ORIGINAL ARTICLE

Resistance Training Improves Gait Kinematics in Persons With Multiple Sclerosis

Gregory M. Gutierrez, MS, John W. Chow, PhD, Mark D. Tillman, PhD, Sean C. McCoy, MS, Vanessa Castellano, MA, Lesley J. White, PhD

ABSTRACT. Gutierrez GM, Chow JW, Tillman MD, McCoy SC, Castellano V, White LJ. Resistance training improves gait kinematics in persons with multiple sclerosis. Arch Phys Med Rehabil 2005;86:1824-9.

Objective: To evaluate the effects of an 8-week lower-body resistance-training program on walking mechanics in persons with multiple sclerosis (MS).

Design: Repeated-measures design, evaluating gait kinematics before and after an 8-week progressive resistance-training intervention.

Setting: Biomechanics laboratory and fitness center (with conventional, commercially available resistance-training equipment).

Participants: Eight ambulatory subjects with MS (age, 46.0±11.5y) with Expanded Disability Status Scale scores ranging from 2.5 to 5.5.

Intervention: An 8-week progressive resistance-training program.

Main Outcome Measures: Kinematic gait parameters including knee range of motion, duration of stance, swing, and double-support phases in seconds and as percentages of the stride time, percentage of stride time spent in stance, swing, and double-support phases, step length, foot angle, stride length, velocity, step width, and toe clearance for both the more affected and less affected lower limbs. Isometric strength, 3-minute stepping, fatigue, and self-reported disability were also measured.

Results: After 2 months of resistance training, there were significant increases ($P<.05$) in percentage of stride time in the swing phase, step length, stride length, and foot angle; and significant decreases ($P<.05$) in percentage of stride time in the stance and double-support phases, duration of the double-support phase, and toe clearance. Isometric leg strength improved ($P<.05$) in 2 of the 4 muscle groups tested. Fatigue indices decreased ($P=.04$), whereas self-reported disability tended to decrease ($P=.07$) following the training program. Three-minute stepping increased by 8.7%.

Conclusions: Resistance training may be an effective intervention strategy for improving walking and functional ability in moderately disabled persons with MS.

Key Words: Multiple sclerosis; Rehabilitation; Walking.

MULTIPLE SCLEROSIS (MS) is a degenerative disease of the central nervous system affecting myelin, oligodendrocytes, and axons.[1] MS is the most common progressive neurologic disease in young adults[2] and is usually diagnosed between the ages of 20 and 40 years. Compromised neural functioning leads to both sensory and motor dysfunction and thus contributes to problems with balance, coordination, postural control, and walking mechanics (gait).[3,4] Impaired walking compromises functional ability in persons with neurologic deficits[5] such as MS, Parkinson's disease, and stroke. A survey of subjects who have had a stroke by Chiou and Burnett[6] identified walking as the most important activity of daily living and Hobart et al[7] reported that 75% of persons with MS experienced mobility problems.

Muscle weakness and fatigue contribute to reduced daily activity in persons with MS. Inactivity further compromises muscle function, ambulatory ability, and thus physical fitness. The vicious cycle of decreased activity contributes to increased disability, and reduced quality of life. However, regular exercise can improve daily activity,[8] cardiovascular fitness,[8,9] muscle strength,[10] health perception,[8] and fatigue indices[8] in persons with MS. Debolt and McCubbin[11] found that a home-based resistance-training program was well tolerated by subjects with MS and increased their lower-extremity extensor muscle power.

Strength training is known to promote neural adaptations such as improved motor unit activation and synchronization of firing rates, which may deteriorate with periods of inactivity.[12] Neural adaptations gained through physical activity may have favorable functional outcomes in MS subjects, depending on MS lesion load and location. Moreover, improving strength in muscle capable of adaption to overload stimuli may also help maintain or improve overall fitness and functional ability including ambulatory status, although this has not been explored in people with moderate MS. Rodgers et al[13] found that aerobic-exercise training improved cardiovascular fitness while gait mechanics remained essentially unchanged. The impact of short- or long-term implications of exercise on gait remains unclear.

Considering that ambulatory function is necessary for daily activity, intervention strategies to attenuate loss in ambulatory status or improve walking ability may have significant functional importance. Therefore, the purpose of this study was to evaluate the effects of an 8-week resistance-training program on walking mechanics in persons with MS. We hypothesized that MS subjects would show significant changes in gait characteristics after an 8-week progressive resistance-training program and, specifically, that their gait parameters would be altered to be more consistent with the normal gait patterns of unimpaired people. This investigation was a part of a larger study to

From the Department of Applied Physiology and Kinesiology, University of Florida, Gainesville, FL.

Presented in part to the American College of Sports Medicine, June 2–5, 2004, Indianapolis, IN.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the author(s) or upon any organization with which the author(s) is/are associated.

Reprint requests to Lesley J. White, PhD, Dept of Applied Physiology and Kinesiology, University of Florida, PO Box 118207, Gainesville, FL 32611, e-mail: *lwhite@hhp.ufl.edu.*

0003-9993/05/8609-9862$30.00/0

doi:10.1016/j.apmr.2005.04.008

evaluate the impact of progressive resistance training on functional capacity in persons with MS.[14]

METHODS

Participants

Eight subjects with MS (7 women, 1 man) with Expanded Disability Status Scale (EDSS)[15] scores ranging from 2.5 to 5.5 (mean ± standard deviation [SD] age, 46.0±11.5y; height, 1.66±0.08m; mass, 77.0±19.6kg; EDSS score, 3.6±0.8) were recruited and had physician clearance for participation. To be included, subjects were diagnosed with relapsing-remitting MS (in remission) by a neurologist and had been participating in light physical activity for the previous 3 months to ensure that subjects were not sedentary. Subjects using MS medications (glatiramer acetate) were included, but those using prednisone or antispasmodic medications were excluded. In addition, subjects with known metabolic diseases or orthopedic limitations were also excluded. Participants completed an informed consent approved by the Institutional Review Board at the University of Florida before participation.

Study Design

During the 2 weeks before training, baseline measurements of lower-limb muscle strength, gait kinematics, 3-minute stepping, fatigue, and self-reported disability were collected (pretests). Self-reported disability was assessed using the self-assessed EDSS and fatigue was evaluated using the Modified Fatigue Impact Scale (MFIS). Each subject was given standard instructions to complete the questionnaires.[16,17] Subjects were also asked to identify which limb was more or less affected in terms of strength, sensation, and/or coordination. For the next 8 weeks, subjects participated in twice-weekly supervised resistance training, with a minimum of 48 hours of rest between consecutive exercise sessions. Within a week following the training intervention, all initial measures were reevaluated (posttests).

Instrumentation

Force platform. Two Bertec force platforms[a] (60×40cm) were used to determine critical instances of gait. The force platforms were aligned and staggered in the fore-aft direction (line of progression) with a lateral offset of 20cm. In each gait trial, the force platform data were collected for 5 seconds and sampled at 900Hz.

Video. Six genlocked JVC video cameras[b] sampling at 60Hz recorded the subjects' motions as they walked across the force platforms. Reflective markers were placed on both of the subject's lower extremities according to the marker set-up described by Vaughan et al.[18] In brief, reflective markers were placed on the greater trochanter, lateral thigh, lateral knee, lateral shank, ankle, heel, and toe on both limbs. We used a Peak Motus 2000 Motion Analysis System[c] to synchronize the ground reaction force and video recordings and to digitize the marker locations. For 3-dimensional space reconstruction, we placed a calibration frame (20 control points, 1.6×2.3×1.6m) above the force platforms and videotaped before each data collection session. The calibration errors for different sessions were all less than 0.5% of the object space.

Isokinetic dynamometer. We used a KinCom isokinetic dynamometer[d] for strength testing. The dynamometer was operated in isometric mode, and thus quantified resistive force generated by the subject at a preset joint angle. Although subjects trained isotonically, isometric testing was performed because it is reliable.[19] Maximal isometric torque of knee flexor and extensor muscles can be reliably measured using isokinetic dynamometry in MS subjects.[20] Isometric strength data were available in the literature for comparison; isometric testing has been used previously to evaluate strength in MS.[21-23] Furthermore, isometric testing has also been used to evaluate strength gained from isotonic training[24]; although not in subjects with MS. During testing, subjects were seated and restrained using shoulder and lap belts and the axis of the joint being studied was aligned with the axis of the dynamometer. Subjects' seat position and orientation on the dynamometer were stored in the computer database as well as on data sheets to ensure reproducibility of body position during follow-up testing.

Table 1: Muscle Groups Tested, the Movement They Produce, and Corresponding Joint Angles

Muscle Group Tested	Exercise	Joint Angle
Quadriceps	Knee extension	Knee angle ≈90°
Hamstrings	Knee flexion	Knee angle ≈90°
Ankle plantarflexors	Plantarflexion	Ankle angle ≈0° (neutral)
Ankle dorsiflexors	Dorsiflexion	Ankle angle ≈0° (neutral)

Experimental Protocol

Subjects reported to the laboratory twice for both pre- and posttesting. Gait was assessed during 1 visit and isometric leg strength was assessed in the other. The order of testing sessions was based on subject or investigator availability, and was thus semirandomized. Testing within sessions remained consistent throughout the study. Furthermore, all testing was performed at the same time of day for each subject to minimize the influence of fatigue on experimental outcomes.

Gait testing. Gait analysis consisted of subjects walking barefoot at a self-selected speed along a 7-m long walkway containing 2 embedded force platforms. The subjects were asked to avoid altering their normal gait to accommodate the testing environment. Gait trials were discarded from analysis if the subjects' feet did not make clean contact with the force platforms or if visible alterations in gait occurred in order to strike the platforms (targeting). An investigator experienced in gait evaluation conducted all testing. Trials were repeated until 3 successful trials were recorded. After gait testing, subjects were tested for functional stepping ability using a 3-minute step test, in which subjects were asked to step up onto a 6-in platform with both feet as many times as possible within the 3-minute period, and the total number of steps were recorded.

Strength testing. Subjects were tested for isometric strength on their self-reported more-affected limb to minimize testing time. The muscle groups and corresponding joint angle used during testing are listed in table 1. The order of strength testing remained consistent throughout the study, with the knee extensors tested first, followed by the knee flexors, plantarflexors, and dorsiflexors. The subjects were asked to perform a maximal voluntary isometric contraction for each exercise, for a period of 3 to 5 seconds per trial. Two trials were completed for each exercise with 1 minute of rest between trials.

Resistance-training program. For 8 consecutive weeks, the subjects performed twice-weekly resistance-training sessions supervised by staff trained in exercise safety for people with disabilities. The training protocol was adopted from American College of Sports Medicine's resistance-training

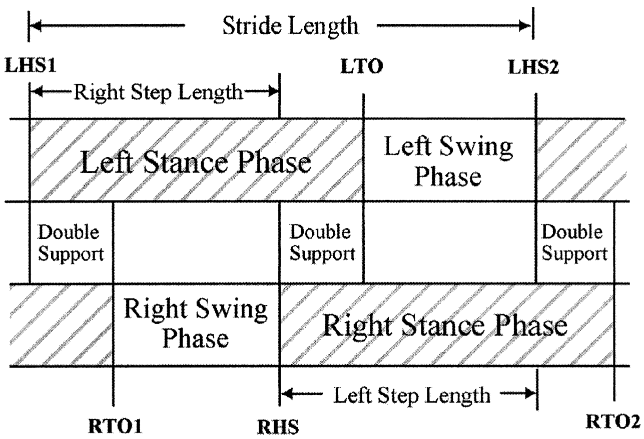

Fig 1. A representative diagram of gait showing the critical instants used for analyses. Abbreviations: LTO, left-toe off; RHS, right-heel strike.

guidelines and recognized criteria for load assignment in older individuals.[25]

During the first training session, subjects were asked to lift a submaximal load until they reached fatigue for each exercise (2–20 repetitions). A predicted 1-repetition maximum (1-RM) was determined using the Kuramoto and Payne[26] prediction equation for older women. During the second training session, subjects performed 1 set of 6 to 10 repetitions at 50% of the predicted 1-RM. In subsequent sessions, subjects completed 1 warm-up and 1 training set for each exercise. Their warm-up consisted of 5 repetitions at 40% of the predicted 1-RM on each of the weight machines. The training set consisted of 10 to 15 repetitions at 70% of predicted 1-RM for lower limb exercises, including knee flexion and extension, plantarflexion, trunk flexion, and trunk extension in that order every time. Exercises were performed at a self-selected, comfortable pace with at least 1 minute of rest between exercises. Training sessions did not exceed 30 minutes. When subjects were able to complete 15 repetitions for any exercise, in consecutive sessions, the resistance was increased by 2% to 5%.

Data Reduction

A computer program, coded in Matlab software[e] and based on equations described by Vaughan et al,[18] was used to process the collected data files and compute different kinematic gait parameters for both limbs. For the purpose of this study, the left stride starts at the instant of left-heel strike (LHS1) and ends at the next left-heel strike (LHS2). For the right leg, the stride starts at the instant of right-toe off (RTO1) and ends at the next right-toe off (RTO2). Critical instants used for determining different phases of a stride are illustrated in figure 1. Instants of heel strike and toe off were determined using vertical ground-reaction-force data, except the instants of RTO1 and LHS2, which were determined from the vertical coordinates of the toe and heel markers, respectively. The critical instants were used to determine the stride time, and the duration (in seconds) and percent of stride time spent in stance, swing, and double-support phases.

From the video data, the knee range of motion (ROM) was computed as the difference between the largest and smallest knee flexion angles during a stride. The foot angle was defined as the angle between the line from the heel marker to the toe marker and the direction of progression from an overhead view. Toe clearance was defined as the highest point reached by the toe marker in the swing phase. Step width was defined as the horizontal distance between the heel markers at LHS1 and right-heel strike in the mediolateral direction. Gait velocity was computed as the stride length divided by the stride time.

Isometric muscular strength was defined as the maximum isometric torque produced by the subject for each exercise and was calculated as the product of the maximum force recorded by the KinCom load cell and the distance between the load cell and the axis of rotation (moment arm). For each exercise, we used the higher torque value of the 2 trials for subsequent analysis.

Data Analysis

Descriptive statistics (means, SDs) were calculated for each of the gait parameters evaluated. Nonparametric Wilcoxon signed-rank tests were used to determine if any changes in gait parameters occurred. Comparisons between pre- and posttraining isometric strength measures were analyzed using paired t tests. Self-reported EDSS and fatigue measures were analyzed with the Wilcoxon signed-rank test. All tests were performed using the traditional level of significance (α=.05).

RESULTS

All subjects completed the 8-week resistance-training program (16 sessions) with no MS-related exacerbations reported. The protocol was occasionally adjusted when subjects missed days between workouts for personal reasons, although adherence remained at 100%. Three subjects reported mild muscle soreness during the first 2 weeks of training, but their symptoms resolved within 2 to 3 days.

For the more-affected limb, subjects significantly decreased the percentage of time spent in stance phase and increased the percentage of time in the swing phase. For the less-affected limb, significant increases were found in step length and foot angle, and a significant decrease was noted in toe clearance. For measures involving both limbs, significant decreases were found in the time and percentage of time spent in double support, and a significant increase in stride length was also found (table 2).

Self-reported EDSS scores decreased from 3.7 to 3.2 after 8 weeks of strength training and approached statistical significance (P=.072). The average MFIS score decreased significantly from 32 to 26 after the 8-week training period (P=.04). Isometric knee extension and plantarflexion strength increased by 7.2% (P=.03) and 55% (P=.04), respectively, whereas knee flexion (14.5%) and dorsiflexion (0%, dorsiflexors were not trained) isometric strength remained statistically unchanged (table 3). Steps performed in 3 minutes improved by 8.7%. Isometric strength, fatigue, stepping, and self-reported EDSS data have been previously reported by White et al.[14]

DISCUSSION

We hypothesized that lower-limb resistance training in MS subjects would alter gait characteristics to more closely resemble the patterns of persons without neurologic dysfunction. We found significant increases for percentage of stride time in the swing phase, step length, stride length, and foot angle, and significant decreases in percentage of stride time in the stance and double-support phases, duration of the double-support phase, and toe clearance. These changes are more indicative of normative stride patterns of subjects without known impairments and thus support our hypothesis. Furthermore, our subjects showed improvements in 3-minute stepping, fatigue, self-reported disability scores, and lower-extremity isometric muscle strength.

Table 2: Mean Values for Gait Characteristics Evaluated

Measure	Most-Affected			Least-Affected		
	Pre	Post	*P*	Pre	Post	*P*
Knee ROM (deg)	52.8±6.4	51.7±6.1	.484	53.8±8.2	52.3±4.9	.208
Stride time (s)	1.22±0.22	1.20±0.18	.779	1.23±0.18	1.21±0.18	.484
Stance time (s)	0.83±0.18	0.80±0.17	.293	0.84±0.15	0.82±0.15	.674
Stance* (%)	67.4±3.9	66.4±3.9	.036	67.4±2.7	67.7±2.7	.674
Swing time (s)	0.39±0.04	0.4±0.03	.671	0.4±0.04	0.39±0.05	.236
Swing* (%)	32.6±3.7	33.6±3.9	.036	32.6±2.7	32.3±2.7	.674
Step length* (m)	0.53±0.09	.58±0.07	.063	0.53±0.07	0.56±0.07	.025
Foot angle* (deg)	13.9±9.1	9.82±7.0	.327	10.7±5.4	18.1±11	.036
Toe clearance* (m)	0.16±0.03	0.14±0.05	.401	0.17±0.06	0.14±0.06	.021

	Pretest	Posttest	*P*
Double support time* (s)	0.23±0.07	0.21±0.06	.046
Double support* (%)	18.3±2.8	16.8±2.8	.012
Stride length* (m)	1.06±0.16	1.14±0.12	.017
Velocity (m/s)	0.91±0.23	0.98±0.22	.116
Step width (m)	0.19±0.04	0.22±0.09	.208

NOTE. Values are mean ± SD.
*Significant difference between pretest and posttest in at least 1 limb ($P<.05$).

Limited research has been conducted on strength training in persons with MS. Kraft et al[27,28] found improved function, strength, and psychosocial well-being in 8 MS patients who strength trained for 3 months. Debolt and McCubbin[11] found that a home-based resistance-training program was well tolerated (caused no exacerbations) by persons with MS and improved their leg extensor muscle power. All subjects in our study completed the 8-week program with no appreciable musculoskeletal problems or exacerbation of MS symptoms. In addition, isometric strength (knee extensors, plantarflexors) and fatigue indices improved with training, suggesting that persons with MS can safely participate in a resistance-training program.

Falls in the elderly often occur while walking.[29] Research findings have shown that aging is associated with deterioration of normal stride parameters such as slower walking (a function of a shorter step length) and increased time in double limb support.[30,31] This gait pattern, which is consistent with a more conservative strategy that favors stability and balance at the expense of speed, is shared by persons with MS,[32] and suggests that they may be compensating for a reduction in physical capacity by being more cautious.[33] Although the true origin of a fall may vary, these gait characteristics are considered risk factors for falling because of their correlation with falling behavior.[34]

On enrollment in the study, our cohort of subjects showed gait patterns similar to elderly fallers. Specifically, they displayed a more conservative gait strategy than unimpaired persons. For example, they spent less time in the swing phase (32.6% of gait cycle), and more time in the stance (67.4% of gait cycle) and double-support phases (18.3% of gait cycle) than normative walking. Normative gait data has shown a 60/40 relation between the percentage of time spent in the stance and swing phases, respectively, with 10% of the gait cycle spent in double support.[18,35] Subjects in this study displayed a decreased step length (53cm vs 60cm), stride length (1.06m vs 1.40m), and a slower velocity (0.91m/s vs 1.12m/s) than normal walking.[29,35]

The results of this preliminary study suggest that lower-limb resistance training facilitates gait modifications toward the patterns of unimpaired persons. Specifically, after training, subjects had longer strides, spent more time in the swing phase, and less time in the stance and double-support phases. The less conservative gait of our subjects suggests improved lower-extremity coordination and perhaps efficiency. This assertion is supported by the observed increase in 3-minute stepping and trend toward improvement in self-reported disability, as determined by the self-reported EDSS scale, which relies heavily on ambulation as a determinant of disability level.

There were also significant changes in other gait parameters, including toe clearance. Patients with neurologic disorders often experience foot drop, which is characterized by an impairment in dorsiflexor strength and a subsequent decrease in toe clearance during gait.[36] Previous research suggests persons with pathologies or disabilities increase foot clearance to assure safe walking.[37] After 8 weeks of strength training, toe clearance became more symmetrical between sides. Ankle plantarflexor strength has been determined to be a predictor of gait symmetry,[38] which may help to explain the more symmetrical toe clearance seen in our subjects after training (.16m and .18m before vs .14m and .14m after training). These findings suggest that subjects were perhaps more coordinated and adopted a pattern of walking more closely resembling that of unimpaired persons.

Muscle strength has been determined to be an important predictor of ambulatory function in persons who have survived an incomplete spinal cord injury, stroke, and various orthopedic injuries.[39-41] Specifically, lower-extremity muscle strength has a significant effect on gait speed with hip flexors and knee

Table 3: Isometric Strength Before and After an 8-Week Resistance-Training Program

Exercise	Pretest	Posttest	% Change	*P*
Knee extension*	74.7±20.6	80.1±20.7	7.23	.03
Knee flexion	39.3±10.9	45.6±24.1	14.55	.10
Plantarflexion*	60.2±20.3	93.4±45.3	55.16	.04
Dorsiflexion	29.1±9.9	29.1±11.6	0.03	.30

NOTE. All isometric strength (torque) values are mean Nm ± SD.
*$P<.05$.

extensors having the highest correlations with gait speed.[38,39,42] In our study, both the isometric knee extensor and plantarflexor strength improved significantly after training. Although not statistically significant, our subjects' self-selected walking speed tended to be faster after training (.91m/s before vs .98m/s after training, $P=.116$). The increase in isometric quadriceps strength may help to explain the tendency toward increased gait velocity.

Analysis of individual subject data based on EDSS scores revealed some trends. For example, the least disabled subject (EDSS score, 2.5) increased the percentage of time spent in the swing phase, while decreasing the percentage of time in the stance phase in both limbs; however, the changes represented less than 1% of the entire gait cycle. Furthermore, stride length and velocity remained essentially unchanged. The 5 moderately disabled subjects (EDSS score, 3.5) increased the percentage of time spent in the swing phase while decreasing the percentage of time in the stance phase for the more affected limb (changes in the less affected limb were more variable among these subjects), representing changes of 0.4% to 3%. In addition, they all decreased the percentage of time they spent in the double-support phase (range, 0.2%–3.4%), while increasing their stride length (range, 3–12cm) and velocity (range, .01–.24m/s).

After training, the subject with an EDSS score of 4.0 had an increased step length in both limbs (4 and 8cm, respectively), stride length (12cm), and velocity (0.13m/s), while decreasing the stride time (−.04 and −.07s) and percentage of time spent in double support (−3.6%). The greatest change was observed in the subject with an EDSS score of 5.5. There was an increase in the percentage of time spent in the swing phase, while decreasing the percentage of time in the stance phase in both limbs (2.4%, respectively) and also increased step length in both limbs (5 and 13cm, respectively), stride length (20cm), and velocity (0.18m/s). In our small cohort of subjects, the most disabled appeared to show the greatest changes in gait.

Unsolicited comments by study participants revealed some potentially important study findings. For example, after the training program, subjects were capable of participating in activities they had discontinued, such as using stairs instead of elevators, shopping at the mall, and hiking. These observations suggest possible improvements in activities of daily living and quality of life not formally measured in this study.

Leg strength, fatigue, and gait improved in our subjects, providing preliminary support for strength training as a strategy to improve ambulatory status. However, with a small sample size and lack of a control group, additional studies are needed to confirm these observations. In addition, the strength protocol used in this study may not have highlighted the full benefit or dangers of strength training in persons with MS. Strength gains observed in this study should be interpreted cautiously because subjects trained isotonically, whereas strength testing was isometric and only performed on 1 limb (the more-affected limb); therefore, the strength gains reported may not represent the entire range of motion. Despite these limitations, there were significant improvements in several gait parameters in our subjects. Studies that include quality of life measures, with larger sample size, control groups, and increased duration and/or intensity of training, are recommended.

CONCLUSIONS

This study represents the first attempt to explore the effects of resistance training on gait kinematics in ambulatory subjects with MS. Our results suggest that an 8-week resistance-training program can improve lower-extremity strength and self-reported disability in persons with MS. Our subjects' gait changed from a more conservative to a less conservative gait, which is closer to normative values and less like the gait characteristics shared by elderly persons prone to falling. Resistance training holds promise as an effective strategy to minimize the often deleterious affect of MS on physical function.

Acknowledgments: We thank all those who made the study possible, specifically the personal trainers who sacrificed their time to improve the lives of some brave people. We also acknowledge the undergraduate student interns, without whom data collection would not have been possible.

References

1. Noseworthy JH, Lucchinetti C, Rodrigues M, Weinshenker BG. Multiple sclerosis. N Engl J Med 2000;343:938-52.
2. Kraft AM, Wessman HC. Pathology and etiology in multiple sclerosis. Phys Ther 1974;54:716-20.
3. Ashburn A, DeSouza LH. An approach to the management of multiple sclerosis. Physiother Pract 1988;4:139-45.
4. Frzovic D, Morris ME, Vowels L. Clinical tests of standing balance: performance of persons with multiple sclerosis. Arch Phys Med Rehabil 2000;81:215-21.
5. Holden MK, Gill KM, Magliozzi MR. Gait assessment for neurologically impaired patients. Phys Ther 1986;66:1530-9.
6. Chiou IL, Burnett CN. Values of activities of daily living: a survey of stroke patients and their home therapists. Arch Phys Med Rehabil 1985;65:901-6.
7. Hobart JC, Lamping DL, Fitzpatrick R, Riazi A, Thompson AJ. The multiple sclerosis impact scale (MSIS-29): a new patient-based outcome measure. Brain 2001;124:962-73.
8. Mostert S, Kesselring J. Effects of a short-term exercise-training program on aerobic fitness, fatigue, health perception and activity level of subjects with multiple sclerosis. Mult Scler 2002;8:161-8.
9. Petajan JH, Gappmaier E, White AT, Spencer MK, Mino L, Hicks RW. Impact of aerobic training on fitness and quality of life in multiple sclerosis. Ann Neurol 1996;39:432-41.
10. Gehlsen GM, Grigsby SA, Winant DM. Effects of an aquatic fitness program on the muscle strength and endurance of persons with multiple sclerosis. Phys Ther 1984;64:653-7.
11. Debolt LS, McCubbin JA. The effects of home-based resistance exercise on balance, power, and mobility in adults with multiple sclerosis. Arch Phys Med Rehabil 2004;85:290-7.
12. Frontera WR, Hughes VA, Krivickas LS, Kim SK, Foldvari M, Roubenoff R. Strength training in older women: early and late changes in whole muscle and single cells. Muscle Nerve 2003;27:601-8.
13. Rodgers MM, Mulcare JA, King DL, Mathews T, Gupta SC, Glaser RM. Gait characteristics of individuals with multiple sclerosis before and after a 6-month aerobic training program. J Rehabil Res Dev 1999;36:183-8.
14. White LJ, McCoy SC, Castellano V, et al. Resistance training improves strength and functional capacity in persons with multiple sclerosis. Mult Scler 2004;10:668-74.
15. Kurtzke JF. Rating neurologic impairment in multiple sclerosis: an expanded disability status score (EDSS). Neurology 1983;33:1444-52.
16. Scheinberg LC, Feldman FM, Ratzker EA. Self-assessment of neurological impairment in multiple sclerosis. Neurology 1986;36(Suppl):284.
17. Flachenecker P, Kumpfel T, Kallmann B, et al. Fatigue in multiple sclerosis: a comparison of different rating scales and correlation to clinical parameters. Mult Scler 2002;8:523-6.
18. Vaughan CL, Davis BL, O'Connor JC. Dynamics of human gait. Cape Town: Kiboho Publ; 1999.

19. Todd G, Gorman RB, Gandevia SC. Measurement and reproducibility of strength and voluntary activation of lower-limb muscles. Muscle Nerve 2004;29:834-42.
20. Surakka J, Romberg A, Ruutiainen J, Virtanen A, Aunola S, Maentaka K. Assessment of muscle strength and motor fatigue with a knee dynamometer in subjects with multiple sclerosis: a new fatigue index. Clin Rehabil 2004;18:652-9.
21. Kent-Braun JA, Ng AV, Castro M, et al. Strength, skeletal muscle composition, and enzyme activity in multiple sclerosis. J Appl Physiol 1997;83:1998-2004.
22. Ng AV, Miller RG, Gelinas D, Kent-Braun JA. Functional relationships of central and peripheral muscle alterations in multiple sclerosis. Muscle Nerve 2004;29:843-52.
23. Surakka J, Romberg A, Ruutiainen J, et al. Effects of aerobic and strength exercise on motor fatigue in men and women with multiple sclerosis: a randomized controlled trial. Clin Rehabil 2004; 18:737-46.
24. Kollmitzer J, Ebenbichler GR, Sabo A, Kerschan K, Bochdansky T. Effects of back extensor strength training versus balance training on postural control. Med Sci Sports Exerc 2000;32:1770-6.
25. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. 6th ed. Philadelphia: Lippincott Williams & Wilkins; 2000.
26. Kuramoto AK, Payne VG. Predicting muscular strength in women: a preliminary study. Res Q Exerc Sport 1995;66:168-72.
27. Kraft GH, Alquist AD, de Lateur BJ. Effect of resistive exercise on function in multiple sclerosis (MS) [abstract]. Arch Phys Med Rehabil 1996;77:984.
28. Kraft GH, Alquist AD, de Lateur BJ. Effect of resistive exercise on strength in multiple sclerosis (MS) [abstract]. Arch Phys Med Rehabil 1996;77:984.
29. Cali CM, Keil DP. An epidemiological study of fall-related fractures among institutionalized older people. J Am Geriatr Soc 1995;43:1336-40.
30. Oberg T, Karzania A, Oberg K. Basic gait parameters: reference data for normal subjects, 10–79 years of age. J Rehabil Res Dev 1993;30:210-23.
31. Lord SR, Lloyd DG, Li SK. Sensori-motor function, gait patterns, and falls in community dwelling women. Age Ageing 1996;25: 292-9.
32. Benedetti MG, Piperno R, Simoncini L, Bonato P, Tonini A, Giannini S. Gait abnormalities in minimally impaired multiple sclerosis patients. Mult Scler 1999;5:363-8.
33. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear? J Am Geriatr Soc 1997;45:313-20.
34. Imms FJ, Edholm OG. Studies of gait and mobility in the elderly. Age Ageing 1981;10:147-56.
35. Chao EY, Laughman RK, Schneider E, Stauffer RN. Normative data of knee joint motion and ground reaction forces in adult level walking. J Biomech 1983;16:219-33.
36. Vinci P, Perelli SL. Footdrop, foot rotation, and plantarflexor failure in Charcot-Marie-Tooth disease. Arch Phys Med Rehabil 2002;83:513-6.
37. Said CM, Goldie PA, Patla AE, Sparrow WA. Effect of stroke on step characteristics of obstacle crossing. Arch Phys Med Rehabil 2001;82:1712-9.
38. Hsu AL, Tang PF, Jan MH. Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. Arch Phys Med Rehabil 2003;84:1185-93.
39. Kim CM, Eng JJ, Whittaker MW. Level walking and ambulatory capacity in persons with incomplete spinal cord injury: relation with muscle strength. Spinal Cord 2004;42:156-62.
40. Teixeira-Salmela LF, Olney SJ, Nadeau S, Brower B. Muscle strengthening and physical conditioning to reduce impairment and disability in chronic stroke survivors. Arch Phys Med Rehabil 1999;80:1211-8.
41. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. Clin Biomech (Bristol, Avon) 2002;17: 56-63.
42. Nadeau S, Gravel D, Arsenault AB, Bourbonnais D. Plantarflexor weakness as a limiting factor of gait speed in stroke subjects and the compensating role of the hip flexors. Clin Biomech (Bristol, Avon) 1999;14:125-35.

Suppliers

a. Type 4060; Bertec Corp, 6185 Huntley Rd, Columbus, OH 43229.
b. Model TK-1380; JVC Americas Corp, 1700 Valley Rd, Wayne, NJ 07470.
c. Peak Performance Technologies Inc, 7388 S Revere Pkwy, Ste 603, Englewood, CO 80112.
d. Model AP 125; Chattecx Corp, Chattanooga Group, 4717 Adams Rd, Hixson, TN 37343.
e. The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760.