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Effect of Surgery on Gait and Sensory Motor Performance in Patients With Cervical Spondylotic Myelopathy

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Abstract

BACKGROUND—Cervical spondylotic myelopathy (CSM) is a common disease of aging that leads to gait instability resulting from loss of leg sensory and motor functions. The results of surgical intervention have been studied using a variety of methods, but no test has been reported that objectively measures integrative leg motor sensory functions in CSM patient.

OBJECTIVE—To determine the feasibility of using a novel Single Leg Squat (SLS) test to measure integrative motor sensory functions in patients with CSM before and after surgery.

METHODS—Fifteen patients with CSM were enrolled in this prospective study. Clinical data and scores from standard outcomes questionnaires were obtained before and after surgery. Patients also participated in experimental test protocols consisting of standard kinematic gait testing, the Purdue pegboard test, and the novel SLS test.

RESULTS—The SLS test protocol was well tolerated by CSM patients and generated objective performance data over short test periods. In patients who participated in postoperative testing, the group measures of mean SLS errors decreased following surgery. Gait velocity measures followed a similar pattern of group improvement postoperatively. Practical barriers to implementing this extensive battery of tests resulted in subject attrition over time. Compared to kinematic gait

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testing, the SLS protocol required less space and could be effectively implemented more efficiently.

CONCLUSION—The SLS test provides a practical means of obtaining objective measures of leg motor sensory functions in patients with CSM. Additional testing with a larger cohort of patients is required in order to utilize SLS data to rigorously examine group treatment effects.

Keywords

Cervical myelopathy; gait velocity; cervical fusion; proprioception; gait kinematic; pegboard test; sensory motor; gait performance; gait in CSM; CSM; Single Leg Squat; SLS

Cervical spondylotic myelopathy (CSM) is the most common cause of spinal cord dysfunction.¹ It is also the leading cause of spinal-cord-related disability in the elderly. It results from the degenerative narrowing of the spinal canal, causing spinal cord compression in a slow, progressive manner.² The degree and location of spinal cord compression is heterogeneous. Spinal cord compression can result from ventral pathologies such as herniated disks and disk osteophyte complexes or from dorsal compression from facet and ligamentum flavum hypertrophy. These changes can be confined to one level or can involve multiple levels. Likewise, the spectrum of clinical presentations can vary from asymptomatic states (with or without objective neurological signs) to gait imbalance, quadriparesis, and severe disability.^{2,3} CSM is known to affect motor control in the upper and lower extremities, resulting in symptoms reflecting balance and dexterity impairments.^{4,5} These symptoms are often progressive in older adult patients. Balance and gait impairments can lead to falls, thus increasing the risk of spinal cord injury. The mainstay of treatment is surgical decompression with or without fusion. Numerous clinical scores have been developed to help define the severity of patient's symptoms.^{6,7} While helpful, many scoring systems are not quantitative in nature, are difficult to apply efficiently to the patient population, and are largely subjective.^{6,7} Additionally, most scoring systems are not designed to detect and quantify subtle changes in a patient's clinical course. To provide quantitative measures of surgical outcomes, gait analysis methods comparing pre- and postoperative measures to findings from normal controls are now being increasingly used.^{8–13} Methods for quantifying changes in upper extremity functions have been reported as well.^{14–17}

Gait velocity has become a commonly used assessment tool that reflects meaningful recovery of patients' ability to return to community ambulation. It is considered to have robust psychometric properties and has good test-retest reliability coefficients.^{18–21} Gait velocity is related to lower extremity (LE) strength,²² LE motor control,²³ balance,²⁴ functional mobility,^{23,24} gait endurance,¹⁹ energy expenditure,^{25,26} and disability. Additionally, it is able to predict discharge destination and the probability of falls.^{25,27–29} Furthermore, Fulk et al. demonstrated that change in gait velocity correlated with survivors' and physical therapists' perception of change in walking ability following a stroke. A 10 cm/s change in gait velocity (5 times standard errors of measurement) has been considered a clinically meaningful change.^{30,31}

Gait instability in CSM is thought to be due in part to impairment in proprioceptive sensory processing. To date, there have been no reports of a practical test that can be used to provide objective measures reflecting sensory-motor integrative functions in this patient population. In this pilot study we made use of an experimental Single Leg Squat (SLS) device to determine the feasibility of this tool to study the changes in sensory-motor processing of patients with CSM.^{32,33}

METHODS

Subjects

All subjects presented to the University of Iowa Hospitals and Clinics and were diagnosed with cervical spinal canal stenosis as confirmed by magnetic resonance imaging (MRI) and computed tomography (CT). All subjects signed a written consent, and the University of Iowa institutional review board approved the study. Patients with prior surgical intervention for myelopathy or neurologic pathology other than CSM were excluded from this study.

Subjects who enrolled in this study were scheduled to participate in testing on 3 separate days. On each test day, subjects completed the SF-36 health inventory, Nurick score, modified Japanese Orthopedic Association (mJOA) score,^{6,7} a gait performance task, and an upper extremity performance task. The first evaluation day (Day 1) was scheduled 24–48 hours prior to cervical decompressive surgery. Subjects then returned for a second evaluation 6–10 weeks after the surgery (Day 2) and again at greater than 25 weeks after the surgery (Day 3). Of the 15 subjects that were evaluated on day 1, 8 subjects returned for the second follow-up and 5 returned for the third follow-up evaluation.

Gait Performance Task

We evaluated each subject's gait using a 10-camera Vicon motion capture system (Vicon, Oxford, UK) paired with 3 AMTI floor force measurement plates (AMTI, Watertown, MA). Motion capture markers were adhered over specific surface anatomical points of the lower extremity as per the manufacturer's lower extremity gait protocol. Subjects performed a single static trial to calibrate the motion capture system. Subjects were then asked to perform 3 walking trials at their self-selected pace. Subjects then performed 6 walking trials, 3 trials with a target cadence 15% faster than their self-selected pace and 3 trials with a target cadence 15% slower than their self-selected pace.

All gait trials were analyzed using Vicon Nexus to determine the cadence, step length, stride length, and walking speed. For this analysis, each trial was clipped at the start and end to ensure all markers were visible to at least 2 cameras. The gait parameters for each trial type (self-selected, 15% faster cadence, 15% slower cadence) were averaged for each subject.

Movement Performance

Subjects also performed an upper extremity (Purdue Pegboard) and lower extremity movement performance task. The Purdue Pegboard task was performed 3 times, the first with the dominant arm, the second with the nondominant arm, and the third with both arms together. The number of pegs successfully placed in the board during a 30-second period

was recorded as the performance for that task. The position of the board relative to the patient was recorded, to ensure a similar board placement for all follow-up tests.

Sensory-Motor Control during Weight Bearing

Subjects performed a lower extremity task using a custom Single Leg Squat (SLS) apparatus. The movement performance apparatus has been previously described.³² A custom-built apparatus was used to provide a constant resistance to the knee as a subject performed a weight-bearing Single Leg Squat.^{33–36} Briefly, the device consisted of a rack and pinion gearbox mounted to a support frame. A load cell was mounted at the end of a horizontal shaft and secured to the anterior surface of the knee. A potentiometer measured the linear displacement of the horizontal shaft. Previous studies showed horizontal translation of the knee strongly correlated to knee flexion angle,³² with a linear displacement of ~10 cm corresponding to ~15° of knee flexion. A monitor displayed a computer-generated sinusoidal target superimposed with the subject's current position. Subjects were instructed to track the target by flexing and extending their knee during the task. The monitor provided real-time feedback of the subject's position relative to the target during the task. The total cost of the SLS equipment is approximately \$5,000, most subjects saturate their task performance curve within 2 practice test sessions, and the total test time is approximately 20 minutes.

The SLS task consisted of a set of 5 cycles performed 9 times at varying velocities and levels of resistance applied at the knee. A cycle is defined by a flexion phase and an extension phase. The flexion phase required the subject to flex the knee ~25°, while the extension phase required the subject to extend the knee, returning to the start position. The velocity of knee flexion and extension was controlled by the target frequency. Three target frequencies were used, 0.2 Hz, 0.4 Hz, and 0.6 Hz, resulting in a slow, medium, and fast velocity of knee flexion and extension. The appearance of the target and the subject's position was scaled on the monitor during the task, decreasing the influence of screen resolution on task performance.

A computer-controlled electromagnetic brake provided constant resistance during knee flexion and extension. Three levels of resistance normalized to subject's total body weight (BW) were used: 5% BW, 10% BW, and 15% BW. We have previously shown that an SLS during low resistance predominantly uses the quadriceps muscles to resist gravity, while during high resistance the hamstring muscles are recruited.³²

A custom application (Labview v12.0f3 National Instruments Corp., Austin, TX) generated and displayed the target signal superimposed with the subject's signal, analyzed the subject's signal to determine when to deliver a perturbation, and controlled the braking system. All signals (target signal, subject's signal, and subject's force) were collected at 2000 Hz using an analog to digital data acquisition board (PCI-6221 National Instruments Corp., Austin, TX)

The performance of each subject was calculated after completing all testing sessions using a custom algorithm implemented within Diadem (Diadem 2012, National Instruments Corp., Austin, TX). The mean absolute error during knee flexion for a testing set was calculated for

each subject. Absolute error is defined as the maximal absolute deviation of the subject's signal from the target signal. The average absolute error for knee flexion is defined as the average absolute error during knee flexion for each condition within a testing or training set.

Surgical Intervention

All subjects underwent cervical spine surgical decompression with fusion performed by University of Iowa neurosurgeons. The staff neurosurgeon determined the levels of spinal decompression and the specific approach to be used. Patients were treated either with an anterior cervical fusion, posterior laminectomy, and fusion, or a combined anterior and posterior approach, depending on the extent and location of the patient's pathology. In all cases, the level with the most significant cord compression on the MRI was decompressed.

Statistical Analysis

All results are reported at group mean $\pm$ standard deviation unless otherwise noted. A *t* test was performed on all data to evaluate for statistical significance. Statistical significance was defined as *P* $\leq$.05.

RESULTS

Demographics

There were 15 participants (10 males and 5 females) with a mean age of 58.1 ± 7.2 years old. Symptom duration ranged from 2 to 36 months with an average of 15.4 ± 11.8 . Of the 15 subjects, 8 (6 males and 2 females) returned for the 6–10 week (6.9 ± 1.3) follow-up testing (Day 2) and 5 (3 males and 2 females) returned for their greater than 25 week (45.5 ± 24.2) follow-up testing (Day 3). The average body mass index (BMI) of the group was 28.5 ± 6.3 , 26.9 ± 8.7 , and 23.1 ± 2.9 on Days 1, 2, and 3, respectively, without statistical significance. There was an overall improvement in the Nurick and mJOA scores following surgery for the subjects with postoperative data, but these trends were not statistically significant (Table 1).

SF-36 Quality of Life Assessment

The SF-36 data were compared by pairing the same group of subjects' data from testing Day 1 to Day 2, and this same method was used to compare changes between testing Day 1 and Day 3. On Day 2 there was a trend for improvement in the physical health but not the mental health summary scores, and neither reached statistical significance. In the Day 3 testing group there was, again, a trend showing a directional improvement in both the physical and mental summary, but this also did not achieve statistical significance at the .05 level.

Upper Extremity Performance

We also compared the results of the Purdue Pegboard Test by pairing the same group of patient data from testing Day 1 to Day 2. This same method was used to compare the change between testing Day 1 and Day 3. There was no statistical difference in the groups' pre- and postoperative Purdue Pegboard times.

Lower Extremity Performance

There was a pattern suggesting improvement of gait velocity, stride length, and step length from testing Day 1 to Day 3, for both the slow and fast gait test analysis; however, this did not achieve statistical significance (Table 2 and Figure 1).

Sensory-Motor Control during Weight Bearing

There was an improvement in the mean absolute error from baseline testing on Day 1 to that on Days 2 and 3. The mean absolute error was 0.47 ± 0.20 , 0.42 ± 0.15 , and 0.39 ± 0.14 , respectively, on testing Days 1, 2, and 3. These did not reach statistical significance at the .05 level (Figure 2). There was an inverse relationship between gait velocity change and mean absolute error (Figure 3). This suggests improving sensory-motor control over the days of testing may account for the gait velocity change.

DISCUSSION

Gait instability is the most common and often the earliest symptom associated with cervical myelopathy due to cervical spondylosis.³⁷ This can lead to frequent falls and, hence, increases the risk of traumatic spinal cord injury. Although the exact mechanism leading to the development of symptoms associated with CSM is unclear, static and dynamic compression as well as ischemic changes have been implicated. Surgical decompression is widely accepted as a standard treatment. There is a large body of evidence showing improvement in quality of life and neurological outcomes following surgical intervention; however, most of these outcome measures are subjective in nature.^{6,7} Recently, there have been reports describing the use of gait kinematic testing techniques to study functional changes following surgical intervention for cervical myelopathy.^{8–13} In the current study, we implemented a protocol to objectively measure upper extremity movement and dexterity, gait kinematics, and sensory motor performance in patients with cervical myelopathy. Additionally, validated subjective outcome measures such as the Nurick, SF-35, and mJOA scores were obtained. The main objective of our study was to determine the practical feasibility of performing the experimental SLS test in patients with CSM. The patients in this series also participated in a comprehensive battery of well-established tests that are used to assess spinal cord functions and clinical management outcomes. The number of participants was too small to allow for statistically meaningful comparisons and correlations to be made between SLS test results and findings from the more established methods. However, it was possible to gain preliminary insights into the comparative practical feasibility of different testing methods.

Pertaining to upper extremity fine motor movement, there was no improvement in the Purdue Pegboard following surgical intervention, although there was an improvement in overall Nurick and mJOA scores (Table 1). This suggests that improvement in these validated overall clinical outcome measures is not necessarily accompanied by improvement in upper extremity functionality and dexterity.

Gait velocity is routinely used to assess the elderly and patients who have suffered from strokes.^{30,31} This objective measure has been shown to predict discharge destination and the

probability of falls.^{25,27–29} In that study, an increase in gait velocity of 10 cm/s was found to correlate with a meaningful clinical change evidenced by an improvement in community ambulation.^{30,31} It is well documented that gait velocity is reduced in CSM, which was also noted in our study.^{9,38} Previous studies have reported gradual improvement in gait velocity for the first 6 months postoperatively, which can range from 3cm/s to 49cm/s.^{8,9,11,39} We also observed postoperative increases in gait velocity in our study; however, our small sample size precluded performing meaningful group statistical analyses. Although gait kinematics studies are well suited for determining CSM functional changes, our experience suggests they are somewhat impractical in the clinical setting. Gait testing requires a large space, expertise in the image capture technology and analytical techniques, and a substantial time commitment by specially trained staff.

Alternatively, several aspects of the novel SLS device proved more practical than the gait analysis method. Patients tolerated SLS testing well, only a small space was required, the equipment is relatively inexpensive (~\$5,000), and the protocol generated large volumes of objective performance data over an approximately 20-minute test period. However, as with the gait analysis method, there is a requirement for skilled data analyses when calculating SLS error measures. Of interest, we observed a relationship in which postoperative increases in gait velocity were associated with decreases in SLS errors.

Beyond practical clinical testing considerations, the SLS method has the attractive feature of examining a specific attribute of spinal cord mediated function; integration of sensory and motor systems. The SLS test requires fine control of the extensor and flexors of the lower extremities in response to sensory feedback in order to complete the task. Tracing these sinusoidal targets requires precise communication between the muscle spindle fibers and fine control of the lengthening and shortening of the lower extremity musculature. Furthermore, because the SLS resistance is normalized to the patient's body weight, it simulates the individual's environmental load that they are required to control during daily activities. An improvement in the subject's ability to perform the SLS task, as seen by the decrease in SLS error postoperatively, from 0.47 ± 0.20 on Day 1 to 0.42 ± 0.15 and 0.39 ± 0.14 on Days 2 and 3, respectively, likely reflects an improvement in sensory-motor function (proprioception) following surgical decompression. Results from earlier studies of serial SLS testing performed in a different group of subjects indicate that session-to-session learning effects, in the absence of a therapeutic intervention, are minimal.⁴⁰

Limitations

There are several limitations to the study that should be noted. The most significant of these is the small number of patients who were studied at all pre- and postoperative test periods. This shortcoming precluded meaningful group statistical analyses. Practical scheduling issues inherent to a research protocol requiring patients to participate in experiments carried out in a separate research facility negatively impacted patient participation. This experience further reinforced our conclusion that a useful clinical testing system must be located within the outpatient clinic. The SLS test equipment is compatible with this requirement, and in future studies we plan to enroll and test a larger group of patients during their clinically scheduled outpatient visits in the clinic facility.

CONCLUSION

In this pilot study we demonstrated the practical feasibility of using a novel experimental research test, the Single Leg Squat (SLS), to objectively measure lower extremity sensory-motor functions in patients with CSM. The test is well tolerated by patients and generates large amounts of objective performance data over relatively short test sessions. Future studies using a clinic-based apparatus to test large numbers of patients will be required to rigorously examine correlations between the SLS test results and other performance and outcome measures.

REFERENCES

1. Ghogawala Z, Benzel EC, Heary RF, et al. Cervical spondylotic myelopathy surgical trial: randomized, controlled trial design and rationale. *Neurosurgery*. 2014; 75(4):334–346. [PubMed: 24991714]
2. Kalsi-Ryan S, Singh A, Massicotte EM, et al. Ancillary outcome measures for assessment of individuals with cervical spondylotic myelopathy. *Spine*. 2013; 38(22 Suppl 1):S111–S122. [PubMed: 23963009]
3. Dahdaleh NS, Lawton CD, El Ahmadieh TY, et al. Evidence-based management of central cord syndrome. *Neurosurgical focus*. 2013; 35(1):E6.
4. Edwards CC 2nd, Riew KD, Anderson PA, Hilibrand AS, Vaccaro AF. Cervical myelopathy. current diagnostic and treatment strategies. *The spine journal : official journal of the North American Spine Society*. 2003; 3(1):68–81. [PubMed: 14589250]
5. Swagerty DL Jr. Cervical spondylotic myelopathy: a cause of gait disturbance and falls in the elderly. *Kansas medicine : the journal of the Kansas Medical Society*. 1994; 95(10):226–227. 229. [PubMed: 7815775]
6. Nurick S. The pathogenesis of the spinal cord disorder associated with cervical spondylosis. *Brain : a journal of neurology*. 1972; 95(1):87–100. [PubMed: 5023093]
7. Yue WM, Tan SB, Tan MH, Koh DC, Tan CT. The Torg--Pavlov ratio in cervical spondylotic myelopathy: a comparative study between patients with cervical spondylotic myelopathy and a nonspondylotic, nonmyelopathic population. *Spine*. 2001; 26(16):1760–1764. [PubMed: 11493847]
8. Engsberg JR, Lauryssen C, Ross SA, Hollman JH, Walker D, Wippold FJ 2nd. Spasticity, strength, and gait changes after surgery for cervical spondylotic myelopathy: a case report. *Spine*. 2003; 28(7):E136–E139. [PubMed: 12671368]
9. Kuhtz-Buschbeck JP, Johnk K, Mader S, Stolze H, Mehdorn M. Analysis of gait in cervical myelopathy. *Gait & posture*. 1999; 9(3):184–189. [PubMed: 10575079]
10. Maezawa Y, Uchida K, Baba H. Gait analysis of spastic walking in patients with cervical compressive myelopathy. *Journal of orthopaedic science : official journal of the Japanese Orthopaedic Association*. 2001; 6(5):378–384. [PubMed: 11845345]
11. Malone A, Meldrum D, Bolger C. Three-dimensional gait analysis outcomes at 1 year following decompressive surgery for cervical spondylotic myelopathy. *European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society*. 2015; 24(1):48–56.
12. McDermott A, Bolger C, Keating L, McEvoy L, Meldrum D. Reliability of three-dimensional gait analysis in cervical spondylotic myelopathy. *Gait & posture*. 2010; 32(4):552–558. [PubMed: 20832318]
13. Singh A, Crockard HA. Quantitative assessment of cervical spondylotic myelopathy by a simple walking test. *Lancet*. 1999; 354(9176):370–373. [PubMed: 10437865]
14. Doita M, Sakai H, Harada T, et al. Evaluation of impairment of hand function in patients with cervical myelopathy. *Journal of spinal disorders & techniques*. 2006; 19(4):276–280. [PubMed: 16778663]

15. Hosono N, Sakaura H, Mukai Y, Kaito T, Makino T, Yoshikawa H. A simple performance test for quantifying the severity of cervical myelopathy. *The Journal of bone and joint surgery. British volume*. 2008; 90(9):1210–1213. [PubMed: 18757962]
16. Igarashi K, Shibuya S, Sano H, Takahashi M, Satomi K, Ohki Y. Functional assessment of proximal arm muscles by target-reaching movements in patients with cervical myelopathy. *The spine journal : official journal of the North American Spine Society*. 2011; 11(4):270–280. [PubMed: 21474078]
17. Miwa T, Hosono N, Mukai Y, Makino T, Kandori A, Fuji T. Finger-tapping motion analysis in cervical myelopathy by magnetic-sensor tapping device. *Journal of spinal disorders & techniques*. 2013; 26(6):E204–E208. [PubMed: 23563330]
18. Evans MD, Goldie PA, Hill KD. Systematic and random error in repeated measurements of temporal and distance parameters of gait after stroke. *Archives of physical medicine and rehabilitation*. 1997; 78(7):725–729. [PubMed: 9228875]
19. Fulk GD, Echternach JL. Test-retest reliability and minimal detectable change of gait speed in individuals undergoing rehabilitation after stroke. *Journal of neurologic physical therapy : JNPT*. 2008; 32(1):8–13. [PubMed: 18463550]
20. Hill KD, Goldie PA, Baker PA, Greenwood KM. Retest reliability of the temporal and distance characteristics of hemiplegic gait using a footswitch system. *Archives of physical medicine and rehabilitation*. 1994; 75(5):577–583. [PubMed: 8185453]
21. Stephens JM, Goldie PA. Walking speed on parquetry and carpet after stroke: effect of surface and retest reliability. *Clinical rehabilitation*. 1999; 13(2):171–181. [PubMed: 10348398]
22. Bohannon RW, Walsh S. Nature, reliability, and predictive value of muscle performance measures in patients with hemiparesis following stroke. *Archives of physical medicine and rehabilitation*. 1992; 73(8):721–725. [PubMed: 1642521]
23. Turani N, Kemiksizoglu A, Karatas M, Ozker R. Assessment of hemiplegic gait using the Wisconsin Gait Scale. *Scandinavian journal of caring sciences*. 2004; 18(1):103–108. [PubMed: 15005669]
24. Tyson SF, DeSouza LH. Reliability and validity of functional balance tests post stroke. *Clinical rehabilitation*. 2004; 18(8):916–923. [PubMed: 15609847]
25. Cunha IT, Lim PA, Henson H, Monga T, Qureshy H, Protas EJ. Performance-based gait tests for acute stroke patients. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*. 2002; 81(11):848–856.
26. Kelly JO, Kilbreath SL, Davis GM, Zeman B, Raymond J. Cardiorespiratory fitness and walking ability in subacute stroke patients. *Archives of physical medicine and rehabilitation*. 2003; 84(12):1780–1785. [PubMed: 14669183]
27. Friedman PJ. Gait recovery after hemiplegic stroke. *International disability studies*. 1990; 12(3):119–122. [PubMed: 2096120]
28. Rabadi MH, Blau A. Admission ambulation velocity predicts length of stay and discharge disposition following stroke in an acute rehabilitation hospital. *Neurorehabilitation and neural repair*. 2005; 19(1):20–26. [PubMed: 15673840]
29. Salbach NM, Mayo NE, Higgins J, Ahmed S, Finch LE, Richards CL. Responsiveness and predictability of gait speed and other disability measures in acute stroke. *Archives of physical medicine and rehabilitation*. 2001; 82(9):1204–1212. [PubMed: 11552192]
30. Judge JO, Schechtman K, Cress E. The relationship between physical performance measures and independence in instrumental activities of daily living. *The FICSIT Group. Frailty and Injury: Cooperative Studies of Intervention Trials. Journal of the American Geriatrics Society*. 1996; 44(11):1332–1341. [PubMed: 8909349]
31. Perera S, Mody SH, Woodman RC, Studenski SA. Meaningful change and responsiveness in common physical performance measures in older adults. *Journal of the American Geriatrics Society*. 2006; 54(5):743–749. [PubMed: 16696738]
32. Shields RK, Madhavan S, Gregg E, et al. Neuromuscular control of the knee during a resisted single-limb squat exercise. *The American journal of sports medicine*. 2005; 33(10):1520–1526. [PubMed: 16009991]

33. Ballantyne BT, Shields RK. Quadriceps fatigue alters human muscle performance during a novel weight bearing task. *Medicine and science in sports and exercise*. 2010; 42(9):1712–1722. [PubMed: 20164810]
34. Madhavan S, Burkart S, Baggett G, et al. Influence of age on neuromuscular control during a dynamic weight-bearing task. *Journal of aging and physical activity*. 2009; 17(3):327–343. [PubMed: 19799103]
35. Madhavan S, Shields RK. Weight-bearing exercise accuracy influences muscle activation strategies of the knee. *Journal of neurologic physical therapy : JNPT*. 2007; 31(1):12–19. [PubMed: 17419885]
36. Madhavan S, Shields RK. Neuromuscular responses in individuals with anterior cruciate ligament repair. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*. 2011; 122(5):997–1004. [PubMed: 20884289]
37. Harrop JS, Naroji S, Maltenfort M, et al. Cervical myelopathy: a clinical and radiographic evaluation and correlation to cervical spondylotic myelopathy. *Spine*. 2010; 35(6):620–624. [PubMed: 20150835]
38. Yoon JY, Chang H, Park KB, Lee SJ, Choi BW. Effect of the number of involved spinal cord segments on gait function in patients with cervical spondylotic myelopathy. *Asian spine journal*. 2012; 6(4):233–240. [PubMed: 23275806]
39. Singh A, Choi D, Crockard A. Use of walking data in assessing operative results for cervical spondylotic myelopathy: long-term follow-up and comparison with controls. *Spine*. 2009; 34(12):1296–1300. [PubMed: 19412138]
40. Madhavan S, Shields RK. Movement accuracy changes muscle-activation strategies in female subjects during a novel single-leg weight-bearing task. *PM R*. 2009; 1(4):319–328. [PubMed: 19627914]

FIGURE 1.

Group mean gait velocities for all patients tested are shown for preoperative and early and late postoperative time periods. Testing was performed at slow, self-selected, and fast gait speeds.

SLS Mean Absolute Error

FIGURE 2.

Group Single Leg Squat (SLS) mean and standard error values for all subjects tested preoperatively (Day 1) and during early (Day 2) and late (Day 3) postoperative epochs.

FIGURE 3.

Scatter plot depicting the relationship between mean SLS error values and mean gait velocity values for subjects tested preoperatively and during early and late postoperative epochs.

Table 1

Demographics

Demographics			
	Day 1	Day 2	Day 3
Age (yrs)	58.1±7.2	61.1±7.0	55.6±4.7
Gender (M/F)	9/5	6/2	3/2
BMI	28.5±6.3	27.0± 8.7	23.1±2.9
Body Fat (%)	27.9±6.9	24.9±8.4	23.2±6.4
Nurick Score	1.8±0.8	1.4±0.7	1±0.7
JOA Score	15.5±2.5	16.3±1.0	17.4±0.5

Table 2**Gait Kinematics**

Day 1			
	Self-Selected Gait	Fast Gait	Slow Gait
Cadence (steps/min)	98.9±8.9	112.6±11.8	89.6±8.2
Velocity (cm/s)	81.1±18.7	97.2±23.8	77.6±15.8
Stride Length (cm/s)	97.9±18.4	104.0±20.5	103.7±18.5
Step Length (cm/s)	50.2±10.5	52.6±9.8	52.0±9.0
Day 2			
	Self-Selected Gait	Fast Gait	Slow Gait
Cadence (steps/min)	98.3±15.4	112.9±20.6	90.3±15.5
Velocity (cm/s)	86.2±23.7	97.7±35.1	78.3±22.2
Stride Length (cm/s)	104.2±17.9	102.4±21.8	101.9±17.4
Step Length (cm/s)	52.0±9.7	51.5±10.4	51.0±7.6
Day 3			
	Self-Selected Gait	Fast Gait	Slow Gait
Cadence (steps/min)	98.6±10.0	113.0±12.8	92.8±10.2
Velocity (cm/s)	98.3±29.3	117.4±33.1	91.5±27.7
Stride Length (cm/s)	117.2±25.3	122.6±24.4	117.4±27.3
Step Length (cm/s)	58.5±11.8	61.3±12.1	57.7±13.8