Effect of Thoracolumbosacral Orthoses on Reachable Workspace Volumes in Children With Spinal Cord Injury

Mitell Sison-Williamson, MS¹; Anita Bagley, PhD¹; Adrian Hongo, BS¹; Lawrence C. Vogel, MD²; Mary Jane Mulcahey, PhD, OTR/L³; Randal R. Betz, MD³; Craig M. McDonald, MD¹

¹Shriners Hospitals for Children, Sacramento, California; ²Shriners Hospitals for Children, Chicago, Illinois; ³Shriners Hospitals for Children, Philadelphia, Pennsylvania

Received October 30, 2006; accepted January 16, 2007

Abstract

Background/Objective: Wheelchair users often use trunk motion to facilitate or augment their upper extremity reach. Children with spinal cord injury (SCI) are often prescribed thoracic lumbar sacral orthoses (TLSO) to delay or prevent spinal curve progression. The impact of wearing a TLSO while reaching has not been studied. Therefore, the purpose of this study was to see the quantitative effect of the TLSO on reachable workspace volumes and reach of children with SCI.

Methods: Twenty children with SCI aged 5 to 18 years participated in the present study. Three-dimensional upper extremity motion analysis was used to assess the reachable workspace patterns of children reaching for targets at varying heights. Volumes in and out of TLSO and kinematic ranges of reach were statistically analyzed using paired Student's *t* tests with a *P* value set at 0.05.

Results: Reachable workspace volumes were significantly greater for the non-TLSO condition compared with the TLSO condition (112,836 vs 80,711 cm³; *P* = 0.0002; a decrement of 28%). Anterior posterior and medial lateral ranges of reach were statistically greater in the non-TLSO condition (*P* = 0.002, *P* = 0.01). Nondominant hand medial lateral reaches were statistically greater in the non-TLSO condition (*P* = 0.003). Dominant hand anterior posterior reaches were greater in the non-TLSO condition (*P* = 0.009).

Conclusions: Results suggest the reachable workspace of children with SCI is lessened with the use of a TLSO. This may be an important negative factor for brace compliance in children with SCI. The TLSO interferes with their ability to reach; therefore, children may prefer not to wear the orthosis.

J Spinal Cord Med. 2007;30:S184–S191

Key Words: Orthoses, spinal; Neuromuscular scoliosis; Spinal cord injuries; Reach; Wheelchair

INTRODUCTION

Paralytic scoliosis is a common secondary comorbidity seen in children with spinal cord injury (SCI) (1,2). In preadolescent youth with SCI, Mayfield and colleagues (2) reported a 92% incidence of scoliosis, with 68% of the patients requiring fusion. Lancourt and colleagues (3) reported an overall 62% incidence of scoliosis, with 100% of those injured prior to 11 years of age developing scoliosis. Dearolf and colleagues (1) supported the earlier literature with their report of a 97%

scoliosis rate in the preadolescent, with 33% requiring fusion.

Although common, paralytic spine deformity can have a devastating impact on children. For example, spinal deformity greater than 35° can lead to pelvic obliquity and asymmetric ischial weight bearing, which may predispose the child to chronic skin breakdown (4). Additionally, because of subsequent poor posture due to spine deformity, individuals with tetraplegia may realize increasing difficulty during table-top activities (4). Progression of the curve greater than 80° can compromise pulmonary function in able-bodied children with idiopathic scoliosis (5) and presumably in children with SCI who have curves of similar magnitude. The goal of fusion for paralytic scoliosis in the child with SCI is to improve sitting balance, decrease pelvic obliquity, and prevent pressure ulcers, as well as halt progression of the curve and prevent systemic compromise. Indications for

Please address correspondence to Mitell Sison-Williamson, MS, Motion Analysis Laboratory, Shriners Hospitals for Children, 2425 Stockton Blvd, Sacramento, CA 95817; phone: 916.453.2282; fax: 916.453.2352 (e-mail: msison@shrinenet.org).

This work was funded by Shriners Hospitals Clinical Outcome Studies Advisory Board grant #9155.

surgery often include curves greater than 40° in a growing child, age older than 10 years, or functional problems and/or pain in the mature patient (6).

Although consensus on treatment to prevent the development and progression of paralytic scoliosis is lacking, there is some evidence in support of using a thoracolumbosacral orthosis (TLSO) to delay or prevent the progression of paralytic scoliosis (1,4,7). Betz and Mulcahey (8) proposed prophylactic bracing for prevention of paralytic scoliosis, recognizing that the decrease in function that accompanies brace wearing during childhood may be offset by the advantage of a straight but flexible spine thereafter. Most recently, Mehta and colleagues (7) reported that orthotic treatment given prior to scoliotic curve formation of greater than 20° had a significant impact on decreasing the need for surgical intervention.

Despite evidence that the use of a TLSO is most likely beneficial, noncompliance is still as high as 25 to 50% in adolescents with idiopathic scoliosis or kyphosis (9). According to Vandal and colleagues (10), some of the variables that affect patients' treatment compliance include "social and demographic factors, nature of the health problem, the type and conditions of treatment, the nature of the relations between health professional and the client, certain intrinsic characteristics of the patient such as self-image and beliefs, and extrinsic factors such as psychosocial support." There are many studies evaluating brace compliance; however, one major limitation to the brace studies is the unknown actual time the brace is worn. Although work has been conducted on the development and validation of compliance monitors (11–16) resulting in better insight into actual wearing time, there has been little attention focused on the effect of the brace on performance of activities of daily living (ADL).

Research by Chafetz and colleagues (17) was one of the few studies to document the effects of a TLSO on function. This study compared the performance of 9 standardized ADL tasks by children with SCI with and without their brace. With the TLSO on, subjects were significantly slower in donning a shirt ($P < 0.05$), donning pants ($P < 0.05$), performing even-level transfers ($P < 0.01$), performing uneven-level transfers ($P < 0.01$), and propelling a wheelchair ($P < 0.01$). Although this study provided insight into the effects of the TLSO on timeliness of task completion, it did not study the effect of TLSO on upper extremity reaching, a task identified as important among persons using wheelchairs (18). Therefore, the purpose of this study was to quantify the effect of a TLSO on the reachable workspace volumes and reach of children with SCI.

METHODS

Design and Criteria

The study design was a with-and-without intervention quasiexperiment. As shown in Table 1, participants consisted of a convenience sample of 20 subjects from

5 to 18 years of age with SCI at or below C7. Eighteen subjects were American Spinal Injury Association (ASIA) neurologic level A, and 2 were ASIA C (19). Written consent was obtained from the parent or adolescent as appropriate. All subjects had a TLSO as part of their clinical care to prevent the progression of paralytic scoliosis.

Testing Procedures

As shown in Figure 1, subjects were positioned on a standard chair to decrease sitting and posture differences, introduced by variations in wheelchair designs. Subjects' hips, knees, and ankles were positioned at 90°.

Reflective markers were placed on the C7, sternal notch, acromion joints, olecrons, ulnar and radial styloids, and hands (Figure 2) as described by Rab and colleagues (20). Pelvic markers were not used for this study because the subjects were seated and this position obscures the cameras' view of the pelvic markers. Three-dimensional upper extremity motion analysis using an 8-camera Motion Analysis System was used to capture the subjects' reaches. Targets of varying heights were attached on 3 poles that were placed just out of reach to the left, front, and right of the subject (Figure 3). The targets included the floor and every 20° increment above and below the measured seated shoulder height of the individual tested. Subjects were instructed to sweep their arm through a radius at the specific target height while reaching as far as they could. Subjects were tested in and out of their TLSO brace in random order.

Data Reduction

Three-dimensional motion data were processed and converted into text files for each reach trial. Trials for each arm were combined into 2 files (right-hand reach data and left-hand reach data). The combined text files were further processed using a data-thinning mobility measure program using Microsoft.net framework. Data were thinned via sequential and proximal methods. In sequential thinning, algorithms were based on a weighting factor of 0.50 and the average distance between sequential raw data points. In proximal thinning, algorithms were based on a weighting factor of 0.50, the average distance between raw data points spatially, and a fidelity factor of 0.35. The outputs of the thinning programs were 2 combined files (right and left) used for subsequent volume calculations.

Volumes of reach were calculated from the thinned data utilizing a calculation method published by Kukke and Triolo (21). This method first created a grid output file developed to visualize the surface of the functional workspace by superimposing a 3-dimensional grid of 27,000 points over the raw data. Thirty-five percent of the average distance between points for each combined file was used as the kernel smoothing parameter. After the surface of the reachable workspace was created (Figure 4), a volume of that surface was calculated using

Table 1. Subject Demographics

Patient Study No.	Gender	Age at Time of Testing (y)	Injury Level	ASIA Level*	Dominant Arm	Arm Span (cm)
N01	M	14	T8	A	R	169
N02	M	14	T1	A	R	172
N04	F	10	T2	A	R	144
N06	F	5	C7	A	R	117
N07	F	12	T12	A	R	145
N08	F	6	T4	A	R	141
N10	F	12	T12	C	R	166
N11	F	12	T2	A	R	149
N14	M	15	T3	A	R	174
P01	M	9	T3/T4	A	R	97
P02	F	11	T4/T5	A	R	139
P03	M	11	L1	A	R	160
P04	M	14	T4/T5	A	R	173
P05	M	6	T9/T10	A	R	93
P06	M	12	T5	A	R	145
P07	M	7	T12	A	R	101
C19	F	13	T5	A	R	156
C20	F	10	T3	A	R	141
C21	F	10	L3	A	R	165
C22	M	14	T10	C	R	183

*American Spinal Injury Association (ASIA) Impairment Level.¹⁹

an algorithm developed in Mat Lab (The MathWorks, Inc, Natick, MA). The volume calculated for each subject was the edge of his or her individual workspace as defined by a chosen threshold, which was kept at 0.70 for the present study.

Statistical and Data Analysis

Data were statistically analyzed using paired, 2-tailed Student's *t* tests. Volumes of subjects reaching while wearing vs not wearing their TLSO were compared.

Kinematic ranges of reach data were compared between TLSO and non-TLSO conditions. *P* values were set at a 0.05 level.

RESULTS

Volume results are shown in Figure 5 and Table 2. Each subject had 4 volumes calculated. These volumes included left and right non-TLSO volumes, as well as left and right TLSO volumes. One subject had only left-hand volumes calculated due their right hand data set's being

Figure 1. Padded bench.

Figure 2. Upper extremity marker set.

Figure 3. Testing apparatus.

corrupt. The total number of volumes analyzed was 39: 20 volumes for the left hand and 19 volumes for the right hand.

Without the TLSO, the average reaching volume was $112,836 \text{ cm}^3$. In contrast, with the TLSO, the average reaching volume was $80,711 \text{ cm}^3$, which represents a 28% decrease in volume of reach ($P = 0.0002$). The largest increase in volume of reach without the TLSO was 77.3%, while the smallest increase in volume was 4.9%.

Figure 4. Estimated volume surface (black) for volume calculation. Original data are in grey.

*Significant ($p < 0.05$)

Figure 5. Average reachable workspace volumes in and out of thoracic lumbar sacral orthoses.

Ten of 39 cases had less than a 10% change between the TLSO and non-TLSO conditions, while 6 cases had increases in volume greater than 50%. In contrast, there were also 6 cases in which volumes were larger in the TLSO condition compared with the non-TLSO condition. The percent differences between these particular cases ranged from 5 to 28%.

Kinematic ranges of reach for each 3-dimensional direction were calculated. The x direction represented anterior-posterior (AP) reach, the y direction represented medial-lateral (ML) reach, and the z direction represented vertical (V) reach. Ranges were calculated by taking the difference between maximal and minimal reach points.

Overall, the non-TLSO average ranges of reach in the AP, ML, and V directions were $80 \pm 26 \text{ cm}$, $118 \pm 24 \text{ cm}$, and $97 \pm 21 \text{ cm}$, respectively. The TLSO average ranges of reach in AP, ML, and V directions were $72 \pm 19 \text{ cm}$, $113 \pm 24 \text{ cm}$, and $94 \pm 21 \text{ cm}$, respectively. The AP and ML average ranges of reach were statistically greater in the non-TLSO condition vs the TLSO condition ($P = 0.002$, $P = 0.01$), whereas the V reach showed no significant difference (Figure 6).

Patterns of reach between the left and right arms were also analyzed to see whether differences in hand dominance occurred. All subjects in the present study were right-hand dominant. When comparing non-TLSO condition to TLSO condition, the nondominant ML reach was significantly greater in the non-TLSO condition vs the TLSO condition ($118 \pm 25 \text{ cm}$ vs $110 \pm 24 \text{ cm}$; $P = 0.003$), as shown in Figure 7. Anterior-posterior and V reaches showed no significant difference. Figure 8 displays average dominant hand ranges of reach. For the non-TLSO condition, AP reach was significantly greater vs the TLSO condition ($81 \pm 25 \text{ cm}$ vs $73 \pm 18 \text{ cm}$; $P = 0.009$). Medial-lateral and V reaches showed no significant difference.

There were no significant differences between AP, ML, and V ranges of reach when comparing nondominant and dominant arms in the non-TLSO condition. In

Table 2. Reach Volumes In and Out of Thoracolumbosacral Orthoses (TLSO)

Patient Study No.	Hand	TLSO cm ³	No TLSO cm ³	% Difference
N01	L	95033	90198	−5.4
	R	88745	156700	43.4
N02	L	47393	77090	38.5
	R	129000	135670	4.9
N04	L	32523	84362	61.4
	R	83590	72007	−16.1
N06	L	20108	27995	28.2
	R	26232	44085	40.5
N07	L	86650	187500	53.8
	R	65637	144670	54.6
N08	L	68684	125820	45.4
N10	L	279680	378670	26.1
	R	337810	454470	25.7
N11	L	37496	39900	6.0
	R	77600	73571	−5.5
N14	L	84618	90403	6.4
	R	108390	84662	−28.0
P01	L	20900	54900	61.9
	R	29300	57300	48.9
P02	L	30118	53500	43.7
	R	27071	52963	48.9
P03	L	27200	46700	41.8
	R	10900	32300	66.3
P04	L	55100	74500	26.0
	R	72800	78300	7.0
P05	L	18265	19601	6.8
	R	17100	30300	43.6
P06	L	73000	79000	7.6
	R	23900	52500	54.5
P07	L	18227	29923	39.1
	R	24640	21827	−12.9
C19	L	128740	124280	−3.6
	R	84198	70331	−19.7
C20	L	73690	99607	26.0
	R	103000	113720	9.4
C21	L	222590	343070	35.1
	R	245650	273250	10.1
C22	L	103020	120790	14.7
	R	69113	304180	77.3

the TLSO condition, statistically greater ML reach was recorded for the dominant arm vs the nondominant arm (116 ± 25 cm vs 111 ± 25 cm; $P < 0.05$).

DISCUSSION

Previous studies have shown that reaching is 1 of the 10 important functional tasks for an individual to perform seated in a wheelchair (18,22,23). Sprigle and colleagues (23) investigated reach in SCI subjects and the effects of differing seating cushions and backrest heights. That study reported that upper extremity reach was affected by posture but not by the cushion types or backrest

heights used in the study. It was also reported that pelvic tilt was a significant predictor of upper extremity reaching tasks and function. Curtis and colleagues (24) stated that functional reach in the sagittal plane increases with the use of a chest belt in subjects with both high and low (T1-L1) thoracic paraplegia. Use of a thigh belt, however, did not enhance functional reach. Kukke and Triolo (21) assessed workspace of subjects with SCI and the effects of functional electrical stimulation of lumbar trunk extensors on seated workspace. In 2 of 4 subjects, workspace volumes increased as a result of functional electrical stimulation.

*Significant ($p<0.05$)

Figure 6. Ranges of reach (no thoracic lumbar sacral orthoses [TLSO] vs TLSO).

These studies have assessed numerous factors that affect reach, but there have been no studies documenting the quantitative effect of reaching while wearing a TLSO vs reaching without a TLSO. The results of the present study report that the TLSO decreases a child's volume of reach by an average of 28%.

During testing, it appeared that subjects were more comfortable reaching in trials without the TLSO. When the TLSO was worn, it tended to rub beneath axillary areas as the child reached toward targets. A similar result was reported by Chafetz and colleagues (17); they stated that the TLSO rubbed under the subjects' arms while they propelled their wheelchairs or prevented them from leaning forward to strengthen their push.

It has been stated that the upper extremity function of wheelchair users is affected by seated posture and trunk control. The ability to move one's trunk and pelvis increases the ranges of motion of subjects in wheelchairs (23). In the current study, the TLSO affected forward and lateral trunk lean. Average AP and ML reach were reported to be significantly greater in the non-TLSO than in the TLSO condition. Differences in hand dominance

*Significant ($p<0.05$)

Figure 7. Nondominant reach trials (no thoracic lumbar sacral orthoses [TLSO] vs TLSO).

*Significant ($p<0.05$)

Figure 8. Dominant arm ranges of reach trials (no thoracic lumbar sacral orthoses [TLSO] vs TLSO).

were also compared in the current study. Dominant arm ranges of reach reported a significantly greater forward reach in the non-TLSO condition vs the TLSO condition. Comparisons within the TLSO condition also reported that lateral reach was significantly greater for the dominant arm compared with the nondominant arm. The differences in ranges of reach could be due to limited trunk flexion caused by the bottom edge of the TLSO (17). Significant increases in forward reach with dominant arms could also be attributed to better posture and trunk control (23) by the subject who may primarily use the dominant arm for reaching forward.

Although the average reachable workspace volumes decreased when subjects wore their TLSOs, there were some trials in which volumes in the TLSO condition were larger. For example, there was one case in which a subject had a 28% increase in volume in the TLSO condition. This particular subject's overall range of reach showed an increase in both the AP and ML directions in the TLSO condition. Individual reach trials also showed that for lower targets, this subject reached further while wearing the TLSO compared with not wearing it. This subject, however, was an older child who could have been a more experienced TLSO wearer than the other subjects, who may have had their TLSO a shorter period. Qualitative video analysis also indicated that subjects with increases in reachable workspace volume in the TLSO condition appeared to be more stable and able to reach toward targets easier, whereas the trials without their TLSO showed them to have jerky, less stable reaches.

The volumes calculated in the present study were an approximate estimation of the edge of reach for the individual subject. The current protocol takes raw data from the reaching hand and paints an outer surface of reach. The subsequent volume calculations were measured from this surface and do not take into account the volume of space between the subject and the reaching arm. The volumes calculated for subjects reflected differences in motivation, seating stability, and subject size (eg, arm length). Therefore, volumes ranged from

subject to subject. If between-subject comparisons were needed, volumes could be normalized to arm span.

The volumes calculated for each subject could be seen as their limit of reach from an origin specified by the researcher. Because an outer surface volume of reach was calculated, it can be assumed that the subject could reach for objects or perform tasks within the volume calculated. If objects or tasks are placed outside the volume shell, it can be assumed that the subject could not perform tasks or reach beyond that limit.

The magnitude of workspace volumes reported by Kukke and Triolo (21) differed from the volumes reported in this study. The previous study reported volumes ranging from 72,900 to 158,300 cm³, whereas the current study had workspace volumes ranging from 10,900 to 454,470 cm³. The difference in volume magnitude could be due to many factors, including sample size, sample populations, arm lengths, and differing protocols. The previous study involved 4 subjects, whereas the current study involved 20 subjects. Also, the current study tested a pediatric population wearing TLSOs for prevention of paralytic scoliosis, whereas the Kukke and Triolo (21) study tested an adult population 9 to 22 months after surgery who were implanted with intramuscular stimulating electrodes to activate the lumbar erector spinae. Differences in arm lengths could also account for the differences in volumes obtained.

The present study also took steps to refine Kukke and Triolo's (21) method of analysis. The smoothing and threshold parameters in the algorithms used to calculate volumes were kept the same throughout this work so that subsequent volume calculations would not be arbitrarily altered by the researcher. (The kernel smoother centers a normal distribution on each point and averages all neighboring points in 3 dimensions. Nearby points are weighted most heavily, and points further away are given less weight, resulting in a normal distribution of weights between 0 and 1. The threshold value identifies the cut-off weight below which points are not included in the surface volume calculation.) Kukke and Triolo (21) chose smoothing and threshold values manually for each subject. The present study also had a different reaching protocol with more trials and more data points compared with the work of Kukke and Triolo (21). In this study, to account for raw data differences, the data were preprocessed using a program to thin and equivalently weigh the data points.

There were some limitations involved in the present study. Children were asked to reach as far as they possibly could towards poles situated out of reach. It is possible that children were not reaching to their full potential, even though researchers tried to motivate subjects. The bench used for the present study had an arm rest on only one side of the chair. For some of the lower targets, the arm rest could have interfered with the normal sweep of the subject's arm. In addition, during reaching it was noted that some subjects held onto the arm rest with one

hand while not being able to do the same when reaching with the opposite arm.

This is one of many methods of assessing reachable workspace volumes. Future studies using this protocol should continue to refine the methods of analysis. Other methods of assessing reachable workspace that include measurement of the whole volume of reach and areas of functional control would be beneficial. The next step planned with the current protocol is to study children with SCI before and after spine fusion to quantify whether the edge of reachable workspace volumes change postoperatively.

CLINICAL IMPLICATIONS

This was the first study to quantify outcomes of TLSO use on the reachable workspace of children with SCI. The study findings have clinical implications regarding the potential functional penalty of TLSO brace wear, particularly for children with tetraplegia who may use trunk motion to augment their reachable workspace. Such decrements in functional reach could contribute to noncompliance in brace wear among children with SCI. Our group recently documented noncompliance to be a significant issue in children with SCI who are prescribed a TLSO.

We have also demonstrated decrements in performance of functionally important activities in children with SCI (17) with TLSO wear and preferences of the children to perform these activities without a TLSO. The additional factor of limited reachable workspace with a TLSO may further contribute to noncompliance with prescribed brace wear.

Physicians who prescribe a TLSO to prevent or delay the development of scoliosis need to weigh and discuss with the patient and family the potential benefits of brace wear and the potential disadvantages in terms of functional performance. This may be particularly relevant to children with tetraplegia. Efforts should be made to minimize the functional penalty of brace wear with provision of adaptive aids, environmental modifications, or altered wearing schedules.

Future work will need to document the community brace wear patterns of children with SCI in light of the documented functional penalties of TLSO wear. Prophylactic brace prescription will need to be prospectively assessed with regard to timing and duration of brace wear in addition to the efficacy in terms of preventing or delaying scoliosis.

CONCLUSIONS

The results of this study demonstrate that the reachable workspace of children with SCI is affected and lessened with the use of a TLSO. This may be an important negative factor for brace compliance in children with SCI. If brace wear hinders normal activities of daily living, such as the ability to reach, children with SCI may not be willing to wear the TLSO the prescribed number of hours,

reducing compliance and possibly affecting the efficacy of the treatment.

ACKNOWLEDGMENTS

We acknowledge Colleen Kirk, PhD, for her input on data thinning and reduction and Irmi Feldman for her assistance in manuscript preparation.

REFERENCES

1. Dearolf WW, Betz RR, Vogel LC, Levin J, Clancy M, Steel HH. Scoliosis in pediatric spinal cord-injured patients. *J Pediatr Orthop*. 1990;10:214–218.
2. Mayfield JK, Erkkila JC, Winter RB. Spine deformity subsequent to acquired childhood spinal cord injury. *J Bone Joint Surg Am*. 1981;63:1401–1411.
3. Lancourt JE, Dickson JH, Carter RE. Paralytic spinal deformity following traumatic spinal-cord injury in children and adolescents. *J Bone Joint Surg Am*. 1981;63:47–53.
4. Betz RR, Mulcahey MJ. Pediatric spinal cord injury. In: Weinstein SL, ed. *The Pediatric Spine: Principles and Practice*. Philadelphia, PA: Lippincott, Williams & Wilkins; 2001:601–616.
5. Weinstein SL, Dolan LA, Spratt KF, Peterson KK, Spoonamore MJ, Ponseti IV. Health and function of patients with untreated idiopathic scoliosis: a 50-year natural history study. *JAMA*. 2003;289(5):559–567.
6. Lubicky JP, Betz RR. Spinal deformity in children and adolescents after spinal cord injury. In: Betz RR, Mulcahey MJ, eds. *The Child With a Spinal Cord Injury*. Rosemont, IL: The American Academy of Orthopaedic Surgeons; 1996.
7. Mehta S, Betz RR, Mulcahey MJ, McDonald CM, Vogel LC, Anderson C. Effect of bracing on paralytic scoliosis secondary to spinal cord injury. *J Spinal Cord Med*. 2004;27:88–92.
8. Betz RR, Mulcahey MJ. Rehabilitation of pediatric spinal cord injury. In: Weinstein SL, ed. *The Pediatric Spine: Principles and Practice*. New York, NY: Raven Press; 1994:781–810.
9. Gurnham RB. Adolescent compliance with spinal brace wear. *Ortho Nurs*. 1983;2(6):13–17.
10. Vandal S, Rivard C, Bradet R. Measuring the compliance behavior of adolescents wearing orthopedic braces. *Issues Comp Ped Nurs*. 1999;22:59–73.
11. Helfenstein A, Lankes M, Ohlert K, et al. The objective determination of compliance in treatment of adolescent idiopathic scoliosis with spinal orthoses. *Spine*. 2006;31(3):339–344.
12. Havey R, Gavin T, Patwardhan A, et al. A reliable and accurate method for measuring orthosis wearing time. *Spine*. 2002;27(2):211–214.
13. Nicholson GP, Ferguson-Pell MW, Smith K, Edgar M, Morley T. The objective measure of spinal orthosis use for the treatment of adolescent idiopathic scoliosis. *Spine*. 2003;28(19):2243–2251.
14. Takemitsu M, Bowen JR, Rahman T, Glutting JJ, Scott CB. Compliance monitoring of brace treatment for patients with idiopathic scoliosis. *Spine*. 2004;29(18):2070–2074.
15. Lou E, Hill D, Raso J, Moreau M, Mahood J. Smart orthosis for the treatment of adolescent idiopathic scoliosis. *Med Bio Eng Comp*. 2005;43:746–750.
16. Rahman T, Bowen JR, Takemitsu M, Scott C. The association between brace compliance and outcome for patients with idiopathic scoliosis. *J Pediatr Orthop*. 2005;25(4):420–422.
17. Chafetz R, McDonald CM, Mulcahey MJ, et al. Timed motor test for wheelchair users: initial development and application in children with spinal cord injury. *J Spinal Cord Med*. 2004;27:38–43.
18. Mills T, Holm MB, Trefler E, Schmeler M, Fitzgerald S, Boninger M. Development and consumer validation of the functional evaluation in a wheelchair (FEW) instrument. *Disabil Rehabil*. 2002;24:38–46.
19. ASIA Neurological Standards Committee. International standards for neurological classification of spinal cord injury, 6th ed. *J Spinal Cord Med*. 2003;26:550–556.
20. Rab G, Petuskey K, Bagley A. A method for determination of upper extremity kinematics. *Gait Posture*. 2002;15(2):113–119.
21. Kukke SN, Triolo RJ. The effects of trunk stimulation on bimanual seated workspace. *IEEE Trans Neur Sys Rehabil Eng*. 2004;12(2):177–185.
22. Holliday PJ, Mihailidis A, Rolfson R, Fernie G. Understanding and measuring powered wheelchair mobility and maneuverability. Part I: reach in confined spaces. *Disabil Rehabil*. 2005;27(16):939–949.
23. Sprigle S, Wootten M, Sawacha Z, Theilman G. Relationships among cushion type, backrest height, seated posture, and reach of wheelchair users with spinal cord injury. *J Spinal Cord Med*. 2003;26(3):236–243.
24. Curtis KA, Kindlin CM, Reich KM, White DE. Functional reach in wheelchair users: the effects of trunk and lower extremity stabilization. *Arch Phys Med Rehabil*. 1995;76:360–367.