

SUPPLEMENTARY MATERIAL

for

NeurEx: digitalized neurological examination offers a novel high-resolution disability scale

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Fine-tuning of the rules for translating NeurEx into the four clinical scales.

We fine-tuned feature mapping and scale computation in the NeurEx algorithms to minimize differences between clinician-graded and App-computed disability scores. For example, SNRS rating for the motor examination of upper extremities as “normal, mild, moderate, and severe” was first mapped to upper extremities strength in the NeurEx App (i.e., NeurEx Panel 8 in Fig. S1). The SNRS rating “normal” was assigned a NeurEx strength rating 0 (i.e., no detectable weakness). To achieve a starting position for codification of SNRS ratings “mild, moderate, and severe” we divided the theoretical maximum of NeurEx strength rating for upper extremities (i.e., 50) equally between the remaining three semi-quantitative SNRS options: (i.e., SNRS “mild” deficit = NeurEx subscore 1-17, “moderate” deficit = 18-34, and “severe” deficit = 35-50). These cut-offs were adjusted in the iterative process when pilot data demonstrated that the NeurEx App consistently under- or overestimate disability in comparison to clinician’s ratings. In the results section, we compared differences between clinician- and NeurEx App-based disability scores using the algorithm that emerged from such iterative optimization.

Figure S1: 18 panels of the NeurEx App specifying the number of features, maximum score and % of total NeurEx score for each panel.

Figure S2: Bland-Altman plots for retrospectively (Clinician #1 vs Clinician #2) (**A**) and prospectively (App vs Clinician) (**B**) assigned values of EDSS, SNRS, AI, and IPEC. The y-axis displays the differences between measurement pairs and the x-axis displays the average values of measurement pairs. The dashed-grey line represents the mean of the measurement differences, while the dashed-red line represents the mean difference plus/minus two standard deviations of the differences. The individual points have been slightly jittered to avoid over-plotting.

Table S1: Demographic data

Video S1: An example of NeurEx App grading of a real-MS patient

Figure S1

Panel 1: Cognitive functions

features: **32**

Max score: **120**

% of NeurEx: **8.9**

Select signs/complaints/dysfunctions first, then assigned the dysfunction rating:

Pathological signs & complaints:

- Glabella
- Sucking reflex
- Grasp reflex
- Palmomentary reflex
- Gegenhalten
- Inappropriate affect
- Dysinhibition
- Problems with concentrating
- Problems with learning new material
- Difficulties with multitasking

R

L

- Problems with motor sequences
- Poor response inhibition on Go-no Go test

- Problems with motor sequences
- Poor response inhibition on Go-no Go test

Dysfunction rating

No pathological signs

- Mild
- Moderate
- Severe

Specific dysfunctions:

- Alexia (problems with reading)
- Agraphia (problems with writing)
- Abulia
- Acalculia
- Amnesia
- Broca's Aphasia
- Wernicke's Aphasia
- Anomic Aphasia
- Global Aphasia
- Ideomotor Apraxia
- Constructional Apraxia
- Spatial disorientation
- Temporal disorientation
- Corpus Callosum dysfunction

Dysfunction rating

No specific dysfunctions

- Mild
- Moderate
- Severe

- Cognitive fatigue
- Drowsiness
- Stupor
- Coma

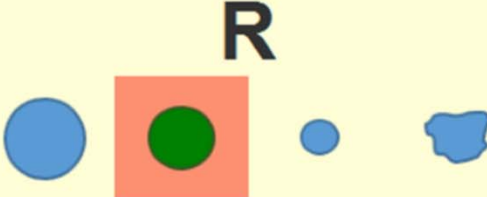
Panel 2: Eyes

features: 14

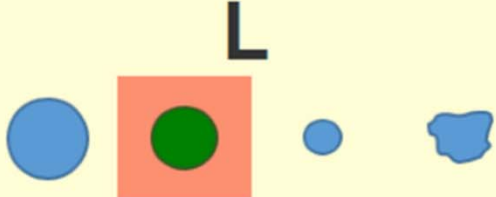
Max score: 30

% of NeurEx: 2.2

Pupils:



Reactive to direct light	Non-reactive
Reactive to contralateral light	Non-reactive
Reactive to accomodation	Non-reactive
Afferent pupillary defect present	



Reactive to direct light	Non-reactive
Reactive to contralateral light	Non-reactive
Reactive to accomodation	Non-reactive
Afferent pupillary defect present	

Vision:

Vision should be corrected with patient's glasses; please, indicate below:

- Corrected
- Uncorrected

R

20/20
20/25
20/30
20/40
20/50
20/70
20/100
20/200
20/400
20/800
Red color desaturation present

L

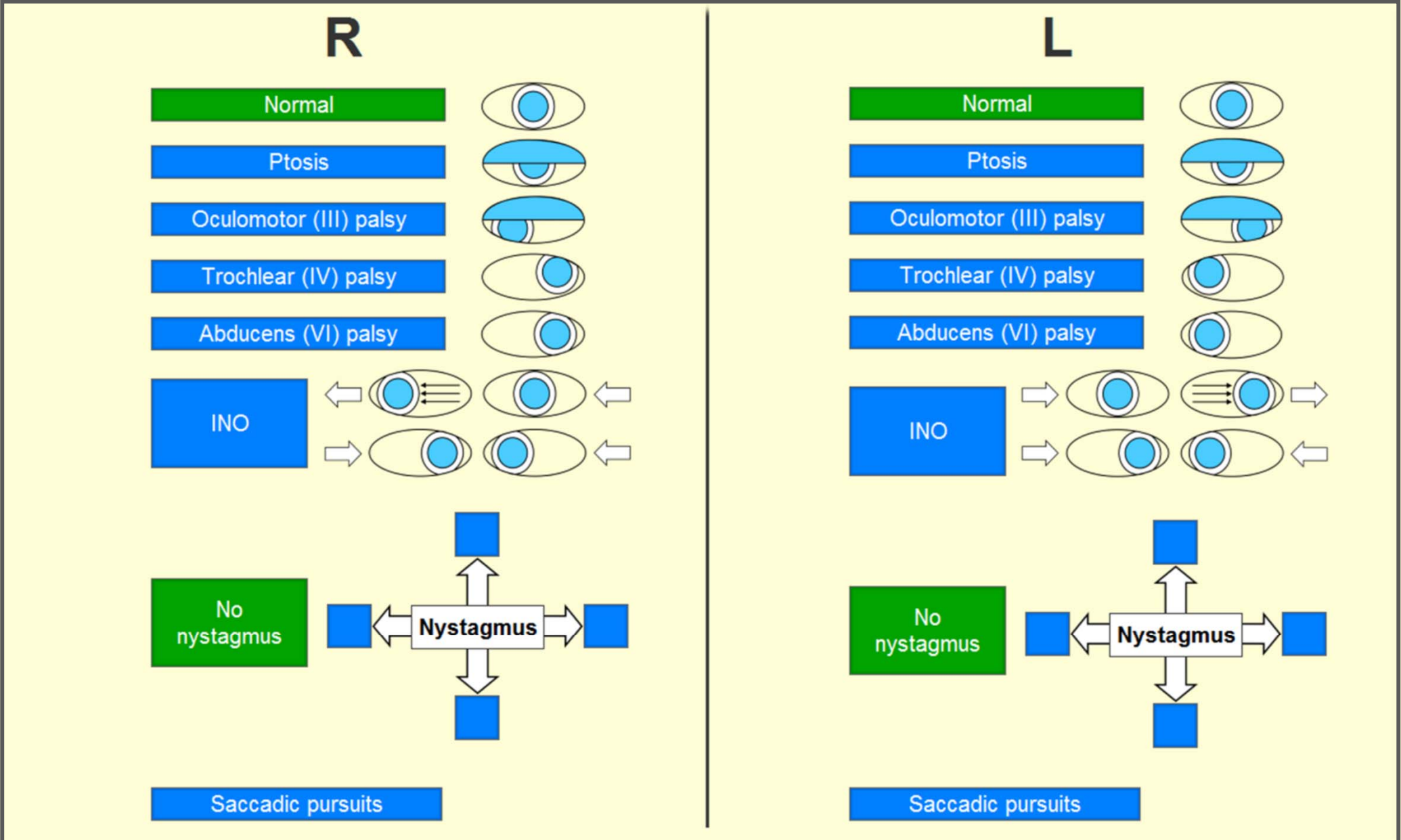
20/20
20/25
20/30
20/40
20/50
20/70
20/100
20/200
20/400
20/800
Red color desaturation present

Panel 3: Eye movements

features: 20

Max score: 30

% of NeurEx: 2.2



Panel 4: Visual fields

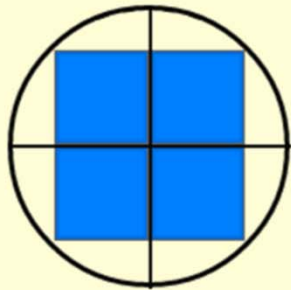
features: 12

Max score: 24

% of NeurEx: 1.8

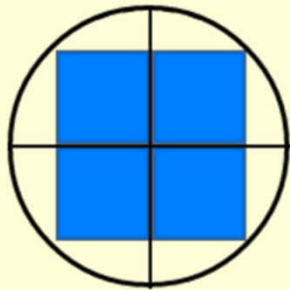
R

- Normal
- Small scotoma
- Large scotoma

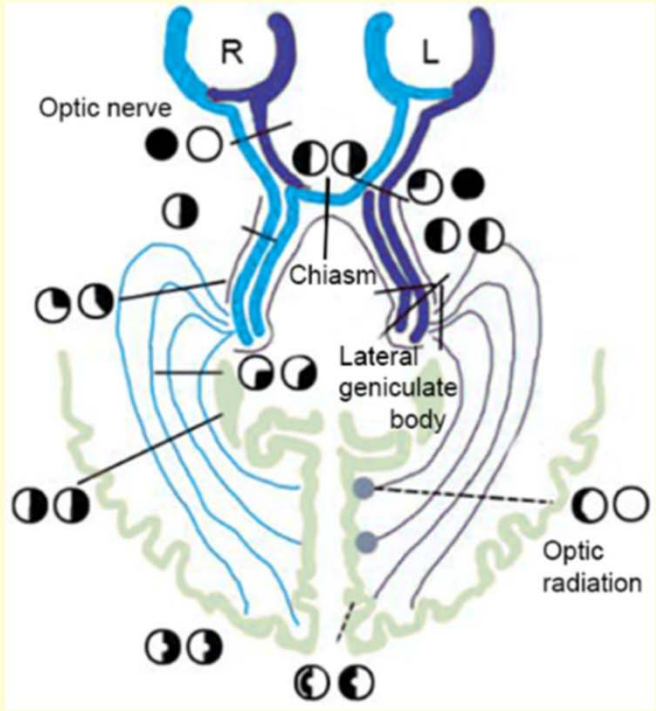


L

- Normal
- Small scotoma
- Large scotoma



Note:



Fundi:

R

- Normal
- Mild atrophy
- Severe atrophy

Note:

L

- Normal
- Mild atrophy
- Severe atrophy

Note:

Panel 5: Brainstem/Remaining cranial nerves

features: 45

Max score: 38

% of NeurEx: 2.8

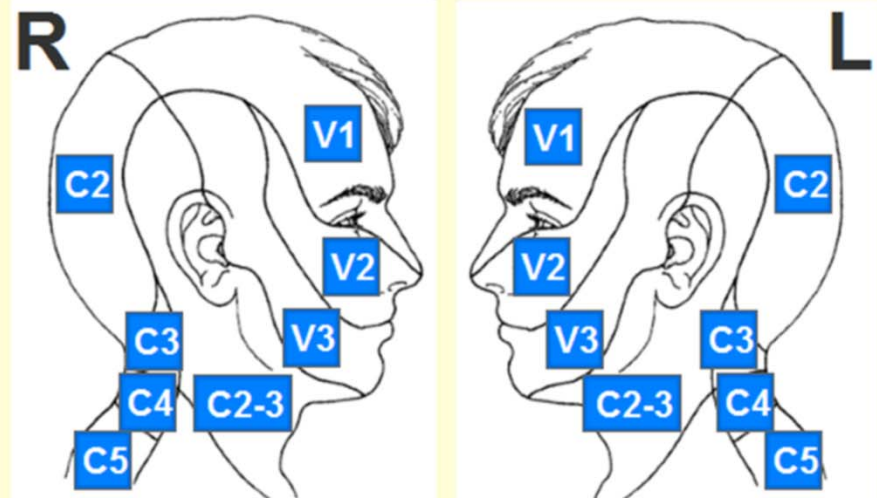
I. Olfactory:

- Normal smell
- Mild anosmia
- Severe anosmia

V. Trigeminal:

- Normal light touch sensation
- Abnormal light touch sensation
 - Mild
 - Moderate
 - Severe
- Normal pin prick sensation
- Abnormal pin prick sensation
 - Mild
 - Moderate
 - Severe

Select location first, then assigned the dysfunction rating:



VII. Facial:

- | | R | L |
|--|---|---|
| <input checked="" type="checkbox"/> Normal | <input type="checkbox"/> Paralysis - Upper | <input type="checkbox"/> Paralysis - Upper |
| | <input type="checkbox"/> Loss of corneal reflex | <input type="checkbox"/> Loss of corneal reflex |
| | <input type="checkbox"/> Xerophthalmia | <input type="checkbox"/> Xerophthalmia |
| | <input type="checkbox"/> Paralysis - Lower | <input type="checkbox"/> Paralysis - Lower |
| | <input type="checkbox"/> Loss of taste | <input type="checkbox"/> Loss of taste |
| | <input type="checkbox"/> Hyperacusis | <input type="checkbox"/> Hyperacusis |

Panel 6: Brainstem/Lower cranial nerves

features: **23**

Max score: **24**

% of NeurEx: **1.8**

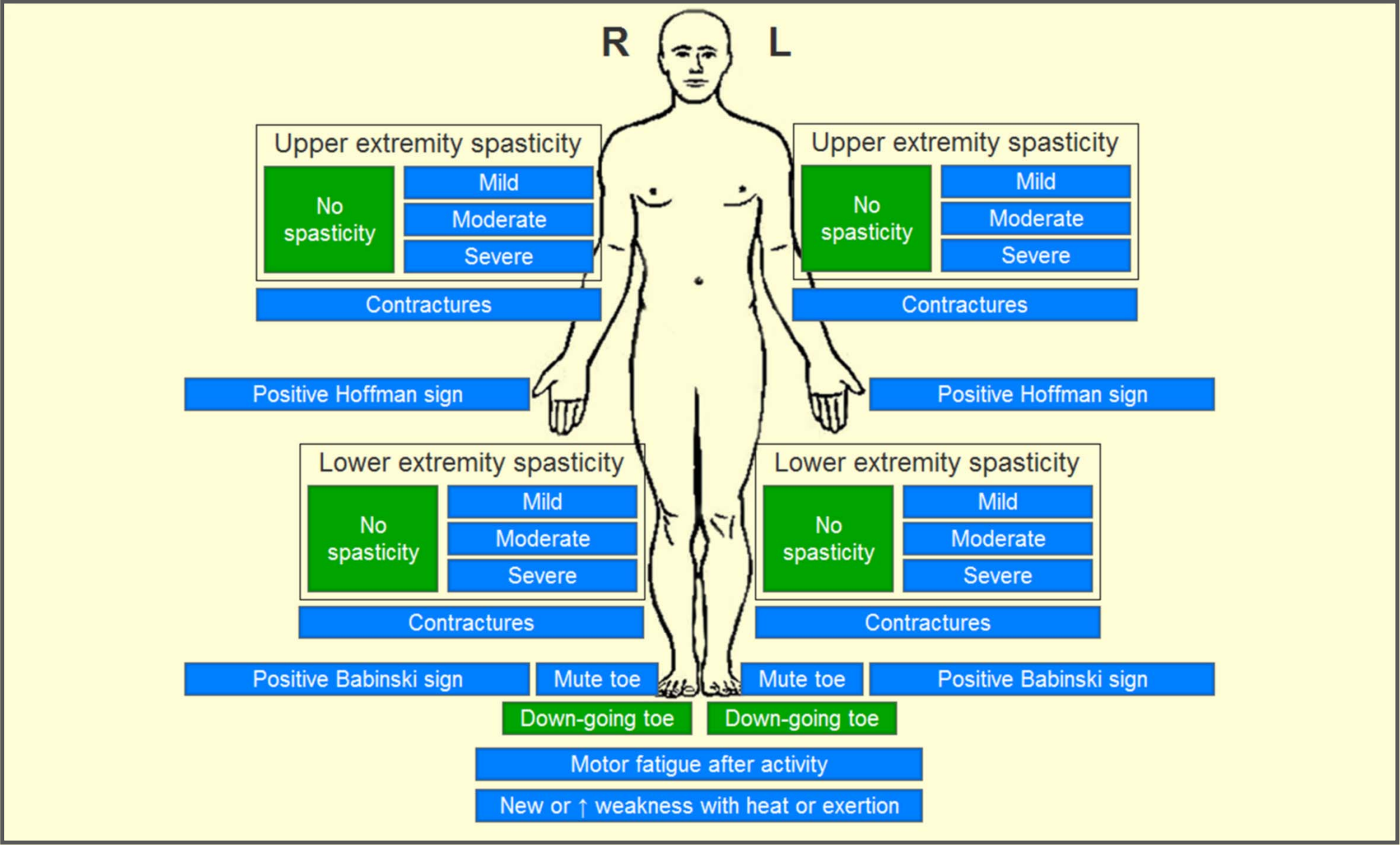
		R	L
VIII. Vestibulo-Cochlear:	Normal	Decreased hearing Tinnitus or Weber/Rinne Abnormality	Decreased hearing Tinnitus or Weber/Rinne Abnormality
		Vertigo	
IX. Glosso-Pharyngeal:	Normal	Swallowing difficulties - liquids Loss of gag reflex Swallowing difficulties - solids Loss of carotid sinus reflex	
X. Vagus:	Normal	Dysphonia Loss of cough reflex Dysarthria (palatal) Dysautonomia	
		R	L
XI. Spinal accessory:	Normal	Sternocleidomastoid palsy Trapezius (shoulder) palsy	Sternocleidomastoid palsy Trapezius (shoulder) palsy
		R	L
XII. Hypoglossal:	Normal	Tongue deviation to R Tongue atrophy Tongue fasciculations	Tongue deviation to L Tongue atrophy Tongue fasciculations

Panel 7: Motor exam: Pyramidal signs & Motor fatigue

features: 14

Max score: 28

% of NeurEx: 2.1

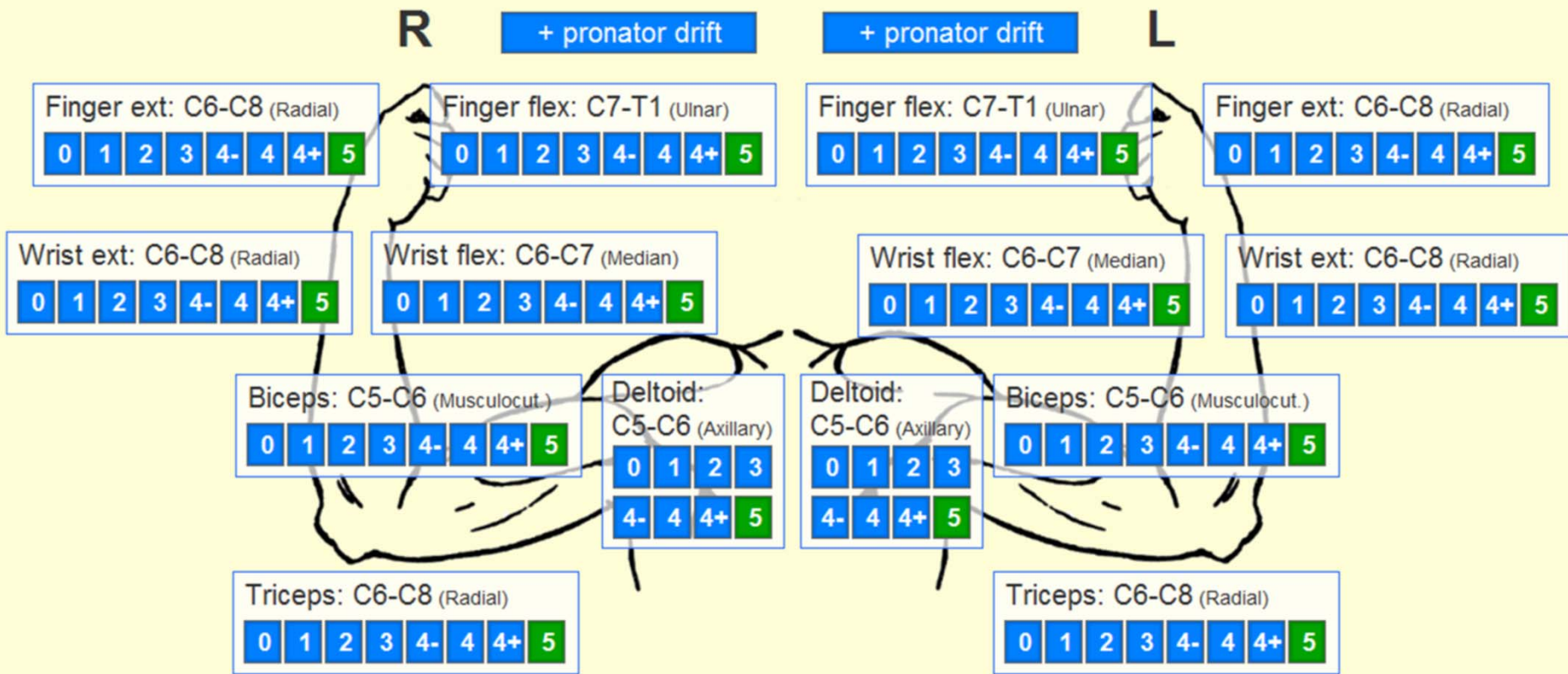


Panel 8: Motor exam: Pyramidal signs & Motor fatigue

features: **16**

Max score: **100**

% of NeurEx: **7.4**



Rating of strength:

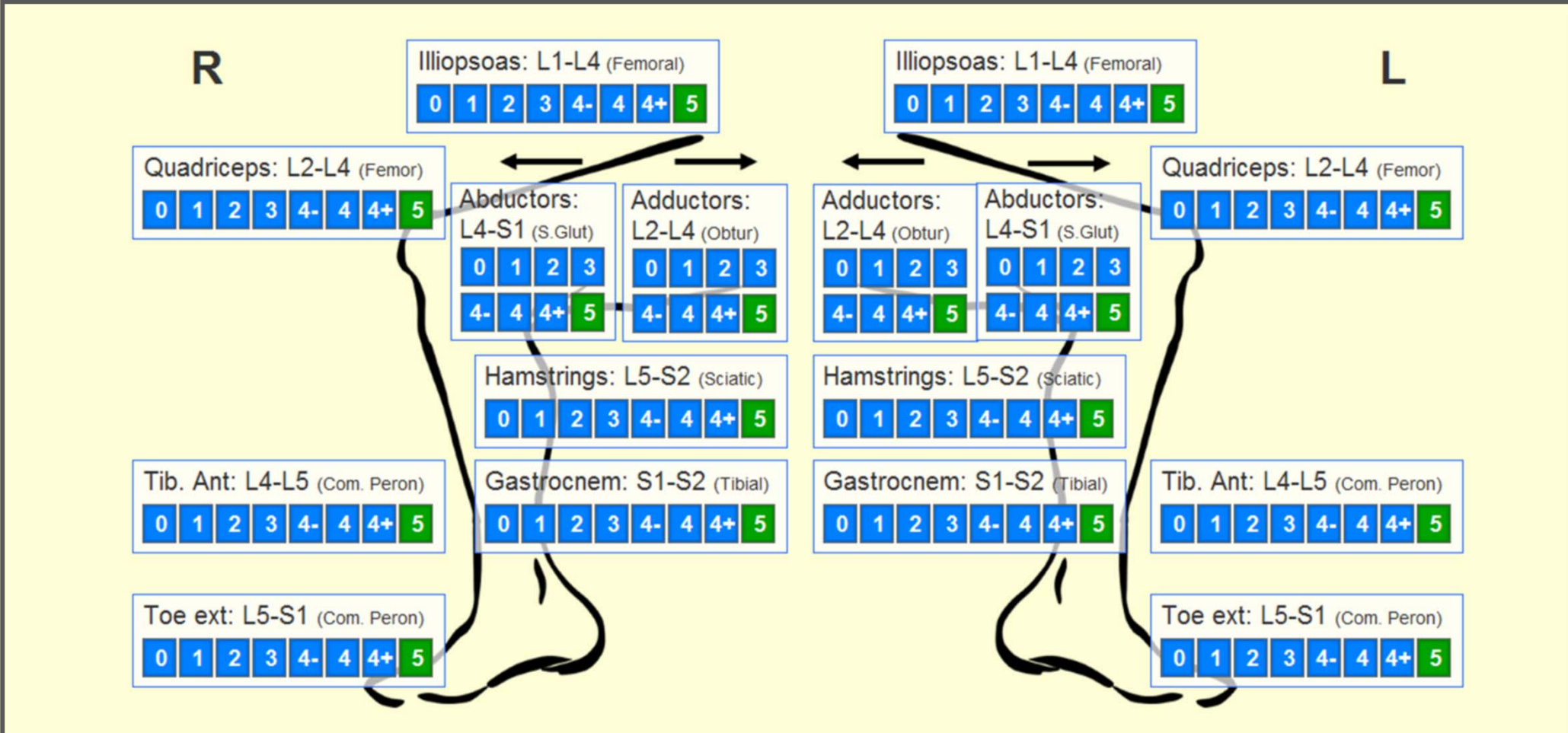
0 No movement/no contraction	3 Movement against gravity but no resistance	4+ Strong movement against resistance
1 No movement/+contraction	4- Mild movement against resistance	5 Normal strength
2 Partial movement not against gravity	4 Moderate movement against resistance	

Panel 9: Motor exam: Pyramidal signs & Motor fatigue

features: 16

Max score: 112

% of NeurEx: 8.3



Rating of strength:

- | | | |
|---|---|--|
| 0 No movement/no contraction | 3 Movement against gravity but no resistance | 4+ Strong movement against resistance |
| 1 No movement/+contraction | 4- Mild movement against resistance | 5 Normal strength |
| 2 Partial movement not against gravity | 4 Moderate movement against resistance | |

Panel 10: Motor exam: Reflexes

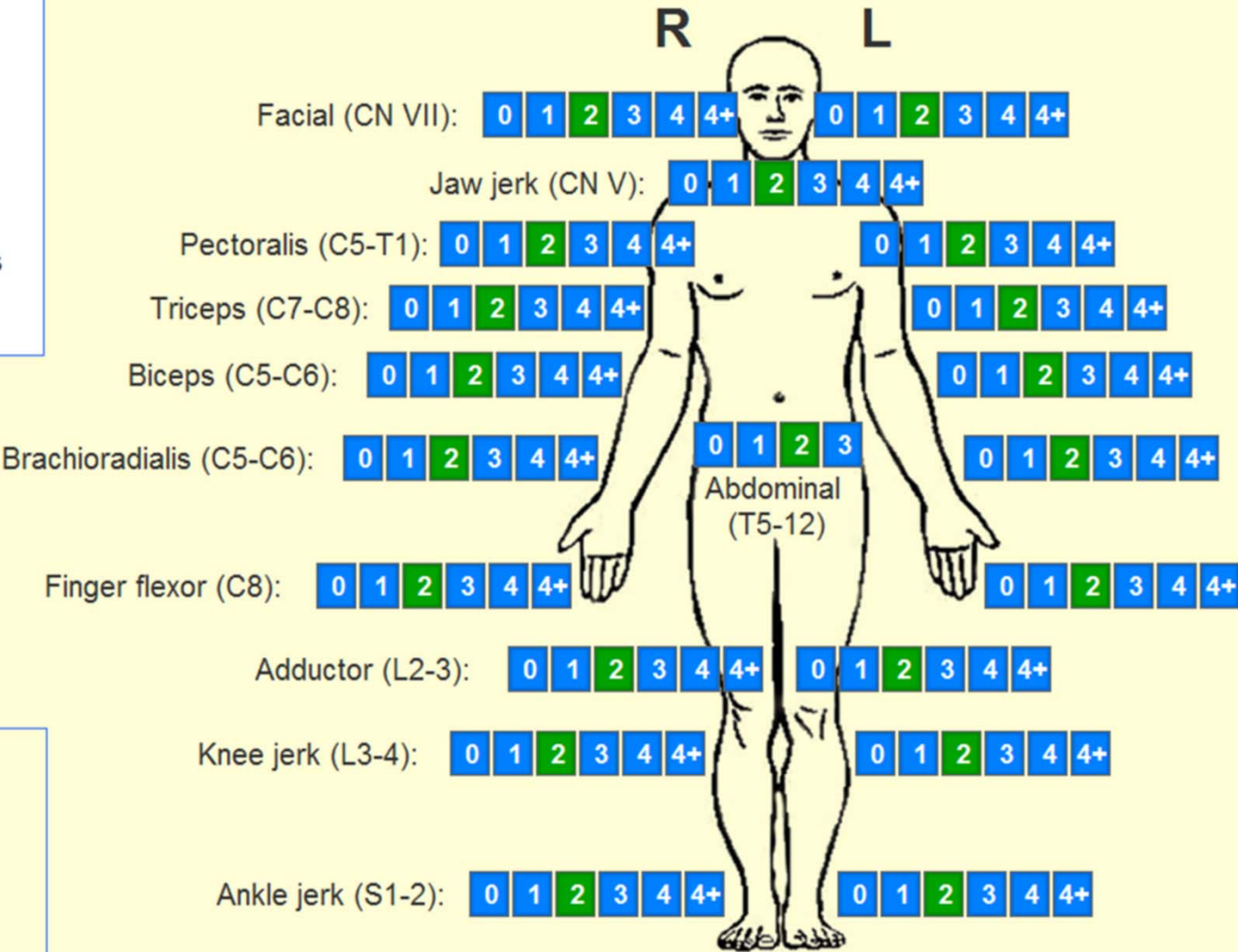
features: **22**

Max score: **41**

% of NeurEx: **3.0**

Rating of reflexes:

- 0 Absent
- 1 Decreased
- 2 Normal
- 3 Exaggerated
- 4 Un-sustained clonus
- 4+ Sustained clonus



Non-routine reflexes:

Cremasteric (L1-2):

0 1 2 3

Anal (S3-4):

0 1 2 3

Panel 11: Motor exam: Reflexes

features: **24**

Max score: **72**

% of NeurEx: **4.0**

Right Upper Extremity

No atrophy	Mild
	Moderate
	Severe

Left Upper Extremity

No atrophy	Mild
	Moderate
	Severe

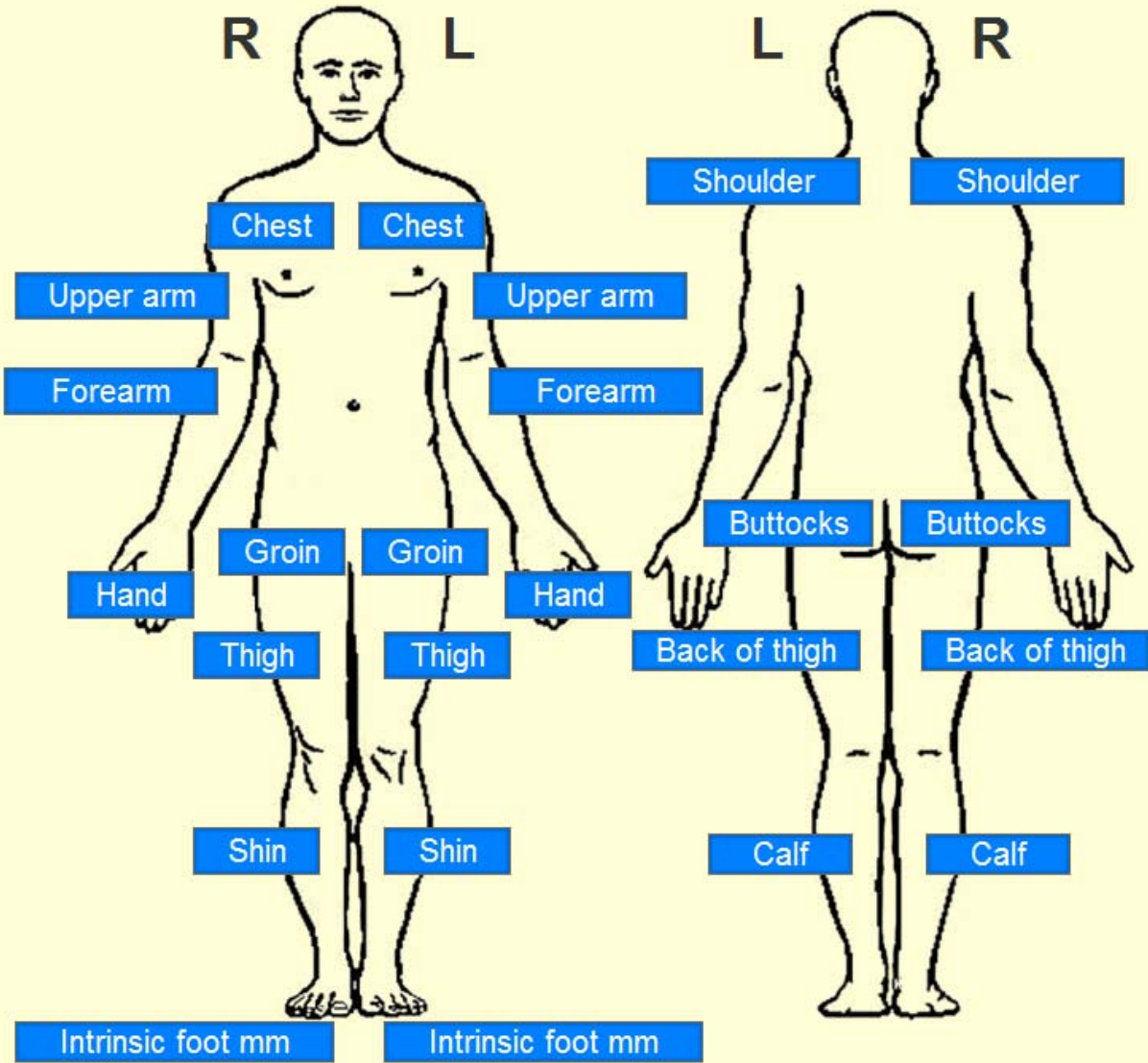
Right Lower Extremity

No atrophy	Mild
	Moderate
	Severe

Left Lower Extremity

No atrophy	Mild
	Moderate
	Severe

Select location first, then assigned the dysfunction rating:



Panel 12: Motor exam: Reflexes

features: 20

Max score: 60

% of NeurEx: 4.4

For each limb select dysfunction(s) first, then assigned dysfunction rating:

"Unable to test" on upper extremities will replicate scoring from the opposite limb. Please, make sure you grade the opposite limb before clicking "Unable to test".

R L

Cerebellar speech

Ataxia	Tremor
Dysdiadochokinesis	
Past-pointing	
Rebound	
Dysfunction rating	
Normal	Mild
	Moderate
	Severe

Unable to test

Ataxia	Tremor
Dysdiadochokinesis	
Past-pointing	
Rebound	
Dysfunction rating	
Normal	Mild
	Moderate
	Severe

Unable to test

Ataxia	Tremor
Dysdiadochokinesis	
Rebound	
Dysfunction rating	
Normal	Mild
	Moderate
	Severe

Unable to test

Ataxia	Tremor
Dysdiadochokinesis	
Rebound	
Dysfunction rating	
Normal	Mild
	Moderate
	Severe

Unable to test

Truncal ataxia with open eyes

"Unable to test" on lower extremities will replicate scoring from the corresponding upper limb. Please, make sure you grade the upper limb before clicking "Unable to test".

Panel 13: Sensory exam: Dermatome distribution

features: 208

Max score: 156

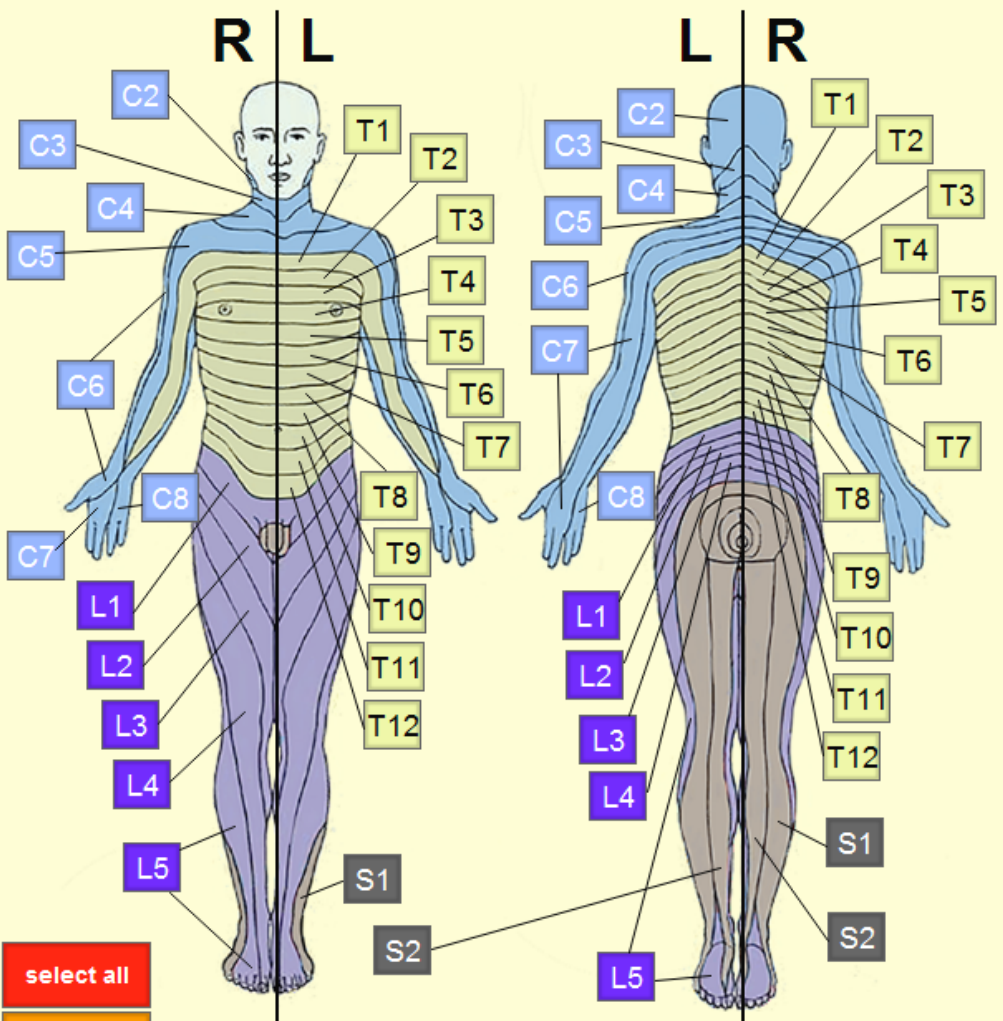
% of NeurEx: 11.6

Normal

Abnormal: Dermatome distribution

Abnormal: Stocking-gloves distribution

Select location first, then assigned the dysfunction rating:



Abnormal light touch sensation

Normal light touch sensation	R	C2	<input type="checkbox"/>	C2	<input type="checkbox"/>	L
		C3	<input type="checkbox"/>	C3	<input type="checkbox"/>	
		C4	<input type="checkbox"/>	C4	<input type="checkbox"/>	
	T1	C5	<input type="checkbox"/>	C5	<input type="checkbox"/>	T1
	T2	C6	<input type="checkbox"/>	C6	<input type="checkbox"/>	T2
	T3	C7	<input type="checkbox"/>	C7	<input type="checkbox"/>	T3
	T4	C8	<input type="checkbox"/>	C8	<input type="checkbox"/>	T4
	T5					T5
	T6					T6
	T7					T7
	T8					T8
	T9	L1	<input type="checkbox"/>	L1	<input type="checkbox"/>	T9
	T10	L2	<input type="checkbox"/>	L2	<input type="checkbox"/>	T10
	T11	L3	<input type="checkbox"/>	L3	<input type="checkbox"/>	T11
	T12	L4	<input type="checkbox"/>	L4	<input type="checkbox"/>	T12
		L5	<input type="checkbox"/>	L5	<input type="checkbox"/>	
		S1	<input type="checkbox"/>	S1	<input type="checkbox"/>	
		S2	<input type="checkbox"/>	S2	<input type="checkbox"/>	

Mild

Moderate

Severe

Abnormal pin prick sensation

Normal pin prick sensation	R	C2	<input type="checkbox"/>	C2	<input type="checkbox"/>	L
		C3	<input type="checkbox"/>	C3	<input type="checkbox"/>	
		C4	<input type="checkbox"/>	C4	<input type="checkbox"/>	
	T1	C5	<input type="checkbox"/>	C5	<input type="checkbox"/>	T1
	T2	C6	<input type="checkbox"/>	C6	<input type="checkbox"/>	T2
	T3	C7	<input type="checkbox"/>	C7	<input type="checkbox"/>	T3
	T4	C8	<input type="checkbox"/>	C8	<input type="checkbox"/>	T4
	T5					T5
	T6					T6
	T7					T7
	T8					T8
	T9	L1	<input type="checkbox"/>	L1	<input type="checkbox"/>	T9
	T10	L2	<input type="checkbox"/>	L2	<input type="checkbox"/>	T10
	T11	L3	<input type="checkbox"/>	L3	<input type="checkbox"/>	T11
	T12	L4	<input type="checkbox"/>	L4	<input type="checkbox"/>	T12
		L5	<input type="checkbox"/>	L5	<input type="checkbox"/>	
		S1	<input type="checkbox"/>	S1	<input type="checkbox"/>	
		S2	<input type="checkbox"/>	S2	<input type="checkbox"/>	

Mild

Moderate

Severe

Abnormal temperature sensation

Normal temperature sensation	R	C2	<input type="checkbox"/>	C2	<input type="checkbox"/>	L
		C3	<input type="checkbox"/>	C3	<input type="checkbox"/>	
		C4	<input type="checkbox"/>	C4	<input type="checkbox"/>	
	T1	C5	<input type="checkbox"/>	C5	<input type="checkbox"/>	T1
	T2	C6	<input type="checkbox"/>	C6	<input type="checkbox"/>	T2
	T3	C7	<input type="checkbox"/>	C7	<input type="checkbox"/>	T3
	T4	C8	<input type="checkbox"/>	C8	<input type="checkbox"/>	T4
	T5					T5
	T6					T6
	T7					T7
	T8					T8
	T9	L1	<input type="checkbox"/>	L1	<input type="checkbox"/>	T9
	T10	L2	<input type="checkbox"/>	L2	<input type="checkbox"/>	T10
	T11	L3	<input type="checkbox"/>	L3	<input type="checkbox"/>	T11
	T12	L4	<input type="checkbox"/>	L4	<input type="checkbox"/>	T12
		L5	<input type="checkbox"/>	L5	<input type="checkbox"/>	
		S1	<input type="checkbox"/>	S1	<input type="checkbox"/>	
		S2	<input type="checkbox"/>	S2	<input type="checkbox"/>	

Mild

Moderate

Severe

Abnormal proprioception

Normal proprioception	R	C2	<input type="checkbox"/>	C2	<input type="checkbox"/>	L
		C3	<input type="checkbox"/>	C3	<input type="checkbox"/>	
		C4	<input type="checkbox"/>	C4	<input type="checkbox"/>	
	T1	C5	<input type="checkbox"/>	C5	<input type="checkbox"/>	T1
	T2	C6	<input type="checkbox"/>	C6	<input type="checkbox"/>	T2
	T3	C7	<input type="checkbox"/>	C7	<input type="checkbox"/>	T3
	T4	C8	<input type="checkbox"/>	C8	<input type="checkbox"/>	T4
	T5					T5
	T6					T6
	T7					T7
	T8					T8
	T9	L1	<input type="checkbox"/>	L1	<input type="checkbox"/>	T9
	T10	L2	<input type="checkbox"/>	L2	<input type="checkbox"/>	T10
	T11	L3	<input type="checkbox"/>	L3	<input type="checkbox"/>	T11
	T12	L4	<input type="checkbox"/>	L4	<input type="checkbox"/>	T12
		L5	<input type="checkbox"/>	L5	<input type="checkbox"/>	
		S1	<input type="checkbox"/>	S1	<input type="checkbox"/>	
		S2	<input type="checkbox"/>	S2	<input type="checkbox"/>	

Mild

Moderate

Severe

Panel 13: Sensory exam: Stocking-glove distribution

features: **72**

Max score: **156**

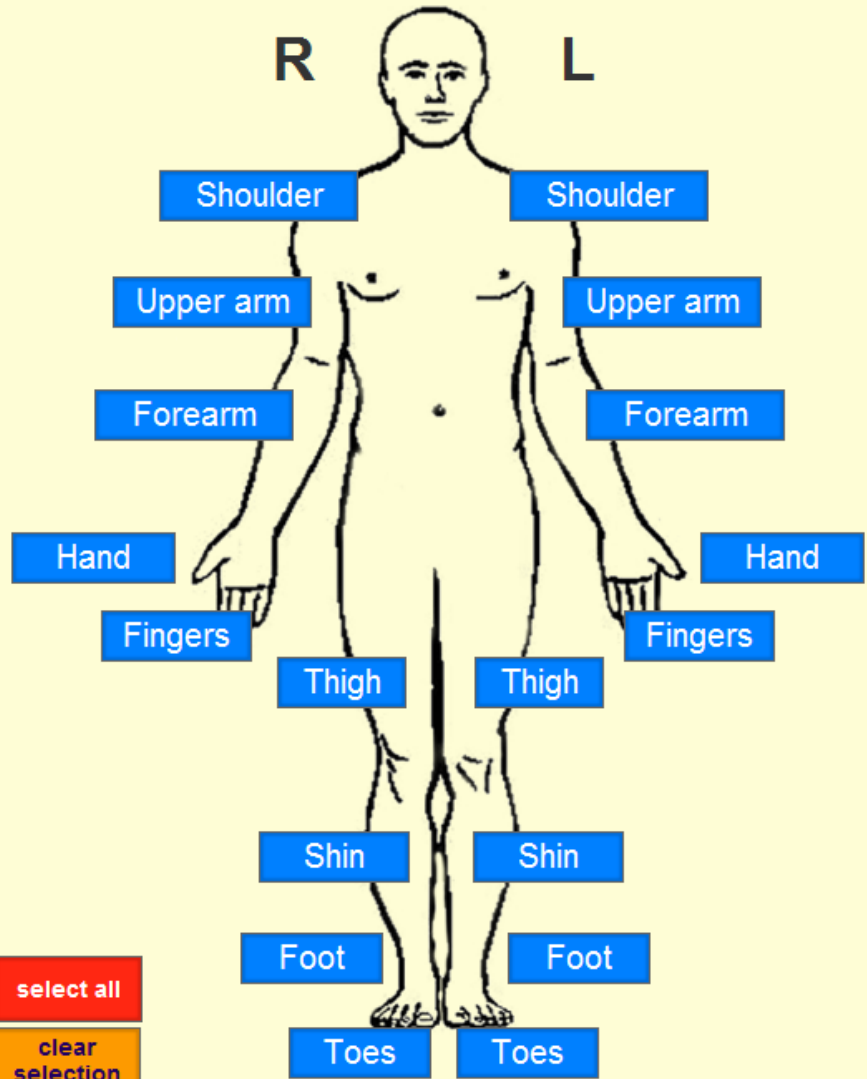
% of NeurEx: **11.6**

Normal

Abnormal: Dermatome distribution

Abnormal: Stocking-gloves distribution

Select location first, then assigned the dysfunction rating:



select all

clear selection

Abnormal light touch sensation

Normal light touch sensation

Mild

Moderate

Severe

Abnormal pin prick sensation

Normal pin prick sensation

Mild

Moderate

Severe

Abnormal temperature sensation

Normal temperature sensation

Mild

Moderate

Severe

Abnormal proprioception

Normal proprioception

Mild

Moderate

Severe

Panel 14: Sensory exam: Pains/Paresthesias

features: **56**

Max score: **152**

% of NeurEx: **11.3**

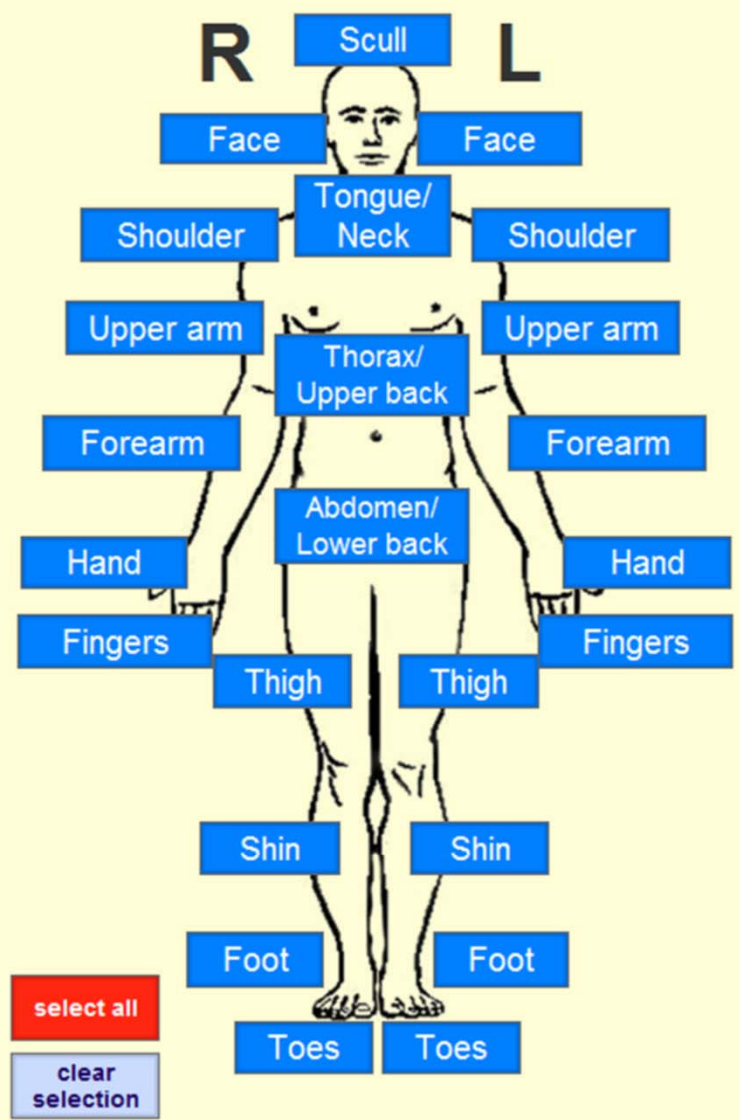
Abnormal sensation:

- Paresthesias
- Pains

Vibration sense: quantitative 128 Hz (sec)

	R	L
Fingers:	25	25
Wrists:	25	25
Toes:	15	15
Knees:	15	15

Select location first, then assigned the dysfunction rating:



Paresthesias rating:

- No dysfunction
- Mild
- Moderate
- Severe

Pains rating:

- No dysfunction
- Mild
- Moderate
- Severe

Panel 15: Positive phenomena

features: 36

Max score: 216

% of NeurEx: 16.0

Select abnormalities and location first, then assigned dysfunction rating:

Abnormal movements:

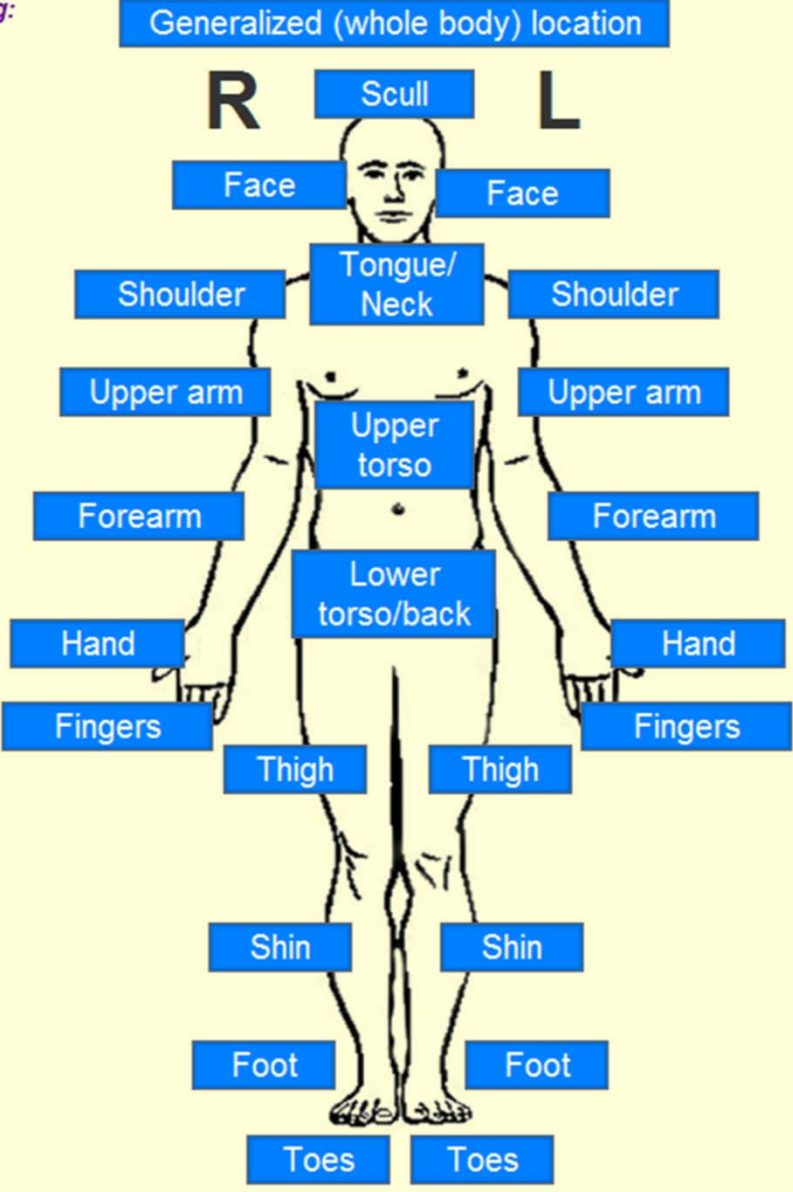
- L'hermittes sign
- Flexor/Extensor spasms
- Resting tremor
- Choreiform/Athetoid movements
- Tics
- Hemibalismus
- Myoclonus
- Seizures
- Dystonia

Abnormal signs:

- Myotonia
- Tetany
- Fibrillations/Fasciculations

Dysfunction rating

No abnormal positive phenomena	Mild
	Moderate
	Severe



clear selection

Panel 16: Stance & Gait

features: 16

Max score: 59

% of NeurEx: 4.4

Select dysfunction(s) first, then assigned dysfunction rating:

Cerebellar gait: wide-based, high steps	Dysfunction rating:	Normal
Sensory ataxia		Mild
Spastic gait		Moderate
		Severe

Tandem gait step-outs (out of 10 steps):

0 1 2 3 4 5 6 7 8 9 10 Unable

Positive Romberg sign

Standing/Transfer:

Able

Unable

Jumping:

Each leg independently

R-leg only

L-leg only

Legs together only

With support only

Unable to jump

Falls:

None

Few per year

Few per month

Few per week

Few per day

No injury

With injury

Walking distance:

> 5 miles

1-5 miles

> 500 meters

> 300 meters

> 200 meters

> 100 meters

< 100 meters

< 5 steps

Unable to walk

Assisting device:

No AFO or Bioness

1 AFO or Bioness

Bilateral AFO or Bioness

No other assisting device

Cane/unilateral support

Walker/bilater support

Wheelchair/Scooter

Bed/Unable to sit unsupported

Running:

Normal

Slow/fatigued

Unable to run

Climbing stairs:

Normal

With support only

Unable

Walking on heels:

Able

Unable

Walking on toes:

Able

Unable

Panel 17: Bowel, Bladder, Sexual and Autonomic Functions

features: **24**

Max score: **87**

% of NeurEx: **6.4**

Select dysfunction(s) first, then assigned dysfunction rating:

Bladder abnormalities:		Dysfunction rating
Frequency		No bladder abnormalities
Urgency		
Hesitancy		Mild
Incomplete emptying		Moderate
Occasional incontinence		Severe
Permanent incontinence	Self-catheterization	Idwelling catheter

Select dysfunction(s) first, then assigned dysfunction rating:

Bowel abnormalities:		Dysfunction rating
Urgency		No bowel abnormalities
Constipation		
Diarrhea		Mild
Occasional incontinence		Moderate
		Severe
Permanent incontinence/ Inability to move bowels		

Select dysfunction(s) first, then assigned dysfunction rating:

Sexual abnormalities:		Dysfunction rating
Lack of libido		No sexual abnormalities
Problems with sensation		
Problems with arousal		Mild
Problems with erection		Moderate
Problems with erection		Severe
Problems with ejaculation		
Problems with lubrication		
Problems with orgasm		

Select dysfunction(s) first, then assigned dysfunction rating:

Autonomic abnormalities:		Dysfunction rating
Problems with sweating		No autonomic abnormalities
Orthostatic hypotension		
Fainting		Mild
		Moderate
Edema and trophic changes		Severe

Panel 18: Summary

Kurtzke Functional Systems Scores (FSS)

Pyramidal Functions	0
Cerebellar Functions	0
Brainstem Functions	0
Sensory Function	0
Bowel and Bladder Function	0
Visual Function	0
Cerebral (or Mental) Functions	0
EDSS	0

The IPEC Disability Scale

Motor Score: Gait	0
Motor Score: Running	0
Motor Score: Climbing Stairs	0
Motor Score: Jumping	0
Spasticity Score: Clonus	0
Spasticity Score: Flexor/Extensor Spasm	0
Sensory Score: Paresthesias	0
Lumbar and/or Lower Limb Pain	0
Sphincter Score: Bladder Control	0
Sphincter Score: Bowel Continence	0
IPEC	0

Hauser Ambulation Index 0

Scripps Neurological Rating Scale

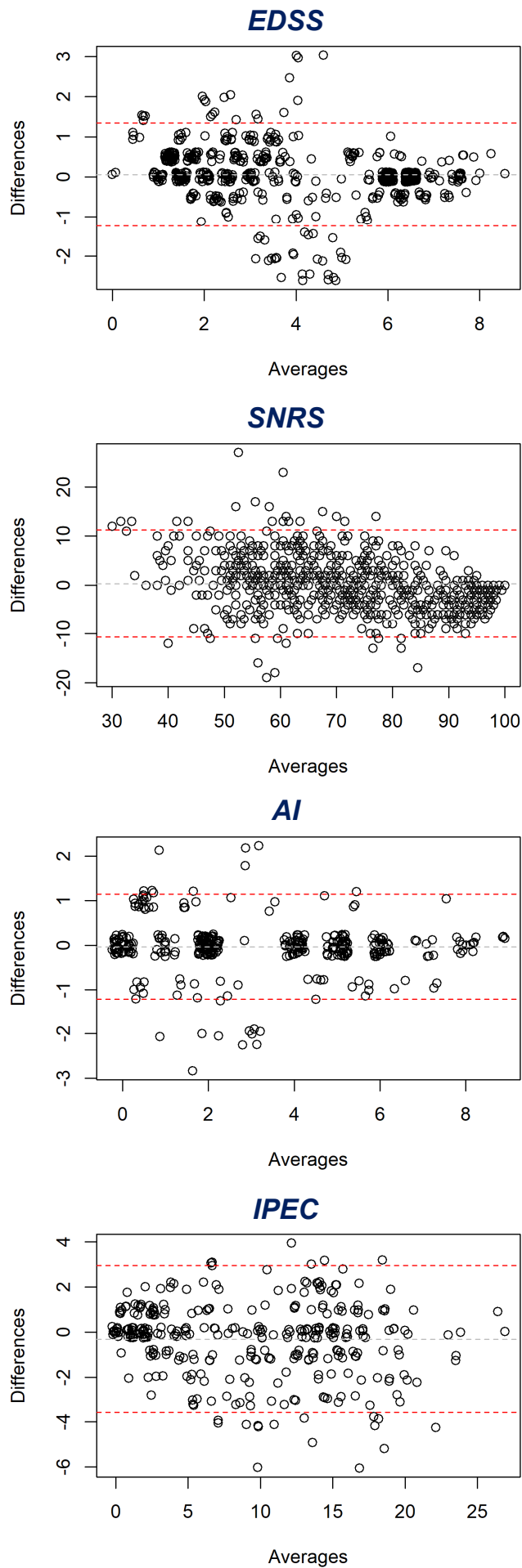
Mentation and Mood	10	Normal
Cranial Nerves: Visual Acuity	5	Normal
Cranial Nerves: Fields, Disc, Pupils	6	Normal
Cranial Nerves: Eye Movements	5	Normal
Cranial Nerves: Nystagmus	5	Normal
Lower Cranial Nerves	5	Normal
Motor: RU	5	Normal
Motor: LU	5	Normal
Motor: RL	5	Normal
Motor: LL	5	Normal
DTRs: UE	4	Normal
DTRs: LE	4	Normal
Babinsky: R; L (2 each)	4	Normal
Sensory: RU	3	Normal
Sensory: LU	3	Normal
Sensory: RL	3	Normal
Sensory: LL	3	Normal
Cerebellar: UE	5	Normal
Cerebellar: LE	5	Normal
Gait; Trunk and Balance	10	Normal
Bladder/Bowel/Sexual Dysfunction	0	Normal

Scripps NRS 100

0.0/120	0%	1. Cognitive functions
0.0/30	0%	2. Eyes
0.0/30	0%	3. Eye movements
0.0/24	0%	4. Visual fields
0.0/38	0%	5. Brainstem/Remaining cran nerves
0.0/24	0%	6. Brainstem/Lower cran nerves
0.0/28	0%	7. Pyramidal signs & Motor fatigue
0.0/100	0%	8. Upper extremities strength
0.0/112	0%	9. Lower extremities strength
0.0/41	0%	10. Reflexes
0.0/72	0%	11. Muscle atrophy
0.0/60	0%	12. Cerebellar functions
0.0/156	0%	13. Sensory exam: dermatome/S-G
0.0/152	0%	14. Sensory exam: pains, paresthesias
0.0/216	0%	15. Positive phenomena
0.0/59	0%	16. Stance & Gait
0.0/87	0%	17. Bowel, Bladder, Sexual functions
0.0/1349	0%	NeurEx total

Figure S2

A



B

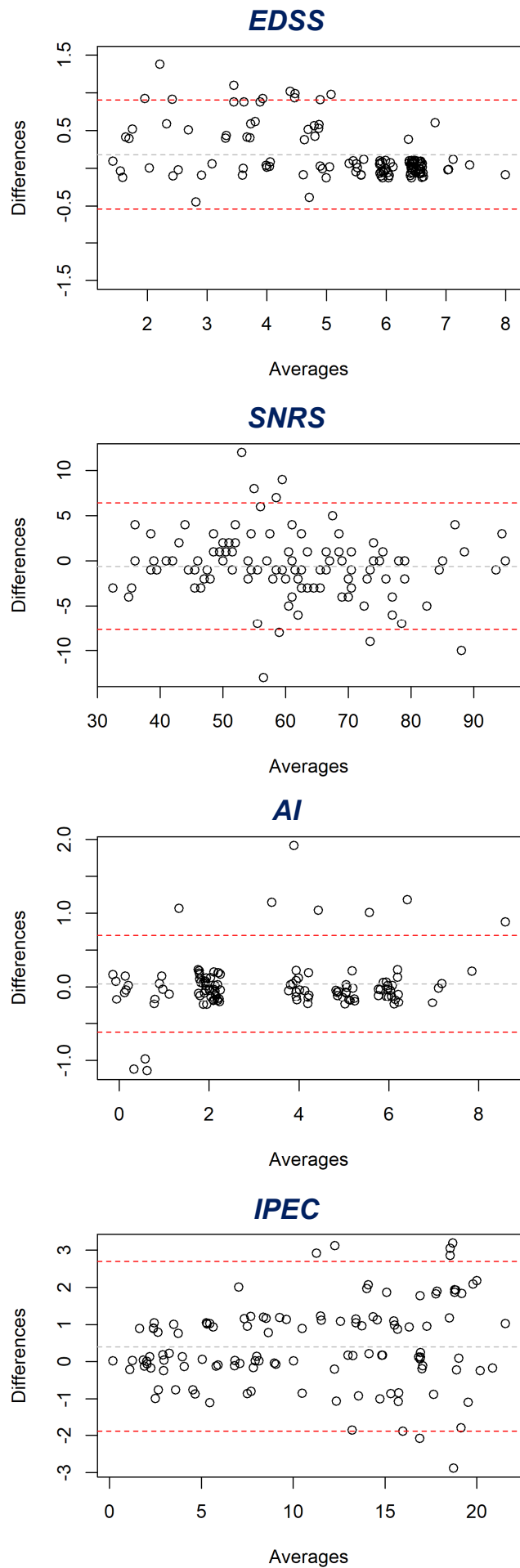


Table S1: Demographic data

diagnosis	<i>RR-MS</i>	<i>PP-MS</i>	<i>SP-MS</i>	<i>CIS/RIS</i>
N (F/M)	48/40	50/58	55/6	3/2
Age				
mean	40.1	54.8	52.9	44.1
SD	10.3	8.6	10	10
range	18.3 - 67.9	25.3 - 74.7	22 - 70	26.8 - 52.6
Disease Duration				
mean	5.9	11.6	21.2	0.7
SD	7.8	8.1	9.8	0.8
range	0 - 36.2	0.2 - 38.7	1.4 - 42.3	0.1 - 1.9
EDSS				
mean	2	5.1	5.7	1.9
SD	1.3	1.7	1.3	1.2
range	0 - 6	1.5 - 8	1.5 - 7.5	0 - 3
SNRS				
mean	89	68	62	88
SD	10	13	11	8
range	54 - 100	27 - 98	36 - 87	80 - 100

SD = standard deviation