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REVIEW ARTICLE

MUSCLE STRENGTH AND MUSCLE TRAINING AFTER STROKE*

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For many individuals who have experienced a stroke, muscle weakness is the most prominent impairment. Both the theoretical and statistical relationships between muscle weakness and performance at functional activities suggest that weakness may be an appropriate target for therapeutic interventions. Researchers investigating the outcomes of strengthening regimens after stroke have routinely shown that resistance exercise leads to increased muscle strength, but that strength is typically measured using the same maneuvers that were used in training. Evidence supporting the use of strengthening regimens to reduce limitations in functional activity is equivocal.

Key words: muscles, exercise, activities of daily living.

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INTRODUCTION

The annual incidence of stroke in the USA is currently about 700,000; the prevalence is approximately 5.5 million (1). For these individuals and others with stroke, motor deficits are probably the most commonly recognized impairment. Bonita & Beaglehole (2) reported such deficits among 89.1%, 72.1% and 61.0% of patients who experienced a stroke 1 week, 1 month and 6 months earlier. Motor deficits can take various forms, but reductions in strength (maximum voluntary force or torque) are probably the most obvious. Nevertheless, some clinicians have argued against the measurement of muscle strength and the use of muscle strengthening exercise for patients who have experienced a stroke (3, 4). Residual opposition to the application of resistance exercise after stroke is the impetus for the present paper, the purpose of which is to review the evidence supporting the provision of such training. Prior to dealing with this purpose, however, 3 other issues will be addressed. They are: the relevance of muscle strength after stroke; the quantification of muscle strength after stroke; and the nature of strength after stroke.

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RELEVANCE OF MUSCLE STRENGTH AFTER STROKE

The relevance of muscle strength for patients with stroke has both a theoretical and statistical basis. The theoretical foundation for the importance of muscle strength after stroke is simple: force equals mass times acceleration. Consequently, acceleration or deceleration of the mass of any body segment or the entire body requires the generation of force by the muscles. To the extent that the stroke affects the forces that muscles can generate, acceleration or deceleration will be compromised accordingly. The degree to which muscle force is relevant will vary depending on the demand of the functional activities for which muscle force is required. Fig. 1 illustrates the theoretical relationship between strength and performance at functional activities. Fig. 1 basically suggests that for any activity, a certain amount of strength is required to perform it. The amount depends on the demand of the activity. However, increases in strength will not prove useful until a certain threshold is reached. Thereafter, increases in strength will be accompanied by improvement in performance at the functional activity until a point is reached that further strength provides no additional advantage. As functional activities differ in the demands they place on individuals, the point at which strength begins to affect functional activity performance and the point after which additional strength is superfluous will vary accordingly. Consequently, a functional activity such as bringing food to the mouth requires little strength (5) and

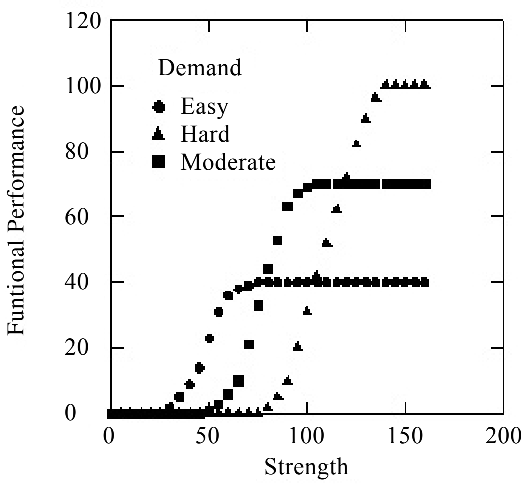

Fig. 1. The hypothetical relationship between strength and functional activity performance at tasks differing in demand.

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would be expected to improve rapidly with small increases in strength so long as adequate hand dexterity is present. Further increases in strength of the elbow and shoulder muscles would be of no consequence for such an easy activity. An activity such as standing from a chair, on the other hand, can be quite demanding (6). Considerable strength is required before it can be accomplished, even with the assistance of the upper limbs and a device (7). Increases in strength will allow the activity to be performed without a device or without assistance from the upper limbs (8). Further increases in strength may allow it to be accomplished more rapidly (6). Still, there will come a point when additional strength will not be associated with further improvement in the activity. Strengthening after such a point is reached may be of value for establishing a functional reserve, but it will not improve present performance at a functional activity.

The statistical foundation for the importance of muscle strength after stroke is based on research showing that muscle strength is related to functional activity performance. More than 50 papers have described such relationships, with most focusing on the activities involving the lower limbs. The functional activities commonly addressed by the research are sit-to-stand and stand-pivot-sit transfers, ambulation, and curb or stair climbing (Table I).

The strength of multiple muscle groups of both the paretic and non-paretic lower limbs has been shown to correlate with independence in the stand-pivot-sit transfer (9). Independence in the sit-to-stand maneuver, the most physically demanding component of the stand-pivot-sit transfer, is correlated with knee extension force (10). This is true whether or not use of the hands is allowed during sit-to-stand. Although the strength of the knee extensors of each side is correlated with sit-to-stand independence, the highest correlations tend to be realized when the strength of the knee extensors of both sides is considered together with body weight. In combination, these variables explain between 68% and 70% of the variance in sit-to-stand independence.

Lower limb muscle strength has been found to correlate with several measures of ambulatory performance after stroke, but correlations with gait speed have been examined most often. The studies are consistent in demonstrating significant bivariate correlations (0.56–0.85) between the strength of individual paretic lower limb muscles, most often the knee extensors, and gait performance (11–15). However, the studies do not always show significant bivariate correlations (0.09–0.66) between the strength of individual non-paretic lower limb muscles and gait performance (11–15). The results of studies examining the statistical relationship of lower limb strength and other non-strength variables with gait performance uphold the explanatory power of muscle strength, particularly that of the paretic lower limb (16, 17).

Only 2 studies were identified that examined the relationship of lower limb strength with stair climbing performance after stroke. Both found significant correlations (0.58–0.85) between strength of the paretic limb and stair climbing performance (12, 18). The study including strength measures from the non-paretic lower limb did not find significant correlations (–0.06–0.07) with stair climbing speed (12).

QUANTIFICATION OF MUSCLE STRENGTH AFTER STROKE

Its prevalence notwithstanding, muscle weakness is not experienced by all patients with stroke. Identifying patients who are weak and for whom strengthening regimens may be indicated requires appropriate measures. Instruments such as the Fugl-Meyer (19), National Institute of Health (NIH) Stroke Scale (20), and Scandinavian Stroke Scale (21) are quite legitimate for characterizing stroke severity, but the measures of motor performance that they incorporate do not challenge muscles sufficiently to indicate their strength accurately. Bohannon has demonstrated this quite convincingly for the NIH Stroke Scale (22). In his study, the 8 patients who received the best possible score on the arm item had mean upper limb strength measures that were only 45.6–48.2% of predicted. Even manual muscle testing, which involves the application of external force by the examiner lacks sensitivity. A secondary analysis of data from a previously reported study (8) demonstrates a clear ceiling effect for manual muscle testing. For 25 patients with grade 5/5 for the left knee extensors, the mean (range) of strengths relative to predicted normal was 53.7% (35.8–80.5). For the right knee extensors, the mean (range) strength was 56.4% (36.6–80.9) of predicted. In contrast, dynamometry does not suffer from the insensitivity of the above mentioned tests. Hand-grip, hand-held, and isokinetic dynamometers can all be used to obtain objective, precise and reliable measurements of strength in patients with stroke (23–25).

NATURE OF STRENGTH AFTER STROKE

Studies employing dynamometry have revealed 3 facts about the nature of muscle strength impairments that may not otherwise be apparent but that have relevance. First, strength measures obtained from different muscle groups of the same limb tend to correlate (26, 27), have internal consistency (27), and represent a common underlying factor (26, 27). Thus, the extent of a patient's weakness can be estimated from a limited number of measures. Second, limb muscles of the side referred to herein and elsewhere as non-paretic may actually be impaired, particularly early after stroke. Strength ipsilateral to a brain lesion, which can be less than 60% of predicted, tends to be more impaired proximally than distally (28). For demanding functional activities requiring the engagement of muscles on both sides of the body (e.g. sit-to-stand), strengthening of the supposedly non-paretic muscles may therefore be important. Third, muscles of the trunk can also be impaired after stroke (29). As such impairments have functional activity implications, they should not be overlooked when a strengthening regimen is initiated.

Table I. *Summary of selected studies reporting bivariate correlations between individual lower limb muscle strengths and functional activity performance*

Functional activity performance measure	Strength measure	Statistical findings*	Study author, year (ref)
Sit-to-stand (independence)	Paretic knee extension (isometric force)	r = 0.72	Bohannon, 2007 (10)
	Non-paretic knee extension (isometric force)	r = 0.73	Bohannon, 2007 (10)
Stand-pivot-sit transfer (independence)	Paretic ankle plantarflexion & dorsiflexion, knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r = 0.30–0.64	Bohannon, 1988 (9)
	Non-paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r = 0.38–0.73	Bohannon, 1988 (9)
Gait (maximum speed)	Paretic knee extension (isokinetic torque)	r = 0.85	Suzuki et al., 1990 (11)
	Paretic knee extension & flexion (isokinetic torque)	r = 0.65 & 0.67	Flansbjer et al., 2006 (12)
	Paretic knee extension (isometric torque)	r = 0.74	Bohannon, 1992 (13)
	Non-paretic knee extension (isokinetic torque)	r = 0.43	Suzuki et a., 1990 (11)
	Non-paretic knee extension & flexion (isokinetic torque)	r = 0.19	Flansbjer et al., 2006 (12)
	Non-paretic knee extension (isometric torque)	r = 0.45	Bohannon, 1992 (13)
Gait (comfortable speed)	Paretic knee extension & flexion (isokinetic torque)	r = 0.61	Flansbjer et al., 2006 (12)
	Paretic knee extension (isometric torque)	r = 0.75	Bohannon, 1992 (13)
	Paretic knee extension (isometric torque)	r = 0.63–0.68	Bohannon, 1991 (14)
	Paretic knee extension (isometric force)	r = 0.60–0.62	Bohannon, 1991 (14)
	Paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r_s = 0.73–0.83	Bohannon, 1989 (15)
	Non-paretic knee extension & flexion (isokinetic torque)	r = 0.09–0.19	Flansbjer et al., 2006 (12)
	Non-paretic knee extension (isometric torque)	r = 0.52	Bohannon, 1992 (13)
	Non-paretic knee extension (isometric torque)	r = 0.14–0.24	Bohannon, 1991 (14)
	Non-paretic knee extension (isometric force)	r = 0.05–0.15	Bohannon, 1991 (14)
	Non-paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r_s = 0.34–0.57	Bohannon, 1989 (15)
Gait (distance)	Paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r_s = 0.68–0.79	Bohannon, 1989 (15)
	Non-paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r_s = 0.31–0.57	Bohannon, 1989 (15)
Gait (independence)	Paretic ankle plantarflexion & dorsiflexion, knee extension & flexion, hip flexion, extension, & abduction (isometric force)	r_s = 0.56–0.84	Bohannon, 1989 (15)
	Non-paretic ankle plantarflexion & dorsiflexion; knee extension & flexion; hip flexion, extension, & abduction (isometric force)	r_s = 0.37–0.66	Bohannon, 1989 (15)
Stair ascent (speed)	Paretic knee extension & flexion (isokinetic torque)	r = –0.58 & –0.61	Flansbjer et al., 2006 (12)
	Non-paretic knee extension & flexion (isokinetic torque)	r = –0.06 & –0.07	Flansbjer et al., 2006 (12)
Stair ascent (performance score)	Paretic hip flexion & extension; knee flexion & extension; and ankle dorsiflexion (isometric force)	r_s = 0.73–0.85	Bohannon & Walsh, 1991 (18)

*Correlations are rounded to the hundredth place.
r: Pearson correlation; r_s: Spearman correlation.

EVIDENCE FOR USING RESISTANCE TRAINING AFTER STROKE

To find literature addressing the use of resistance training after stroke, a comprehensive search was conducted using 4 databases: Medline/PubMed, CINAHL (Cumulative Index to Nursing & Allied Health Literature), Science Citation Index, and EMBASE (Excerpta Medica Database). The terms stroke, muscle, and strength were used in various combinations with the terms exercise, training, and resistance. In addition, the reference lists of identified articles were examined for potentially relevant publications. As few randomized controlled trials were

Table II. *Summary of studies describing the results of resistance exercise on strength and function after stroke*

Study	Design	Subjects	Intervention(s)*	Findings
Inaba et al., 1973 (33)	Randomized controlled trial: Functional training + stretching (F+S) vs active exercise & F+S vs resistance exercise & F+S	Rehabilitation inpatients, ≤ 3 months since stroke, unable to walk independently (n = 77)	Resistance: Weights Exercise: Leg press (paretic limb) Bout: ?? sets of 5 reps at ½ maximum & ?? sets of 10 at max Frequency: ?? Duration: 1 or 2 months	At 1 month, resistance group demonstrated a mean 101% increase in strength. The group had a significantly greater increase in strength and function. At 2 months, groups did not differ significantly in either.
Moreland et al., 2003 (34)	Randomized controlled trial: Conventional therapy vs resistance exercise & conventional therapy	Rehabilitation inpatients, < 6 months since stroke, (n = 133)	Resistance: Weights & body weight Exercises: 9, mostly functional (both limbs) Bouts: 2 sets of 10 at subjective moderate Frequency: 3 times/week Duration: Median 62 days	At discharge, resistance group exercised with weights that were a mean 79–300% higher than at baseline. The increase was significant. Improvements in Disability Inventory and 2-minute walk test did not differ between groups.
Oullette et al., 2004 (35)	Randomized controlled trial: Upper extremity stretching vs resistance exercise	Community-dwelling, > 6 months since stroke, independently ambulatory (n = 42)	Resistance: Weights & pneumatic Exercises: 4 (both limbs) Bout: 3 sets of 8–10 reps at 70% 1RM Frequency: 3 times/week Duration: 12 weeks	At 12 weeks, resistance group demonstrated mean strength increases of ~11–67%. Resistance group strength gains were significantly greater for most tests. Resistance group showed greater improvement in some self-reported function but not in performance-based function.
Weiss et al., 2000 (36)	Time series trial: Baseline vs 4, 8, & 12 weeks	Home-dwelling, > 12 months since stroke, unable to stand > 15 seconds on paretic lower limb (n = 7)	Resistance: Weights & pneumatic Exercises: 5 (both limbs) Bout: Up to 3 sets of 8–10 reps at 70% 1RM Frequency: 2 times/week Duration: 12 weeks	Over training period, strength improved a mean –2–77%. Improvements were significant for 4 of 5 tests. Significant improvements occurred in sit-to-stand performance, Motor Assessment Scale, and Berg Balance Scale, but not in walking or stair climbing speed or unipedal stance time.
Cramp et al., 2006 (37)	Non-randomized, self-controlled trial	Recently discharged, 6–12 months since stroke, independently ambulatory (n = 10)	Resistance: Weights, elastic bands, & body weight Exercises: 5 focused on hips and knees (both limbs) Bout: 3 sets of 10 reps at 50% max after initial 20% max Frequency: 2 times/week Duration: 6 months	At cessation of training, isometric and isokinetic knee extension strength increased a mean 0–34%. Increase was significant in paretic limb. Only isometric strength increased significantly in paretic limb. Knee flexion strength did not increase significantly in either limb.
Badics et al., 2002 (38)	Pre-test–post-test trial	Residential rehabilitation patients, 3 weeks – 10 years since stroke, moderate weakness (n = 56)	Resistance: Weights Exercise: Leg press (both limbs) Bout: 3–5 sets of 20 reps at 30–50% max Frequency: 2–3 day interval Duration: 4 weeks	At 4 weeks leg-press strength increased 31%.
Kim et al., 2001 (39)	Randomized controlled trial: passive range of motion vs resistance exercise	Community-dwelling, > 6 months since stroke, independently ambulatory (n = 20)	Resistance: Isokinetic Exercises: Flexion and extension of hip, knee, and ankle (paretic limb) Bout: 3 sets of 10 reps at 100% max Frequency: 3 times/week Duration: 6 weeks	At 6 weeks, resistance group strength increased a mean of 7–155%. The group showed a trend for greater strength increases on paretic side. Resistance group did not improve significantly more in gait or stair climbing speed or in health related quality of life.

Table II contd.

Study	Design	Subjects	Intervention(s)	Findings
Sharp & Brouwer, 1997 (40)	Non-randomized, self-controlled trial	Community-dwelling, > 6 months since stroke, independently ambulatory ($n = 15$)	Resistance: Isokinetic Exercises: Flexion and extension of knee (paretic limb) Bout: 3 sets of 6–8 reps at 100% max Frequency: 3 times/week Duration: 6 weeks	At 6 weeks, flexion & extension strength increased 16–154% on paretic side. The increase was significant. At 4 week follow-up, strength remained increased but not significantly except for paretic knee extension at 30°/second. Gait velocity was improved at 6 weeks & follow-up, but stair climbing speed & Timed Up & Go were not better at either time. Human Activity Profile scores were better at follow-up but not at 6 weeks.
Engardt et al., 1995 (41)	Non-randomized trial: concentric vs eccentric exercise	Patients, mean 27 months since stroke, ambulatory ($n = 20$)	Resistance: Isokinetic Exercise: concentric or eccentric of knee extensors-multiple velocities (both limbs) Bout: Up to 15 sets of 10 reps at 100% max after 3 sets of 10 submax Frequency: 2 times/week Duration: 6 weeks	After 6 weeks, both groups increased significantly in both concentric and eccentric strength, but each increased more in its own mode of training. Only the eccentric training group improved in weight-bearing symmetry during sit-to-stand. Only the concentric group improved in any gait variable.
Barreca et al., 2004 (42)	Randomized trial: recreational therapy vs extra sit-to-stands	Rehabilitation inpatients, mean 30.5 days since stroke, ≥ stage 3 postural control on Chedoke-McMaster Stroke Assessment ($n = 48$)	Resistance: Body weight Exercise: Sit-to-stands (both limbs) Bout: 3 sets of 5 reps with assistance if necessary Frequency: 3 times/week Duration: mean 80.4 days	At discharge, a significantly greater proportion in the training group were able to stand up twice (without hands) from a 16-inch surface. Falls did not differ between groups.
Åsberg, 1989 (43)	Non-randomized trial: conventional vs regular stand-ups	Hospital inpatients, 1–2 days since stroke, able to stand on feet ($n = 63$)	Resistance: Body weight Exercise: Sit-to-stands (both limbs) Bout: Once per hour Frequency: Daily (8 am – 8 pm) Duration: 5–12 days	At 5–7 days, the training group had a significantly smaller proportion of severely disabled patients. At 3 month follow-up, the training group still had fewer severely disabled patients, but the number was not significantly less.
Monger et al., 2002 (44)	Pre-test–post-test trial	Home-dwelling, ≥ 1 year since stroke, ambulatory ($n = 6$)	Resistance: Body weight Exercise: Sit-to-stands & step-ups (both limbs) Bout: 3 sets of 10 reps graded by ability Frequency: daily Duration: 3 week	At 3 weeks, significant improvements were demonstrated in Motor Assessment Scale sit-to-stand scores, walking speed, and timing of peak vertical ground reaction force.

*RM: repetition maximum; ??: number not stated.

identified, studies employing less stringent designs (e.g. case series) were also included. Only articles addressing training of the lower limbs were included. Studies were excluded if they examined strength training in combination with other types of training (e.g. aerobic conditioning) or if they involved exercise equipment that is not commercially available.

My search yielded 3 formal systematic reviews (30–32) and 12 research articles focused on strength training after stroke (Table II) (33–44). Five of the research studies were randomized trials (33–35, 39, 42). Most studies involved subjects who were 6 months or more post-stroke (35–41, 44), but other studies included patients who were more acute (33, 34, 38, 42, 43). Resistance exercise was provided by means of weights, pneumatic machines, elastic bands, isokinetic machines, or body weight. Some exercise regimens involved a single exercise and type of resistance. For example, leg-presses on a weight machine were all that Inaba et al. (33) and Badics et al. (38) had their subjects perform. Both Barreca et al. (42) and Åsberg (43) used only sit-to-stands and body weight. Other regimens, however, involved multiple exercises, if not multiple forms of resistance. The frequency of training varied but was at least twice a week. Except in 2 studies (43, 44), the duration of training was at least 4 weeks.

The results of the research reviewed (Table II) show that muscle training regimens result in strength increases in trained maneuvers (33–41). These increases, some of which exceeded 100%, were noted regardless of the type of resistance employed. In studies employing a control group, the increases tended to be greater in the strength training group (33–35, 39). Researchers investigating the effects of strength training on variables other than strength have obtained mixed results. Neither Moreland et al. (34) nor Kim et al. (39) found resistance trained patients to improve more in functional activities than controls. Several researchers have reported patients to improve in some activities but not others (35, 36, 40, 41), or at some times but not others (33, 40). Studies employing a regimen of repeated sit-to-stands have all demonstrated functional benefits (42–44).

DISCUSSION

In previous reviews others have concluded that resistance training programs are effective at increasing strength in patients who have experienced a stroke (30–32). After reviewing the same articles, in addition to several others (35, 37, 42, 43) my conclusion is the same. Based on both theoretical and statistical rationale, it would seem likely that strength training would result in improvement in functional activities as well. Nevertheless, Morris et al. (31) concluded that the ability of strengthening to enhance ”the performance of functional activities or participation in societal roles remains unknown”. Eng (32) concluded that evidence for the effect of strength training on function after stroke was ”poor or insufficient”. Following the present review, I would concur, excepting perhaps regimens involving repeated sit-to-stands or step-ups. All 3 studies that focused on such maneuvers yielded favorable results (42–44). This may be related to the concept of specificity of training. Sit-to-stands and step-ups, as well as other activities such as going from side-lying to sitting in bed, represent everyday activities that can be performed almost anywhere with a minimum of equipment. They have been shown to promote improved functional activity performance in older adults without a history of stroke as well (45–47). Activities such as knee flexion and extension on an isokinetic dynamometer or leg-presses with a weight stack for resistance are neither functional nor portable.

Regardless of the resistance training mode employed, resistance exercise should focus on actions that are impaired. Impairments can involve the non-paretic limbs and the trunk, as well as the more obvious paretic limbs. More objective and precise measures than are often employed may be required to identify relevant targets. Extant research has targeted patients of diverse strength and functional levels. Further research needs to determine which strata benefit from specific regimens. Research also needs to address whether the benefits of training generalize to activities other than those trained. Until there is more positive evidence supporting strength training after stroke, enthusiasm for its use should be bridled.

REFERENCES

1. Heart disease and stroke statistics – 2006 update: a report from the American Heart Association Statistics Committee and Stroke Statistics committee. Circulation 2006; 113: 85–115.
2. Bonita R, Beaglehole R. Recovery of motor function after stroke. Stroke 1988; 19: 1497–1500.
3. Bobath B, editor. Adult hemiplegia: evaluation and treatment (3rd edn). Oxford: Heinemann Medical Books; 1990.
4. Davies PM, editor. Steps to follow: a guide to the treatment of adult hemiplegia. Berlin. Springer-Verlag; 1995.
5. Bohannon RW, Warren ME, Cogman KA. Motor variables correlated with the hand-to-mouth maneuver in patients with stroke. Arch Phys Med Rehabil 1991; 72: 682–684.
6. Corrigan D, Bohannon RW. Relationship between knee extension force and stand-up performance in community-dwelling elderly women. Arch Phys Med Rehabil 2001; 82: 1666–1672.
7. Eriksrud O, Bohannon RW. Effectiveness of the Easy-Up Handle in acute rehabilitation. Clin Rehabil 2005; 19: 381–386.
8. Eriksrud O, Bohannon RW. Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. Phys Ther 2003; 83: 544–551.
9. Bohannon RW. Determinants of transfer capacity in patients with hemiparesis. Physiother Can 1988; 40: 236–239.
10. Bohannon RW. Knee extension strength and body weight determine sit-to-stand independence after stroke. Physiother Theory Pract 2007; in press.
11. Suzuki K, Nakamura R, Yamada Y, Handa T. Determinants of maximum walking speed in hemiparetic stroke patients. Tohoku J Exp Med 1990; 162: 337–344.
12. Flansbjer U-B, Downham D, Lexell J. Knee muscle strength, gait performance, and perceived participation after stroke. Arch Phys Med Rehabil 2006; 87: 974–980.
13. Bohannon RW. Knee extension power, velocity and torque: relative deficits and relation to walking performance in stroke patients. Clin Rehabil 1992; 6: 125–131.
14. Bohannon RW. Correlation of knee extension force and torque with gait speed in patients with stroke. Physiother Theory Pract 1991; 7: 185–190.

15. Bohannon RW. Selected determinants of ambulatory capacity in patients with hemiplegia. Clin Rehabil 1989; 3: 47–53.
16. Nakamura R, Watanabe S, Handa T, Morohashi I. The relationship between walking speed and muscle strength for knee extension in hemiparetic stroke patients: a follow-up study. Tohoku J Exp Med 1988; 154: 111–113.
17. Hsu A-L, Tang P-F, Jan M-H. Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. Arch Phys Med Rehabil 2003; 84: 1185–1193.
18. Bohannon RW, Walsh S. Association of paretic lower extremity muscle strength and standing balance with stair-climbing ability in patients with stroke. J Stroke Cerebrovasc Dis 1991; 1: 129–133.
19. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient: a method for evaluation of physical performance. Scand J Rehabil Med 1975; 7: 13–31.
20. Goldstein LR, Bertels C, Davis JN. Interrater reliability of the NIH Stroke Scale. Arch Neurol 1989; 46: 660–662.
21. Scandinavian Stroke Study Group. Multicenter trial of hemo dilution in ischemic stroke- background and study protocol. Stroke 1985; 16: 885–890.
22. Bohannon RW. Adequacy of simple measures for characterizing impairment in upper limb strength following stroke. Percept Motor Skills 2004; 99: 813–817.
23. Hammer A, Lindmark B. Test-retest intra-rater reliability of grip force in patients with stroke. J Rehab Med 2003; 35: 189–194.
24. Bohannon RW. Knee extension torque in stroke patients: comparison of measurements obtained with a hand-held and a Cybex dynamometer. Physiotherapy Canada 1990; 42: 284–287.
25. Eng JJ, Kim M, MacIntyre DL. Reliability of lower extremity strength measures in persons with chronic stroke. Arch Phys Med Rehabil 2002; 83: 322–328.
26. Demeurisse G, Demol O, Robaye E. Motor evaluation in vascular hemiplegia. Eur Neurol 1980; 19: 382–389.
27. Bohannon RW, Andrews AW. Relationships between impairments in strength of limb muscle actions following stroke. Percept Motor Skills 1998; 87: 1327–1330.
28. Andrews AW, Bohannon RW. Limb-muscle strength is impaired bilaterally after stroke. J Phys Ther Sci 1995; 7: 1–7.
29. Bohannon RW, Cassidy D, Walsh S. Trunk muscle strength is impaired multidirectionally after stroke. Clin Rehabil 1995; 9: 47–51.
30. Riolo L, Fisher K. Clinical question? Is there evidence that strength training could help improve muscle function and other outcomes without reinforcing abnormal movement patterns or increasing reflex activity in a man who has had a stroke? Phys Ther 2003; 83: 844–851.
31. Morris SL, Dodd KJ, Morris ME. Outcomes of progressive resistance strength training following stroke: a systematic review. Clin Rehabil 2004; 18: 27–39.
32. Eng JJ. Strength training in individuals with stroke. Physiother Can 2004; 56: 189–201.
33. Inaba M, Edberg E, Montgomery J, Gillis MK. Effectiveness of functional training, active exercise, and resistance exercise for patients with hemiplegia. Phys Ther 1973; 53: 28–35.
34. Moreland JD, Goldsmith CH, Huijbregts MP, Anderson RE, Prentice DM, Brunton KB, et al. Progressive resistance strengthen ing exercises after stroke: a single-blind randomized controlled trial. Arch Phys Med Rehabil 2003; 84: 1433–1440.
35. Ouellette MM, LeBrasseur NK, Bean JF, Phillips E, Stein J, Frontera WR, Fielding RA. High-intensity resistance training improves muscle strength, self-reported function, and disability in long-term stroke survivors. Stroke 2004; 35: 1404–1409.
36. Weiss A, Suzuki T, Bean J, Fielding RA. High intensity strength training improves strength and functional performance after stroke. Am J Phys Med Rehabil 2000; 79: 369–376.
37. Cramp MC, Greenwood RJ, Gill M, Rothwell JC, Scott OM. Low intensity strength training for ambulatory stroke patients. Disabil Rehabil 2006; 28: 883–889.
38. Badics E, Wittmann A, Rupp M, Stabauer B, Zifko UA. Systematic muscle building exercises in rehabilitation of stroke patients. Neurorehabilitation 2002; 17: 211–214.
39. Kim CM, Eng JJ, MacIntyre DL, Dawson AS. Effects of isokinetic strength training on walking in persons with stroke: a double-blind controlled pilot study. J Stroke Cerebrovasc Dis 2001; 10: 265–273.
40. Shyarp SA, Brouwer BJ. Isokinetic strength training of the hemiparetic knee: effects on function and spasticity. Arch Phys med Rehabil 1997; 78: 1231–1236.
41. Engardt M, Knutsson E, Jonsson M, Sternhag M. Dynamic muscle strength training in stroke patients: effects on knee extension torque, electromyographic activity, and motor function. Arch Phys Med Rehabil 1995; 76: 419–425.
42. Barreca S, Sigouin CS, Lambert C, Ansley B. Effects of extra training on the ability of stroke survivors to perform an independent sit-to-stand: a randomized controlled trial. J Geriatr Phys Ther 2004; 27: 59–64.
43. Åsberg KH. Orthostatic tolerance training of stroke patients in general medical wards. Scand J Rehabil Med 1989; 21: 179–185.
44. Monger C, Carr JH, Fowler V. Evaluation of a home-based exercise and training programme to improve sit-to-stand in patients with chronic stroke. Clin Rehabil 2002; 16: 361–367.
45. Drabsch T, Lovenfosse J, Fowler V, Adams R, Drabsch P. Effects of task specific training on walking and sit-to-stand after total hip replacement. Austr J Physiother 1998; 44: 193–198.
46. Nishimoto K, Nakamura S, Imai T, Tanaka S, Fujimoto S. Increasing gait performance in elderly women using a step exercise training program. J Phys Ther Sci 1999; 11: 71–78.
47. Alexander NB, Galecki AT, Grenier ML, Nyquist LV, Hofmeyer MR, Grunawalt JC, et al. Task-specific resistance training to improve the ability of activities of daily living-impaired older adults to rise from a bed and from a chair. J Am Geriatr Soc 2001; 49: 1418–1427.