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Development of the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP): reviewing measurement specific to the upper limb in tetraplegia

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Object. Primary outcome measures for the upper limb in trials concerning human spinal cord injury (SCI) need to distinguish between functional and neurological changes and require satisfying psychometric properties for clinical application.

Methods. The Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) was developed by the International GRASSP Research and Design Team as a clinical outcome measure specific to the upper limbs for individuals with complete and incomplete tetraplegia (that is, paralysis or paresis). It can be administered across the continuum of recovery after acute cervical SCI. An international multicenter study (involving centers in North America and Europe) was conducted to apply the measure internationally and examine its applicability.

Results. The GRASSP is a multimodal test comprising 5 subtests for each upper limb: dorsal sensation, palmar sensation (tested with Semmes-Weinstein monofilaments), strength (tested with motor grading of 10 muscles), and prehension (distinguishes scores for qualitative and quantitative grasping). Thus, administration of the GRASSP results in 5 numerical scores that provide a comprehensive profile of upper-limb function. The established interrater and test-retest reliability for all subtests within the GRASSP range from 0.84 to 0.96 and from 0.86 to 0.98, respectively. The GRASSP is approximately 50% more sensitive (construct validity) than the International Standards of Neurological Classification of SCI (ISNCSCI) in defining sensory and motor integrity of the upper limb. The subtests show concurrence with the Spinal Cord Independence Measure (SCIM), SCIM self-care subscales, and Capabilities of Upper Extremity Questionnaire (CUE) (the strongest concurrence to impairment is with self-perception of function [CUE], 0.57–0.83, $p < 0.0001$).

Conclusions. The GRASSP was found to demonstrate reliability, construct validity, and concurrent validity for use as a standardized upper-limb impairment measure for individuals with complete or incomplete tetraplegia. Responsiveness (follow-up from onset to 1 year postinjury) is currently being tested in international studies (in North America and Europe). The GRASSP can be administered early after injury, thus making it a tool that can be administered in acute care (in the ICU), rehabilitation, and outpatient clinics.
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Key Words • **tetraplegia** • **tetraparesis** • **upper limb** • **impairment** • **outcome measure** • **clinical trial** • **spinal cord injury**

It is essential to clinical studies that the available outcome measures provide high sensitivity and responsiveness to allow for the detection of potential treatment effects. Based on successful preclinical studies, several novel therapeutics for spinal cord injury (SCI) are now at the stage of clinical trials, such as AC105 (Acorda Therapeutics, Phase 2 trial in planning stage), SUN13837 (Asubio Pharmaceuticals, Inc., NCT01502631), riluzole (SpineNet, NCT00876889), and autologous Schwann cell transplants.[20] Translation of these therapies into clinical practice could be problematic, as existing clinical outcome measures may not be adequate to detect the spectrum of changes associated with biological experimental therapeutics. The purpose of the current paper is to review the available clinical outcome measures specific to the upper limbs in tetraplegia and to focus on the development of the GRASSP version 1.0. The GRASSP was developed to fill an identified gap in the field of clini-

Abbreviation used in this paper: SCI = spinal cord injury.

cal outcome measures, with the specific aim of creating a measure suitable for testing natural recovery and outcomes in clinical trials. This article reviews the rationale for the development of the GRASSP as well as the background and the process by which the measure was validated. We have included a table (Table 1) to explain the acronyms that are used in this review. Tetraplegia is defined in this paper as including complete and incomplete tetraplegia (that is, paralysis and paresis).

There are 2 important elements in the development of new outcome measures: 1) establishing the psychometric properties and 2) providing insights into functional and neurological impairment while revealing effects that are beyond spontaneous recovery. This manuscript investigates both of these elements in relation to the GRASSP.

Why Measurement of the Upper Limbs?

Measurement of the upper limbs has become increasingly important over the past 10 years in clinical trials for a number of reasons. Most importantly, the recovery of upper-limb function after a cervical SCI has been proven to be of high clinical value, as the upper limbs are a primary factor in functional independence. Thus, improvement in upper-limb function after cervical SCI is one of the most significant factors in improving quality of life according to individuals with tetraplegia.[1,43] Secondly, there has been a shift in research practice toward engaging patients with cervical SCI rather than thoracic SCI in clinical trials. This is due to the fact that changes and improvements in upper-limb function may be more feasible than within the trunk or lower limbs, when applying new treatments to the cord, due to a lesser distance from the injury.[49] In addition, regulatory agencies (such as the Food and Drug Administration) require that Phase II/III studies of new interventions must not only improve the neurological state (that is, body structure and capacity) but also need to enhance function and independence leading to improved quality of life; this makes the upper limbs a sensible target for new trials.

The Gap: Lack of Validated, Sensitive, and Specific Outcome Measures

What is the Gap in Existing Upper-Limb Outcome Measures?

In light of the neurological recovery that does occur in patients with tetraplegia, the necessity to assess neurological integrity is crucial. Measuring the upper limb with a specific and sensitive measure will allow researchers to evaluate the subtle change occurring in the upper limb secondary to natural recovery and interventions. Although a number of measures specific to SCI and upper-limb SCI (some specific to tetraplegia) exist, impairment of the upper limb (the construct of interest) is not measured with enough precision. Curtin et al.[6] reported that there was inconsistency in the evaluation and documentation as well as the sensitivity of the available measures and that they were insufficient to detect significant but small changes. It is crucial that measures have specificity to detect small but clinically significant improvements in hand function.[8]

Many of the measures used to date have either not been specifically designed for use in the SCI population[8,47] or, in the case of those that are specific to SCI, have minimally established psychometric properties. Identifying the measures that are reliable, valid, and have specificity is one key to translating new knowledge. Tests such as the FIM,[17] SCIM,[12] and QIF,[28] although measuring different functional gains, are not sufficient to determine the efficacy of neurobiological interventions, as they do not reliably identify changes in neurological integrity. It is worthwhile to apply common measures across interventions and time frames to provide comparability, but specific measures need to be employed to account for the underlying physiology of each intervention during each phase of recovery. This determines the choice of outcome measure selected. Table 2 presents the available and commonly used measures in SCI, with their applications, constructs, and psychometric properties.

The measures currently used most often in the SCI

TABLE 1: Summary of instruments

Abbreviation	Instrument Name or Description
GRASSP	Graded Redefined Assessment of Strength, Sensibility and Prehension
SWM	Semmes-Weinstein Monofilaments (for examining sensitivity to light touch)
SCI	Spinal Cord Injury
ISNCSCI	International Standards for the Neurological Classification of Spinal Cord Injury
SCIM	Spinal Cord Independence Measure
ISNCSCI (-LT)	International Standards for the Neurological Classification of Spinal Cord Injury (–Light Touch)
SCIM (-SS)	Spinal Cord Independence Measure (–Self-care Subscore)
CUE	Capabilities of Upper Extremity Questionnaire
FIM	Functional Independence Measure
QIF	Quadriplegia Index of Function
RULER SCI	RITZ Upper-Limb Evidence-based Rehabilitation in SCI (unpublished) A 5-level designation for upper-limb function related to motor innervation, which can be used to benchmark upper-limb measures in general, the RULER SCI has been defined by a group of SCI researchers in Zurich (at Balgrist University Hospital).

TABLE 2: Outcome measures used for SCI and upper-limb assessment*

Measure & Description	Construct & Population	Mode†	Construct Validity: InR	ItR TrT	KG	ConcV	Res	Qualities‡
impairment								
International Standards of Neurological Classification of SCI (ISNCSCI)—classification measure, used to determine severity of injury[25,33]	whole body; pts w/ SCI	M	0.89–0.99					▲ ■ ♦
Grip and Pinch Dynamometry—measure of grip force[30]	hand strength; pts w/ peripheral hand injury	M	0.98§	0.99§				● ♦
International Classification for Surgery of the Hand—upper-limb motor strength test & 2-point discrimination of digits[31]	upper-limb motor strength; pts w/ tetraplegia	M						■ ● ♦
function								
Van Lieshout Test—upper-limb capacity seated in a wheelchair[36,45]	upper-limb function; pts w/ tetraplegia	M	0.98§			0.87 w/ Grasp & Release§	R§	▲ ■ ● ◘
Grasp and Release Test—functional test specific to ability after neuroprosthetic implantation[34]	hand function; pts w/ tetraplegia	M	0.87§					▲ ■ ● ◘
Capabilities of Upper Extremity Questionnaire—self-perception of functional ability w/ upper limbs (CUE)[29]	upper-limb function; pts w/ tetraplegia	SR	0.96§	0.94§		0.74 w/ FIM§		▲ ■ ● ◘
Jebsen Hand Function Test—generic hand function test w/ outcome of time[7,13]	hand function; pts w/ hand injury	M						● ◘
Sollerman Hand Function Test—hand function test[44]	hand function; pts w/ musculoskeletal conditions	M	0.98§				R	▲ ● ◘
Action Research Arm Test (ARAT)—upper-limb reach & grasp test[22]	upper-limb function; pts w/ stroke	M	0.92§	0.97§		0.81 w/ WMFT§		● ◘
Wolf Motor Function Test (WMFT)—hand function test[22]	hand function; pts w/ stroke	M	0.92§	0.97§		0.81 w/ ARAT§		● ◘
Fugl-Meyer Hand Subtest—hand function test[3,10,22]	hand function; pts w/ stroke	M	0.92§	0.97§		0.81 w/ ARAT§		● ◘
global function/independence								
Functional Independence Measure—generic outcome which measures burden of care[17,19]	independence; pts w/ any disabilities	O	0.70					
The Spinal Cord Independence Measure II (SCIM)—measure of global independence[5,12]	independence; pts w/ SCI	O	0.94§			0.79 w/ FIM§		▲ ■ ◘
Quadriplegia Index of Function—measure of global function[25,28]	independence; pts w/ tetraplegia	O						■ ◘
Lamb and Chan Questionnaire—ADL inventory specific to tendon transfer[21]	independence; pts w/ tetraplegia	SR						■ ● ◘

* ADL = activities of daily life; ConcV = Concurrent Validity; InR = Interrater Reliability; ItR = Intrarater Reliability; KG = Known Groups; M = clinician administers measure and rates individual; O = clinician observes activity of an individual and rates the individual; pts = patients; R = responsiveness established at acceptable level; Res = Responsiveness; SR = self-reported measure; TrT = Test-Retest Reliability.

† Mode is the manner by which the measure is administered.

‡ Qualities of the measure: ▲ = psychometric properties evaluated with the SCI population; ■ = construct of measure specific to SCI; ● = construct of measure specific to the upper limb; ♦ = construct of measure specific to impairment; ◘ = construct of measure specific to function.

§ Interrater reliability above 0.8 intraclass correlation coefficient; intrarater or test-retest reliability above 0.8 intraclass correlation coefficient; concurrent validity above 0.7 correlation with a comparator measure, construct validity established.

population are either too global in nature (incorporating the whole body), are designed for different populations, assess a construct other than impairment of the upper limb, do not include sensory testing specific to the hand, or do not possess the psychometric properties required (see Table 2). Impairment of the upper limb is not the defined construct for any of the available measures. Although measurements of function and independence address very important clinical outcomes, they do not provide an understanding of neurological integrity, which underlies any change in level of function.

The literature in the field of "hand rehabilitation" places emphasis on impairment as well as functional assessment. Core impairments and how they relate to the performance of functional tasks are well understood[23,37] and acknowledged to be integral during therapeutic intervention. Based on the anatomy of the upper limb and the integrative nature of refined and complex hand movement, assessment of sensation and strength as well as performance of functional tasks is essential when making connections between the state of impairment and residual neurological integrity and function. The GRASSP was developed to measure neurological integrity, performance, and function.

Filling the Gap

An Impairment Measure Specific to the Upper Limb in Tetraplegia

The GRASSP is an assessment strategy that provides a detailed profile of integrated sensorimotor function of the upper limb for individuals with tetraplegia, both at a single time point and longitudinally. It was designed and developed by an international research and design team brought together in May 2006 by the Christopher and Dana Reeve Foundation (http://www.sci-grassp.org/).

Severity of injury and the spinal cord structures affected contribute to the degrees of presentation of impairment and to the potential for recovery. Therefore, an outcome measure needs to capture the changes occurring due to restoration of neurological integrity as well as changes related to compensatory behaviors and changes due to therapeutic interventions. The neurological and functional changes that occur postinjury are influenced by 2 main factors: 1) completeness of injury, with incomplete injuries[26,42] tending to show increased rates and magnitudes of recovery, and 2) development of interventions that are applied to the CNS such as pharmacological agents and biological agents with the potential for neural repair, neuroprotection, and regeneration.[2,40,48] With the shift in the type of patients included in clinical trials, changing recovery potential and the emphasis on restoring function, a need to establish a reliable, valid, sensitive upper-limb impairment measure is at the forefront of the SCI clinical trials agenda.

Conception and Development of the GRASSP Framework

Developing a new measure requires establishing a purpose and conceptual framework.[32] Subtests were selected based on how well they assessed the domains within the constructs. Items within the subtests were selected to ensure that the 3 components of reach, prehension, and manipulation of upper-limb movement were captured.[4,16,42] These domains represent core and integrated elements of integrity/impairment. The purpose of incorporating an integrated domain was to provide the opportunity to assess how sensation and strength contributed to an integrated function such as prehension, which may be increasingly important in understanding the recovery process. The GRASSP consists of 5 subtests that are performed separately and yield 5 subtest scores for both right and left. The scores are interpreted separately rather than as one global score, because each score provides specific information about the upper limb and all subtests do not share internal consistency. Table 3 and Fig. 1 define the theory underlying the measure and the components of the GRASSP.[15] The GRASSP was tested for sensibility, reliability, and validity and currently is being tested for responsiveness.

Properties of the GRASSP Version 1.0

Sensibility

"Sensibility," as described by Rowe and Oxman,[38] is "an aggregate of properties that make up the common sense aspect of an instrument, including face and content validity." As defined by Feinstein,[9] the dimensions of sensibility should include: comprehensibility, replicability, suitability of scale, ease of usage, face validity, content validity and scale purpose. Sensibility of the GRASSP was established by having 12 experienced clinicians administer the measure and then complete a sensibility questionnaire. The results of the questionnaire led to some modifications to the test. Included in these modifications were the following: clarification of the administration instructions for assessors and for patients and the addition of descriptors for scaling. Sensibility assessment of the GRASSP was conducted during a training workshop where clinicians had the opportunity to administer the GRASSP 2 or 3 times and then completed the sensibility survey.

Reliability

Reliability is considered to be a basic and essential quality of a scientific measure. Both interrater (between raters) and intrarater (between repeated measurements by the same rater) reliability of a test should be established. Test-retest reliability replaces intrarater reliability when the repeated tests are conducted more than 3 days apart.[35,46] Scientific investigation can only be performed with a reliable measure, as a change in measurement can then be attributed to clinical change, and the number of individuals required for a clinical trial can be reduced. Reliability was calculated using intraclass correlation coefficients. Interrater and test-retest reliability for all subtests within the GRASSP were above the hypothesized value of 0.80; interrater reliability ranged between 0.84 and 0.96, and test-retest reliability ranged between 0.86 and 0.98.[14]

Validity

A "valid" instrument assesses what it is intended to

TABLE 3: Summary of GRASSP version 1.0*

Subtests	Items	Origin of Test/Method of Administration	Scoring
Domain—Sensation			
1. Dorsal Sensation	SWM tested across 3 dorsal surface locations for each hand. Points 1–3 are dorsal digit I tip (C-6), dorsal digit III tip (C-7), & dorsal digit V tip (C-8)	conventional SWM minikit testing;[24] log of grams of force is represented by numeric values ranging from 0 to 4; 3.61 = 4, 4.31 = 3, 4.56 = 2, 6.65 = 1, no response = 0	each test location is scored from 0 to 4, & the 3 test locations for dorsal side of each hand are summed to yield a subtest total score btwn 0 & 12
2. Palmar Sensation	SWM tested across 3 palmar surface locations for each hand: palmar digit I tip (C-6), palmar digit III tip (C-7), palmar digit V tip (C-8)	testing performed as described in instructions of SWM minikit[24]	each test location is scored from 0 to 4, & the 3 test locations for palmar side of each hand are summed to yield a subtest total score btwn 0 & 12
Domain—Strength			
3. Strength	motor grading of 10 arm & hand muscles C-5: anterior deltoid, biceps C-6: wrist extensor C-7: triceps, opponens policis C-8: extensor digitorum; digit III finger flexor, flexor policis longus T-1: digit V finger abductor, first dorsal interossei	traditional motor grading is performed, each muscle is tested w/ resistance through full range & given a muscle grade btwn 0 & 5: 0 = flaccid, 1 = flicker, 2 = full range w/ gravity eliminated, 3 = full range against gravity, 4 = full range w/ moderate resistance, 5 = full range w/ maximal resistance Specific details regarding stabilization points, resistance points & positioning for testing are available in the GRASSP manual. This testing was adapted from Daniels & Worthingham,[11] & Kendall & McCreary.[18]	each muscle is graded from 0 to 5, & the 10 grades for each side are summed to yield a total strength score btwn 0 & 50 for each upper limb
Domain—Prehension			
4. Prehension Ability	grades ability to generate 3 grasps: 1) Cylindrical Grasp, 2) Lateral Key Pinch, & 3) Tip to Tip Pinch	Each grasp is graded by the assessor using specific components of grasp acquisition outlined in the GRASSP manual. In general the scoring ranges between 0 & 4. A score of 0 represents no ability to use the wrist, fingers, or thumb to perform a grasp, & 4 represents the ability to keep the wrist in neutral & generate the grasp w/ full thumb & finger movement. This subtest was created by the GRASSP Research & Design Team.	Prehension Ability total score = 12
5. Prehension Performance	performance of 6 prehension tasks, scored from 0 to 5. 1) pour water from a bottle, 2) open jars, 3) pick up & turn a key, 4) transfer 9 pegs board to board, 5) pick up 4 coins & place in slot, 6) screw 4 nuts onto bolts	This test is adapted from the Sollerman Hand Function Test.[44] Each task is scored on a 0–5 scale (details of scoring available in the GRASSP manual).	Prehension Performance total score = 30

* The GRASSP version 1.0 is a test kit with all of the standardized apparatus included along with a manual that gives the instructions for administration in great detail. Each subtest (5 in all) renders a subtest score for right and left. Subtest scores are used to characterize an individual's upper-limb impairment. All tests are completed for right and left sides separately.

measure. Face validity exists if the measure appears to assess what it is intended to measure, and content validity exists if the components represent the construct that the measure is intended for. In this case, the intended construct is sensorimotor upper-limb function. Face and content validity are established by a review of the measure, usually by an expert or a panel of experts. This is often incorporated into the sensibility testing. The GRASSP face and content validity were evaluated in the sensibility testing and were adequate. Construct validity is usually established by comparing the new measure to an existing measure that assesses the construct of interest. However, if a comparable measure does not exist, other available measures in the field of interest can be used.[46] Unlike in the analysis of reliability, a wide variety of approaches can be used to establish construct validity.

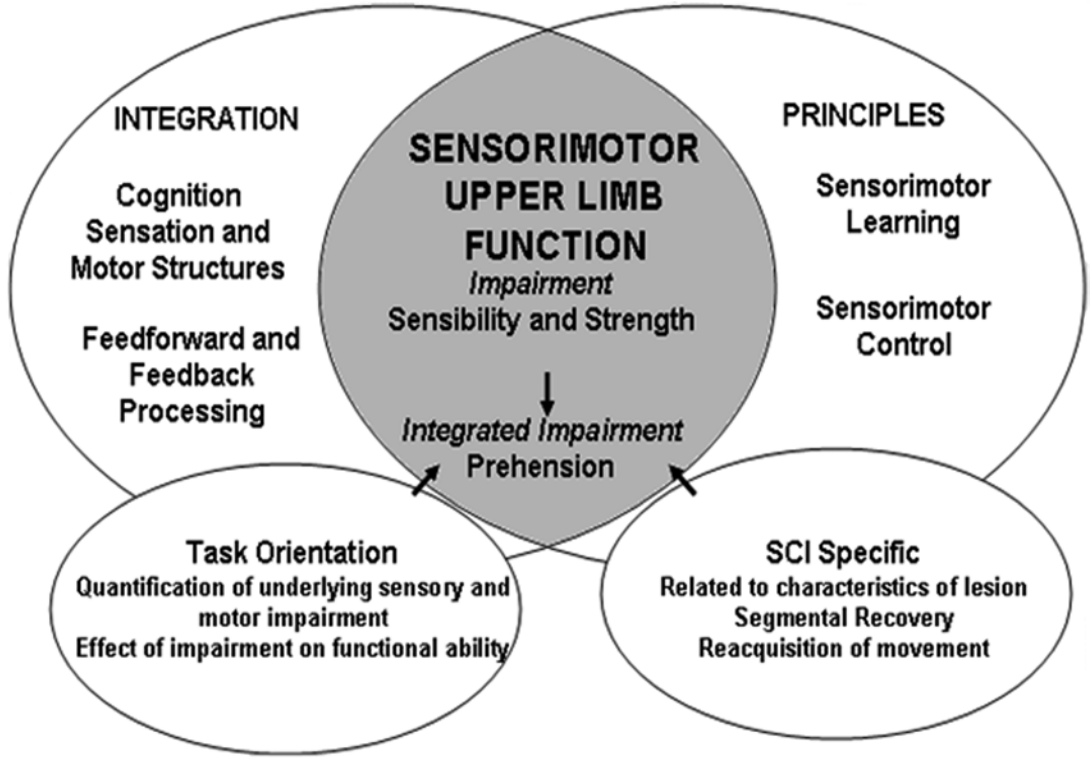

Fig. 1. Theoretical framework for the construct of sensorimotor upper-limb function used for the development of the GRASSP. This figure illustrates the concepts, principles, and structures associated with upper-limb function.

For the GRASSP, construct validity was established by comparing the additional items in the GRASSP to the ISNCSCI items. On average, 54% of the sample showed discordance in sensory innervation between GRASSP and ISNCSCI, due to the additional palmar test locations and the modality selected for testing (Semmes-Weinstein monofilaments [SWM]). On average 50% of the sample showed discordance in motor innervation when assessed with GRASSP as compared with the ISNCSCI due to the additional muscles (n = 5) of the motor testing and the use of a summative numeric score to define strength out of 50. Table 4 demonstrates the proportion of agreement and discordance among the sensory and motor items in both the GRASSP and ISNCSCI.

Furthermore, the level of agreement between ISNCSCI-LT and GRASSP-SWM for the C-6, C-7, and C-8 dorsal test locations was calculated with kappa coefficients (0.412, 0.474, and 0.511 respectively). These analyses revealed poor agreement among the sensory tests in the GRASSP and ISNCSCI, with patients revealing greater levels of sensitivity on the GRASSP. This indicates that the palmar sensory testing used in the GRASSP is more sensitive than the ISNCSCI-LT.

Concurrent validity was calculated with Spearman correlation coefficients to establish the association between GRASSP subtests and the CUE, SCIM II, and SCIM-SS. It was noted that the total SCIM score shows the least association with subtests of the GRASSP, but the association is positive and significant, with a p value of less than 0.0001 (Table 5). The SCIM-SS shows a stronger association with the subtests of the GRASSP. This is similar to the result reported by Rudhe and van Hedel,[39] showing the specificity of the self-care subscale in SCIM to the motor testing done in the GRASSP for a smaller sample. The CUE shows the strongest associations with the GRASSP subtests that represent a strong association between self-perceived function and impairment. As the secondary measures become more specific to the upper

TABLE 4: Construct validity agreement/discordance of sensory and motor results between GRASSP and ISNCSCI in 72 patients*

ISNCSCI Subtest & Subgroup	Agreement	Discordance	
		1	2
Sensory Level†			
rt total sample	32 (45)	16 (22)	24 (33)
lt total sample	34 (47)	13 (18)	25 (35)
Motor Level‡			
rt total sample	36 (50)	19 (26)	17 (24)
lt total sample	34 (48)	20 (28)	17 (24)

* Values represent numbers of patients (%).

† Sensory Level: Agreement—GRASSP and ISNCSCI are consistent with assessment of sensation; Discordance 1—due to added palmar test locations in GRASSP; Discordance 2—due to the increased response levels (SWM) used in the GRASSP; ISNCSCI levels are used only to subgroup the whole sample.

‡ Motor Level: Agreement—GRASSP and ISNCSCI are consistent with assessment of strength; Discordance 1—due to added muscles in GRASSP; Discordance 2— due to deriving a level from numeric score; ISNCSCI levels are used only to subgroup the whole sample.

TABLE 5: Concurrent validity of GRASSP subtests and functional measures*

Subtest Score	SCIM	SCIM-SS	CUE
Sensory total	0.57	0.74	0.77
Strength total	0.59	0.74	0.76
Prehension Performance total	0.68	0.79	0.83

* All values statistically significant at $p < 0.0001$, Pearson Correlation Coefficient. The value range 0.61–0.79 indicates moderate concurrence; 0.80–1.00, substantial concurrence.

limb, it is noted that the association between impairment and function becomes stronger for all domains. Subtests within the GRASSP demonstrate moderate to substantial concurrent validity with the SCIM and the CUE. This is indicative of a positive relationship between impairment, function, and independence. Of note, the strongest associations linking impairment (GRASSP subtests) to function are those between self-perceived function (CUE), confirming that individuals' perception of their own ability is comparable to quantitative testing in the chronic SCI population.

Scoring

Attention to the scoring system and best possible options for use is significant in development of the measure as a whole. However, the meaning of individual subtest total scores is of greater significance to defining neurological deficit than a single global score in the GRASSP. The separate domains—sensation, strength, and prehension—are not intended to have internal consistency; instead, they have definitive contributions to and interactions with one another as well as contributions to overall upper-limb function. Table 6 provides a general understanding of GRASSP subtest scores and how they relate to ISNCSCI scoring and classification. In essence, the 5 subscore totals are used to define an individual's impairment and associated hand function as demonstrated in Fig. 2. The GRASSP scores define an individual's degree of impairment with 5 numeric values that represent the neurological impairment at the periphery, not the spinal cord level. Therefore, the numeric scores do not define SCI as is the case with the ISNCSCI. The differentiation between upper and lower cervical injuries can be seen, but because individuals can have partial innervation, the GRASSP represents it as an increasing numeric value. Therefore, adding scores across subtests for a global score would not represent the multidimensional construct of "sensorimotor upper-limb function" adequately.

When interpreting subtest sum scores for dorsal sensation, palmar sensation, strength, prehension ability, and prehension performance, a score closer to zero represents a greater deficit, while a score closer to the maximum represents a lesser deficit. These numerical values, when interpreted according to Table 6, enable the assessor to understand the general degree of impairment of an individual. Subtest items can be added for subtest total scores but should not be summed across subtests. The most meaningful way to observe GRASSP subtest totals is to plot the scores on a radar graph for each limb. Scores are normalized before they are plotted on the graph. Normalizing the subtest scores before combining was employed by Rosén and Lundborg[37] in the development of a multidomain measure for peripheral hand injury. Figure

TABLE 6: ISNCSCI sensory and motor level benchmarks for GRASSP discriminative score ranges*

GRASSP Subtest (no. of items, item score range, subtest score range)	Intended Meaning of Score (levels of GRASSP scores)	ISNCSCI & AIS		
		AIS Class	S or M Level	ZPP
Dorsal Sensation (3, 0–4, 0–12)	0–4: C-6	A–D	C4–7	C4–8
	5–8: C-7	A, B, D	C4–7	C7–8
	9–12: C-8	A–D	C4–T1	C-8
Palmar Sensation (3, 0–4, 0–12)	0–4: C-6	A, B, D	C4–6	C5–8
	5–8: C-7	A–D	C4–7	C7–8
	9–12: C-8	A–D	C4–8	C-8
Strength (10, 0–5, 0–50)	0–10: C-5	A	C4–5	C5–7
	11–15: C-6	A, B	C4–6	C5–7
	16–25: C-7	A, B, C	C6–7	C6–8
	26–40: C-8	B, C, D	C4–8	C7–T1
	41–50: T-1	B, C, D	C6–T1	T-1
Prehension Ability (3, 0–4, 0–12)	0–6: C5–6	A–D	C4–7	C5–8
	7–12: C7–T1	A–D	C7–T1	T-1
Prehension Performance (6, 0–5, 0–30)	0–5: C5–7	A	C4–5	C5–7
	6–10: C5–7	A, B	C5–7	C6–7
	1–15: C5–7	A, B, C	C5–7	C6–8
	16–20: C5–T1	A, B, C	C6–8	C7–T1
	21–25: C5–T1	B, C, D	C6–8	C7–T1
	26–30: C5–T1	A–D	C5–T1	T-1

* AIS = ASIA Impairment Scale; ZPP = Zone of Partial Preservation score; S or M Level = ISNCSCI sensory or motor level.

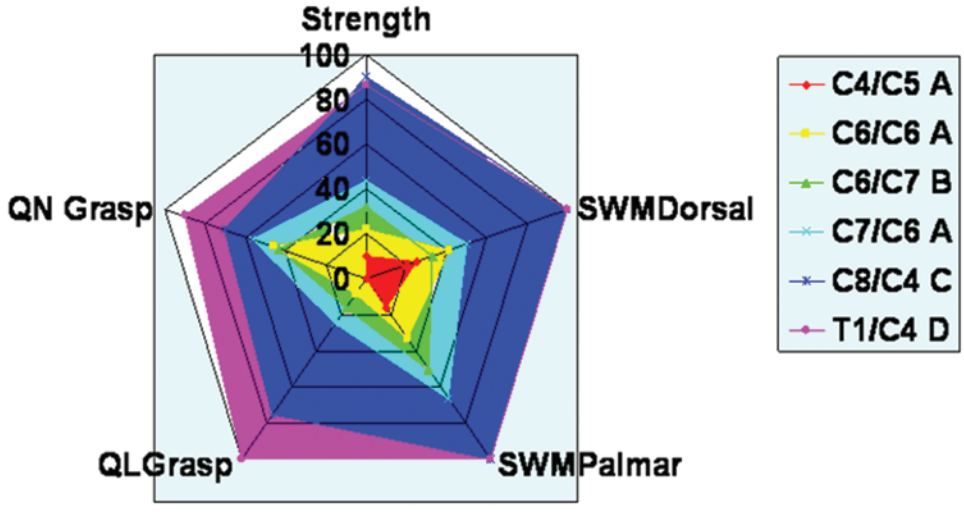

Fig. 2. Visual representation of GRASSP subtest scores. Superimposing consecutive assessments of the GRASSP in a polar diagram would allow an illustration of scores over time. This figure shows the scores from 6 individuals chosen from the cross-section of 72 to demonstrate different ratings. A diagram such as this would be generated for each hand separately. QL = qualitative; QN = quantitative.

2 illustrates the results in 6 individuals from the sample (right hands only), with their subtest scores. This method allows one to view multiple individuals or repeated measurements of the same individual collectively in a single diagram. Scores defined this way enable the assessor to make comparisons over time and thus to assess recovery or change over varying time frames.

Known-Groups Validity

The Known-Groups method is a common method to support construct validity and is used when a test can discriminate between groups of individuals known to have differing levels or severity of a trait,[35] in this case severity of SCI. Ranges of GRASSP subtest scores were benchmarked against the ISNCSCI motor levels, RULER SCI (Table 7), and SCIM-SS. The RULER SCI is a 5-level designation for upper-limb function related to motor innervation, which can be used to benchmark upper-limb measures in general; it has been defined by a group of SCI researchers in Zurich (at Balgrist University Hospital). The purpose of analyzing the GRASSP subtest scores in this manner was to define the place of GRASSP scores relative to a known measure of impairment (ISNCSCI), known functional measure (SCIM-SS) specific to SCI, and a classification of upper-limb function (RULER SCI). The ISNCSCI assigns impairment according to the most caudal "normal" neurological level; any sensory and motor function below the designated level is not accounted for except by the zone of partial preservation, which is also a sensory or motor level. Therefore, the ISNCSCI does not provide a true representation of impairment. Using ISNCSCI to identify levels of GRASSP scores would not provide distinct groupings, only ranges, whereas the GRASSP impairment measure accounts for the partial or cumulative neurological status between neurological levels, by presenting the deficit as a numeric value that represents impairment or lack thereof in the upper limb.

Strength subtest sum scores were placed in ascending order to establish the ranges of GRASSP scores and associated RULER SCI levels of hand function. The associated SCIM-SS score ranges, ISNCSCI motor level ranges, and remaining GRASSP subtest score ranges were also defined. The results in Table 6 define the ranges of scores for SCIM-SS, ISNCSCI motor levels, and all GRASSP subscores. It is evident that the score ranges for all the tests included are discriminative to some degree. There are clearly differences between upper-cervical and lower-cervical injuries, whereas midcervical injury scores overlap in both directions. No single measure stratifies the entire sample, but some aspects of each subtest do provide greater discrimination than the ISNCSCI and SCIM-SS. The stratification of subjects can be seen across all measures for Levels 1, 2, and 3. In Levels 4 and 5, however, the SCIM-SS and ISNCSCI do not differentiate the groups as well as the GRASSP strength subscore.

Discussion

The GRASSP sensitively and specifically assesses key functional domains for the upper limb in individuals with complete or incomplete tetraplegia. This outcome measure has the advantage of being applicable in the early stage after injury and can be administered throughout the recovery process. Data collection early after injury allows one to establish a reliable baseline, which can be used to compare subsequent assessments done in either the same facility or across institutions. Table 8 provides a summary of the GRASSP and its characteristics.

Measuring the 3 domains adds value to upper-limb assessment. Sensory and motor domains define the neurological deficit as they relate to anatomy and physiology (dermatomes and myotomes), while prehension defines how the deficits impact function. The relationships of the 3 domains characterize the cause of the functional deficit. The GRASSP was not designed to measure or evaluate compensation or one's ability to accomplish a task, but rather how the task is performed and the quality of

TABLE 7: RULER SCI sub-items and GRASSP discriminative score ranges with corresponding SCIM-SS and ISNCSCI motor level benchmarks*

RULER SCI Sub-Items	GRASSP					SCIM-SS	ISNCSCI Motor Level
	DS	PS	Str	QLP	QNP		
Level 1: no hand function no voluntary control of elbow, wrist, or hand muscles; no grasping function & severely limited active placing or reaching of arm	0–6	0–6	5–11	0–1	0–4	0–6	C4–5
Level 2: passive tenodesis hand passive hand functions w/ neither voluntary control of extrinsic & intrinsic hand muscles nor ability to actively extend wrist; opening & closing of hand only possible by supination or pronation of forearm (passive tenodesis effect) w/ no active grasping movements of hand; bimanual grasping by stabilizing objects btwn 2 hands or passive tenodesis grasp effective only in limited workspace	2–0	3–10	7–18	0–7	0–16	1–10	C5– 6
Level 3: active tenodesis hand no voluntary control of extrinsic & intrinsic hand muscles but active wrist extension allowing for passive movements of fingers dependent on a tenodesis effect; limited single-handed grasping function in restricted workspace	2–12	4–12	12–30	2–7	8–25	8–17	C6–7
Level 4: active extrinsic-tenodesis hand voluntary control of wrist & some extrinsic hand muscles allowing for grasping w/ or w/o tenodesis enabling some active opening & closing of hand but reduced dexterity & reduction of workspace	8–12	9–12	31–40	6–12	12–30	9–20	C6–8
Level 5: active extrinsic-intrinsic hand voluntary control of extrinsic & intrinsic hand muscles w/ full workspace & ability to perform different grasp forms (pulp pinch) but potential limitations of muscle strength & dexterity	8–12	8–12	36–50	8–12	21–30	10–20	C6–T1

* DS = Dorsal Sensation; PS = Palmar Sensation; Str = Strength; QLP = Qualitative Prehension; QNP = Quantitative Prehension.

the performance. The value in the information gathered by GRASSP allows one to understand more about the neurological integrity of the upper limb and its impact on function, which may in turn allow clinicians and researchers to understand how to influence the deficit. The multidomain feature of the GRASSP means the measure can be used in two ways: 1) to test new approaches and determine what aspect of deficit is influenced and 2) to track the natural recovery process. The GRASSP provides greater precision or sensory reporting than existing tests because of the use of Semmes-Weinstein monofilaments. The strength testing provides greater robustness to the motor testing due to the assessment of additional muscles. The prehension testing defines the functionality of the neurological integrity. These features of the GRASSP make it a superior measure for use in clinical trials assessing neurological change in the upper limb.

The GRASSP yields data that characterize the impairment of the upper limb with greater detail than any currently available SCI-specific measure, enabling researchers to understand the process of spontaneous recovery and the effects of interventions. It allows the assessor to make connections between impairment and function with greater accuracy, precision, and meaning. This research presents a novel upper-limb impairment measure for individuals with complete and incomplete tetraplegia and shows substantial promise as a new outcome measure in the field; the work also has some limitations.

Limitations of the GRASSP itself are defined by the purpose of the measure. The GRASSP has been designed as a clinical measure, so implementation and access to the test is simple and inexpensive. Nevertheless, a clinical measure always includes some degree of human error. Implementation of the measure is clearly defined in the instruction manual, but administration of the measure may vary slightly due to the level of understanding and the preferences of the clinicians administering the test. This approach requires establishment of a clear implementation strategy—including training, recording, and analysis—that is evaluated routinely. Furthermore, the test can only be administered if the patient is conscious and able to communicate. It is possible to perform a GRASSP on a very alert intubated patient, but it is clearly challenging.

Despite the sample size being sufficient for the reliability analysis, when the sample was grouped into cervical levels according to ISNCSCI subgroups, the cohorts were not large enough to confirm definitively some of the results noted. To use a more rigorous statistical analysis methodology such as Rasch analysis or Mokken Scale analysis, to determine the true predictability of the items and subtests, a much larger sample will be required.

The sample used in this study included individuals with chronic tetraplegia; therefore, future results of similar analyses may differ if results are based on individuals in a more acute stage. Individuals with chronic tetraplegia often develop compensatory patterns and functions otherwise known as "maladaptive patterns," which are not always accommodated for by the GRASSP. Although, the

TABLE 8: Attributes of the GRASSP Version 1.0

Attribute	Description
purpose of the measure	designed to measure impairment of the upper limb in pts w/ tetraplegia (cervical SCI)
theoretical framework	defines the underlying anatomical & neurophysiological concepts & theories that play a role in upper-limb function, explains why the construct for the measure is "sensorimotor upper-limb function," defines core & integrated elements of impairment that contribute to upper-limb function
description of measure	construct: sensorimotor upper-limb function; domains: hand sensation, strength of upper limb & prehension tasks; multi-modality measure, consisting of 5 subtests
scoring	the 5 subtests (dorsal sensation, palmar sensation, strength of upper limb, prehension ability, prehension performance) each yield a numerical value that represents the impairment manifested peripherally & at the spinal cord
reliability	interrater & test-retest reliability for all subtests w/in the measure are above 0.80
validity	construct validity: sensation & strength domains have greater sensitivity in defining upper-limb impairment than currently available measures for SCI; concurrent validity: the subtests w/in the measure hold concurrent validity w/ measures of function used w/ the SCI population (SCIM, CUE)
uses of the measure	intended use as a clinical assessment of impairment of the upper limb in pts w/ tetraplegia; the numerical values yielded by the measure can be used to establish relationships btwn impairment & function for individuals w/ chronic tetraplegia

prehension domain is designed to differentiate between maladaptive and normal movement patterns, individuals with chronic tetraplegia have very strong compensatory behaviors that may not be distinguishable from normal behaviors. Furthermore, the ability to complete tasks in the GRASSP is based on experience with activities of daily living. For individuals who live in the community, many of the tasks are familiar. However, individuals with acute injuries would be challenged by the same tasks as they may not have had the opportunity to practice or perform them. This difference between acute and chronic conditions may warrant modifications in testing and scoring in the future.

Future Directions

The psychometric property of responsiveness has not been established for the GRASSP to date. Currently, longitudinal studies are being conducted in Canada (by M.C.V. and S.K.R.) and Europe (by A.C. and co-investigator Velstra) to establish responsiveness of the GRASSP. The current trial includes serial testing of individuals from the time of injury to 1 year postinjury. The data will be used to establish the responsiveness of the GRASSP, to define a recovery profile of the upper limb after SCI, and to establish elements of minimum clinically important difference. The trial will provide data to determine the most appropriate scoring of the GRASSP for individuals during the acute phase after injury and the relationships between impairment and function throughout the continuum of recovery. In addition it will be used predictively to determine the temporal association of upper-limb recovery and how it influences function, to determine the optimal time frame and type(s) of intervention, and to build algorithms for informing clinical decision making.

This study focused on the development of GRASSP in traumatic tetraplegia. However, individuals with nontraumatic tetraplegia often present with similar upper-limb impairments. The GRASSP will be applied in 2 nontraumatic SCI longitudinal studies to examine the impairment changes that occur after surgical and drug interventions. Modifications to the measure may be required to accommodate the nontraumatic group.

Conclusions

In conclusion, development of the GRASSP version 1.0 was a response to the gap in measurement for the upper limb in tetraplegia. Table 8 summarizes the content and qualities of the measure. An impairment measure with robust measurement properties that assesses the domains most likely to change with new therapeutic interventions directed toward neural repair and recovery was lacking. The GRASSP is a new measurement tool used to determine the status of upper-limb function. Once sensitivity to detect change in sensorimotor impairment has been established, the GRASSP will have the potential to be an important assessment tool to detect specific changes across the postinjury process. In clinical trials, where the primary outcome of sensorimotor integration needs to be decoupled to determine efficacy of interventions, the GRASSP will be useful to determine the integrated contribution of the underlying neural substrates of sensation and motor function. This new knowledge gained has the potential to characterize the effectiveness of sensorimotor therapeutic interventions.

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