Assessment of the Hand in Tetraplegia Using the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP): Impairment Versus Function

Sukhvinder Kalsi-Ryan, Armin Curt, Michael G. Fehlings, and Mary C. Verrier

Objective: To refine the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) as a measure of upper limb impairment following cervical SCI. **Method:** A cross-sectional study assessed a cohort of neurologically stable patients with tetraplegia using a preliminary version of the GRASSP. Regression analysis was performed to determine the association between subcomponents of the GRASSP (impairment) and measures of function. The GRASSP was modified based on results. **Results:** Eliminated static two-point discrimination, tone, and one muscle. **Conclusion:** The GRASSP Version I consists of Semmes Weinstein monofilaments, manual muscle testing, and qualitative and quantitative prehension testing. **Key words:** *assessment, measurement, sensory motor impairment, tetraplegia, upper limb*

The ability to use the upper limbs is of central importance for individuals with tetraplegia as upper limb function determines overall function for these individuals. Not only do they use their hands to perform normal functions, but they also use their upper limb function as a substitute for other functions that are no longer possible. The upper limbs of an individual with tetraplegia are integral for

Sukhvinder Kalsi-Ryan, MSc, BSc PT, *is a PhD student, Graduate Department of Rehabilitation Science, University of Toronto, Research Physical Therapist, Krembil Neuroscience Centre, University Health Network, and member, International GRASSP Research and Design Team Toronto, Ontario, Canada.*

Armin Curt, MD, *is an Associate Professor of Neurology, University of British Columbia, Associate Director and Chair in Spinal Cord Rehabilitation Research, International Collaboration on Repair Discoveries (ICORD), and member, International GRASSP Research and Design Team , Vancouver, British Columbia, Canada.*

Michael G. Fehlings, MD, PhD, *is a Professor, Department of Surgery, University of Toronto, Neurosurgeon and Chair in Neural Repair and Regeneration, Krembil Neuroscience Centre, University Health Network and member, International GRASSP Research and Design Team, Ontario, Canada.*

Mary C. Verrier, MHSc, Dip POT, *is an Associate Professor, Department of Physical Therapy, University of Toronto, Senior Scientist, Toronto Rehabilitation Institute, and member, International GRASSP Research and Design Team, Toronto, Ontario, Canada.*

Top Spinal Cord Inj Rehabil 2009;14(4):34–46

www.thomasland.com

doi:10.1310/sci1404-34

activities such as locomotion, bowel and bladder care, recreation, and employment. Individuals with tetraplegia have identified upper limb function as one of the most significant factors contributing to quality of life.[1,2] Therefore, the more extensive upper limb recovery is following tetraplegia, the more functional an individual should be. In essence, upper limb function can equate to independence and global function for someone with tetraplegia.

Many investigators have studied ways to enhance upper limb movement (e.g., functional electrical stimulation and tendon transfer)[3,4] and have subsequently assessed outcomes by measuring elements that were thought to be impacted by the interventions as opposed to changes in impairment or global function of the upper limb. Existing approaches to assessment have measured targeted parameters such as force, magnitude, and duration of grasp.[5–7] Values for grasp parameters, however, do not necessarily reflect subtle neurological change[8,9]—change that may facilitate a more optimal movement pattern and improved hand function. Furthermore, subtle neurological change may be the only initial positive result observed with neuroprotective and neuroregenerative therapies in humans.[10,11] To assess efficacy, one needs to determine the degree of change required to optimize function. Therefore, a comprehensive and sensitive measure of upper limb impairment/function is needed to document change post injury. Such a measure, which would depend on multiple factors such as the interplay between the sensory and motor domains of movement, is essential for future interventions intended to improve neurological recovery after spinal cord injury (SCI).

Assessment of upper limb recovery after tetraplegia will also be important to future pharmaceutical trials. Recently, due to the difficulty with assessment of the thoracic area, increased consideration is being given to enrolling subjects with cervical SCI in trials studying biological and pharmacological agents.[12,13] It is hypothesized that neurological improvement in the cervical spinal cord is more likely to be reflected and detected as a change in upper limb function as compared to thoracic changes, which are difficult to assess. Furthermore, enrolling individuals with tetraplegia increases the number of potential subjects for studies, as almost two thirds of SCIs are cervical.[14] Increasing survival rates for cervical SCI have also driven interest in the development of a sensitive outcome measure for upper limb impairment. Researchers and experts have criticized prior trials[15] that used the International Standards for Neurological Classification of SCI, including the American Spinal Injury Association Impairment Scale (AIS),[16] as a primary outcome measure. The AIS was created and intended to be used as a clinical measure to classify injury severity, not as an outcome measure for efficacy in clinical trials. Nonetheless, the AIS has been utilized in many studies, and progress from human clinical trials has been hampered by the absence of a sensitive test for upper limb impairment, specifically the hand.

The first concentrated attempts by Sollerman and Ejeskar to measure hand function in the tetraplegic population met with limited success.[17] The Sollerman Hand Function Test was designed based on the conceptualization of normal hand function and did not adequately account for the impact of varying degrees and levels of cervical cord damage on hand impairment. Another outcome measure, the Danish Tetraplegia Hand Mea-

sure,[18] was designed to measure the ability to complete functional tasks performed using a passive tenodesis grasp. Approaches to the use of tenodesis grasp are not universal, and the lack of specific protocols limits the utility of the test to certain parts of the world and a selective subgroup of individuals. The Jebsen-Taylor Hand Function Test[19] is commonly used in SCI but was neither validated nor designed specifically for neurological populations. The Rehabilitation Engineering Laboratory Hand Function[20] and Grasp and Release[21] tests are specifically designed to assess the effects of functional electrical stimulation and neuroprosthetic interventions and have not been adopted universally. The Van Lieshout Test[22] was designed to assess upper limb capacity in tetraplegia and tests performance on tasks related to daily living. It has inter- and intrarater reliability of 0.98 and 0.99 (n = 12), respectively, and moderate concurrent validity with the Grasp and Release Test. Although useful during the subacute phase of recovery, the aforementioned functional tests are not feasible for use in the acute phase where new biological and pharmacologic interventions are targeted. Assessment of subtle change is paramount. Improved measures of upper limb impairment and function are required to determine efficacy in clinical trials and will need to be incorporated into Phase 2 and Phase 3 trials.[23]

Development of the GRASSP

It became clear to the pharmaceutical industry and scientists in the field that approaches to measure and determine the efficacy of emerging therapies were lagging and an outcome measure was needed that was both sensitive and responsive to change—one that could be used to track natural recovery and the response of individuals receiving treatment. These issues served as the rationale for the development of the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP).

In May 2006, the North American Clinical Trials Network held a workshop in Chicago, Illinois, funded by the Christopher and Dana Reeve Foundation and Novartis International AG, Basel, Switzerland. The focus of the workshop was the discussion of the measurement of hand impairment and function in patients suffering from cervical SCI. Clinical specialists in hand measurement, rehabilitation practitioners, and SCI researchers with expertise in upper limb neurophysiology, engineering, and computer technology discussed the development of a comprehensive protocol to assess upper limb impairment and recovery post cervical SCI. At the conclusion of the meeting, a task force was formed to develop a new clinical protocol to assess upper limb (hand) impairment by modifying existing tools and introducing new measures intended to quantify changes in hand impairment starting immediately post injury. This led to the development of the alpha version of the GRASSP.

Theoretical Framework

The overall objective for the assembly of the GRASSP was the development of a clinical research measure that could (a) capture information on upper limb impairment for the cervical (C0-T1) SCI population, including data on integrated sensory and motor impairment; (b) discriminate according to the level of lesion; and (c) capture changes in hand impairment throughout the recovery

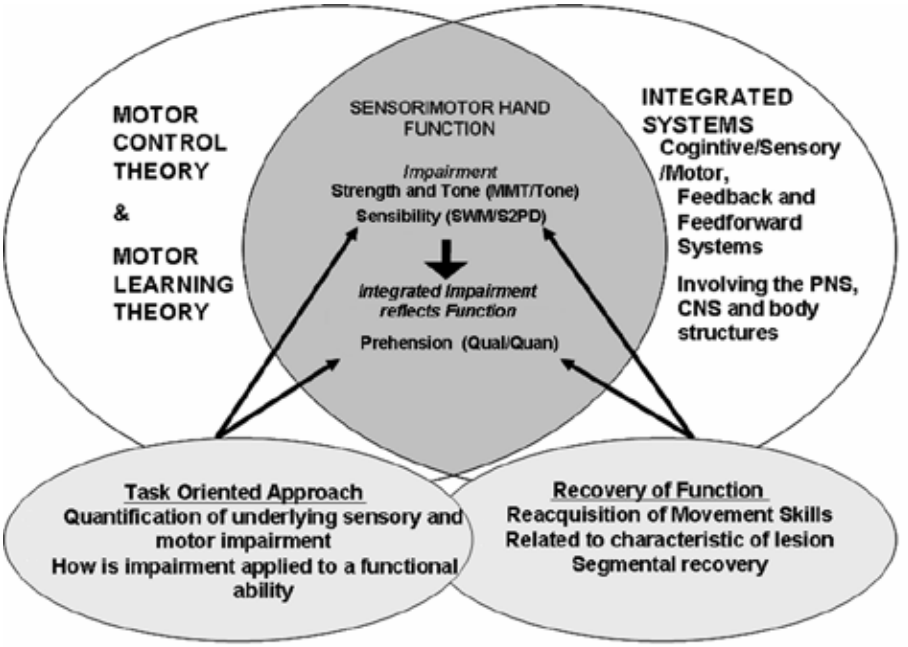

Figure 1. Theoretical framework for the development of the GRASSP.

phase. Sensorimotor function was defined as the major construct for the GRASSP, and a theoretical framework (**Figure 1**) was designed to guide development of the measure. The framework incorporated the concepts of motor control and motor learning theory,[24] which involve the interactions of the function (task), the individual, and the environment.[25] Task performance, which is dependent on integrated systems of sensation, motor, and cognition, was also incorporated. An integrated component was incorporated to assess how sensory and motor impairments contribute to an integrated function; this issue becomes increasingly important during the recovery process. When scoring is directed toward the quality and performance of movement (noting how the grasp is produced) more so than the ability alone (task performed or not), the results indicate which neurological elements are intact.

The initial GRASSP combined the preexisting Link Hand Function Test (LiHFT)[26] and the Tetraplegia Hand Measure (THM)[27] and incorporated three domains: strength and tone, sensibility (sensation), and prehension (integrated). The three domains provide the basis for the name of the measure, the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP). The inclusion of multiple domains ensures comprehensiveness of assessment. Each domain can be tested individually or in conjunction with another. Prior to 3 to 4 weeks post injury,

it is recommended that a partial GRASSP be administered that consists of sensibility, strength and tone, and qualitative prehension only, because it is unlikely that the patient will tolerate enough sitting for the quantitative grasp portion of the test. However, if an individual is able to tolerate 45 minutes of sitting, a full GRASSP should be administered.

Phase I

Clinimetric development of the LiHFT and THM occurred during individual test development by Link[26] and Kalsi-Ryan et al,[27] respectively. Clinimetric development refers to the process of evaluating the clinical measurement properties of an assessment, such as feasibility, face, and content validity. The components of each test that met the criteria of the framework (see **Figure 1**) were selected and combined to create the GRASSP. Components adapted from the LiHFT included five prehension tasks. In a similar fashion, the sensory module, part of the motor testing, and the scoring scale from the prehension tasks (combined with the LiHFT scoring scale) were adapted from the THM. All components included in the GRASSP are presented in **Table 1**. The sensibility domain was assessed using Semmes Weinstein monofilaments (SWM) for light touch and static two-point discrimination (S2PD) for functional sensation. The strength/tone domain was assessed using manual muscle testing (MMT) for strength[28,29] and the Modified Ashworth Scale for tone.[30] Both descriptive and performance-based prehension tests were incorporated to address the prehension domain. The descriptive prehension test evaluates whether the thumb and digits can assume three specific grasps or can perform any active movement at all. The performance-based prehension test is a modified version of the Sollerman Hand Function Test.[17] The Sollerman was modified by Link and Kalsi-Ryan et al during the development of the LiFHT and the THM. The prehension domain in the GRASSP retains the Sollerman concept of evaluating specific activity of daily living (ADL) tasks performed with specific grasps for evaluation. Details of the modifications made to the Sollerman Hand Function Test are available in the **Appendix**. **Table 1** provides a summary of how the GRASSP is administered.

Phase II

Following initial development of the GRASSP, a cross-sectional study was used to determine which preliminary components should be included in the final GRASSP (GRASSP Version I). Seven centers collected data: Rehabilitation Institute of Chicago, Chicago, Illinois; Toronto Rehabilitation Institute, Toronto, Ontario; Vancouver Coastal Health, Vancouver, British Columbia; Thomas Jefferson University, Philadelphia, Pennsylvania; Balgrist University Hospital, Switzerland; Krakenhaus Hohe Worte, Germany; Traumacenter Murnau, Germany. Descriptive details for the study cohort ($n = 72$) are provided in **Table 2**. Additional details of Phase II are outlined below.

Initial Evaluation and Refinement of the GRASSP

Regression analysis was conducted to determine which tests to include in the final GRASSP and to create a clinical index and/or global score; however, sample size was not sufficient to perform the latter analysis. The GRASSP, Spinal Cord Independence Measure (SCIM),[31] Capabilities of Upper

Table 1. Components of the GRASSP and methods of administration

Components of the GRASSP			Method for administration	
Test	**Details**	**Rationale**	**Position time required**	**How to test**
Sensibility domain: test sites selected by dermatome				
Light touch/SWM[33]	6 palmar/dorsal test sites	Inter/intra-reliability = 0.965	Supine/ sitting, 10 min	-Apply monofilaments to all test locations -Summate the score for each hand separately
Static 2 Point Disc[33]	3 palmar test sites	Inter/intra-reliability = 0.989	Supine/ sitting, 5 min	-Apply stimulus to all test locations -Summate score for each hand
Strength and tone domain: muscle selection based on myotomes				
Strength[34]	MMT-4 arm & 7 hand muscles	Inter-reliability = 0.880	Supine/ sitting, 10 min	-Assess each muscle and grade -Summate all scores for each hand
Tone[30]	Modified Ashworth for hand & arm	Inter-reliability = 0.750	Supine/ sitting, 5 min	-Assess elbow and hand for flexor/ extensor tone
Prehension domain: segmental influence movement pattern				
Qualitative (descriptive)	3 grasps rated on scale of 0–4		Supine/ sitting, 5 min	-Have subject perform grasps and rate
Quantitative (performance)[17]	5 grasps/6 tasks rated on scale of 0–5	Adapted from Sollerman, inter-reliability = 0.980	Sitting, 15 min	-Set patient up in sitting at table and have patient perform all 6 tasks for each hand separately

Note: In Version I of the GRASSP, MMT, SWM palmar, SWM dorsal, Qualtiative Prehension, and Quantitative Grasp totals are then plotted on a polar diagram for interpretation. GRASSP = Graded Redefined Assessment of Strength, Sensibility and Prehension; MMT = manual muscle testing; SWM = Semmes Weinstein monofilaments.

Table 2. Study cohort

Study site	*N*	Description of sample
Toronto Rehabilitation Institute, Canada	15	C6-C7 AIS motor level, 52.5% C4-C6 AIS sensory level, 66.0% *AIS grades* A, 38.8% B, 25.2% C, 16.6% D, 19.4%
Vancouver Coastal Health Canada	10	
Rehabilitation Institute of Chicago, USA	10	
Thomas Jefferson University, USA	10	
Balgrist University Hospital, Switzerland	9	
Krakenhaus Hohe Worte, Germany	8	
Traumacenter Murnau, Germany	10	
Total	**72**	

Extremity Questionnaire (CUE),[32] and International Standards for Neurological Classification of SCI (ISNCSCI) were administered to all study participants. General linear modeling was then used to establish the strength of the association between the components of the GRASSP (impairment) and function as defined by the SCIM (a measure of global function), the SCIM self-care subscore (a measure of upper limb function), and performance-based prehension tasks from the GRASSP (a measure of hand function). Individual subscores for each test within the GRASSP were calculated. SWM scores were separated into palmar and dorsal scores. GRASSP subscores were then compared to functional measures (SCIM, SCIM self-care subscore, and prehension). Functional measures were defined as the response variables and GRASSP subtests as the covariates. In addition, specific muscles within the MMT were also compared to functional measures including quantitative prehension tasks, again using general linear modeling. The strength of observed relationships between GRASSP impairment components and functional measures were used to exclude items and tests from the final GRASSP.

Preliminary components of the GRASSP were retained if there was a significant association with one of the three functional measures (SCIM, SCIM self-care subscore, and prehension). Strength of association was established by the p value. A p value $\leq .05$ was considered significant and $\leq .10$ approaching significance. General linear modeling results are summarized in **Table 3**. There were no significant associations between tone (Ashworth), SWM dorsal sensation, and S2PD with the three response (functional) variables. These elements were subsequently eliminated from the GRASSP. The most significant associations were found for strength, SWM palmar sensation, and grasp function. Pearson correlation coefficients were conducted between S2PD and quantitative prehension tasks. Individual neurological levels (C6 and C7) showed weak, although significant, correlations with the three fine motor tasks of quantitative prehension (Task 3, 0.496; Task 5, 0.388; Task 6, 0.355; $p < .001$). The results of the linear modeling and poor correlations with prehension tasks justified removal of S2PD from the GRASSP.

In addition to applying general linear

Table 3. Modeling for GRASSP components

Response variables	Step 1		Step 2		Step 3		Step 4	
	Covariates	***p***	**Covariates**	***p***	**Covariates**	***p***	**Covariates**	***p***
Prehension total	Strength	*.0001*	Strength	*.0001*	Strength	*.0001*	Strength	*.0001*
	Tone	.1516	Tone	.1376	SWM-D	.5229	SWM-P	*.0729*
	SWM-D	.6785	SWM-D	.6825	SWM-P	*.0613*	Tone	.1156
	SWM-P	.1516	SWM-P	.1456				
	S2PD	.9279						
SCIM self-care (subscore)	Strength	.1413	Strength	.1372	Strength	.1349	Strength	.1011
	Tone	.9115	Tone	.8783	SWM-D	.4464	SWM-P	*.0280*
	SWM-D	.5064	SWM-D	.4414	SWM-P	.3865	Qn-Grasp	*.0289*
	SWM-P	.5122	SWM-P	.4198	Qn-Grasp	*.0259*		
	S2PD	.8266	Qn-Grasp	.0316				
	Qn-Grasp	*.0330*						
SCIM total	Strength	.3028	Strength	.3090	Strength	.3793	Strength	*.0002*
	Tone	.3328	Tone	.3991	SWM-D	.3177	Qn-Grasp	*.0098*
	SWM-D	.1974	SWM-D	.2692	SWM-P	.6852		
	SWM-P	.8253	SWM-P	.5641	Qn-Grasp	*.0059*		
	S2PD	.4212	Qn-Grasp	*.0103*				
	Qn-Grasp	*.0103*						

Note: Additional combinations of linear regression were conducted to ensure that the combinations presented in this table were the most optimal. GRASSP = Graded Redefined Assessment of Strength, Sensibility and Prehension; SWM-D = Semmes Weinstein monofilaments-dorsal; SWM-P = Semmes Weinstein monofilaments-palmar; S2PD = static two-point discrimination; Qn = quantitative.

modeling to determine which subtests to retain in the final GRASSP, a similar method was used to determine which individual muscles from the MMT should be retained based on the strength of association to function. Functional measures were again used as the response variables and individual muscles from MMT as the co-variates. A rating system was devised where individual muscles scored 1 for every significant association ($p \leq .05$) to a response variable and a 0.5 if a relationship approached significance ($p \leq .10$). Nine associations were evaluated for each individual muscle, and scores were summed for a maximal possible score of 9 (**Table 4**). Individual muscles were eliminated if their rating was less than 1. Based on the regression analysis, 10 muscles had a rating 1 or above. One muscle, the abductor policis brevis, was eliminated. Wrist extension only approached significance for the SCIM self-care subscore; however, a decision was made to retain it in the final GRASSP due to its role as a key muscle in the ISNCSCI.

Summary and Future Steps

The GRASSP was conceived as an impairment measure for the upper limb that would be useful for assessing subtle neurological changes post cervical SCI during the acute, subacute, and postacute phases. Currently there is no validated and widely accepted measure for assessing the upper limb following cervical SCI. The preliminary work, presented in this article, successfully demonstrated a relationship among components of the GRASSP, measuring impairment, and function. To substantiate the efficacy and use of experimental agents for enhancing neurological recovery, future investigators will need to demonstrate both a change in impairment and a meaningful change in function through a responsiveness study. The GRASSP was developed to fill this gap and facilitate the performance of future clinical trials.

Based on the results of our analyses, the preliminary GRASSP was modified to maximize the link between impairment and function. Static two-point discrimination, magnitude of tone (Ashworth), and one muscle (abductor policis brevis) failed to demonstrate significant associations between impairment and function. These items were subsequently eliminated from the GRASSP. The current version (Version I) consists of SWM, MMT (10 muscles), and prehension testing. The development of the GRASSP represents one of the first steps to develop an upper limb impairment measure for SCI based on a large cohort of data.

The findings presented in this article are a small part of a larger, ongoing study designed to establish the reliability and validity of the GRASSP. A longitudinal study that will analyze the results of repeated measures of the GRASSP and functional measures of change on the same individuals over the course of a year will be undertaken. The results will provide data for responsiveness of the test, a recovery profile of the upper limb, and minimal clinically important differences of the upper limb for the tetraplegic population.

Acknowledgments

This work was supported by the Toronto Rehabilitation Institute Student Scholarship Fund, the Christopher and Dana Reeve Foundation, and the Rick Hansen Foundation. The International GRASSP Research and Design Team: Sukhvinder Kalsi-Ryan, Claudia Rudhe, Susan Duff, Armin Curt, Michael Fehlings, and Mary C. Verrier.

Table 4. Relationship between individual muscles and functional tests/tasks of quantitative prehension

Co-variates / Muscles	Response variables: Prehension total	SCIM Self-care subscore	SCIM total	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Rating /9
S1	.410	.3791	*.0080*	.6051	.3327	.9503	.4302	.2396	.7147	1
S2	.220	.7811	*.0014*	.2101	.7110	.1029	.1016	.3724	.4301	1
S3	*.0398*	.7698	.1722	.1337	*.0047*	*.0165*	.1155	.4137	.8227	3
S4	.8755	*.0658*	.1584	.9102	.4919	.3162	.4095	.6752	.5987	0.5
S5	.0795	*.0180*	*.0003*	.1751	.0947	.9013	*.0934*	*.0729*	*.0720*	3.5
S6	.349	.4162	*.0050*	.9536	.1276	.4458	.3365	.1987	.8850	1
S7	*.0015*	.5595	.8152	*.0878*	*.0110*	*.0209*	*.0059*	*.0007*	*.0974*	5.5
S8	.1886	*.0638*	*.0477*	.3646	.4000	.1797	.1631	.1089	.9554	1
S9	.8655	*.0881*	*.0458*	.4956	.8268	.8164	.4980	.4455	.9053	1.5
S10	.4318	.7081	.3687	.5067	.2313	.8020	.3457	.6691	.2656	0
S11	*.0188*	*.0656*	.4723	*.0233*	*.0320*	*.0694*	.2521	*.0520*	.1742	4.5

Note: Underlined values indicate muscles with significant or approaching significance association to function. SCIM = Spinal Cord Independence Measure. S1 = anterior deltoid; S2 = elbow extensor; S3 = elbow flexor; S4 = wrist extensor; S5 = extensor digitorum; S6 = flexor digitorum; S7 = flexor policis longus; S8 = abductor digiti minimi; S9 = first dorsal interossei; S10 = abductor policis brevis; S11= opponens policis.

REFERENCES

1. Anderson KD. Targeting recovery: Priorities of the spinal cord-injured population. *J Neurotrauma.* 2004;21(10):1371–1383.
2. Snoek GJ. Survey of the needs of patients with spinal cord injury: Impact and priority for improvement in hand function in tetraplegics. *Spinal Cord.* 2004;42:526–532.
3. Mangold S, Keller T, Curt A, et al. Transcutaneous functional electrical stimulation for grasping in subjects with cervical spinal cord injury. *Spinal Cord.* 2005;43(1):1–13.
4. Douglas W, Chan KM. Surgical reconstruction of the upper limb in traumatic tetaplegia. *J Bone Joint Surg.* 1983;65B(3):291–298.
5. Mulcahey MJ, Betz RR, Kozin SH, et al. Implantation of the Freehand System during initial rehabilitation using minimally invasive techniques. *Spinal Cord.* 2004;42(2):146–155.
6. Taylor P, Esnouf J, Hobby J. The functional impact of the Freehand System on tetraplegic hand function. Clinical results. *Spinal Cord.* 2002;40(11): 560-6
7. Prochazka A, Gauthier M, Wieler M, et al. The bionic glove: An electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Arch Phys Med Rehabil.* 1997;78(6):608–614.
8. Van der Linde H, Snoek GJ, Geurts ACH, van Limbeek J, Mulder T. Kinematic assessment of manual skill following functional hand surgery in tetraplegia. *J Hand Surg.* 2000;25A:1140–1146.
9. Popovic DP, Stojanovic A, Pjanovic A, Radosavljevic S, Popovic M, Jovic S, Vulovic D. Clinical evaluation of the bionic glove. *Arch Phys Med Rehabil.* 1999;80:299–304.
10. Schwab JM, Brechtel K, Mueller CA, Failli V, Kaps HP, Tuli SK, Schulesener HJ. Experimental strategies to promote spinal cord regeneration—an integrative perspective. *Prog Neurobiol.* 2006;78(2):91–116.
11. Wells JE, Hurlbert RJ, Fehlings MG, Yong VW. Neuroprotection by minocycline facilitates significant recovery from spinal cord injury in mice. *Brain.* 2003;126(Pt 7):1628–1637.
12. Baptiste DC, Fehlings MG. Pharmacological approaches to repair the injured spinal cord. *J Neurotrauma.* 2006;23:318–324.
13. Baptiste DC, Fehlings MG. Update on the treatment of spinal cord injury. *Progress Brain Res.* 2007;161:217–234.
14. International Campaign for Cures of Spinal Cord Injury Paralysis. General information. 2003. Available at: www.campaignforcure.org. Accessed September 15, 2008.
15. Anderson K, et al. Functional recovery measures for spinal cord injury: An evidence based review for clinical practice and research. *J Spinal Cord Med.* 2008;31(2):133–144.
16. Marino RJ, Jones L, Kirshblum S, Tal J, Dasgupta A. Reliability and repeatability of the motor and sensory examination of the international standards for neurological classification of spinal cord injury. *J Spinal Cord Med.* 2008;13(2):166–170.
17. Sollerman C, Ejeskar A. Sollerman Hand Function Test: A standardized method and its use in tetraplegic patients. *Scand J Plastic Reconstruct Hand Surg.* 1995;29:167–176.
18. Gregersen H, Hagen E, Ingemarsson A, Koerhuis E, Leiulfsrud A, Lybæk M, Biering-Sørensen F. Reliability and validity of Danish tetraplegia hand function test in a four country multicenter trial. International Spinal Cord Society Website, Annual ISCos Conference Proceedings. 2004. Available at: http://www.iscos.org.uk/page.php?content=38.
19. Jebsen RH, Taylor N, Trieshmann RB, Trotter MJ, Howard LA. An objective and standardized test of hand function. *Arch Phys Med Rehabil.* 1969;50(6):311–319.
20. Popovic MR, Thrasher TA, Adams ME, Takes V, Zivanovic V, Tonak MI. Functional electrical therapy: Retraining grasping in spinal cord injury. *Spinal Cord.* 2006;44:143–151.
21. Lo IK, Turner R, Connolly S, et al. The outcome of tendon transfers for C6-spared quadriplegics. *J Hand Surg.* 2003;23(2):156–161.
22. Post MW, Van Lieshout G, Seelen HA, Snoek GJ, Ijzerman MJ, Pons C. Measurement properties of the short version of the Van Lieshout test for arm/hand function of persons with tetraplegia after spinal cord injury. *Spinal Cord.* 2006;44(12):763–771.
23. Steeves JD, Lammertse D, Curt A, et al. A Guidelines for the conduct of clinical trials for spinal cord injury (SCI) as developed by the ICCP Panel: Clinical trial outcome measures. *Spinal Cord.* 2007;45(30):206–221.
24. Kandel E. *Principles of Neural Science.* 4th ed. New York: McGraw-Hill; 2000.
25. Shumway-Cook A. *Motor Control: Translating Research into Clinical Practice.* 3rd ed. St.

Louis: Lippincott, Williams & Wilkins; 2007.
26. Link C. *The Link Hand Function Test for Patients with a Cervical Spinal Cord Injury: An Intra-Rater and Inter-Rater Reliability and Expert Opinion Evaluation Study* [graduate thesis]. Hogeschool van Amsterdam, Institute of Occupational Therapy, The Netherlands; University College-South, School of Occupational Therapy and Physiotherapy, Denmark; Karolinska Institutet Division of Occupational Therapy, Sweden. 2004.
27. Kalsi-Ryan S, Beaton D, McIlroy W, Fehlings M, Verrier M. The development of the Quadriplegia Hand Assessment Tool (Q-HAT): A discriminative and evaluative approach. *J Spinal Cord Med.* 2004;27(2):164.
28. Daniels L, Worthingham C. *Daniels and Worthingham's Muscle Testing: Techniques of Manual Examination.* 6th ed. Philadelphia: WB Saunders; 1995.
29. Kendall F, McCreary EK, Provance PG. *Muscles: Testing and Function.* 4th ed. Philadelphia: Williams & Wilkins; 1993.
30. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther.* 1993;67(2):206–207.
31. Catz A, Greenberg E, Itzkovich M, Bluvshtein V, Ronen J, Gelernter I. A new instrument for outcome assessment in rehabilitation medicine: Spinal cord injury ability realization measurement index. *Arch Phys Med Rehabil.* 2004;85(3):399–404.
32. Marino RJ, Shea JA, Stineman MG. The Capabilities of Upper Extremity instrument: Reliability and validity of a measure of functional limitation in tetraplegia. *Arch Phys Med Rehabil.* 1998;79(12):1512–1521.
33. Mackin E, Callahan A, Skiver T, Schneider L, Osterman A. *Hunter, Mackin and Callahan's Rehabilitation of the Hand and Upper Extremity.* 5th ed. St. Louis: Mosby; 2002.
34. Cuthbert SC, Goodheart GJ. On the reliability and validity on manual muscle testing: A literature review. *Chiropr Osteopat.* 2007;15:4.

APPENDIX

Modifications to the Sollerman Hand Function Test

The zero to four scoring scale was increased to zero to five, terminology was modified, and timing was eliminated. All tasks requiring both hands were eliminated. Below summarizes all of the modifications made to the SHFT to design the performance based prehension testing for the GRASSP.

Sollerman Hand Function Test[4]	**Modified Sollerman Hand Function Test**
20 tasks	6 tasks
1 to 3 tasks for each grip	1 to 2 tasks per grip
7 grips: pulp pinch, lateral key pinch, tripod pinch, five finger pinch, spherical grasp, diagonal grasp, transverse grasp	5 grips: pulp pinch, lateral key pinch, tripod pinch, spherical grasp, transverse grasp
5-point scale	6-point scale
Incorporated bilateral tasks	Unilateral tasks only
Functional tasks	Functional tasks
Timed each task	Eliminated timing as part of scoring

Scoring (a maximum of 1 minute and 15 seconds is allowed for each task)

0 - the task cannot be conducted at all

1 - the task cannot be completed (less than 50% of the task) and the expected grasp is not used

2 - the task is not completed (50% or more of the task) and the expected grasp is not used

3 - the task is completed using tenodesis or an alternative grasp other than the expected grasp

4 - the task is completed using the expected grasp with difficulty (lack of smooth movement or difficult slow movement)

5 - the task is completed without difficulties using expected grasping pattern and unaffected hand function

Note: 50% of Task 1 is when the participant has begun to pour the water, 50% of Task 4 is when the participant is able to get the key to insertion point.