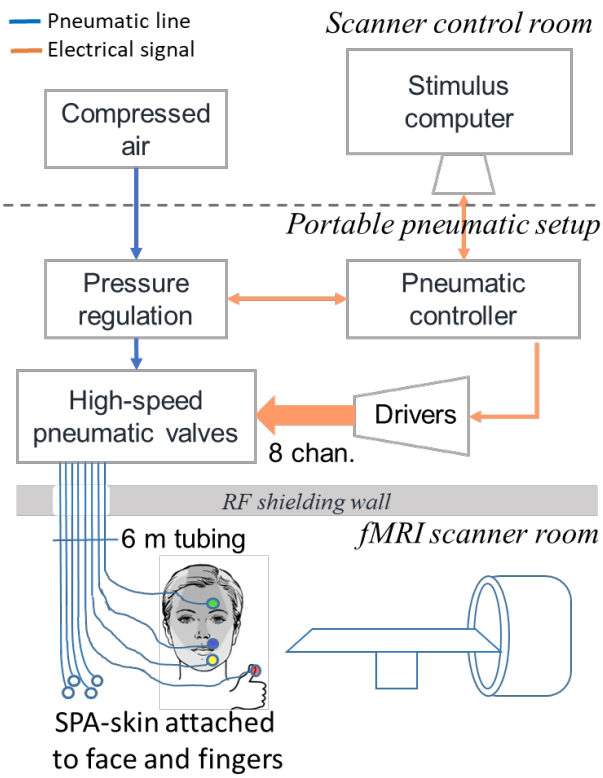

Figure 1: Schematic illustration of the SPA setup. The pneumatic controller was composed of the following components: a stimulus computer, a portable air compressor, a portable pneumatic setup, and pneumatic tubes. Stimulation intensity and frequency could be controlled using a stimulus computer in the scanner control room. An air compressor placed in the scanner control room provided airflow to a pressure regulator that was controlled by the microcontroller in the portable pneumatic setup. The stimulation intensity could be adjusted using the pressure regulator and an array of high-speed pneumatic valves which were driven through high-power switches and inputs from the micro-controller. A 50mm diameter hole in the RF shielding wall then carried the 5-6m long and 4mm thick tubes to the SPAs that were placed on the face or the fingers in the fMRI scanner room.

MR interference artefact testing

MR interference artefacts were not expected since all materials inside the MRI scanner room were MR safe. Nevertheless, for the sake of validation, we conducted pilot testing to ensure that no MRI interference artefacts would be induced when the device was turned on with the SPA-skins attached to a water-filled phantom bottle placed inside the MR head coil. To test for artefacts we used the same sequence as used during the fMRI acquisition (see "MRI

acquisition" section). As expected, no MR interference artefacts were observed and the presence of the tubing and SPAs inside the scanner room could not be detected in the MRI images.

Experimental paradigm

The SPA-skins were attached to the forehead (~1cm above the eyebrow), above the upper lip, and on the chin (see Figure 2A). These sites were chosen to ensure that an SPA-skin was placed on each of the trigeminal nerves' innervated skin areas. Care was taken to not place SPA-skins on skin areas that are on the border of trigeminal nerve innervations. To ensure good grounding of the SPAs on the face, we placed in-house 3D printed plates on top of the SPA-skins and used a custom-made fabric face mask to apply light pressure to the SPA-skins placed on the face (see Figure 2B). Five further SPA-skins were attached to the fingertips of the left hand using adhesive tape.

Participants viewed a visual display positioned at the head of the scanner bore through a mirror mounted on the head coil. Participants 1-9 were presented with horizontally (for the finger stimulation runs) or vertically (for the face stimulation runs) aligned white circles, corresponding to the different stimulation locations. To cue the participant which location would be stimulated, the circle corresponding to this location turned red 0.8s prior to stimulation onset and remained red until stimulation offset. Participants 10-17 were cued with the words "Forehead", "Lips", "Chin", and "Thumb" in white centred on a black screen. To cue the participant which location would be stimulated, the text cue appeared on the screen 0.8s prior to stimulation onset and remained on the screen until stimulation offset.

Participants were instructed to attend to the highlighted stimulation location as long as the cue was on the screen. Stimulation was presented for 8s at 8Hz with 400ms bursts of stimulation 'on' periods followed by a 100ms 'off' period to minimise peripheral adaptation.

240 To ensure stable attention during the fMRI runs, stimulations were interrupted in a small
241 percentage of the stimulation blocks (10-20% of trails per run). In these interrupted stimulation
242 trials, stimulation was provided for 4s, after which a 2s silent period was introduced, following
243 by another 2s of stimulation. Care was taken to ensure that the interrupted stimulation trials
244 were equally distributed across the stimulation locations within each run. Participants were
245 instructed to count the number of interrupted stimulation trials and verbally report this at the
246 end of each run.

247 Since a stronger sensation is expected to lead to a stronger BOLD response, we aimed
248 to match the sensation intensity across stimulation locations prior to the fMRI runs. A
249 stimulation intensity matching task was carried out for the face and finger stimulation runs
250 separately. First, participants were asked to set the optimal stimulation intensity for a reference
251 location. The forehead was chosen as the reference location for the face stimulation runs, and
252 the little finger was chosen as the reference location for the finger stimulation runs. We chose
253 these stimulation locations as references since they are innervated by least mechanoreceptors
254 and can be assumed to be least sensitive (Corniani and Saal, 2020). Participants were instructed
255 that an optimal stimulation intensity would be as strong as possible while remaining focal (i.e.,
256 no spread to skin locations not directly underneath the stimulator), comfortable, and stable over
257 the 8s stimulation period (i.e., minimal peripheral adaptation). Participants were asked to
258 respond by means of a button box whether the intensity should be decreased, increased, or
259 should not change. Based on the participants' responses the air pressure provided to the SPAs
260 was decreased or increased in steps of 5 kPa (leading to a lower or higher stimulation intensity,
261 respectively) or remained stable. If the participant responded twice in a row that the stimulation
262 intensity should not be changed, then the stimulation pressure for the reference location was
263 set at this level for all fMRI tasks. Since the SPAs become fragile when using an air pressure
264 exceeding 80 kPa, this was the maximum pressure setting that could be chosen by participants.

The minimum air pressure provided was set at 20 kPa above atmospheric pressure. Once the optimal stimulation intensity was chosen for the reference location, participants were asked to match the stimulation intensity for the other stimulation locations to the stimulation intensity of the reference location. To enable this matching, participants were initially given 8s of stimulation on the reference location, immediately followed by stimulation of one of the other stimulation locations. Participants were instructed to change the stimulation intensity of the 2nd location to match the stimulation intensity of the reference location as closely as possible. For the face stimulation runs, participants were instructed to match the stimulation intensity of the lips, chin, and thumb to the reference forehead stimulation intensity. For the face stimulation runs, participants were instructed to match the stimulation intensity of the thumb, index, middle, and ring finger to the reference little finger stimulation intensity. As before, if the participant responded twice that the stimulation intensity should not be changed, the stimulation pressure for this stimulation location was set at this level for all fMRI tasks.

Instructions and stimulations were delivered using Psychtoolbox (v3) implemented in Matlab (v2014b). Matlab then communicated with the Arduino board implemented in the SPA controller set-up via a serial port over a proprietary protocol. Head motion was minimized using over-ear MRI-safe headphones or padded cushions.

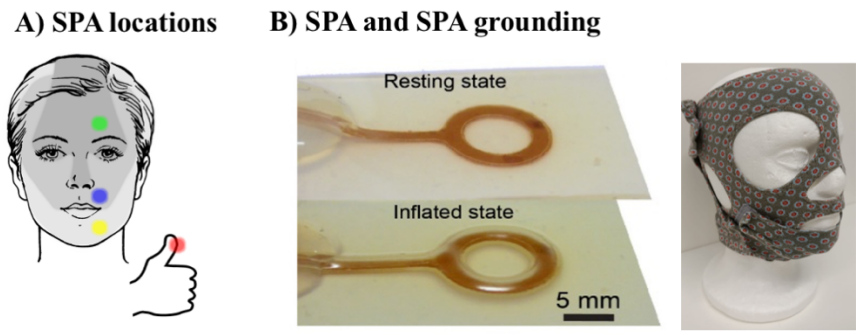

Figure 2: SPA locations and grounding on the face. A) SPAs were attached to the forehead, upper lip, chin, and thumb. We either tested the right or the left side of the face and the right of the left thumb. Shaded areas on

the face indicate the skin areas innervated by different branches of the trigeminal nerve. B) SPAs were grounded to the face using a custom made fabric mask.

Fingers stimulation runs

The finger stimulation blocked design consisted of six conditions: Stimulation conditions for each of the five fingers of the left hand and a rest (no stimulation) condition. The visual cue during the finger stimulation blocks was as described above and the presentation of the word "Rest" indicated the rest condition. Each of these six conditions had a block duration of 8.8s and was repeated five times per run in a counterbalanced order. Each run comprised a different block order and had a duration of 4min and 39.4s. We acquired four blocked design runs, with a total duration of 18min and 37.6s.

Face stimulation runs

All face stimulation runs involved stimulation of the forehead, lips, chin, and thumb. 14 participants were stimulated on the left side of their face and the left thumb. Three participants were stimulated on the right side of the face and their right thumb. We included thumb stimulation in these runs as the thumb representation borders the face area in S1 (Kikkert et al., 2021, 2016; Kolasinski et al., 2016; Penfield and Rasmussen, 1950; Roux et al., 2018). To uncover face somatotopy we used a blocked design consisting of five conditions: Stimulation conditions for each of the three face locations and the thumb, as well as a rest (no stimulation) condition. The visual cue during the face stimulation blocks were as described above and the presentation of the word "Rest" indicated the rest condition. Each of these five conditions had a block duration of 8.8s and was repeated 8 times per run in a counterbalanced order. Each run comprised a different block order and had a duration of 6min and 7.4s. We acquired four blocked design runs, with a total duration of 24min and 29.6s.

311

312 **MRI acquisition**

313 MRI data was acquired using a Philips 3 tesla Ingenia system (Best, The Netherlands). Data of
314 participants 1-9 was collected using a 32-channel head coil and data of participants 10-18 was
315 collected using a 15-channel head coil. fMRI data was acquired using an echo-planar-imaging
316 (EPI) sequence with partial brain coverage: 36 sagittal slices were centred on the postcentral
317 gyrus with coverage over the thalamus and brainstem. We used the following parameters:
318 2.3mm^3 spatial resolution, TR: 2200ms, TE: 30ms, flip angle: 82˚, SENSE factor: 2.1, 36 slices.
319 We acquired 127 and 167 volumes for the finger and face stimulation runs,
320 respectively. Anatomical T1-weighted images for participants 1-9 were acquired using the
321 following acquisition parameters: TR = 7.7ms, TE = 3.6ms, flip angle = 8°, voxel size = 1mm
322 isotropic, transversal slices = 160. Anatomical T1-weighted images for participants 10-17 were
323 acquired using the following acquisition parameters: 0.7mm^3 spatial resolution, TR: 9.3ms,
324 TE: 4.4ms, flip angle: 8˚.

325

326 **MRI analysis**

327 fMRI analysis was implemented using tools from FSL v6.0
328 (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki) in combination with the RSA toolbox (Nili et al., 2014;
329 Wesselink and Maimon-Mor, 2017) and in-house scripts developed using Matlab (R2018a).
330 Cortical surface analysis and visualisations were realised using Freesurfer
331 (https://surfer.nmr.mgh.harvard.edu/; Dale et al., 1999; Fischl et al., 2001).

332

333 ***Preprocessing and image coregistration***

334 Common preprocessing steps were applied to each individual fMRI run using FSL's Expert
335 Analysis Tool FEAT (version 6.0; https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FEAT). The following

336 preprocessing steps were included: motion correction using MCFLIRT (Jenkinson et al., 2002),
337 brain extraction using automated brain extraction tool BET (Smith, 2002), spatial smoothing
338 using a 2.3mm full-width-at-half-maximum (FWHM) Gaussian kernel, and high-pass temporal
339 filtering using a cut-off of 90s.

340 Image coregistration was done in separate, visually inspected, steps. For each
341 participant, a midspace (i.e., an average space in which images are minimally reoriented) was
342 calculated between the 4 face stimulation blocked design runs and, if the fingers were also
343 tested, between the four finger stimulation blocked design runs. We then transformed all fMRI
344 data to these functional midspaces using purely rigid probability mapping in ANTs. Next, we
345 registered each participant's midspace to the T1-weighted image, initially using 7 degrees of
346 freedom and the mutual information cost function, and then optimised using boundary based
347 registration (BBR; Greve and Fischl, 2009). Each coregistration step was visually inspected
348 and, if needed, manually optimised using blink comparison in Freeview. Structural images
349 were transformed to Montreal Neurological Institute (MNI) standard space using nonlinear
350 registration (FNIRT).

351

352 ***Univariate analysis***

353 First-level parameter estimates were computed using a voxel-based general linear model
354 (GLM) based on the gamma hemodynamic response function and its temporal derivatives.
355 Time series statistical analysis was carried out using FILM (FMRIB's Improved Linear Model)
356 with local autocorrelation correction. To reduce noise artefacts, CSF and WM scan wise time
357 series were added to the model as nuisance regressors. Data were further assessed for excessive
358 motion, and volumes with an estimated absolute mean displacement > 1.15mm (half of the
359 functional voxel size) were scrubbed. Contrasts were defined for each stimulation condition
360 versus rest, for overall face or finger stimulation conditions versus rest, and for each stimulation

361 condition versus all other stimulation conditions. We then used a fixed-effects higher-level
362 analysis to average across the finger stimulation runs and across the face stimulation runs
363 separately for each individual participant. Z-statistic images were thresholded using clusters
364 determined by $Z > 2.3$ and $p < .05$ family-wise-error-corrected cluster significance thresholding
365 was applied.

366 To visualise inter-participant consistency of somatotopic finger and face selective
367 representations, we calculated cortical activation probability maps. Cortical surface projections
368 were constructed from participants' T1-weighted images. Each participant's cortical surface
369 was inflated into a sphere and aligned to the Freesurfer 2D average atlas using sulcal depth and
370 curvature information. The thresholded stimulation site selective (i.e., condition versus all
371 other stimulation conditions) contrast maps from each participant's fixed effects higher-level
372 analysis were resampled to the Freesurfer 2D average atlas and binarized. We then calculated
373 finger-specific and face part-specific inter-participant probability maps.

374 Lastly, to visualise which brain areas were activated during overall face and fingers
375 stimulation, whole-brain group averages were assessed for the stimulation of all fingers versus
376 rest and stimulation of all face locations versus rest contrasts. Group-level analysis was
377 performed for the finger and face stimulation runs separately using FMRIB's Local Analysis
378 of Mixed Effects (Woolrich et al., 2004). Data collected for individuals of whom we tested the
379 right side of the face was flipped on the midsagittal plane before conducting group analysis to
380 ensure that the tested hemisphere was consistently aligned. Z-statistic images were thresholded
381 using clusters determined by $Z > 3.1$ and $p < .05$ family-wise-error-corrected cluster
382 significance thresholding was applied.

383

384 ***Representational similarity analysis***

385 A fuller description of somatotopic representations can be obtained by taking into account the
386 entire fine-grained activity pattern of stimulated fingers or face parts. Representational
387 dissimilarity was therefore estimated between fingers or between face locations using the cross-
388 validated squared Mahalanobis distance (or crossnobis distance; Nili et al., 2014; Wesselink
389 and Maimon-Mor, 2017b). We closely followed previously described procedures (Kikkert et
390 al., 2021; Wesselink et al., 2019).

391 We first defined an anatomical S1 hand and an S1 face ROI using the probabilistic
392 Brodmann area parcellation provided by recon-all in Freesurfer. Each participant's cortical
393 parcellations for Brodmann areas 1, 2, 3a and 3b were converted to volumetric space and
394 merged to form a single S1 mask. Next, any holes in these converted masks were filled and the
395 non-zero voxels in the mask were mean dilated. We restricted this S1 mask such that it spanned
396 a 2cm strip medial/lateral to the anatomical location of the hand knob to form the S1 hand ROI
397 (Yousry et al., 1997). The S1 area inferior to this S1 hand ROI was then extracted to form the
398 S1 face ROI.

399 We computed the dissimilarity between the activity patterns measured for each pair of
400 stimulation conditions within the S1 hand or S1 face ROI for the fingers and face stimulation
401 runs, respectively. We extracted the voxel-wise parameter estimates (betas) and the model fit
402 residuals under the ROI and prewhitened the betas using the model fit residuals. We then
403 calculated the cross-validated squared Mahalanobis distances between each pair of conditions,
404 using the four runs as independent cross-validation folds, and averaged the resulting distances
405 across the folds.

406 The dissimilarity values for all pairs of conditions were initially assembled in a
407 representational dissimilarity matrix (RDM), with a width and height corresponding to the
408 number of conditions (i.e., a 5x5 RDM for the finger stimulation runs and a 4x4 RDM for the
409 face stimulation runs). Since the RDM is mirrored across the diagonal with meaningless 0's on

410 the diagonal, all statistical analysis was conducted on the unique values of the RDM (10 unique
411 values for the finger stimulation runs and six unique values for the face stimulation runs).
412 Finally, we performed multidimensional scaling (MDS) to visualise the dissimilarity structure
413 of the RDM in an intuitive manner. MDS projects the higher-dimensional RDM into a lower-
414 dimensional space while preserving the inter-condition dissimilarity values as well as possible
415 (Borg and Groenen, 2005). MDS was performed for each individual participant and then
416 averaged per group after Procrustes alignment to remove arbitrary rotation induced by MDS.
417 We estimated the strength of the representation or "representational separability" by
418 averaging the unique off-diagonal values of the RDM. If it is impossible to statistically
419 differentiate between conditions (i.e., when a parameter is not represented in the ROI), the
420 expected value of the distance estimate would be 0. If it is possible to distinguish between
421 activity patterns this value will be larger than 0. To further ensure that our S1 face ROIs
422 contained face information, we created a cerebral spinal fluid (CSF) ROI that would not contain
423 somatotopic face information. We then repeated our face RSA analysis in this ROI and
424 statistically compared the separability of the CSF ROI to the separability in the S1 face ROI.
425
426 **Statistics**
427 Statistical analysis was carried out using SPSS (v25). Non-parametric statistical testing was
428 used for analysis of the finger stimulation data. Parametric statistical analysis was carried out
429 for the face stimulation data after checking for normality using the Shapiro-wilk test. Non-
430 parametric statistical testing in case of normality violations. All testing was two-tailed and we
431 used the Benjamini-Hochberg procedure to control the false discovery rate with $q < 0.05$.
432
433 **Data availability**

434 Full details of the experimental protocol are available on clinicaltrials.gov under the number

435 NCT03772548. Data is shared on <link will be made available upon publication>.

436

437 ## Results

438 In the current study, we aimed to validate the use of our newly developed SPA-setup for
439 somatotopic mapping using fMRI. We first explored whether SPA tactile stimulation would
440 elicit characteristic finger representations in S1. Next, we used our SPA setup to uncover the
441 somatotopic layout of the face in S1.

442

443 **Vibrotactile SPA-skin stimulation induces activity in somatosensory processing areas**

444 We first examined task-related brain activity elicited by tactile stimulation applied to the
445 fingers (Figure 3A) and the face (Figure 3B) using our SPA-skin setup. As expected, we found
446 that both stimulation on the fingers and the face activated S1 and secondary somatosensory
447 cortex (S2) contralateral to the stimulation site. Ipsilateral S1 and S2 activity was less
448 widespread for both the fingers and face stimulation. Note that a direct comparison with regards
449 to the level of activity between the finger and face stimulation runs is challenging given that
450 activity elicited by fingers stimulation was only tested on a subset of eight participants and
451 seventeen participants were tested to examine activity elicited by face stimulation.

452

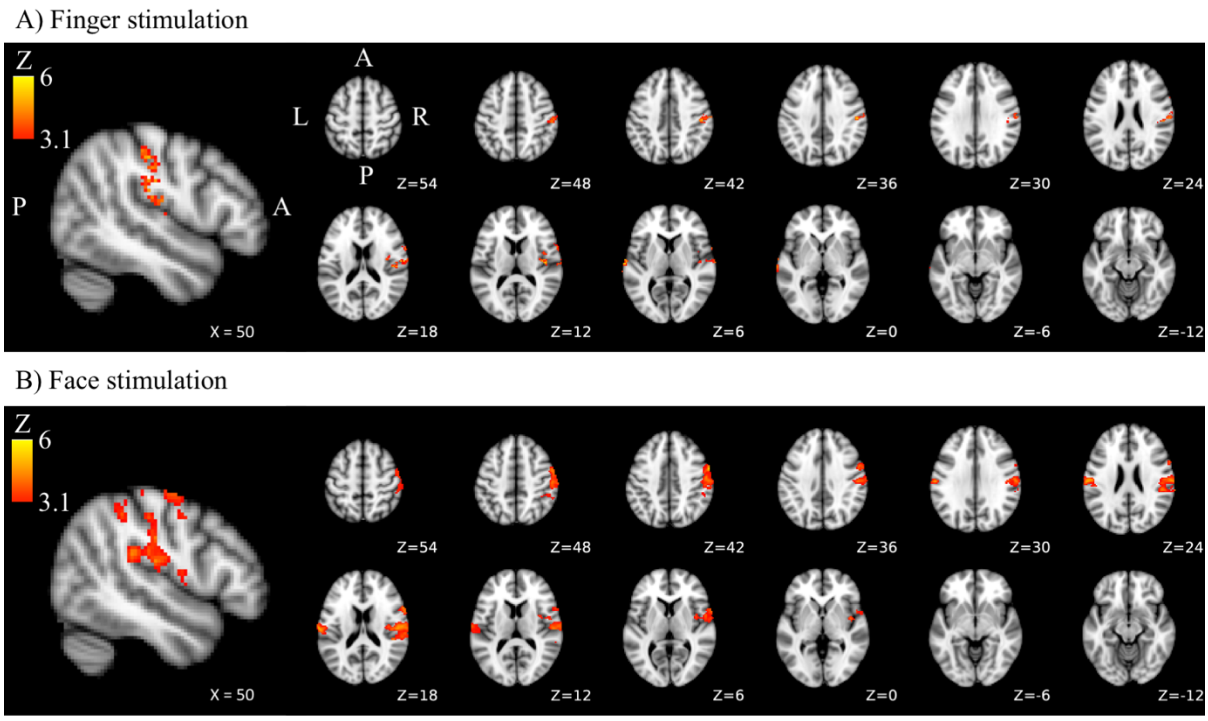

Figure 3: Brain activity in the contralateral hemisphere during sensory stimulation using SPA technology. Both fingers (A) and face (B) stimulation elicited activity in S1 and secondary somatosensory cortex. L = left; R = right; P = posterior, A = anterior.

Finger representations

We first explored finger selective representations. We contrasted activity elicited during each finger stimulation against activity during stimulation of all other fingers and binarized the resulting finger selective maps. We then created inter-participant probability maps representing the number of participants exhibiting specific finger selectivity (i.e., using a winner-take-all approach) for each vertex in S1. These maps exhibited, as expected (Kolasinski et al., 2016), that finger selectivity was not perfectly consistent across participants (Figure 4A). We did however observe a characteristic gradient of finger preference progressing from the thumb, for which inter-subject probability was highest lateral of the S1 hand area, to the little finger, for which inter-subject probability was highest medial of the S1 hand area. Qualitative inspection

468 suggests that inter-participant consistency was highest for the thumb and lowest for the little
469 finger representation.

470 Next, we explored a 2nd somatotopic principle that is known to be consistent across
471 individuals: the pattern of distances between finger representations. We examined this intricate
472 relationship between finger representations using representational dissimilarity analysis. We
473 found a typical pattern of inter-finger representational distances where neighbouring fingers
474 have relatively lower representational distances compared to fingers that are further apart.
475 Furthermore, fingers that we use more frequently together in daily life (e.g., the ring and little
476 fingers) had lower representational distances compared to fingers we use more separately in
477 daily life (e.g., the thumb and index finger (Ejaz et al., 2015)). This inter-finger representational
478 distance pattern found using SPA tactile stimulation of fingers (Figure 4B) was highly similar
479 to the inter-finger representational distance patterns that we and others have described
480 previously in fMRI experiments using individual finger movements (Ejaz et al., 2015; Kikkert
481 et al., 2021, 2016; Sanders et al., 2019; Wesselink et al., 2019) or individual finger tactile
482 stimulation (Sanders et al., 2019). The inter-finger representational distances were averaged
483 across finger pairs within each participant to obtain an estimate for average inter-finger
484 representational separability (see Figure 5C), or 'representation strength'. We found that inter-
485 finger separability in the S1 hand area was greater than 0 ($Z = -2.52$, $p = 0.01$), showing that
486 the S1 hand area contained information about individual finger representations. Furthermore,
487 there was significant greater separability in the S1 hand area compared to a control cerebral
488 spinal fluid (CSF) ROI that would not be expected to contain finger specific information ($Z =$
489 -2.52, $p = 0.01$). Together, our results demonstrate that our SPA setup can be used to reliably
490 map the well characterised somatotopic layout of the hand.
491

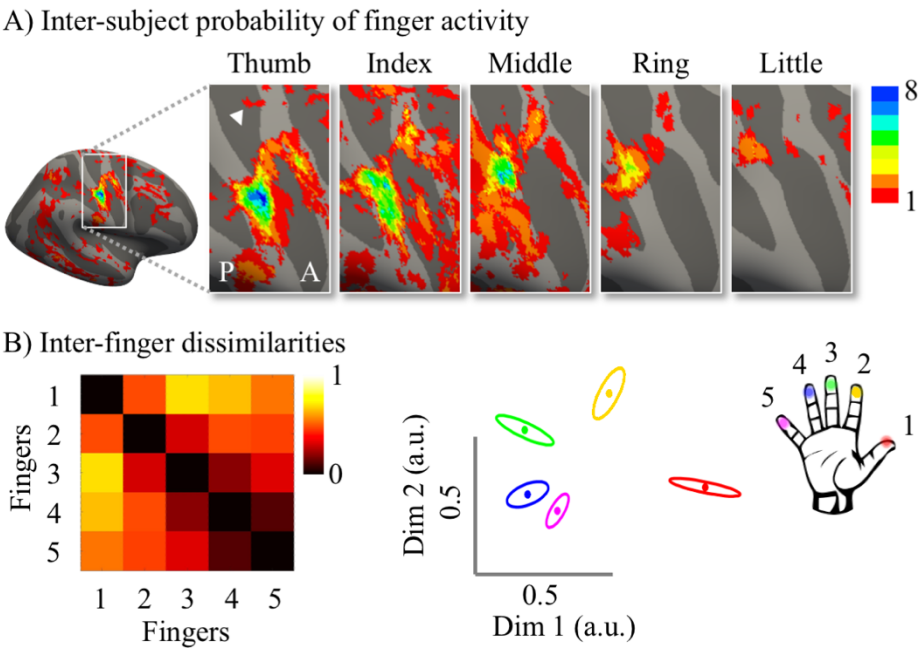

Figure 4: SPA stimulation uncovers typical finger somatotopy. A) inter-participant probability maps of finger selective representations. Colours indicate the number of participants (ranging from 1 (red) to 8 (blue)) who demonstrated finger selectivity for a given vertex. Typical finger selectivity is characterised by a progression of finger selectivity from the thumb (laterally) to the little finger (medially). We observed a characteristic gradient of finger preference progressing from the thumb, for which inter-subject probability was highest lateral of the S1 hand area, to the little finger, for which inter-subject probability was highest medial of the S1 hand area. Qualitative inspection suggests that inter-participant consistency was lowest for the little finger representation and highest for the thumb representation. The white arrow indicates the central sulcus. A = anterior; P = posterior. B) The representational structure of inter-finger distances. Left: Representational Dissimilarity Matrix (RDM). Individual stimulation sites are represented by numbers: thumb = 1; index finger = 2; middle finger = 3; ring finger = 4; little finger = 5. Right: 2-dimensional projection of the RDM. Inter-finger distance is reflected by the distance in the two dimensions. Individual fingers are represented by different colours: thumb = red; index finger = yellow; middle finger = green; ring finger = blue; little finger = purple. By stimulating fingers using SPA technology, we found a classical and frequently reported inter-finger distance pattern in the hand area of S1. Ellipses represent the between-participants standard error after Procrustes alignment.

Face representations

One advantage of our SPA setup is that, unlike most commercially available vibrotactile devices, it is able to provide vibrotactile stimulation to localised areas of the face (i.e., in the

512 MRI head coil) without causing any imaging artefacts or safety issues. We made use of this
513 advantage by examining the somatotopic layout of the face using our SPA setup. First, as for
514 the fingers, we created inter-participant probability maps of forehead, lip, chin, and thumb
515 selective representations (Figure 5A). The resulting inter-participant probability maps
516 represent the number of participants exhibiting selectivity (i.e., using a winner-take-all
517 principle) for a specific stimulation site for each vertex in S1. Qualitative inspection suggests
518 that the selective thumb and lip activity was more consistent across participants compared to
519 the forehead and chin. Furthermore, stimulation site selective activity was more consistent
520 across participants in the contralateral compared to the ipsilateral hemisphere.

521 We then used RSA in the S1 face area to investigate representational distances between
522 stimulation sites (i.e., between the forehead, lip, chin and thumb) that were stimulated during
523 the face stimulation runs (Figure 5B). The averaged representational distances (i.e.,
524 separability) between face sites (i.e., excluding the face-thumb distances) were markedly lower
525 compared to the representational distances found between fingers in the S1 hand area (Figure
526 5C; $Z = -2.52$, $p = 0.01$) and between the thumb and face sites in the S1 face area (Figure 5C;
527 $t_{(16)} = 6.11$, $p < 0.001$). However, we found that face-face site separability in the S1 face area
528 was greater than 0 (Figure 5C; $t_{(16)} = 6.10$, $p < 0.001$) and greater than separability in a control
529 CSF ROI ($t_{(16)} = -6.00$, $p < 0.001$), indicating that the S1 face area contained information about
530 face sites. We found a clear pattern of inter-face site representational distances in the S1 face
531 area revealing that the forehead had the lowest representational distance from the thumb. The
532 chin had more representational distance from the thumb than the forehead, and the lips were
533 most distant from the thumb.
534

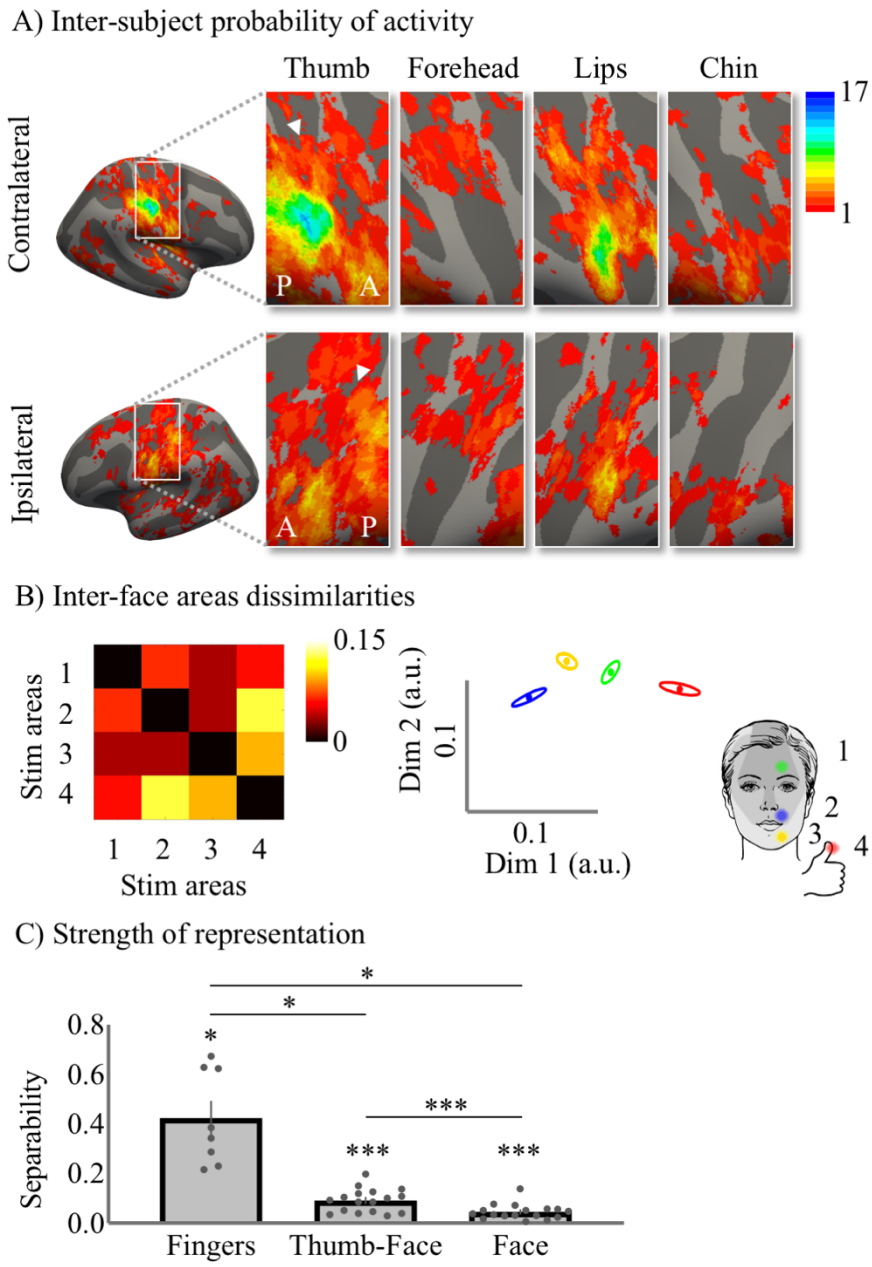

Figure 5: Face somatotopy uncovered using SPA stimulation. A) Inter-participant somatotopic probability face maps. Colours indicate the number of participants (ranging from 1 (red) to 17 (blue)) who demonstrated face part or thumb selectivity for a given vertex (i.e., stronger activity compared to the other stimulation sites). Qualitative inspection suggests that inter-participant consistency contralaterally was lowest for the forehead representation and highest for the thumb representation. Furthermore, inter-participant consistency was higher in contralateral, compared to ipsilateral S1. White arrows indicate the central sulcus. A = anterior; P = posterior. B) The representational structure of inter-stimulation site distances. Left: Representational Dissimilarity Matrix (RDM). Individual stimulation sites are represented by numbers: forehead = 1; upper lip = 2; chin = 3; thumb = 4. Right: 2-dimensional projection of the RDM. Inter-stimulation site distance is reflected by the distance in the

two dimensions. Individual stimulation sites are represented by different colours: forehead = green; upper lip = blue; chin = yellow; thumb = red. Ellipses represent the between-participants standard error after Procrustes alignment. C) Separability (i.e., average dissimilarity), or 'representation strength', for fingers-to-fingers in the S1 hand area, and thumb-to-face and face-to-face in the S1 face area. There was significant separability (i.e., greater than 0) for fingers-to-fingers in the S1 hand area, as well as for thumb-to-face and face-to-face in the S1 face area. Inter-fingers separability in the S1 hand area was greater than thumb-to-face and face-to-face separability in the S1 face area. Lastly, thumb-to-face separability in the S1 face area was higher than face-to-face separability in the S1 face area. * = $p < 0.05$; *** = $p < 0.001$.

554 **Discussion**

555 Providing somatosensory stimulation in an MR environment is challenging. Our results show
556 that somatosensory representations can be mapped using new SPA technology that is MR-
557 compatible and can be used within the MR head coil without causing artefacts. Using our SPA
558 setup, we found a typical somatotopic layout of participants' fingers, both in terms of the
559 gradient of finger selectivity and the inter-finger representational distance pattern. This
560 validates the use of our SPA setup for mapping somatotopic representations.

561 We further probed face somatotopy using automated tactile stimulation to the forehead,
562 lips, and chin – 3 face sites that are innervated by different branches of the trigeminal nerve.
563 Our univariate analysis revealed a great degree of inter-participant variability of face-site
564 selective representations. While the location of the thumb and lip representations were
565 relatively stable across participants, the forehead and chin representations were much less
566 stable. Potentially, the low density of mechanoreceptors in the chin and forehead may have
567 caused their activations to be 'overshadowed' by overlapping thumb and lip representations in
568 this winner-take-all analysis. While we attempted to control for any variability in sensed
569 intensity using our intensity matching task, it is likely that the forehead and chin are represented
570 less prominently in S1 compared to the thumb and lip and may therefore not 'win' in a winner-
571 take-all univariate stimulation site-selective analysis. Indeed, we suggest that it is more
572 appropriate to study face somatotopy using an analysis method that does not adhere to such a
573 winner-take-all principle and instead is sensitive to representational overlap or representational
574 distances between face parts. Using RSA, we revealed that the forehead was least dissimilar to
575 the thumb representation, followed by the chin representation, and lastly by the lip
576 representation. These results are in line with and extend the results of a recent study using RSA
577 and movements of the forehead, nose, lips, and tongue to study face somatotopy in S1. As in
578 our study, Root et al. (2021) reported that the forehead was least distant from the hand

representation. They further found that the nose was representationally least distant from the forehead representation and that the lips were furthest from the forehead representation. Root et al. (2021) could not disentangle the lips and chin representation, due to the nature of their movement task. As such, we extend their results by showing that, in representational space, the chin is in-between the lip and forehead in S1.

The aim of this study was to validate the use of a simple pneumatic vibrotactile device for somatotopic mapping inside an MRI scanner and specifically the head coil. Soft robotics emerged as a new field in robotics over a past decade and has been growing across the applications in medical technologies, personal care, environmental monitoring and entertainment (Bauer et al., 2014; Gibson, 2018; Hawkes et al., 2017; Jafari et al., 2016; Polygerinos et al., 2017). Soft robotics tackles the interactivity and wearability challenges posed to traditional rigid body robotic systems by using soft material based sensors and actuators to replace the traditional sensors and motors. These soft materials enable an inherently safe and mechanically compliant feedback to the environment including a human wearer (Polygerinos et al., 2017, 2015; Pons, 2008; Robertson and Paik, 2017). Wearability of soft technology can further be used to improve traditional haptic communication devices that currently only provide limited wearability due to their bulky and rigid-form factors (Cholewiak and Collins, 2003; Jones, 2011; Yun et al., 2017). Present haptic feedback devices mainly rely on motors and components driven using electromagnetic eccentric mass or piezoelectric motors that have limited wearability due to their bulky rigid mechanisms and cannot be used in environments prone to electromagnetic interference like the MRI environment (Alahakone and Senanayake, 2009; Cholewiak and Collins, 2003; “Smart Tactor Development Kit,” 2021).

While pneumatic tactile stimulators are highly applicable in studies investigating somatotopy, especially when investigating body part representations in or nearby the MR head coil, they generally have a smaller frequency range and more limited actuation control

compared to piezoelectric devices. Due to the length of our plastic tubes, our SPA setup can provide accurate control of frequencies up to 35Hz. While this stimulation frequency is reasonable for somatotopic mapping experiments, it may not be ideal when investigating neural responses to stimulation of specific mechanoreceptors. Furthermore, while our SPA-skin system can stimulate suprathreshold, its stimulation amplitude is limited due to the used materials. As such, for studies requiring highly intense sensations on skin surfaces (< 1N) with very low innervation of mechanoreceptors (e.g., on the neck or ankle), another material combination needs to be examined. Furthermore, the pneumatic supply system components (tubing resistance, compressibility and inertia of the oscillating air, conductance of various components) and the extent of grounding force with which the SPA is fixed to the stimulation site and could influence the exact amount of skin indentation.

Despite these limitations of the current system, we could reveal clear somatotopic representational patterns of different body parts by providing vibrotactile stimulation using the SPA-skin technology. Given that in our SPA-skin system all materials in the MRI scanner room are non-metallic, no MR safety and image quality certifications are required when using this device. SPAs are small and can easily be attached to different sites of the body. The SPA setup is flexible, easy-to-implement, precise, portable, fast and offers a cost-effective solution in comparison to commercially available devices that often induce artefacts, are highly expensive, require active shielding, or hardware modifications.

Author contributions

Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing

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Competing interests

The authors declare that no current competing interests exist.

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