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Validity and reliability of an electromyography-based upper limb assessment quantifying selective voluntary motor control in children with upper motor neuron lesions

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Abstract

Current clinical assessments evaluating selective voluntary motor control are measured on an ordinal scale. We combined the Selective Control of the Upper Extremity Scale (SCUES) with surface electromyography to develop a more objective and interval-scaled assessment of selective voluntary motor control. The resulting Similarity Index (SI) quantifies the similarity of muscle activation patterns. We aimed to evaluate the validity and reliability of this new assessment named SI_{SCUES} (Similarity Index of the SCUES) in children with upper motor neuron lesions. Thirty-three patients (12.2 years [8.8;14.9]) affected by upper motor neuron lesions with mild to moderate impairments and 31 typically developing children (11.6 years [8.5;13.9]) participated. We calculated reference muscle activation patterns for the SI_{SCUES} using data of 33 neurologically healthy adults (median [1st; 3rd quantile]: 32.5 [27.9; 38.3]). We calculated Spearman correlations (ρ) between the SI_{SCUES} and the SCUES and the Manual Ability Classification System (MACS) to establish

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concurrent validity. Discriminative validity was tested by comparing scores of patients and healthy peers with a robust ANCOVA. Intraclass correlation coefficients$_{2,1}$ and minimal detectable changes indicated relative and absolute reliability. The SI_{SCUES} correlates strongly with SCUES ($\rho = 0.76$, $p < 0.001$) and moderately with the MACS ($\rho = -0.58$, $p < 0.001$). The average SI_{SCUES} can discriminate between patients and peers. The intraclass correlation coefficient$_{2,1}$ was 0.90 and the minimal detectable change was 0.07 (8% of patients' median score). Concurrent validity, discriminative validity, and reliability of the SI_{SCUES} were established. Further studies are needed to evaluate whether it is responsive enough to detect changes from therapeutic interventions.

Keywords
Selective motor control, upper motor neuron lesion, cerebral palsy, outcome assessment, surface electromyography, psychometric properties

Introduction

Children and adolescents with upper motor neuron lesions, such as cerebral palsy (CP), stroke, and traumatic brain injury, can be affected by many signs, which contribute to their disability. One of those signs is the lack of selective voluntary motor control (SVMC), which is defined as the *"impaired ability to isolate the activation of muscles in a selected pattern in response to demands of a voluntary posture or movement."*[1]

The importance of SVMC for daily life activities has been recognized both for the lower[2,3] and the upper extremities.[4] Despite this and the fact that a lack of SVMC is a typical feature in children affected by upper motor neuron lesions, assessments specifically tailored towards measuring reduced SVMC have only recently been established.[5,6] However, while these clinical tools[7–9] measuring SMVC are easily performed and need little equipment, they are measured on an ordinal scale. For example, the Selective Control of the Upper Extremity Scale (SCUES) scores the selectivity of shoulder, elbow, forearm, wrist, and finger movements on a scale from 0 (no selective movement control) to 3 (normal selective movement control).[8] The ordinal scale might reduce the sensitivity to changes induced by therapeutic or surgical interventions. Furthermore, these clinical SMVC measures evaluate the overall joint movement and not the underlying muscle activations. Thus a maximal score could be achieved through multiple motor strategies.[5]

To improve the quantification of functionally relevant measures, it has been proposed to use kinematic/kinetic[10] and neurophysiology-based[5,11] methods. In general, the additional information may help make clinical tools/measurements more sensitive to subtle changes that may be missed measuring on an ordinal scale. In the case of surface electromyography (sEMG), the use of neurophysiology-based assessments offers the additional advantage that the underlying muscle activations can be measured even when no visible joint movements are possible. To refine assessments, sEMG sensors have been applied during complex, functional, everyday tasks such as walking[12] or reaching[13] but also during selective, isolated passive movements[14] (testing spasticity), and active[15] joint movements (testing SVMC of

the lower extremity). While these results are promising, there is still a long way to go in terms of standardization of movement batteries[10] and how sEMG output could be used to generate useful metrics.[16]

One such metric is the rating of similarity of muscle activation patterns.[17] Studies have compared the Brain Motor Control Assessment (voluntary joint movements of the lower and upper extremity, breathing maneuvers, and reflexes) between patients with spinal cord injuries and neurologically intact peers. sEMG signals described the similarity, or dissimilarity, between the two groups' patterns of muscle activations.[17–19]

This paper aims to evaluate the validity and reliability of the similarity index of muscle activation patterns performed during the SCUES (SI_{SCUES}) in children with upper motor neuron lesions. We assessed convergent validity by correlating SI_{SCUES} scores with both the regular SCUES scores and how patients handle objects in daily life, as classified by the Manual Ability Classification System (MACS). We expected to find a high, but not a very high, positive Spearman's correlation ($0.7 \leq \rho < 0.9$) between the SI_{SCUES} and the SCUES, because the SI_{SCUES} is derived during the SCUES movements, but still measures muscle activation patterns as opposed to movements. A negative, medium correlation ($-0.7 < \rho \leq -0.5$) between the SI_{SCUES} and the MACS was expected because SVMC is undoubtedly an essential part of how patients handle objects but not the only contributing factor. We further evaluated the discriminative validity by determining differences between patients and typically developing (TD) children. We hypothesized that the SI_{SCUES} would differentiate between patients and TD children, especially for the more affected side. Finally, we determined the relative and absolute reliability of the SI_{SCUES}.

Methods

This observational study investigates the psychometric properties of a novel assessment (SI_{SCUES}) that combines sEMG and the SCUES to quantify SVMC.

Participants

A convenience sample of in- and outpatients of the Swiss Children's Rehab in Affoltern am Albis, Switzerland, was recruited. Patients with a diagnosis of upper motor neuron lesions, between the age of 6 and 18 years, the ability to sit upright for 1 h and understand and follow simple instructions were eligible. Exclusion criteria were surgical interventions and treatment with botulinum toxin on the upper extremity in the past 6 months and, in the case of stroke and traumatic brain injuries, insult/injury onset in the past 3 months.

TD children in the same age range as patients were recruited as reference. Since the occurrence of superfluous movements is age- and task-difficulty-dependent,[20] quota sampling was done, recruiting more children for the younger age groups. Most participating TD children were children of Swiss Children's Rehab

employees, and some were from schools in Affoltern am Albis and Frauenfeld. Furthermore, we recruited neurologically intact adults by convenience sampling. These adults provided the reference score that reflects physiological movement without involuntary movements. Because involuntary movements are reported to increase with age in healthy adults,[21,22] we excluded adults 51 years and older. TD children and neurologically intact adults were excluded if they had neurological or orthopedic diagnoses in the past 12 months.

We recruited participants from June 2017 until May 2019. All participants were characterized using descriptors of age, sex, and handedness (defined as the hand used to write/draw). Moreover, for patients, we noted the diagnosis and more affected hand (if applicable), which was determined by an occupational therapist. We quantified the severity of upper limb limitations with the MACS,[23] a valid and reliable measure that classifies the way children with cerebral palsy (CP) handle objects in daily life. Patients with MACS level 1 handle objects successfully and with ease, while patients with a level of 2 can handle the same objects but do so with reduced quality and/or speed of achievement. A level of 3 indicates that the patients have difficulties handling objects and need help preparing and modifying activities. While patients with a score of 4 still handle objects, they can only do so with a selection of easily manageable objects in adapted situations. Finally, patients with a score of 5 cannot handle objects at all. Medical professionals routinely assess the MACS level in our rehabilitation center for children with CP and were asked to classify children with other upper motor neuron diagnoses for this study in addition.

All legal guardians gave written informed consent. Participants aged 14 years and older also provided written informed consent. Younger participants gave oral informed consent. All methods were in accordance with the necessary guidelines and approved by the ethical committee of the canton of Zurich, Switzerland (PB_2016_01843).

The SCUES

The SCUES[8] is a valid tool for measuring SVMC and consists of performing multiple isolated joint movements bilaterally, always starting with the less affected/dominant arm and then moving to the contralateral side. The assessor demonstrates the target movement three times with the participant's limb and then asks the participant to perform the target movement three times, offering verbal guidance (e.g. "up, down, up"). The SCUES starts with abducting/adducting the shoulder and then flexing/extending the elbow (the therapist holds the upper arm horizontally). The resting arm is placed in the lap of the participant. After that, the lower arm is pro-/supinated with both arms placed on the table. Finally, after placing the lower arms on a 10 cm foam block, allowing the wrist to be moved freely, the wrist and fingers are flexed/extended.

The SCUES assesses SVMC on a 4-point ordinal scale. A score of 3 indicates normal SVMC, while a score of 0 indicates no SVMC at all. Table 1 gives an overview of the SCUES scores and necessary descriptors. In total, the maximal score is

Table 1. SCUES scores, clinical meaning and descriptors.

SCUES	Clinical meaning	Necessary descriptors
3	Normal SVMC	• aROM ⩾ 85% of pROM and • no involuntary movements visible
2	Mildly diminished SVMC	• aROM between 50% and 85% of pROM and/or • exactly one additional movement occurs and/or • slight mirror movements occur and/or • slight trunk movements occur
1	Moderately diminished SVMC	• aROM between 1% and 49% of pROM and/or • more than one additional movement occurs and/or • strong mirror movements and/or • strong trunk movements
0	No SVMC at all	• no observable movement of the joint

aROM: active range of motion; pROM: passive range of motion; SCUES: selective control of the upper extremity scale; SVMC: selective voluntary motor control.

30 points, 15 for each arm. An experienced occupational therapist, who was blinded to the SI_{SCUES}, scored the SCUES.

Similarity index of the SCUES: SI_{SCUES}

The similarity index (SI)[17] quantifies the similarity between two muscle activation patterns of a multichannel sEMG on a scale from 0 (dissimilar) to 1 (identical). The SI is the cosine of the angle between the two activation patterns, expressed as vectors. Figure 1 provides a step-by-step example of how to calculate the SI of a patient in two dimensions, meaning the activity of two muscles is displayed. This can be scaled up to incorporate as many muscles as are deemed relevant for the activation pattern.

When calculating the SI, it is paramount to use standardized and well-defined movements. For that reason, we chose the SCUES. Due to practical issues (e.g. the time needed to prepare the patients or the limited number of EMG channels of our system), we decided to equip only the muscles primarily responsible for performing the above-described movements with sensors. We applied sEMG electrodes to the m. deltoideus medius, m. triceps caput longum, and m. biceps brachii, according to the SENIAM guidelines.[24] The electrodes of the m. extensor carpi ulnaris and m. flexor digitorum superficialis were applied to the largest part of the muscle belly.

For every movement of the SCUES, the muscle activation patterns during the three repetitions were averaged and then compared in similarity to the reference vector. In our case, the reference vector was the average of all neurologically intact adults.

EMG system, set up, and procedure

Participants sat on an adjustable chair at an adjustable table with their elbow, hip, knee, and ankle joints flexed approximately 90°. The skin at the location of the

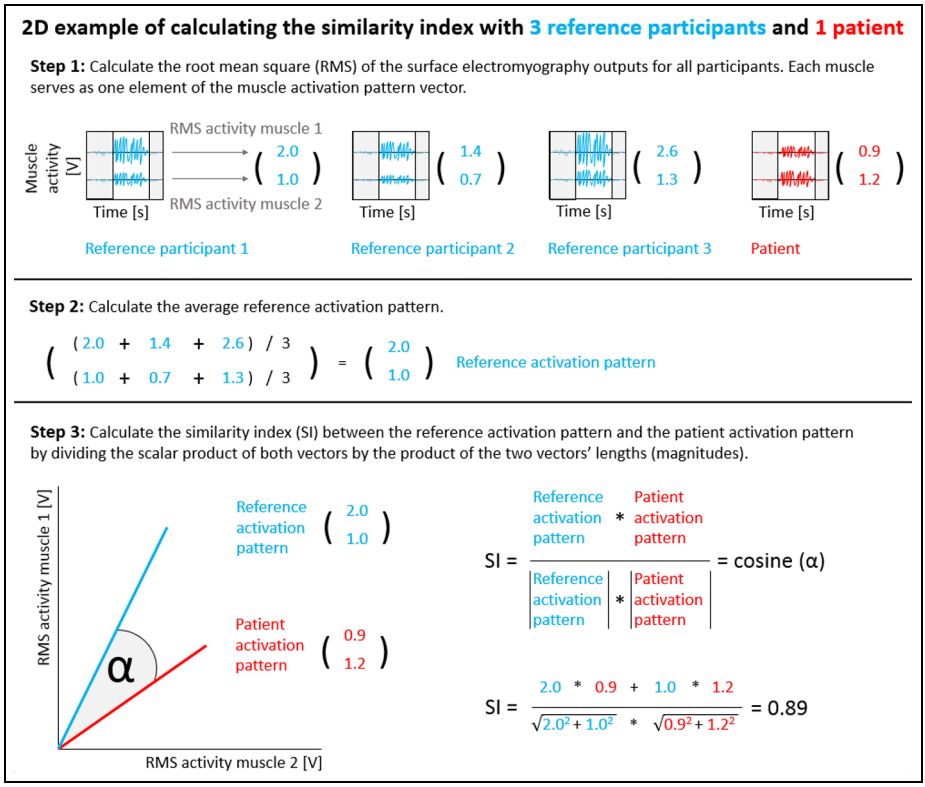

Figure 1. Step-by-step 2-dimensional example of how to calculate the similarity index for a patient. Step 1 indicates how the raw surface electromyography signals are used as activation pattern vector elements. Gray electromyography areas are non-movement phases and thus disregarded. In Step 2, all reference participants are used to calculate the reference muscle activation pattern. Step 3 displays how the two reference activation patterns and the patient activation pattern are used as vectors to calculate the similarity index. The similarity index is the cosine of the angle between the two vectors. Therefore, the similarity index can be calculated by dividing the scalar product of the two vectors by their multiplied lengths/magnitudes. In this example, if the similarity indices were to be calculated for all reference participants using the generated reference activation pattern, participants 1 through 3 would all receive a score of 1.0, because the similarity index is independent on the length/magnitude of a vector. The SI can be expanded to incorporate as many muscle activation elements as are technically possible and deemed relevant to be observed for a given muscle activation pattern.
RMS: root means square; s: seconds; SI: similarity index; V: volts.

muscles (see the previous section) was marked and shaven with a disposable razor. To clean and roughen the skin for better conductivity, OneStep® AbrasivePlus was applied. We used a Myosystem 1400A (Noraxon Inc., Scottsdale, USA) with a bandwidth of 30–500 Hz and a sampling frequency of 1500 Hz. Kendall EMG/ECG electrodes H124SG with a diameter of 24 mm were applied to the prepared

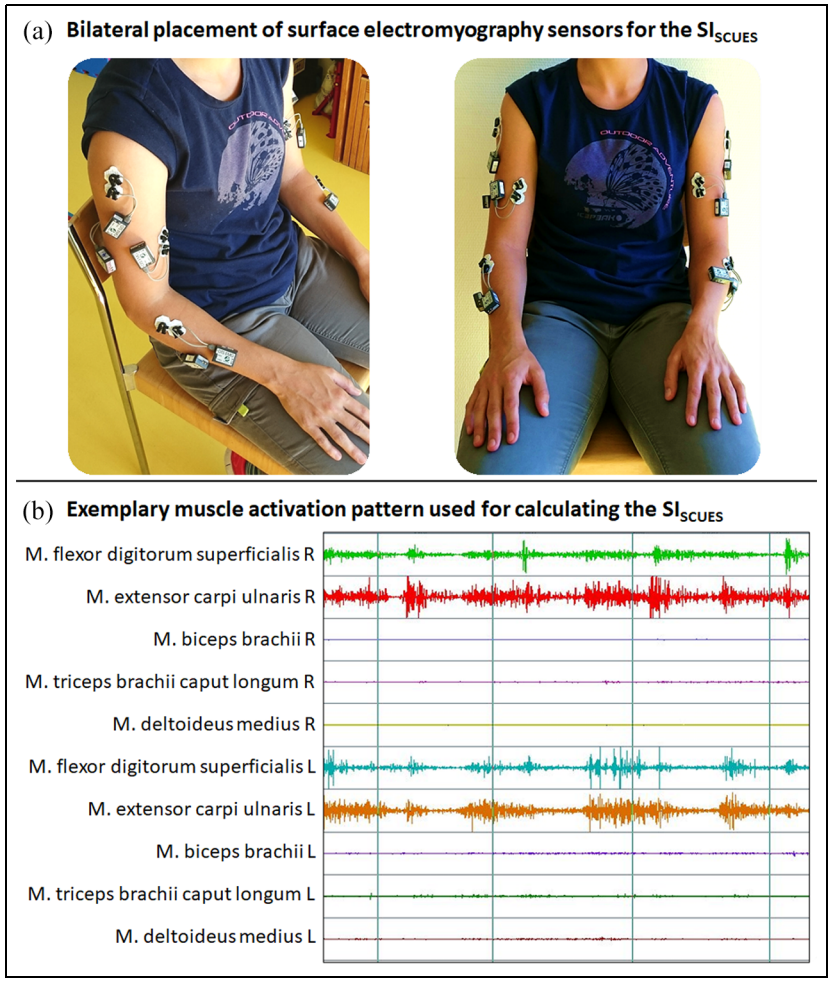

Figure 2. SI_{SCUES} setup and example of a sEMG muscle activation pattern: (a) bilateral placement of sEMG sensors on the arms of a neurologically healthy adult measured as reference group and (b) example of a sEMG activation pattern for flexing and extending the fingers of the right (more affected) hand. The patient (unilateral, spastic cerebral palsy, MACS level I) in this example exhibits mirror movements, that is, simultaneous activation of contralateral, homologous muscle groups.

skin. These electrodes are self-adhesive with a snap connector and a 15 mm diameter gel center containing silver/silver chloride (Ag/AgCl). The sEMG sensors were attached, as can be seen in Figure 2.

After that, the participants performed the SCUES. Both shoulder abduction/adduction and elbow flexion/extension movements were performed while the contralateral arm lay in the lap because, in this position, the neurologically intact

adults showed the least muscle activation contralaterally. However, for the EMG signal to be minimal, some TD children and patients needed to let the contralateral arm hang freely at the side and not lay it in their lap, which they were allowed to do. For the lower arm pro-/supination, the participants placed their lower arms on the height-adjusted table. The lower arms were positioned on a 10 cm foam block to facilitate wrist and finger flexion and extension movements. The neurologically intact adults had to flex their fingers slightly to flex/extend their wrist without touching the table. For that reason, we asked the TD children and patients to do the same, if possible.

After the SCUES, we removed the sEMG electrodes. It took approximately 25 min to administer the entire SI_{SCUES} protocol. We repeated this procedure to obtain independent yet stable measurements for the test-retest reliability 1 to 3 days later with the inpatients and approximately 14 days later with the outpatients.

Data analysis

All sEMG signals were filtered using a finite impulse response, high-pass filter with a cut-off frequency of 20 Hz. If necessary, a 50 Hz rejection filter, removing noise from other electronic devices, and an ECG filter, removing heartbeat noise, were used. Event markers were set offline by looking at the synchronized video recordings and placing the markers at the beginning and end of every individual movement.

The further data analysis of the sEMG was done in Matlab (version 2017b). Motion artifacts were removed from the signal by cutting them out of the signal directly. The reason and position of the artifacts were noted for traceability. Thereafter, the root of the mean squared value was calculated for each epoch/repetition. Epochs varied in length according to the movement speeds of participants. A baseline correction (lowest activity during non-moving phases) for each channel was performed by searching for the lowest mean activity during a 3-s window at any time point during the assessment, down-sampling by 5. Finally, the average muscle activations were calculated for each individual movement (three per target joint) using the root mean square and afterward averaging the three target joint movements to one muscle activation pattern.

The last step was to calculate the SI between a participant's muscle activation pattern and the averaged reference muscle activation pattern derived from all neurologically intact adults. First, the activation patterns were sorted by more/less affected (non-dominant/dominant) side, and then the reference group consisting of neurologically intact adults had to be formed. Finally, the scalar product between the participant's vector and the reference vector was divided by the product of the vectors' lengths, resulting in the SI.

Statistical analysis

The statistical analyses were performed in R (version 3.5.1)[25] with the additional packages boot (v 1.3-20),[26] ICC (v 2.3.0),[27] and WRS2 (v 0.10-0).[28] The outcomes

were sorted by more/less affected (non-dominant/dominant) side for all statistical analyses.

Convergent validity was evaluated by correlating the SI_{SCUES} with the SCUES and the MACS for each joint, the sum score of the more/less affected side, and the total score. Kendall's tau-b,[29] designed to handle ties in the data, was chosen because both the SCUES and the MACS are ordinal-scaled measures with few levels. We calculated Spearman's rho for the sum scores for each side and the total score because these scores have more levels and thus a greater dispersion between individuals.

Discriminative validity of the SI_{SCUES} for each side and the average over all joints was assessed by comparing the patients to the TD children with a robust, bootstrapped ANCOVA (analysis of covariance).[30] This allows for comparisons between the groups at defined levels of the covariate, which, in our case, was age. Comparisons were made at the age levels of 7.5, 9, 10.5, 12, 15 years. The number of bootstrap samples was 2000 without trimming the data, and the 95% confidence intervals were corrected for multiple comparisons. Model flexibility was defined such that group sizes at each age level were at least 12, as suggested by Mair and Wilcox.[30] The same analysis was done for the SCUES scores of both sides and the total score. Furthermore, the influence of age on the SCUES was tested quantitatively with simple linear regressions. We decided this a posteriori since we did not observe an age effect for the SI_{SCUES}.

Relative reliability was established by calculating two-way random effects, absolute agreement, single/measurement intraclass correlation coefficients$_{2,1}$ ($ICC_{2,1}$).[31] $ICCs_{2,1}$ were classified as excellent ($ICC \geq 0.90$), good ($0.75 \leq ICC < 0.90$), moderate ($0.50 \leq ICC < 0.75$), and poor ($ICC < 0.50$).[31] Bootstrap 95% confidence intervals based on 2000 resamples were bias-corrected and accelerated.[32]

Absolute reliability in the form of minimal detectable changes (MDC) were calculated in a robust manner by dividing the difference between the 97.5 and 2.5 percentile by 2. MDC values were set in relation to the median of patient scores (MDC/median) and the percentage of patients able to improve by the MDC without reaching the maximal score.

Results

The reference and control group comprised 33 neurologically intact adults and 31 TD children, respectively. Of 41 patients that gave informed consent, eight dropped out of the study, four of them because of cognitive limitations, and four due to compliance issues. Twenty-three of the remaining 33 patients were available for a second (reliability) assessment. Their characteristics are listed in Table 2. Patients were similar to their control group of TD children with regard to the age distribution (see Supplemental Figure 1) but not the sex distribution. For all except one patient, the dominant arm was also the less affected one. Twenty patients (61%) had a diagnosis where one side was more affected. Of the 22 patients with CP, five had a unilateral spastic, 13 a bilateral spastic (of which seven had one side was more affected than the other), three an ataxic, and one a mixed CP.

Table 2. Characteristics and assessment scores of participant groups.

	NHA	TD children	Patients (validity)	Patients (reliability)
n	33	31	33	23
Age^{M}	32.5 [27.9; 38.3]	11.5 [8.5; 13.9]	12.2 [8.8; 14.9]	9.9 [8.7; 15.0]
Sex: female	18 (55%)	16 (52%)	11 (33%)	9 (39%)
Diagnosis				
Cerebral palsy			22 (67%)	15 (65%)
Stroke			7 (21%)	5 (22%)
Traumatic brain injury			2 (6%)	2 (9%)
Encephalitis			2 (6%)	1 (4%)
MACS				
1			7 (21%)	3 (13%)
2			12 (36%)	11 (48%)
3			13 (40%)	8 (35%)
4			1 (3%)	1 (4%)
Total SCUES^{M}				
Less affected/ dominant		15.0 [14.0; 15.0]	13.0 [11.0; 14.0]	13.0 [11.5; 14.5]
More affected/ non-dominant		14.0 [14.0; 15.0]	9.0 [7.0; 13.0]	8.0 [6.5; 13.0]
Both sides		29.0 [27.5; 30.0]	21.0 [18.0; 26.0]	21.0 [18.0; 26.0]
Avg. SI_{SCUES}^{M}				
Dominant/ less affected	0.96 [0.94; 0.98]	0.95 [0.92; 0.96]	0.92 [0.90; 0.95]	0.93 [0.90; 0.96]
Non-dominant/ affected	0.97 [0.94; 0.98]	0.96 [0.93; 0.98]	0.85 [0.67; 0.93]	0.80 [0.66; 0.93]
Both sides	0.96 [0.94; 0.97]	0.95 [0.94; 0.96]	0.87 [0.80; 0.93]	0.85 [0.80; 0.93]

Avg.: average; ^{M}: median [1st; 3rd quartile]; MACS: manual ability classification system; NHA: neurologically healthy adults; SCUES: selective control of the upper extremity scale; SI: similarity index; TD: typically developing.

To appreciate the variability within the SI_{SCUES}, it was also calculated for the neurologically health adults. Adults whose SI_{SCUES} was calculated, were not part of their reference group, so as not to influence the average reference activation pattern in their favor.

Convergent validity

On the individual joint level, most correlations of the SI_{SCUES} were stronger with the SCUES than with the MACS (Table 2). Furthermore, the correlations were stronger for the more affected than the less affected side and for the distal compared to the proximal joints. For the averaged scores, correlations were higher with the SCUES (Figure 3) than the MACS and also for the more affected than the less affected side.

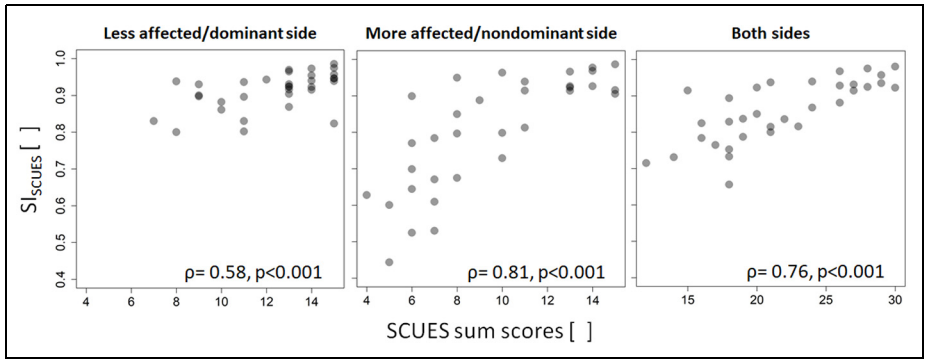

Figure 3. Scatterplots of the SI_{SCUES} and SCUES by side. Correlation coefficients are Spearman's rank correlations.
SCUES: selective control of the upper extremity scale; SI_{SCUES}: similarity index of the SCUES.

Discriminative validity

Figure 4 depicts the results of the discriminative validity tests. After correcting for multiple comparisons within the tested side, the SI_{SCUES} can distinguish between patients and their healthy peers for the more affected side and the average of all joints at any age level but not for the less affected side. The SCUES can distinguish between patients and healthy peers in all cases, except for the less affected/dominant arm at younger ages. Furthermore, it becomes apparent that the participants' age does not influence the SI_{SCUES} score, which is also underlined by the linear regression analyses (see Supplemental Materials for a detailed analysis). In contrast, the SCUES does show a slight age dependency for the dominant side (+ 0.13/year, $p = 0.002$, adjusted $R^2 = 0.27$) and the total score (+ 0.19/year, $p = 0.009$, adjusted $R^2 = 0.18$) of TD children. No such age-dependency was found for patients.

Reliability

The relative and absolute reliability are presented in Table 3. $ICCs_{2,1}$ for the averaged scores by each side and joints were good to excellent. The $ICCs_{2,1}$ for the individual joints were moderate to good, with scores for two joints being poor (elbow more affected and finger less affected side) and one excellent (wrist more affected side). The percentage of patients that can improve by the MDC without reaching the maximum score indicates that on the individual joint level, only a few patients can improve. In contrast, for the averaged scores, 57% to 74% of patients can improve.

Discussion

This study evaluated the validity and reliability of the SI_{SCUES}, which quantifies the similarity between an individual muscle activation pattern and a reference

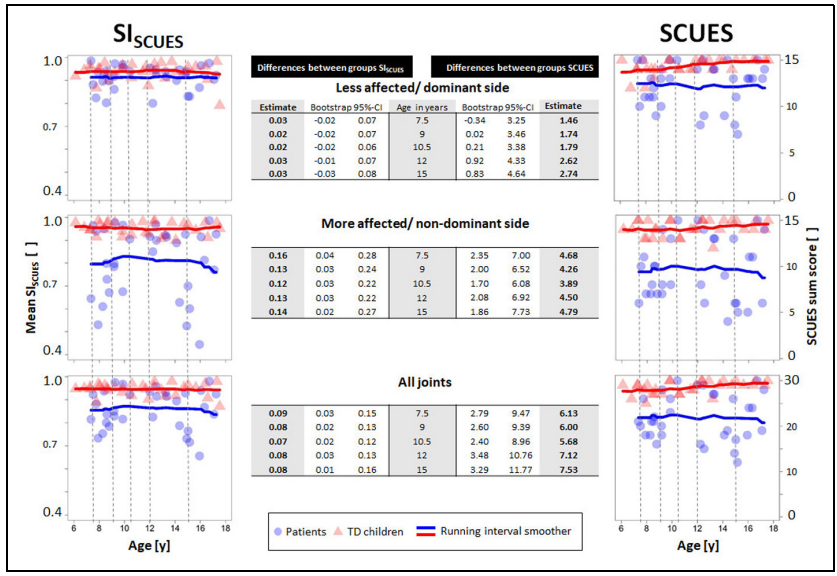

Figure 4. SI_{SCUES} and SCUES for patients and healthy peers by age with corresponding robust ANCOVA results. Robust ANCOVAs using running interval smoothers (no trimming on means, span parameters were 0.8 and 0.7 for patients and peers, respectively) compared patients to their healthy peers at predetermined age levels (dashed lines). The bootstrapped 95% confidence intervals, which are bias-corrected and accelerated and adjusted for multiple testing, indicate whether patients can be discriminated from their peers at certain age levels. For example, comparing the SI_{SCUES} over all joints at age 9 years reveals that the groups differ by 0.08. Looking at the left plot at the 9-year dotted line indicates that TD children have on average a 0.08 higher score than the patients. Furthermore, the 95% CI does not cross zero, which indicates that the result is statistically significant with the *p*-value being smaller than 0.05 (corrected for multiple testing).

95% CI: bootstrapped, bias-corrected and accelerated 95% confidence interval; TD: typically developing; SCUES: selective control of the upper extremity scale; SI_{SCUES}: similarity index of the SCUES.

pattern reflecting the average of many individuals. The activation patterns are made up of multichannel sEMG signals while performing the SCUES assessment. The convergent validity and discriminative validity results indicate that the SI_{SCUES} is valid and can, at least for the more affected side and the total score, discriminate between patients with upper motor neuron lesions and their healthy peers. Relative reliability ranged from good to excellent for the average scores. Further studies are needed to determine whether the MDC values, representing absolute reliability, are acceptable.

Concurrent validity

Our hypotheses about the strength of the correlation coefficients for the SCUES and MACS can be accepted for the more affected side and the average of both sides

Table 3. Convergent validity, relative and absolute reliability for individual joints and mean scores of the SI_{SCUES}.

			MACS	SCUES	$ICC_{2,1}$ (95% CI)	MDC [1st; 2nd; 3rd quartile of all reliability patient scores]	relMDC [%]	impPat [%]
Less affected	Shoulder		−0.25	0.26	0.52 (0.25; 0.86)	0.09 [0.93; 0.98; 0.99]	9	13
	Elbow		−0.04	0.16	0.52 (0.14; 0.85)	0.15 [0.87; 0.93; 0.95]	16	13
	Lower arm		−0.22	0.14	0.84 (0.53; 0.94)	0.14 [0.80; 0.90; 0.96]	16	43
	Wrist		−0.13	0.33*	0.86 (0.26; 0.98)	0.04 [0.96; 0.98; 0.99]	4	26
	Fingers		−0.24	0.26	0.47 (0.26; 0.76)	0.12 [0.92; 0.95; 0.98]	12	22
	Mean		−0.19	0.44**	0.76 (0.57; 0.90)	0.05 [0.90; 0.93; 0.96]	5	70
		ρ	−0.24	0.58***				
More affected	Shoulder		−0.39**	0.16	0.71 (0.27; 0.91)	0.17 [0.84; 0.94; 0.98]	18	22
	Elbow		−0.22	0.29*	0.22 (0.00; 0.81)	0.24 [0.85; 0.93; 0.97]	26	13
	Lower arm		−0.42**	0.47**	0.88 (0.72; 0.95)	0.22 [0.51; 0.77; 0.89]	29	61
	Wrist		−0.43**	0.65***	0.96 (0.90; 0.98)	0.16 [0.46; 0.80; 0.98]	20	52
	Fingers		−0.40**	0.50***	0.89 (0.76; 0.96)	0.24 [0.56; 0.87; 0.98]	28	35
	Mean		−0.47**	0.64***	0.92 (0.72; 0.97)	0.10 [0.64; 0.82; 0.94]	12	57
		ρ	−0.62***	0.81***				
Both sides	Mean		−0.45**	0.59***	0.90 (0.71; 0.95)	0.07 [0.79; 0.85; 0.94]	8	74
		ρ	−0.58***	0.76***				

95% CI: bootstrapped, bias-corrected and accelerated 95% confidence interval; $ICC_{2,1}$: intraclass correlation coefficient$_{2,1}$; impPat: percentage of patients that can improve by the MDC without reaching the maximum score; MACS: manual ability classification system; MDC: minimal detectable change; relMDC: percentage of MDC of median patient score; SCUES: selective control of the upper extremity scale.

All correlation coefficients are Kendall's tau-*b* except for the ones designated with ρ, which are Spearman's rho.

Asterisks indicate the *p*-values of the correlation coefficients: *$0.05 > p \geq 0.01$. **$0.01 > p \geq 0.001$. ***$p < 0.001$.

but not for the less affected side. The reason for that is probably that the dispersion between the SCUES scores of the less affected side was too small, as 50% of the scores are between 11 and 14 points (maximum score 15), whereas they are between 7 and 13 points for the more affected side and 18 and 26 for the total score. This is in line with previous findings. Patients with hemiplegic CP exhibit more mirror movements (movements of the contralateral joint) when performing tasks with their more affected hand than their less affected one.[33,34] Both an insufficient interhemispheric inhibition,[35] causing both motor cortices to be active, and a reorganization of the unaffected motor cortex to represent both sides of the body[36,37] might account for these mirror movements. Both for patients with CP[38] and stroke,[39] which together constitute 91% of our patient population, an increased ipsilateral joint coupling has been demonstrated before. The underlying neural mechanisms of reorganization depend on the timing and severity of the injury and lead to distinct coupling patterns.[38,40] While prenatal brain injuries occurring early in gestation seem to rely on the corticospinal tract for compensation,[41,42] brain lesions occurring postnatal and later in life (adult stroke) might rely more on the reticulospinal tract.[40,43]

As expected, the correlations of the SI_{SCUES} with the MACS are weaker compared to the SCUES. While the SCUES and the SI_{SCUES} try to quantify the same concept, namely the selectivity of isolated voluntary joint movements,[1] albeit differently, the MACS categorizes how patients handle objects in daily activities. Surely, while selective joint control is relevant for handling objects, factors such as inter-joint coordination of the ipsilateral side, the collaborative use of both hands, muscle strength, and spasticity can influence the MACS score in addition. Furthermore, while the MACS is a performance measure (what a person does do in his/her daily environment), the SCUES and SI_{SCUES} are capacity measures (what a person can do in a standardized, controlled environment). These constructs can differ in patient groups.[44,45]

Discriminative validity

The SI_{SCUES} and SCUES can distinguish well between patients and TD children for the more affected/non-dominant side scores and the total scores. The discriminative ability seems less clear for the less affected/dominant side. This can be explained by the reorganization of the central nervous system, as previously discussed (e.g. corticospinal versus reticulospinal tract).

Furthermore, the SI_{SCUES} did not display an age effect in TD children, while the SCUES did. It has been shown that task performance and the occurrence of involuntary movements are dependent on task difficulty and the participant's age for TD children.[46,47] This has been attributed to the maturation of the corticospinal tract.[48] A possible explanation for the discrepancy between the SI_{SCUES} and SCUES is the way they are analyzed. For the SCUES, most of the TD children's point deductions came through movements of additional joints (32/46 = 70%, no TD children lost more than one point per movement). Movements in additional

joints are not evaluated according to their magnitude and frequency of occurrence but simply dichotomously, present, or not present. The SI_{SCUES}, on the other hand, assesses the strength of the muscle activation and then uses nine other muscles to calculate the final score, mitigating the effect of the already small activity. This feature of the score needs to be kept in mind when interpreting the SI_{SCUES} and might be the reason why no age dependency was found. For example, if a TD child abducts the shoulder and slightly flexes the elbow simultaneously, which happens more frequently in younger children, this results in a SCUES score of 2. It will hardly influence the SI_{SCUES} score because the biceps brachii is already actively stabilizing the elbow. If the elbow flexion is strong, the SCUES score stays a 2, but the co-movement clearly shows up in the SI_{SCUES}.

Reliability

The relative reliability of the averaged scores can be deemed acceptable and is in line with previous studies on the topic of SVMC.[7,11,19] Absolute reliability, expressed as the MDC, seemed to be acceptably low for the averaged scores. However, future studies are needed to evaluate if the SI_{SCUES} is sensitive enough to detect changes in SVMC stemming from interventions.

Possible advantages of neurophysiology-based assessments

One of the proposed benefits of neurophysiology-based methods is a finer grading on the movement continuum and a better responsiveness to interventions. The scatter plots in Figure 3, especially for the less affected/dominant side, offer first evidence that the SI_{SCUES} provides a finer grading than the SCUES because the patients with high/maximal SCUES scores show quite some variability in the SI_{SCUES} (approximately 0.8 to 1.0). This could indicate that patients used different motor strategies to achieve the same target movements.[5] This can also be true for movements with reduced SVMC. For example, a patient's active range of motion can be less than the passive range of motion for different reasons. While for patients with CP, the reason seems to be a higher coactivation of antagonistic muscles,[49] patients with acquired brain injuries (i.e. stroke) might lack the ability to sufficiently activate the agonistic muscles.[50] By using sEMG sensors, these different underlying mechanisms can be uncovered, thus informing the appropriate interventional choices.

Limitations

The most important limitation is that this study only investigated concurrent and discriminative validity as well as reliability. Further studies are therefore needed to establish other aspects of validity and responsiveness.

Furthermore, a power analysis for sample size calculation was not done. We based the number of participants on earlier recommendations of the COnsensus-

based Standards for the selection of health Measurement INstruments (COSMIN).[51]

Concerning the SI_{SCUES}, it is important to consider that its scoring depends on the muscles that are measured and their task-specific synergies. Therefore, the SI_{SCUES} activation patterns have to be cautiously evaluated for every movement individually. Even though we tried to cover all primary movers used in the SCUES, it was impossible when using only 10 sEMG channels. The primary muscles responsible for the pro-/supination of the lower arm are not covered with our muscle selection. Instead, we used the biceps for this movement since it is active when supinating the lower arm if the elbow joint is flexed. Furthermore, guidelines might deem three movement repetitions as being too few to estimate variability. However, the goal of this study was to evaluate test-retest reliability, thus quantifying the variability between measurements. While guidelines recommending more repetitions are concerned with more complex, multi-joint movements, the SI_{SCUES} and SCUES use single-joint movements with demonstrations and verbal guidance, reducing variability. However, should the SI_{SCUES} not prove to be responsive enough, using more repetitions is one option to reduce variability further.

Moreover, the tested patient group was mixed in terms of diagnoses, which is clinically relevant but might be less relevant for clinical trials, where patient populations are more restricted.

Finally, although the SCUES tries to reduce the strength component of certain movements, an influence of strength on both the SCUES and the SI_{SCUES} cannot be disregarded entirely. For example, the shoulder ab/adduction is performed with a 90° flexed elbow joint to reduce the lever arm, and elbow flexion/extension movements are performed in the horizontal plane. However, SCUES scores are influenced by the active range of motion, which is related to strength. Although the SI_{SCUES} measures the muscle activation patterns, it is recorded during movement and not, for example, during isometric isolated muscle contractions. Patients could elicit involuntary movements when trying to reach their maximum active range of motion, which could be reduced if patients were asked to concentrate more on activating the correct muscles instead of moving the limb. Future studies should investigate the influence of strength on the SVMC outcome measures.

Conclusion

Concurrent validity, discriminative validity for the more affected/non-dominant side, and reliability were established for the SI_{SCUES}. Deriving sEMG activation patterns of well-defined movements seems a promising approach to deepen our knowledge about the nature of SVMC in TD children and patients with upper motor neuron lesions and the nature of impaired SVMC in relation to other symptoms. Furthermore, it might lead to novel treatment approaches aimed at improving reduced SVMC. Future studies should investigate the minimal clinically important difference and the responsiveness of this assessment.

Clinical messages

- Neurophysiology-based assessments, such as the SI_{SCUES}, could be able to quantify subtle changes in selective voluntary motor control compared to ordinal-scaled assessments.
- The SI_{SCUES} is valid (concurrent, discriminative) and reliable (test-retest) in children with upper motor neuron lesions.

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Author contributions

JK, JB, JL, and HvH conceived and designed the study. JK, AF, JB, and JL were involved in recruiting participants, performing measurements. AF and JB did the data analysis. JK did the statistical analysis and wrote the manuscript. All authors critically reviewed and edited the manuscript. HvH acquired funding and supervised.

Declaration of conflicting interests

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Ethics approval

Ethical approval for this study was obtained from *NAME OF ETHICS COMMITTEE OR INSTITUTIONAL REVIEW BOARD (APPROVAL NUMBER/ID)*. All methods were in accordance with the necessary guidelines and approved by the ethical committee of the canton of Zurich, Switzerland (PB_2016_01843).

Informed consent

All participants and/or their legal guardians gave written informed consent. Underage participants gave oral consent.

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Data accessibility

After a discussion with the ethics committee, we decided that, due to the small number of patients in our rehabilitation center and the heterogeneity of the study group, the data cannot be made available on a public repository. However, the data can be provided to researchers upon reasonable request. For further information, please contact the corresponding author.

Supplemental material

Supplemental material for this article is available online.

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