Psychometric Properties of Lower Limb Somatosensory Function and Body Awareness Outcome Measures in Children with Upper Motor Neuron Lesions: A Systematic Review

Marsico, Petra; Meier, Lea; van der Linden, Marietta L; Mercer, Tom H; van Hedel, Hubertus J A

Abstract: Purpose: A systematic review of the psychometric properties and feasibility of outcome measures assessing lower limb somatosensory function and body awareness in children with upper motor neuron lesion. Methods: We followed the COnsensus-based Standards for the selection of health Measurement INstruments guidelines. Two raters independently judged the quality and risk of bias of each study. Data synthesis was performed, and aspects of feasibility were extracted. Results: Twelve studies investigated eleven somatosensory function measures quantifying four modalities and eight body awareness measures quantifying two modalities. The best evidence synthesis was very low to low for somatosensory function modalities and low for body awareness modalities. Few feasibility aspects were reported (e.g., the percentage or minimum age of participants able to perform the tests). Conclusion: Current evidence on the psychometric characteristics of somatosensory function and body awareness outcome measures are relatively sparse. Further research on psychometric properties and practical application is needed.

DOI: https://doi.org/10.1080/17518423.2021.2011976

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-214206
Journal Article
Published Version

The following work is licensed under a Creative Commons: Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License.

Originally published at:
Marsico, Petra; Meier, Lea; van der Linden, Marietta L; Mercer, Tom H; van Hedel, Hubertus J A (2021). Psychometric Properties of Lower Limb Somatosensory Function and Body Awareness Outcome Measures in Children with Upper Motor Neuron Lesions: A Systematic Review. Developmental Neurorehabilitation: Epub ahead of print.
DOI: https://doi.org/10.1080/17518423.2021.2011976
Psychometric Properties of Lower Limb Somatosensory Function and Body Awareness Outcome Measures in Children with Upper Motor Neuron Lesions: A Systematic Review

Petra Marsico, Lea Meier, Marietta L. van der Linden, Tom H. Mercer & Hubertus J.A. van Hedel

To cite this article: Petra Marsico, Lea Meier, Marietta L. van der Linden, Tom H. Mercer & Hubertus J.A. van Hedel (2021): Psychometric Properties of Lower Limb Somatosensory Function and Body Awareness Outcome Measures in Children with Upper Motor Neuron Lesions: A Systematic Review, Developmental Neurorehabilitation, DOI: 10.1080/17518423.2021.2011976

To link to this article: https://doi.org/10.1080/17518423.2021.2011976

© 2021 The Author(s). Published with license by Taylor & Francis Group, LLC.

Published online: 06 Dec 2021.
Psychometric Properties of Lower Limb Somatosensory Function and Body Awareness Outcome Measures in Children with Upper Motor Neuron Lesions: A Systematic Review

Petra Marsico, Lea Meier, Marietta L. van der Linden, Tom H. Mercer, and Hubertus J.A. van Hedel

ABSTRACT

**Purpose:** A systematic review of the psychometric properties and feasibility of outcome measures assessing lower limb somatosensory function and body awareness in children with upper motor neuron lesion.

**Methods:** We followed the COnsensus-based Standards for the selection of health Measurement INstruments guidelines. Two raters independently judged the quality and risk of bias of each study. Data synthesis was performed, and aspects of feasibility were extracted.

**Results:** Twelve studies investigated eleven somatosensory function measures quantifying four modalities and eight body awareness measures quantifying two modalities. The best evidence synthesis was very low to low for somatosensory function modalities and low for body awareness modalities. Few feasibility aspects were reported (e.g., the percentage or minimum age of participants able to perform the tests).

**Conclusion:** Current evidence on the psychometric characteristics of somatosensory function and body awareness outcome measures are relatively sparse. Further research on psychometric properties and practical application is needed.

Introduction

Somatosensory function is defined as the registration and perceptual processing of somatosensory information. The somatosensory system includes anatomical structures, such as the receptors, the afferent nerves, and the primary and secondary somatosensory cortices. The receptors transmit somatosensory inputs through peripheral afferent nerves to their cell bodies (first-order neurons) in the dorsal root ganglion. Somatosensory information on light touch and position is transmitted through the dorsal column. The spinothalamic tract transmits senses like temperature or nociceptive stimuli through the spinal cord to the thalamus and further to the somatosensory cortices.

In addition, somatosensory processing (spatial and structural) and visual, vestibular and interoceptive input lead to body awareness. De Haan and Dijkerman distinguish spatial and structural body representation based on central processing and perception. While spatial describes the position, distance, speed of touch, and the sensation of movement, structural describes the knowledge and awareness of the positions of body parts, such as distinguishing and assigning right and left sides of the body. Body awareness is now regarded as part of somatosensory function. Several outcome measures assessing different somatosensory functions are available.

Studies have shown that children with Upper Motor Neuron (UMN) lesions have impairments in various somatosensory modalities, such as two-point discrimination, stereognosis, proprioception, and spatial and structural body representation compared to typically developing children. This is likely to have a negative impact on motor function. The relationship between certain somatosensory and motor functions has been well documented for the upper limb. In the last years, some studies have demonstrated an association between somatosensory function and lower limb function, such as walking or balance in children with cerebral palsy (CP). Furthermore, the impact of somatosensory processing on body awareness and body ownership in connection to motor function has been assessed, emphasizing the importance of somatosensory function.

A recent study showed that physical and occupational therapists often neglect the assessment of somatosensory function in children with neurological disorders. When they test these functions, non-standardized or informal assessments such as observation during the child’s play activity are used. One reason for this may be the lack of standardized outcome measures of somatosensory function for children with UMN lesions. Outcome measures of somatosensory function like the Rivermead Assessment of Somatosensory Performance (RASP), the sensory scale of the Fugl-Meyer assessment, and the Nottingham Sensory Assessment showed adequate
psychometric properties in adults with a neurological diagnosis. To date, results of these measures on psychometric properties in the pediatric population are lacking.

Auld and colleagues reviewed the psychometric properties of upper limb tactile measures in children with CP. Tests like the Semmes Weinstein Monofilament (SWM), two-point discrimination, the graphesthesia test, and the stereognosis subtest of the sensory integration and praxis tests (SIPT) demonstrated adequate construct and criterion validity. The SWM, the exteroception test, two-point discrimination, the graphesthesia tests, and stereognosis showed high reliability. In a later study, focusing again on the upper limb, they investigated the reliability of the SWM, single-point localization, two-point discrimination, double stimulation, texture perception, and stereognosis in children with CP (n = 16) and in typically developing children (n = 31). They found high reliability and small measurement errors for all these upper limb assessments.

Clark and colleagues reviewed the psychometric properties of lower limb neurological impairment tests for children with neurological conditions. Only the International Standard for Neurological Classification of Spinal Cord Injury (ISNCSCI) assessed tactile sensitivity (light touch and pinprick) in children and youths after spinal cord injury. The ISNCSCI showed conflicting evidence in intra-rater reliability.

In contrast, our systematic review will focus only on somatosensory function tests, including body awareness, of the lower limb. In the long term, this review should lead to improving the clinical examination and better understand the limitations of current outcome measures, which should lead to refining existing and developing novel assessments. The results should provide a better understanding of somatosensory impairments. Therefore, resulting in refining treatment options for an individual child with lower limb somatosensory impairments.

To our knowledge, the evidence for the psychometric properties and feasibility of outcome measures assessing lower limb somatosensory function in children with UMN lesions has not been systematically reviewed. Therefore, this systematic review will identify and rate the quality of evidence for the psychometric characteristics. Additionally, we will evaluate the feasibility (e.g., ease of administration, time, standardization) of these outcome measures to be used in this group of young participants in clinical practice.

Materials and Methods

Study Design

The study protocol has been registered in the International Prospective Register of Systematic Reviews (PROSPERO) with the number CRD42020160304. This review followed the statement of the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA).

Search Strategy

An electronic search was performed on the 18th of March 2021 of the databases MEDLINE (via PubMed), CINAHL (via EBSCOhost), EMBASE, and PsychINFO. The search strategy used a combination of keywords and Medical Subject Headings (MeSH) terms (supporting information S1). For somatosensory function outcome measures, the constructs somatosensory function; population (such as cerebral palsy [MeSH], nervous system diseases [MeSH]), lower limbs; the measurement properties, and the exclusion filter of Terwee et al., 2009, were used. The search strategy for body awareness comprised the search terms body awareness; population; measurement properties, and the exclusion filter.

The search filters of the construct for somatosensory function and body awareness had undergone previous validation, according to Jenkins 2004. The validation consists of testing the accuracy of the search filters in a defined set of articles. The hits of the search filters are compared to the hits of the manual search. The search filters developed for this study proved to be highly sensitive (0.99 for the construct of somatosensory function and 0.80 for body awareness). At the same time, the specificity of 0.15 was low but sufficient precise for somatosensory function and high for the body awareness search filter. These numbers indicate that seven articles derived from the somatosensory function filter must be read to find a relevant article. In contrast, each article from the body awareness filter is considered relevant (supporting information S2). In addition, the reference list of the included articles was hand searched for further studies, which met the inclusion criteria.

A tailored Microsoft Access database was used for rating the articles according to the inclusion-exclusion criteria and the evaluation of the COnsensus-based Standards for the selection of health Measurement INstruments (COSMIN) criteria.

Inclusion Criteria

Peer-reviewed articles were included in the systematic reviews. For systematic or narrative reviews that met the selection criteria, the original articles were reviewed. The screening was performed independently by the first and second author, according to the following inclusion criteria (1) articles written in English, German, Italian, or French, (2) outcome measures for somatosensory function or body awareness, (3) examination of psychometric characteristics of outcome measures, (4) population: at least 50% with UMN lesions, including diagnoses such as cerebral palsy, acquired brain injuries, myelomeningocele, spinal cord injuries, status after brain tumor, and various other syndromes (5) age: at least 50% of the participants needed to be younger than 19 years, (6) comprises outcome measures of the lower limbs.

Screening and Selection

Titles and/or abstracts were independently screened by the first and second authors to identify studies that potentially met the inclusion criteria, using a top-down inclusion algorithm. If the title and abstract did not provide sufficient information to assess whether the article met the inclusion criteria, the full text was queried. Any discrepancies in inclusion were resolved by discussion with an additional author (HvH).
Data Extraction, Management, Risk of Bias

Characteristics of the included samples, the results of the studies, and indicators of feasibility were summarized. The types of measurement property assessed in each article were then determined, and the methodological quality of these properties was independently evaluated by the first and the third author using the COSMIN Risk of Bias (RoB) checklist. Data from eligible studies were extracted by the first author and discussed with the coauthors. Data extracted included descriptive information about the study (e.g., design, sample size, and setting), demographic information on the participants (e.g., gender, age, and diagnosis), the feasibility of the outcome measures, and interpretability of the results. The results with regard to each of the psychometric properties (e.g., internal consistency, reliability, hypothesis testing, responsiveness) were evaluated according to the criteria of good measuring characteristics (supporting information S3), as sufficient (+), insufficient (-), or indeterminate (?) according to the COSMIN guidelines. In a further step, the evidence was summarized, and the quality of the evidence was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach. The COSMIN guideline includes following feasibility aspects such as patient and clinician comprehensibility, type and ease of administration, length of the instrument (reformulated as duration of the test), completion time (evaluation), patient’s required mental and physical ability level, ease of standardization, ease of score calculation, copyright, cost of an instrument, required equipment, availability in different settings, and regulatory agency’s requirement for approval. We combined two aspects (costs of an instrument and required equipment). We left out three aspects (ease of score calculation, availability in different settings, regulatory agency’s requirement for approval) as these are specifically for patient-reported outcome measures. Following the International Classification of Function, Disability, and Health (ICF) framework, the corresponding ICF codes were allocated to each measure in Table 1.

Results

Study Selection

The systematic searches resulted in 635 articles (without duplicates) for the evaluation of somatosensory function and in 221 articles (without duplicates) for the evaluation of body awareness (for the selection flowchart, see supporting information S4).

Somatosensory Function Outcome Measures

The review process identified nine eligible studies. They included eleven outcome measures (Semmes-Weinstein Monofilament, two-point discrimination, knee position sense, hip position sense, hip movement sense, toe movement sense, Fugl-Meyer assessment, detection of light touch, direction of scratch, vibration sense, ISNCSCI) representing four modalities (tactile function, vibration, and joint position and joint movement sense). The nine Studies investigated reliability, hypothesis testing, and responsiveness.

Results of the RoB ratings are presented in Table 2, allocated to their corresponding modalities. Two studies investigated the Semmes-Weinstein Monofilament test, two-point discrimination, vibration, and knee joint position sense compared to walking abilities and balance. In addition, one of these studies compared the assessed somatosensory functions between children with CP (n = 30) and typically developing children (n = 15). The second study found a low to moderate but not significant correlation with motor function in 10 children with CP. The two-point discrimination test could differ significantly between children with CP and typically developing children and correlated strongly with the Balance Evaluation System Test (BESTest). The Semmes Weinstein Monofilament test distinguished between children with and without CP, but it did not correlate significantly with the BESTest. Abdin et al. found a significant difference of proprioception between the more and the less affected leg in 29 children with unilateral CP, assessed with an isokinetic dynamometer. Nevertheless, the Pearson correlation with the Timed Up and Go Test (corresponding measurement) was low, and insignificant. Another study assessed different outcome measures (light touch, direction of scratch, vibration sense, knee position, and toe movement sense) in 62 children with CP, and 65 typically developing children. Vibrational, directional scratch and big toe movement sense differed significantly between groups, while differences for light touch detection and knee position sense were not significant. De Bode et al. assessed lower extremity sensory function before and after ten days of intensive mobility training in 18 young persons after hemispherectomy as part of the hypothesis testing of responsiveness. They used the sensory scale of the Fugl-Meyer assessment. No significant changes in the modalities, detection of light touch, and joint movement sense were found. The results could be influenced by the short period of training and the fact that no specific attention was placed on somatosensory recovery. These studies did not state a hypothesis for convergent validity (comparison with other outcome measures), discriminative validity (comparison with other populations), or responsiveness. Consequently, this influenced assessment using the COSMIN RoB checklist and led to a lower rating (see Table 2).

Three studies investigated the within-rater agreement for the ISNCSCI in a total of 266 children and youths with spinal cord injury. These studies showed a high agreement by assessing light touch and pinprick in these young people. Nevertheless, the RoB was inadequate, as Intraclass Correlation Coefficients were applied to ordinal-scaled data. Overall, the quality of the studies was considered low (Quality of evidence, Table 3).

Table 4 summarizes the information on the feasibility of the outcome assessments. For most test, information on the feasibility is lacking. An indicator for patient comprehension and ease of use can be the number of children who could complete the test. This can differ between tests, as shown by McLaughlin et al. While several somatosensory function tests could be performed by more than 67% of the children with CP, only...
| Study references (author, year) | Study aim | Outcome Measure | Modality | Study population | ICF-Code |
|-------------------------------|----------|----------------|----------|------------------|---------|
| Uzun Akkaya et al. | Investigate differences in somatosensory function in children with and without CP, and whether somatosensory impairments affect gait quality | 6-item Semmes-Weinstein Monofilament test kit (2.83–6.65) & Two-Point discrimination with a discriminator (128 Hz tuning fork) | Tactile function & Vibration Joint position sense | Diagnoses, number | Children with unilateral CP, n = 15; Children with bilateral CP, n = 15; Typically developing children, n = 15 | B265 B270 B260 |
| Abdin et al. | Assess correlations of the proprioception abilities from the more and less affected leg with postural balance | Knee position: Active reproduction of 45° knee flexion position, measured with a Biodex System 3 Pro isokinetic dynamometer | Joint position sense | Children with unilateral CP, n = 29 (GMFCS I, II) | B260 |
| Zarkou et al. | Assess correlations of somatosensory function, and walking abilities, and balance | 6-item Semmes-Weinstein Monofilament test kit (2.83–6.65) & Two-Point discrimination with a discriminator (128 Hz tuning fork) | Tactile function & Vibration Joint position sense | Children with bilateral CP, n = 10; Children with bilateral CP, n = 10 | B265 B270 B260 |
| De Bode et al. | Assessment of light touch and proprioception before and after ten days of intensive mobility training in individuals after hemispherectomy | Fugl-Meyer assessment Sensory scale (Applying tactile stimulus to the thigh and foot sole. Testing the hip, knee, ankle joint, and the big toe in flexion, and extension.) | Tactile function & Joint movement sense (Kinesthesia) & Joint position sense (Kinesthesia) | Children after a cerebral hemispherectomy, n = 18 | Unclear B265 B260 |
| Wingert et al. | Assessing joint-position sense and kinesthesia in all extremities in participants with diplegic or hemiplegic CP | Hip position: Pointing task to target angles along the semigoniometer axis, with and without vision of the leg; Hip movement: Awareness of the passive moved limb direction, without vision of the leg | Joint position sense & Joint movement sense (Kinesthesia) | Spastic bilateral CP (GMFCS I, II), n = 21; Unilateral CP; (GMFCS I, II), n = 17 | 7–35 B260 8–27 B260 |
| McLaughlin et al. | Assess lower extremity sensory function, and its feasibility, difference between children with and without CP, ability to measure change after a dorsal rhizotomy | Light touch: Stroking the child with a cotton applicator (mid-thigh L2-L3; mid-shin L3-4; mid dorsum of the foot L4-S1); Direction of scratch: Touch application of 2 cm, 5 cm, 10 cm distance with a wooden stick (mid-thigh L2-L3; mid-shin L3-4; mid dorsum of the foot L4-S1); Vibration sense: 128 Hz fork to the medial malleolus, Tibial tuberosity, and first metatarsal head; Knee position: Reproduce active knee angle of 15°, 30°, 45° knee extension, after passive elevation to these positions; Toe movement: Identify movement of the toe up or down | Tactile function & Vibration Joint position sense | Children with CP, n = 62 (Spastic bilateral, n = 48; unilateral, n = 10, athetoid, n = 3 hyptonia = 1); Typically developing children, n = 65 | 3–18 B265 B270 B260 |
| Chafetz et al. | To assess within-rater agreement for the total scores of light touch and pinprick in children and youth | ISNCSi sensory | Tactile function | Children and adolescents with spinal cord injury (n = 187) | 15–19 B265 |
| Mulcahey et al. | To assess rater agreement for the ISNCSi motor and sensory scores | ISNCSi sensory | Tactile function | Adolescents with spinal cord injury (n = 5) | 15–19 B265 |
| Mulcahey et al. | To assess the intra-rater reliability of the ISNCSi in different age groups | ISNCSi sensory | Tactile function | Children with spinal cord injury (n = 74) | 4–21 B265 |
| Nuara et al. | Assessment of asymmetry in self-portraits in children with CP and typically developing peers | Self-portrait: Children made three drawings: a self-portrait, a portrait of their best classmate-fiend, and a portrait of a hemiparetic peer undergoing rehabilitation | Spatial body awareness | Unilateral CP, n = 10; Typically developing children, n = 17 | B180 |

(Continued)
| Study references (author, year) | Study aim | Outcome Measure | Modality | Study population | ICF-Code |
|---------------------------------|-----------|-----------------|----------|------------------|----------|
| Asano et al.⁷ | Assessing tactile localization task, as part of body image in a group of children with different levels of motor function, and investigate the relationship with gross motor function | **Tactile localization task**: Children had to point on a screen the body parts where the tester applied a tactile input | Spatial body awareness | Children with CP, n = 10, Children with autism spectrum disorder, n = 5 Children with intellectual disabilities, n = 3 Child with ADHD, n = 1 (GMFCS I–III) | 3–12 B180 |
| Fontes et al.⁹ | Developing a battery of neuropsychological tasks that assess body schema, body image, and body structural description in children with and without CP | **Visual body-parts localization task**: The child has to recognize a body part in a picture and show it on his/her body  
**Verbal body-parts localization task**: The child has to show a part of his/her body that has been named to him/her  
**Matching body parts by localization task**: The child should show an adjacent body part from a presented body part on a screen.  
**Matching body parts by function**: The child arranges on presented body parts pictures on a screen with the same functions to each other  
**Body parts and object association task**: The child assigns depicted body parts to an associated task, presented on a screen  
**Naming body parts**: The child names body parts which are shown in pictures on a screen | Spatial body awareness Structural body awareness | Unilateral CP (analysis of items), n = 12 Unilateral CP (psychometric analysis), n = 49 Typically developing children (feasibility), n = 30 | 5–10 5–13 4–6 B180 |

Abbreviations: ICF – International Classification of Functioning, Disability, and Health; ISNCSCI – International Standard for Neurological Classification of Spinal Cord Injury; ADHS – Attention Deficit Hyperactivity Disorder
| Outcome Measure | Internal consistency | Reliability | Hypotheses testing | Responsiveness |
|-----------------|----------------------|-------------|--------------------|----------------|
| **Tactile function** |                       |              |                    |                |
| Monofilament    | Na, Na               | Na, Na      | Na, Na             | Na             |
| Monofilament    | Na, Na               | Na, Na      | Na, Na             | Na             |
| Two-point discrimination | Na, Na   | Na, Na      | Na, Na             | Na             |
| Two-point discrimination | Na, Na   | Na, Na      | Na, Na             | Na             |
| Fugl-Meyer assessment sensory scale | Na, Na | NA, Na     | Na, Na             | Na             |
| Light touch     | Na, Na               | Na, Na      | Na, Na             | Na             |
| Direction of scratch | Na, Na | Na, Na      | Na, Na             | Na             |
| ISNCSCI sensory | Na, Na               | Na, Na      | Tetraplegia: LT: ICC 0.97 (0.95–0.98) PP: ICC 0.95 (0.92–0.96) Paraplegia: LT: ICC 0.98 (0.97–0.99) PP: ICC 0.98 (0.96–0.98) | Inadequate | Na, Na |
| ISNCSCI sensory | Na, Na               | Na, Na      | Before Training: ICC 0.82 (0.56–0.98) After Training: ICC 0.77 (0.47–0.98) | Inadequate | Na, Na |
| ISNCSCI sensory | Na, Na               | Na, Na      | Tetraplegia: LT: ICC 0.98 (0.97–0.99) PP: ICC 0.98 (0.97–0.99) Paraplegia: LT: ICC 0.94 (0.90–0.97) PP: ICC 0.94 (0.89–0.97) | Inadequate | Na, Na |
| **Vibration**   |                       |              |                    |                |
| Vibration sense | Na, Na               | Na, Na      | Na, Na             | Na             |
| Vibration sense | Na, Na               | Na, Na      | Na, Na             | Na             |
| Vibration sense | Na, Na               | Na, Na      | Na, Na             | Na             |

(Continued)
| M                        | Outcome Measure                              | Internal consistency | Reliability | Hypotheses testing | Responsiveness |
|--------------------------|-----------------------------------------------|----------------------|-------------|---------------------|----------------|
|                          |                                               | Quality\(^a\) | Rating (RoB)\(^b\) | Quality\(^a\) | Rating (RoB)\(^b\) | Quality\(^a\) | Rating (RoB)\(^b\) | Quality\(^a\) | Rating (RoB)\(^b\) | Quality\(^a\) | Rating (RoB)\(^b\) |
| Joint position sense     | Hip position\(^7\)                            | Na Na Na Na Na Na Na Na + | With vision: CD-DD ns, CN-DN ns, CD-HD ns, CN-HN ns Without vision: CD-DD ns, CN-DN **, CD-HD **, CN-HN ** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Knee position\(^40\)                          | Na Na Na Na Na Na Na Na + | EVGS: r, 0.16 ns Differentiation between groups** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Knee position\(^62\)                          | Na Na Na Na Na Na Na Na + | BESTest overall: \(r_1 = -0.28\); COPA: \(r_1 = 0.23\) COPV: \(r_1 = -0.09\) | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Knee position sense\(^8\)                    | Na Na Na Na Na Na Na Na + | Differentiation between groups ns | Doubtful | Na Na Na Na Na Na Na Na | Na |
| Joint movement sense     | Fugl-Meyer assessment sensory scale\(^45\)   | Na Na NA Na Na Na Na Na Na | Na Na Na Na Na Na Na Na | Before MT: 10.1 ± 3.4 After MT: 10.4 ± 3.9 | Inadequate | Na Na Na Na Na Na Na Na | Na |
|                          | Toe movement\(^8\)                            | Na Na Na Na Na Na Na Na + | Differentiation between groups* | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Hip movement\(^7\)                            | Na Na Na Na Na Na Na Na + | CD-DD ns, CN-DN ns, CD-HD ns, CN-HN ** | Doubtful | Na Na Na Na Na Na Na Na | Na |
| Spatial body representation | Visual body parts localization\(^48\)       | ? 0.67 K-R20 Very good | Na Na Na Na Na Na Na Na | Verbal body parts localization \(r = 31\)** Matching body parts by localization \(r = 33\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Verbal body parts localization\(^48\)        | ? 0.65 K-R20 Very good | Na Na Na Na Na Na Na Na | Verbal body parts localization: \(r = 27\)** Matching body parts by localization: \(r = 33\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Matching body parts by localization\(^48\)   | ? 0.60 K-R20 Very good | Na Na Na Na Na Na Na Na | Visual body parts localization: \(r = 31\)** Verbal body parts localization: \(r = 33\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Tactile localization task\(^47\)             | Na Na Na Na Na Na Na Na Na | GMFM: 3-toe: \(r = 0.24\) ns, 5-toe: \(r = 0.04\) ns, LE: \(r = 0.80\)** Differentiate between groups: toe ns; LE ** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Self-portrait\(^48\)                          | Na Na Na Na Na Na Na Na Na | Differentiation between groups* | Very good | Na Na Na Na Na Na Na Na | Na |
| Structural body representation | Matching body parts by function\(^48\)    | + 0.60 K-R20 Very good | Na Na Na Na Na Na Na Na | Naming body parts: \(r = 0.21\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Body parts and object association task\(^48\) | + 0.60 K-R20 Very good | Na Na Na Na Na Na Na Na | Naming body parts: \(r = 0.21\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |
|                          | Naming body part\(^48\)                      | + 0.63 K-R20 Very good | Na Na Na Na Na Na Na Na | Naming body parts and object association: \(r = 0.21\)** | Doubtful | Na Na Na Na Na Na Na Na | Na |

\(^a\)methodological quality rating of the result by COSMIN; sufficient (+); insufficient (-); or indeterminate (?)

\(^b\)COSMIN Risk of Bias (RoB) checklist rating as for each item as very good; adequate; doubtful; inadequate; not applicable. Overall rating, as the worst score counts

Level of significance: *\(p < 0.01\); **\(p < 0.001\), ns - not significant

Abbreviations: M – Modality; Na – not applicable; \(r\) – Pearson correlation; \(r_s\) – Spearman correlation; ICC – Intraclass correlation coefficient; AI – Asymmetry Index; K-R20 – Kruder Richardson; MT – Mobility Therapy; BR – Body Representation; CD – Control Dominant side; DD – Diplegia Dominant side; CN – Control Non-dominant side; DN – Diplegia Non-dominant side; EVGS – Edinburgh Visual Gait Score; HD – Hemiplegia Dominant side; HN – Hemiplegia Non-dominant side; BESTest – Balance Evaluation System Test; COPA – Center Of Pressure Area; COPV – Center Of Pressure Velocity; LT – Light touch; PP – Pin Prick; LE – Lower Extremity; GMFM – Gross Motor Function Measurement; ISNCSCI – International Standard for Neurological Classification of Spinal Cord Injury
33% of children with CP completed the scratch sensation direction test. In terms of implementation in the clinic, these manual tests do not require any special training to perform, and they are easy to implement in clinical practice. All tests, except for the ISNCSCI sensory test, required a minimum level of physical ability of the children, such as sitting with or without trunk support. One study required a minimum age of 5 years to mentally perform the tactile function (stroking with a cotton applicator; direction of scratch), vibration, knee position, and toe movement sensation assessments. For the ISNCSCI, a minimum cognitive age of 4 years is recommended to perform the test reliably. For all outcome measures, children had to be able to respond to somatosensory input. They had to be able to give a sign (verbally or non-verbally) when they perceived the input, reproduce a limb position at a defined joint angle, or communicate the direction of movement. For the mechanical test of the joint position and movement sense, it is unclear if training for clinicians is needed. One custom-built device is not yet available for clinical use. No studies reported the time required to perform or evaluate the test.

**Body Awareness Outcome Measures**

Three studies describing eight outcome measures (self-portrait, tactile localization task, visual body-parts localization task, verbal body-parts localization task, matching body parts by localization, matching body parts by function, body parts and object association task, naming body parts) reflecting two modalities (spatial and structural body representation) of body awareness met the inclusion criteria (Table 1).

The studies examined internal consistency and hypothesis testing. For body awareness, no specific hypotheses for validity were given in the studies. That includes hypothesis testing, except for one study examining discriminative validity of self-portraits between children with unilateral CP and typically developed children. The RoB of this study was rated as very good. The other two studies were rated as doubtful for hypothesis testing.

Asano et al. assessed 18 children with motor deficits due to CP, autism spectrum disorders, intellectual disabilities, and attention activity hyperactive disorders with a tactile localization task. Tactile localization ability is defined as an indicator for spatial body representation (body image). The tactile lower limb localization task correlated strongly and significantly with the two dimensions (D: standing and E: walking, running, and jumping) of the Gross Motor Function Measure (GMFM-88). In contrast, the correlation with the 5-toe tactile, and 3-toe localization task were low and not significant. The results were also contradictory for construct validity, as the tactile lower limb localization task could differentiate well between children with high and low motor skills. In contrast, the toe tests did not significantly differ between groups.

The study by Fontes et al. was rated very good for internal consistency. The best evidence synthesis of the two body awareness modalities (spatial and structural body representation) was rated as moderate (Table 3). Results on reliability, measurement error, and responsiveness are missing. These parameters would be important to know for clinical practice.

As a test for spatial body representation, the self-portrait was completed and successfully performed by 53% of the children with CP and 89% of typically developing children. Even though the study of Fontes et al. included the development of the individual measures for body awareness in an earlier project, it is not clear whether clinicians need special training, how long the administration of the tests lasts, how to evaluate the tests and whether the material is available. However, such information is essential for the transfer into the clinic. Asano et al. demonstrated in their study that children with intellectual disabilities and attention problems can perform a body awareness test.

**Discussion**

The purpose of this systematic review was to provide an overview of psychometric properties and feasibility aspects of lower limb somatosensory function outcome measures in children with UMN lesions. Overall, the evidence on psychometric properties of somatosensory function assessments for the lower limbs is low. This lack of evidence can be a barrier to using and interpreting the assessment in clinical practice.

The review identified eleven measures for the somatosensory function modalities of tactile function, vibration, joint position sense, and joint movement sense (kinesthesia). Tactile function was assessed with the monofilaments test, light touch, and direction of scratch perception. Vibration sense was assessed using a vibration fork. Joint position sense was assessed with a custom-built device, an isokinetic dynamometer, or electrogoniometers to measure the knee or hip angle. Joint movement sense was assessed manually with the Fugl-Meyer assessment, or an individual procedure, and with a custom-built device (Table 1). No study included the modalities of temperature, stereognosis, haptic discrimination, or sensation of force. As mentioned in the introduction, these modalities are more commonly assessed for the upper limb than for the lower limb. In three studies we identified five different outcome measures for spatial body representation and three outcome measures for structural body representation.

Busse et al. identified outcome measures that should be applied in clinical practice to test somatosensory function in adults after stroke. They recommend applying four tests of the Rivermead Assessment of Somatosensory Performance (RASP). These were detection of touch (tactile function), location of touch (structural body representation), detection of movement, and direction of movement. When they applied these tests to the lower limbs, they stimulated the dorsum and foot sole (tactile function) while testing the sense of movement of the ankle and big toe. Their results indicate a high degree of redundancy between anatomical sites when the patient’s sensation is intact or absent. They concluded that only the foot’s dorsum had to be tested for tactile function from the lower limb. Our study only included the Fugl-Meyer assessment as a test battery assessing two modalities of somatosensory function (tactile function and joint movement sense). All the other outcome measures were designed to assess one specific modality. Psychometric properties of the RASP and other assessment tools are missing in the pediatric population. These
Table 3. Best evidence Synthesis.

| Modality; OM | Quality of evidence<sup>a</sup> | Internal consistency | Reliability | Hypotheses testing (Construct validity) | Responsiveness |
|-------------|--------------------------------|---------------------|-------------|----------------------------------------|----------------|
| Tactile function: Monofilament<sup>30,42</sup> | Very low | - - | - - | - - | 40 Doubtful ?/CP |
| Tactile function: Two-point discrimination<sup>30,42</sup> | Very low | - - | - - | - - | 40 Doubtful ?/CP |
| Tactile function: Light touch, direction of scratch<sup>35,43</sup> | Very low | - - | - - | - - | 62 Doubtful ?/CP |
| Tactile function: ISNCSCI sensory<sup>30,44,45</sup> | Low | - - | - - | - - | 266 Inadequate +/SCI |
| Vibration<sup>35,40,42</sup> | Very low | - - | - - | - - | 102 Doubtful ?/CP |
| JPS: Knee and Hip position<sup>30–42</sup> | Low | - - | - - | - - | 140 Doubtful +/CP |
| JMS: Toe and Hip movement<sup>7,8,43</sup> | Very low | - - | - - | - - | 100 Doubtful ?/CP |
| Spatial body representation<sup>48</sup> | Moderate | 61 Very good +/CP | - - | - - | 61 Doubtful +/CP |
| Structural body representation<sup>40–48</sup> | Moderate | 61 Very good +/CP | - - | - - | 89 Doubtful +/CP, ADHD, ASD, ID |

<sup>a</sup>These definitions were adapted from the GRADE approach<sup>38</sup>.

High = We are very confident that the true measurement property lies close to that of the estimate of the measurement property.

Moderate = We are moderately confident in the measurement property estimate: the true measurement property is likely to be close to the estimate of the measurement property, but there is a possibility that it is substantially different.

Low = Our confidence in the measurement property estimate is limited: the true measurement property may be substantially different from the estimate of the measurement property.

Very low = We have very little confidence in the measurement property estimate: the true measurement property is likely to be substantially different from the estimate of the measurement property.

Abbreviations: CP- Cerebral Palsy; HS – cerebral Hemispherectomies; OM – Outcome Measure; ISNCSCI – International Standard for Neurological Classification of Spinal Cord Injury; JPS – Joint Position Sense; JMS – Joint Movement Sense; ADHD – Attention deficit hyperactivity disorder; ASD – Autism Spectrum Disorder; ID – Intellectual Disabilities.
| Modality         | Outcome Measure                        | Patient’s comprehensibility                          | Clinician’s comprehensibility | Type and ease of administration | Duration of the test | Evaluation of the test | Patient’s required mental and physical ability level | Ease of standardization | Copyright | Requirement and Cost of instrument |
|------------------|----------------------------------------|-----------------------------------------------------|--------------------------------|--------------------------------|----------------------|------------------------|---------------------------------------------------|------------------------|-----------|----------------------------------|
| Tactile function | Monofilament                           | All children completed the test                     | Not stated                     | Not stated                     | Not stated            | Not stated             | Minimum cognitive ability of a 5-year-old child   | Easy                   | No        | Mono-filament set Around $50     |
|                  | Two-point discrimination               | All children completed the test                     | Not stated                     | Not stated                     | Not stated            | Not stated             | Sitting or lying position                         | Easy                   | No        | Aesthesiometer, or discriminator Around $50 |
|                  | Fugl-Meyer assessment sensory scale    | All children completed the test                     | No training                    | Manual test                    | Easy                 | Not stated             | Minimum cognitive ability of a 6-year-old child   | Easy                   | No        | Cotton applicator Test manual Around $2 |
|                  | Light touch                            | 87% of the children with CP, and 95% TD children could successfully complete | No training                    | Manual test                    | Easy                 | Not stated             | Sitting position has to be possible               | Easy                   | No        | Cotton applicator Around $2     |
|                  | Direction of scratch                   | 33% of the children with CP and 75% TD children could successfully complete | No training                    | Manual test                    | Easy                 | Not stated             | Minimum cognitive ability of a 5-year-old child   | Easy                   | No        | Cotton applicator Around $2     |
|                  | ISNCSCI sensory                        | 54% of children younger than 4y could be tested. High reliability values for children aged 6 years and older. | Special training recommender   | Manual test                    | Easy                 | Not stated             | Sitting position has to be possible               | Easy                   | No        | Cotton applicator Around $2     |
| Vibration        | Vibration sense                        | 67% of the children with CP, and 89% TD children could successfully complete | No training                    | Manual test                    | Easy                 | Not stated             | Minimum cognitive ability of a 6-year-old child   | Easy                   | No        | Vibration fork Around $50       |
|                  | Hip position                           | All children, and young people could perform the test | Not stated                     | Mechanical test                | Not clear            | Not stated             | Sitting position                                     | Not clear              | Not stated| Custom built device Costs not available |
|                  | Knee position                          | All children could perform the test                 | Not stated                     | Mechanical test                | Not clear            | Not stated             | Sitting position                                     | Not clear              | Not stated| Electrogoniometer Around $25    |
|                  | Knee position                          | All children could perform the test                 | Not stated                     | Mechanical test                | Not clear            | Not stated             | Sitting position                                     | Not clear              | Not stated| Biodex system 3 Pro Isokinetic dynamo-meter $5000-70000 |
|                  | Knee position                          | 68% of the children with CP, and 79% TD children could complete | No training                    | Manual test                    | Easy                 | Not stated             | Minimum cognitive ability of a 5-year-old child   | Easy                   | No        | No equipment                     |

(Continued)
| Modality              | Outcome Measure                                                                 | Clinician's comprehensibility | Type and ease of administration | Duration of the test | Evaluation of the test | Patient's required mental and physical ability level | Ease of standardization | Copyright | Requirement and Cost of instrument |
|----------------------|----------------------------------------------------------------------------------|-------------------------------|---------------------------------|----------------------|------------------------|-----------------------------------------------|------------------------|-----------|----------------------------------|
| Joint movement sense | Fugl-Meyer assessment sensory scale<sup>a</sup>                                | No training                   | Manual test Easy                | Not stated           | Not stated             | Supine lying position                       | Easy                   | No        | No cost                          |
| Toe movement<sup>b</sup> | 78% of the children with CP, and 95% TD children could complete               | No training                   | Manual test Easy                | Not stated           | Not stated             | Minimum cognitive ability of a 5-year-old child Sitting position has to be possible | Easy                   | No        | No equipment                     |
| Hip movement<sup>c</sup> | All children, and young people could perform the test                         | Not stated                    | Mechanical test                 | Not clear            | Not stated             | Sitting position                           | Not clear              | Not stated | Custom built device               |
| Spatial body representation | Self-portrait<sup>d</sup>                                                          | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Easy                   | No        | Pencil, and sheet                |
| Tactile localization task<sup>e</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Not clear              | Program not available Computer program |
| Visual body parts localization<sup>f</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |
| Verbal body parts localization<sup>g</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |
| Matching body parts by localization<sup>h</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |
| Structural body representation | Matching body parts by function<sup>i</sup>                                   | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |
| Body parts and object association task<sup>j</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |
| Naming body parts<sup>k</sup> | All children completed the test                                                | Not clear                     | Computer program Not clear      | Not stated           | Not stated             | Sitting position                           | Program not available Program not available Program not available Program not available | |

<sup>a</sup>original version 'length of instrument'
<sup>b</sup>original version 'completion time'

Abbreviations: TD – typically developing children; y – years; ISNCSCI – International Standard for Neurological Classification of Spinal Cord Injury
results cannot be transferred directly to the pediatric population, as in children with various diagnoses for UMN lesions, mainly both extremities (right and left) are affected.

The best evidence synthesis (Table 3) shows the very low to low quality of evidence of the psychometric properties that were investigated in the studies (internal consistency, reliability, hypothesis testing, or responsiveness). Data on the minimal detectable difference were missing. Although this parameter is highly relevant for the interpretation of the outcome in clinical practice. The studies did not provide information on content validity, structural validity, or measurement error for these outcome measures in these patient groups. Due to the lack of this information, applying these outcome measures in clinical practice for treatment planning and verification of treatment effectiveness remains problematic. For example, for the ISNCSCI, a high test-retest reliability was shown, but the smallest detectable change values are unknown.28,44,45 Without knowing the measurement errors, the magnitude of change scores are difficult to interpret.

A review of adult neurological patients with a cerebral lesion showed that only two of the 16 included tests of somatosensory function for the lower and upper limbs showed good psychometric characteristics.26 These were the Erasmus MC modification of the Nottingham Sensory Assessment (NSA) and the sensory part of the Fugl-Meyer assessment. The other outcome measures, such as joint position sense with isokinetic dynamometer, electro-goniometer, or robotic technology, were developed for a specific research project and are not available for clinical practice.26 That is also the case for some outcome measures included in our review for the pediatric population.7,41,49 Even therapists working with adults post-stroke are aware of the importance of assessing somatosensory function in their patients. Still, they rarely use standardized assessments for testing somatosensory function in clinical practice. That is comparable to the routine of therapists working with pediatric patients.22,50

When interpreting the feasibility of the outcome measures, we can conclude that manually applied tactile function assessments, vibration, and joint movement sense can be conducted with most children with UMN lesions aged five years and above, who can sit with or without trunk support. These assessments do not require costly test materials. The implementation in clinical practice might be further facilitated if more information on the duration of the test application and evaluation would become available. The computer-based outcome assessment for spatial and structural body representation cannot be replicated for clinical practice, as they are currently not generally available.9,47 Asano et al. showed in their study that children with intellectual and attention deficits can also perform outcome measures for spatial body representation.57 However, they included a small sample of 19 children.

New technologies with motion sensors and apps for measuring joint and body positions are readily available to date. Researchers developing assessments should consider that outcome measures should be child-friendly and applicable in a clinical setting. It is essential to study the psychometric properties in the target population. To enhance our understanding of the influence of lower limb somatosensory function and body awareness on motor function, valid and reliable outcome measures for children with UMN lesions are needed. Hence, more high-quality studies investigating the psychometric characteristics of tests, particularly reliability and measurement error, assessing the different modalities are urgently needed. Such studies must also report the various aspects of feasibility of these assessments to inform therapists on their clinical applicability.

**Limitations**

The COSMIN guidelines were initially developed to evaluate measurement properties of patient-reported outcomes. However, in the last years, the guidelines have been adapted and applied in several systematic reviews observing clinical outcome measurements,51–53 so we considered this a valid approach.

A major limitation of this study is the low number of articles that we could include, which prevents us from making recommendations. On the one hand, applying the COSMIN filter for measurement properties reduced the number of hits for somatosensory function and body awareness to one-third (hits somatosensory function after application of the COSMIN filter n = 652, for body awareness n = 205). Since we judged studies in line with the COSMIN recommendations, we considered this filter essential. As we hand searched the references, we have minimized the risk of missing relevant articles. On the other hand, the low number of studies indicates the relatively weak state of current research in this field.

**Acknowledgments**

We thank the experts for their expertise and references for the validation process of the search filters: Susanne Löw, Beatrice Marth, Billy Cusick, Margret Maayston, Simone Elsig, and Hannu Luomajoki.

**Disclosure Statement**

No potential conflict of interest was reported by the author(s).

**Funding**

We would like to thank the Anna Müller Grocholski Foundation, Switzerland, for their financial support.

**ORCID**

Petra Marsico [http://orcid.org/0000-0002-2503-9142](http://orcid.org/0000-0002-2503-9142)
Marietta L. van der Linden [http://orcid.org/0000-0003-2256-6673](http://orcid.org/0000-0003-2256-6673)
Hubertus J.A. van Hedel [http://orcid.org/0000-0002-9577-5049](http://orcid.org/0000-0002-9577-5049)

**References**

1. de Haan EHF, Dijkerman HC. Somatosensation in the brain: a theoretical re-evaluation and a new model. Trends Cogn Sci. 2020;24:529–541. doi:10.1016/j.tics.2020.04.003.
2. Kaas JH. Somatosensory system. 3rd ed. Elsevier; 2012. doi:10.1016/B978-0-12-374236-0.10030-6.
3. Dijkerman HC, de Haan EHF. Somatosensory processes subserving perception and action. Behav Brain Sci. 2007;30:189–201. doi:10.1017/S0140525X07001392.
4. Auld ML, Boyd RN, Moseley GL, Johnston LM. Tactile assessment in children with cerebral palsy: a clinimetric review. Phys Occup Ther Pediatr. 2012;32:151–66. doi:10.3109/0942638.2011.652804.

5. Cooper J, Majnemer A, Rosenblatt T, Birnbaum R, Birnbaum R. The determination of sensory deficits in children with hemiplegic cerebral palsy. J Child Neurol. 1995;10:300–9. doi:10.1177/088307359501000412.

6. McGregor HR, Cashaback JGA, Gribble PL. Somatosensory perceptual training enhances motor learning by observing. J Neurophysiol. 2018;120:3017–25. doi:10.1152/jn.00312.2018.

7. Sarasso E, Agosta F, Temporiti F, Adamo P, Piccolo F, Copetti M, Gatti R, Filippi M. Brain motor functional changes after somatosensory discrimination training. Brain Imaging Behav. 2018;12:1011-21. doi:10.1007/s12017-017-9763-2.

8. Bonassi G, Biggio M, Bisio A, Ruggeri P, Bove M, Avanzino L. Provision of somatosensory inputs during motor imagery enhances learning-induced plasticity in human motor cortex. Sci Rep. 2017;7:1–10. doi:10.1038/s41598-017-09597-0.

9. Jenkins P, Papadaki C, Beechharati S, Moros V, Gobotto V. Welcoming back my arm: affective touch incases body ownership following right hemisphere stroke. Brain Commun. 2020;2. doi:10.1093/braincomms/fcaa034.
39. Mokkink LB, Prinsen C, Patrick D, Alonso J, Bouter L, de Wet H, Terwee C. COSMIN study design checklist for patient-reported outcome measurement instruments. 2019. 32. https://www.cosmin.nl/wp-content/uploads/COSMIN-study-designing-checklist_final.pdf.

40. Uzun Akkaya K, Elbasan B. An investigation of the effect of the lower extremity sensation on gait in children with cerebral palsy. Gait Posture. 2021;85:25–30. doi:10.1016/j.gaitpost.2020.12.026.

41. Abdin MMN, Abdelazeim F, Elshennawy S. Immediate effect of induced fatigue of the unaffected limb on standing balance, proprioception and vestibular symptoms in children with hemiplegia. J Pediatr Rehabil Med. 2020;13:119–25. doi:10.3233/PRM-180587.

42. Zarkou A, Lee SCK, Prosser LA, Jeka JJ. Foot and ankle somatosensory deficits affect balance and motor function in children with cerebral palsy. Front Hum Neurosci. 2020;14:1–12. doi:10.3389/fnhum.2020.00045.

43. de Bode S, Fritz S, Mathern GW. Cerebral hemispherectomy: sensory scores before and after intensive mobility training. Brain Dev. 2012;34:625–31. doi:10.1016/j.braindev.2011.10.012.

44. Chafetz RS, Gaughan JP, Vogel LC, Betz R, Mulcahey MJ. The international standards for neurological classification of spinal cord injury: intra-rater agreement of total motor and sensory scores in the pediatric population. J Spinal Cord Med. 2009;32:157–61. doi:10.1080/10790268.2009.11760767.

45. Mulcahey MJ, Gaughan J, Betz RR, Vogel LC. Rater agreement on the ISICSCI motor and sensory scores obtained before and after formal training in testing technique. J Spinal Cord Med. 2007;30:146–49.

46. Nuara A, Papangelo P, Avanzini P, Fabbri-Destro M. Body representation in children with unilateral cerebral palsy. Front Psychol. 2019;19:354. https://www.frontiersin.org/article/10.3389/fpsyg.2019.00354/full.

47. Asano D, Morioka S. Associations between tactile localization and motor function in children with motor deficits. Int J Dev Disabilities. 2018;64:113–19. doi:10.1080/10790268.2016.1278316.

48. Fontes PLPLB, Cruz TTKF, Souto DO, Moura R, Haase VG. Body representation in children with hemiplegic cerebral palsy. Child Neuropsychol. 2017;23:838–63. doi:10.1080/09297049.2016.1191629.

49. de Machado ACCP, De Oliveira SR, Bouzada MCF, de Magalhães LC, de Miranda DM. Sensory processing during childhood in preterm infants: a systematic review. Rev Paulista Pediatria. 2017;35:92–101. doi:10.1590/1984-0462/2017;35;1;00008.

50. Pumpa LU, Cahill LS, Carey LM. Somatosensory assessment and treatment after stroke: an evidence-practice gap. Aust Occup Ther J. 2015;62:93–104. doi:10.1111/1440-1630.12170.

51. Oftedal S, Bell KL, Mitchell LE, Davies PSW, Ware RS, Boyd RN. A systematic review of the clinimetric properties of habitual physical activity measures in young children with a motor disability. Int J Pediatr. 2012;2012:1–12. doi:10.1155/2012/976425.

52. Ammann-Reiffer C, Bastiaen CHG, de Bie RA, van Hedel HJA. Measurement properties of gait-related outcomes in youth with neuromuscular diagnoses: a systematic review. Phys Ther. 2014;94:1067–82. doi:10.2522/ptj.20130299.

53. Haberfellner H, Goudriaan M, Bonouvié LA, Jansma EP, Harlaar J, Vermeulen RJ, Van Der Krogt MM, Buizer AI. Instrumented assessment of motor function in dyskinetic cerebral palsy: a literature review. Gait Posture. 2019;73:439–40.