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Type II mechanoreceptors and cuneate spiking neuronal network enable touch localization on a large-area e-skin

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Supplementary Tables

Supplementary Table 1. SAII firing rates (median Q2 and interquartile ranges [Q1, Q3]) for each force range and average SAII firing rates and interspike intervals (ISI) for each stimulus intensity percentage.

Force range (N)	SAII Firing Rate (Hz) (Q2 [Q1, Q3]	Stimulus intensity (%)	SAII Average Firing Rate (Hz)	ISI (ms)
[0.25, 0.75)	10 [10, 10]	**12.5**	8.91	112.23
[0.75, 1.25)	10 [10, 12.73]	**25**	11.92	83.92
[1.25, 1.75)	10 [10, 15.29]	**37.5**	13.77	72.63
[1.75, 2.25)	12.50 [10, 18.57]	**50**	15.48	64.60
[2.25, 2.75)	13.75 [10, 21.62]	**62.5**	17.45	57.30
[2.75, 3.25)	14.67 [10, 23.33]	**75**	18.80	53.19
[3.25, 3.75)	14.50 [10, 25.19]	**87.5**	19.29	51.86
[3.75, 4.25)	14.53 [10, 24.16]	**100**	18.51	54.02

Supplementary Table 2. Median (Q2) and interquartile ranges ([Q1, Q3]) of the CN cumulative spike numbers for different force ranges

Force (N)	CN spikes (Q2 [Q1, Q3])
[0.2, 1)	1472 [367.25, 4931.75]
[1, 1.8)	9155 [4796.25, 21892.75]
[1.8, 2.6)	13947 [7012, 34053.75]
≥ 2.6	26345.5 [12592.5, 58441]

Supplementary Table 3. Median (Q2) and interquartile range ([Q1, Q3]) of localization error for the 4-folds.

	Contact localization (mm) (Q2 [Q1, Q3])	
	Before Training	**After Training**
Fold-1	35.94 [21.61, 52.80]	13.39 [7.44, 28.47]
Fold-2	37.27 [23.07, 53.48]	14.93 [8.28, 29.63]
Fold-3	37.65 [18.35, 53.16]	13.90 [6.74, 28.69]
Fold-4	34.46 [19.27, 49.86]	14.21 [7.39, 27.41]
All Folds	36.26 [20.46, 52.14]	14.11 [7.47, 28.56]

Supplementary Table 4. Contact estimation error of the SNN before and after training and of the FBG weighted average approach. Errors are reported as median values (Q2) and interquartile ranges ([Q1, Q2] and IQR to assess variability).

	Contact estimation error (mm)					
	SNN Before Training		**SNN After Training**		**FBG Weighted Average**	
ROI radius (mm)	**Q2 [Q_1, Q_3]**	**IQR**	**Q2 [Q_1, Q_3]**	**IQR**	**Q2 [Q_1, Q_3]**	**IQR**
20	12.74 [8.12, 20.96]	12.84	7.42 [5.56, 10.75]	5.19	10.31 [6.83, 15.08]	8.25
23	15.23 [8.27,22.66]	14.39	7.42 [5.59, 10.82]	5.22	10.75 [7.12, 16.51]	9.39
25	17.12 [8.27, 24.57]	16.31	7.73 [5.75, 11.67]	5.93	11.50 [7.60, 17.97]	10.37
28	19.02 [8.80, 27.08]	18.29	7.85 [5.65, 11.89]	6.24	13.35 [8.57, 20.78]	12.21
30	19.16 [9.51, 27.43]	17.92	7.73 [5.57, 11.65]	6.08	14.71 [9.46, 22.31]	12.85
33	20.43 [9.90, 28.48]	18.59	7.47 [5.37, 11.63]	6.26	16.87 [5.23, 28.17]	22.94
35	20.74 [10.07, 28.88]	18.81	7.23 [5.19, 11.27]	6.08	17.79 [6.10, 30.11]	24.01
38	20.54 [10.07, 29.08]	19.01	7.03 [4.68, 10.36]	5.68	10.06 [6.40, 16.84]	10.45
40	21.35 [10.59, 30.03]	19.45	7.15 [4.71, 10.07]	5.36	9.48 [6.17, 13.16]	7.00
43	22.01 [10.77, 31.30]	20.53	7.22 [4.68, 10.14]	5.47	10.11 [6.60, 14.33]	7.73
45	23.50 [11.34, 32.45]	21.11	7.44 [4.70, 10.81]	6.11	10.80 [6.95, 15.98]	9.03
48	24.83 [12.07, 35.01]	22.94	8.19 [4.95, 12.01]	7.06	11.06 [7.37, 15.76]	8.40
50	25.75 [12.68, 36.16]	23.49	8.53 [5.25, 12.94]	7.69	11.49 [7.67, 17.33]	9.67
55	27.89 [14.44, 38.98]	24.55	9.52 [5.87, 14.63]	8.76	12.52 [8.30, 18.76]	10.46

Supplementary Table 5. Detection rate and number of trials of the Weber two-point discrimination test. The probe distance of 0 mm corresponds to a single point indentation.

Probe Distance (mm)	**Number of indentations**	**Two-Point Discrimination Rate**
0	305	0.35
20	45	0.24
25	36	0.28
30	40	0.30
35	37	0.54
40	38	0.71
45	39	0.72
50	43	0.77
55	44	0.84
60	48	0.81

Supplementary Table 6. Parameters of the equations describing the input currents of the cuneate neuron model proposed by (28).

Parameter	**Symbol**	**Value**
Membrane capacitance	C_m	4.270e-11 F
Leak conductance	g_L	8.100e-09 S
Leak reverse potential	E_L	-62.309 mV
Width of the spike (EIF model)	Δ_t	1.3063 ms
Spike threshold (EIF model)	V_t	-57.129 mV
Maximum potassium conductance	g_K	2.022e-08 S
EPSP reversal potential	$E_{rev,exc}$	0 mV
IPSP reversal potential	$E_{rev,inh}$	0 mV
Potassium reversal potential	E_K	-104.514 mV
Maximum calcium conductance	g_{Ca}	2.082e-08 S
Calcium reversal potential	E_{Ca}	121.436 mV
Conversion factor between calcium current and concentration	B_{Ca}	3.374e-15
Calcium concentration at rest (equilibrium)	Ca^{2+}_{rest}	1.010e-07
Time constant of the calcium concentration leak	$\tau_{Ca^{2+}}$	0.0063
Time constant of the calcium activation state	$\tau_{Ca,a}$	2.722e-04
Time constant of the calcium inactivation state	$\tau_{Ca,i}$	0.0207
Time constant of the potassium calcium-dependent activation state	$\tau_{K_{ca}}$	0.0013
Time constant of the potassium voltage-gated activation state	$\tau_{K_{V_m}}$	0.0011
Membrane capacitance	C_m	4.270e-11 F
Leak conductance	g_L	8.100e-09 S

Supplementary Information Text

In the following pseudo-code, the synaptic learning protocol for each CN is summarized.

Intrinsic Parameters Initialization ()
$w_{exc,i}$ Initialization
for $cntCyc = 1{:}\,nSti$
    $Tactile\_Sti$ = ***StimuliSelect*** $(cntCyc)$
% IPSP
    if $cntCyc <= 5$
    $w_{inh} \longleftarrow 0.125$
    if $cntCyc > 5$
    $MvAgCa_2SpkFq = \boldsymbol{mean}\ (Ca_2SpkFq\ [cntCyc - 1{:} -1{:}\,cntCyc - 5])$
        % Dual Slope Function
        $\Delta w_{inh} = \boldsymbol{dIPSP}\ (MvAgCa_2SpkFq)$
        $w_{inh} \longleftarrow w_{inh} + \Delta w_{inh}$
    if $w_{inh} < 0$
        $w_{inh} \longleftarrow 0$
%EPSP
    $[w_{exc,i}, Ca_2SpkFq] = \boldsymbol{Ca_2\_Computation}\ (w_{exc,i}, \mathrm{Tactile\_Sti}, \mathrm{SigW})$

First, the intrinsic parameters (Table S3) and the pre-synaptic excitatory weights ($w_{exc,i}$) are initialized following the proposed CN receptive field model. Then, the synaptic weights are updated during the presentation of all $nSti$ (1385) stimuli used for the training phase, which also defines the number of training cycles (cntCyc) of the model. At each training iteration, a tactile stimulus ($Tactile\_Sti$) is selected, as described by function ***StimuliSelect***. Then, w_{inh} is set to 0.125, and its value will remain the same up to the fifth training cycle. The update of w_{inh} is given by a dual slope function zeroing at a preset setpoint of 20 Hz. The range of w_{inh} was initially set between -0.01 and 0.01 for a calcium channel firing rate (Ca_2SpkFq) ranging from 0 to 200 Hz (executed by the function $\boldsymbol{dIPSP}$). To avoid instability and damp of the adaptation rate, the moving average of the last five calcium channel firing rates ($MvAgCa_2SpkFq$) is used as input for the total inhibitory weight update. This mechanism was inspired by the physiological behavior of inhibitory interneurons and avoids extremes in calcium activity (excessive activity or no activity) (18, 28).

Finally, $\boldsymbol{Ca_2\_Computation}$ implements the cuneate nucleus intracellular dynamics, including the LVA and CAP channels activity, the CN membrane potential dynamics, and the excitatory weights potentiation, dependent on $A_{Loc_i}^{Ca^{2+}}$ and $A_{Tot}^{Ca^{2+}}$, as detailed in the following pseudo-code:

$\boldsymbol{Ca_2\_Computation}\ (w_{exc,i}, \mathrm{Tactile\_Sti}, \mathrm{SigW})$
    $Gsyn_{EPSP} = g_{max} * \boldsymbol{sum}\ (w_{exc,i} * \exp(-\tau(t - t^*)))$
    $Gsyn_{IPSP} = g_{max} * \boldsymbol{sum}\ (w_{inh} * \exp(-\tau(t - t^*)))$
    $[\Delta Vm, A_{Tot}^{Ca^{2+}}, Ca_2SpkFq] = \boldsymbol{CN\_EIF}(Gsyn_{EPSP}, Gsyn_{IPSP})$
    $A_{Loc_i}^{Ca^{2+}} = \mathbf{LocalCalciumActivity}\ (\mathrm{Tactile\_Sti})$
    $A_{Loc_i}^{Ca^{2+}} = A_{Loc_i}^{Ca^{2+}} - 0.75 * A_{Loc_i}^{Ca^{2+}}$
    $\Delta w_{exc,i} = \boldsymbol{W_{exc}\ update}(A_{Tot}^{Ca^{2+}}, A_{Loc_i}^{Ca^{2+}}, \mathrm{SigW})$
    $w_{exc,i} = w_{exc,i} + \Delta w_{exc,i}$

The $\boldsymbol{Ca_2\_Computation}$ function first calculates the total excitatory ($Gsyn_{EPSP}$) and inhibitory ($Gsyn_{IPSP}$) synaptic conductance (I_{syn}, Eq. 9). Then, the CN membrane potential dynamics (Eq. 5) and the calcium concentration in the CN membrane (Ca^{2+} - Eq. 12 ($\boldsymbol{CN\_EIF}$)) are computed. Ca^{2+} is used in the model to determine the CN total calcium activity ($A_{Tot}^{Ca^{2+}}$) as in Eq. 13. Thus, this function returnes the CN membrane potential dynamics (ΔVm) for tactile data, where $A_{Tot}^{Ca^{2+}}$ and Ca_2SpkFq are used as inputs for the update of w_{inh}. Since the potentiation of $w_{exc,i}$ is dependent $A_{Loc_i}^{Ca^{2+}}$ and $A_{Tot}^{Ca^{2+}}$, the local calcium activity ($A_{Loc_i}^{Ca^{2+}}$) of a synapse is given by Eq. 14 and **LocalCalciumActivity.**

The last function of the pseudo-code, $\boldsymbol{W_{exc}\ update}$, implements the update of the excitatory weights, as detailed by Eq. 15, where the SigW is the sigmoid function given by Eq. 16.