Role of resistance training for preventing frailty and metabolic syndromes in aged adults

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Abstract In subjects with frailty syndrome, aging-related loss of muscle (sarcopenia) might progress to the extent that an older person loses his or her ability to live independently. Metabolic syndrome is a set of risk factors (abdominal obesity, insulin resistance, hypertension, and dyslipidemia) which markedly increases the risk of arteriosclerotic vascular disease. Due to the ongoing obesity pandemic and growing elderly population, frailty and metabolic syndromes are major emerging concerns in the healthcare system. Recent studies show that resistance training has remarkable beneficial effects on the musculoskeletal system including the prevention and treatment of these syndromes. Resistance training is probably the most effective measure to prevent and treat sarcopenia. With regard to the effect of resistance training on the muscular strength of elderly persons, the rate of improvement increases with intensity. Resistance training also has a favorable effect on metabolic syndrome since it decreases fat mass including abdominal fat, enhances insulin sensitivity, improves glucose tolerance, and reduces blood pressure values. Optimal nutrition enhances the anabolic effect of resistance training. Resistance training should be a central component of public health promotion programs along with aerobic exercise.

Keywords : resistance training, frailty syndrome, metabolic syndrome, muscular strength, intensity

Introduction

As people grow older, physical organs weaken due to the aging phenomenon. In particular, weakening of muscles and bones causes difficulties in daily life activities, leading to the decline of Quality of Life (QOL). Moreover, weakening of muscles reduces the energy consumption called basal metabolism, and it is deeply related to risk factors of metabolic syndrome such as abdominal obesity, hypertension, insulin resistance, and dyslipidemia. Even after a person has become old, it is possible to strengthen the muscles and bones with an efficient combination of exercise, diet, and sleep.

In middle-aged Japanese people, instead of an increase in energy intake due to overeating, a decrease in physical strength and reduction of energy consumption due to “lack of physical activities” is a serious problem. Therefore, it would be better to start with increasing daily life activities, and then take up exercise and sports as the next step.

Today, the most popular exercises among middle-aged people are aerobic exercises such as walking and jogging. While these exercises are effective for improving breathing and cardiovascular function and preventing lifestyle-related diseases, they do not bring adequate benefits for body synthesis such as muscles and bones. Besides, while

stretching is useful for enhancing flexibility, or for preventing and improving back pain, it is hardly beneficial for body synthesis.

Therefore, in Japan, where it is predicted that there will be a rapid rise in elderly people requiring nursing home care because of senility, a fall or fracture, or an arthritic disorder, it can be expected that resistance training, that is effective for increasing muscular strength and preventing the decline of daily life functions in elderly persons, will gain more importance, and many people will start practicing it in the future.

The present paper gives a general overview of factors that cause sarcopenia with aging; and discusses the benefits of resistance training on weakness and disability for elderly persons, and on metabolic syndrome such as obesity, diabetes, and dyslipidemia.

Effects of resistance training on frailty syndrome in elderly persons

Sarcopenia with increasing age. Sarcopenia is age-related decline in muscle mass and muscular strength¹⁾, and it originated from the Greek words sarx (meaning flesh) and penia (meaning loss). The onset of sarcopenia leads to difficulties in performing daily life activities, and it results in a state where a person requires long-term care; and it decreases the Quality of Life (QOL). Moreover, a

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decline in the basal metabolic rate due to a decrease of muscle mass results in the decline of fat and carbohydrate metabolism, which also adversely affects the onset of lifestyle-related diseases such as obesity, diabetes, and hypertension^{2,3)}.

Reasons for the decline in muscular strength with increasing age. In general, maximum muscle strength of humans peaks in the 20s to early 30s; and after that, it hardly changes for approximately 20 years. However, about the 50s, it rapidly starts declining^{4,5)}. After the 60s, it declines at the annual rate of 1.0-1.5%, and the extent of decline in muscular strength is more in the lower limbs than upper limbs^{6,7)}. Around the 70s to 80s, it declines about 20-40% compared to the 20s; and after 90 years of age, the decline is 50% or more⁸⁾.

Concerning the reasons for such decline in muscular strength due to aging, Lexell et al.⁹⁾ have shown that it occurs because of the decrease in the number of muscle fibers as well as the decline in the size of muscle fibers. They reported that the number and size of muscle fibers in the 80s decrease about 40% compared to that of the 20s. Besides, the rate of decline in size of muscle fibers is more prominent for fast twitch (Type II) muscle fibers than slow twitch (Type I) muscle fibers, demonstrating that selective muscle atrophy is likely to occur. This shows the possibility that even if an elderly person does aerobic exercises like walking on a daily basis, atrophy of fast twitch fibers cannot be restrained. Actually, Kuno et al.¹⁰⁾ reported that even in an elderly trained runner who jogged for about 10 km every day as a habit, selective muscle atrophy had occurred.

As the reasons for decline in muscular strength with increasing age, in addition to deleterious influences on muscular capacity, Anthony et al.⁸⁾ mentioned lifestyle-related reasons such as malnutrition, lack of physical activity, and disease (Fig. 1).

Relationship between muscular strength and activity of daily living in elderly persons. It is well known that lower extremity strength and power in elderly persons is closely related to major basic movements in their daily life such as walking, standing up from a chair, and climbing stairs¹¹⁻¹³⁾.

Wolfson et al.¹⁴⁾ compared and studied lower extremity strength, walking speed, stride length and balancing ability of the residents of a nursing home for elderly persons in their 80s. Participants were separated into two groups: people who had the experience of falling down and people who didn't have such an experience. It came to light that lower extremity strength was only half as much in the persons who had the experience of falling down (faller) as compared to the persons without such an experience (nonfaller). The differences were more prominent at the ankle than the knee, and were most pronounced in the ankle dorsiflexors. In addition, walking speed and stride length of the fallers was 55% and 65%, respectively, of the nonfaller controls. Moreover, they reported that their balancing ability had also declined significantly.

Positive effect of resistance training on strength gain in elderly persons. In previous studies that investigated the effects of resistance training on the elderly, many research cases focused on the relationship between training intensity and maximal strength or muscular hypertrophy of the lower extremity muscles. Table 1 shows the list of findings from research outcomes between 1985 up until recently, where statistically significant improvements in muscular strength were confirmed. The type of training used in subsequent research work after Frontera et al.¹⁵⁾ was mostly high-intensity (80% or more of 1 RM) dynamic (isotonic or isokinetic) training, where it was conducted 3 times a week for about 12 weeks. 1RM (Repetition Maximum) shows the maximum amount of weight one can lift in a single repetition.

Evidence that came to light from the data of Table 1 is

Fig. 1 Multiple factors that cause loss of muscle strength with increasing age⁸⁾.

Table 1. Strength gain of the quadriceps muscle following high-intensity ($\geq 80\%$ 1RM) resistance training in older adults

Study	Gender	n	Age (years)	Exercise movement	Duration (weeks)	Strength gain
Frontera et al. ¹⁵⁾	M	12	60–72	Knee extension	12	1RM: 107%
Charette et al. ¹⁶⁾	F	13	64–86	Leg press	12	1RM: 28%
Fiatarone et al. ¹⁷⁾	M/F	100	72–98	Hip and knee extension	10	1RM: 113%
Lexell et al. ¹⁸⁾	M/F	23	70–77	Knee extension	11	1RM: 152%
McCartney et al. ¹⁹⁾	M/F	113	60–80	Leg press	84	1RM: 32%
Hakkinen et al. ²⁰⁾	M/F	20	70	Knee extension	26	1RM: 26%
Hunter et al. ²¹⁾	M/F	11	64–79	Knee extension	12	1RM: 39%
Tracy et al. ²²⁾	M/F	23	65–75	Knee extension	9	1RM: 28%
Yarasheski et al. ²³⁾	M/F	12	76–92	Knee extension	12	1RM: 41%
Hagerman et al. ²⁴⁾	M	9	64	Knee extension	16	1RM: 50%
Hortobagyi et al. ²⁵⁾	M/F	27	66–83	Leg press	10	1RM: 35%
Kalapotharakos et al. ²⁶⁾	M/F	11	65	Knee extension	12	1RM: 76%
Binder et al. ²⁷⁾	M/F	50	83	Knee extension	12	1RM: 43%

1RM: one repetition of maximum weight that could be lifted. All strength gains are statistically significant.

“for increasing the muscular strength of elderly people, resistance training of high- intensity (80% or more of 1RM) is effective.” With regard to mechanisms that increase muscular strength, in addition to improvement of the neuromuscular system, it is found to be due to muscular hypertrophy of both type I muscle fibers and type II muscle fibers^{15,28,29)}.

If the objective is to enhance cardiorespiratory fitness and avoid the lifestyle-related diseases of middle-aged and elderly persons through aerobic exercise like walking and cycling, an intensity of about 50~70% of maximum oxygen intake ($\dot{V}O_2\text{max}$) is recommended. In this case, if intensity is high (80% $\dot{V}O_2\text{max}$ or more), its effect is less likely to appear. Therefore, it is necessary to clearly demarcate the way of setting the intensity of aerobic exercises aimed at good health and the intensity of resistance training aimed at increasing muscular strength.

So, when the intensity of resistance training is kept between medium-to-low intensity, does it mean that it will not have any effect on improving muscular strength in the elderly? And, when compared to high intensity, would there be any difference in the effect?

Table 2 summarizes the recent research that looked into the comparison of the effects of low-moderate intensity and high intensity. In all of these studies, even at a low intensity (40-50% 1RM) training load, statistically significant improvement in lower extremity muscle strength of elderly persons was seen.

Besides, Hortobagyi et al.²⁵⁾ and Vincent et al.³¹⁾, who conducted a comparative study of the effect of low intensity and high intensity, it was reported that no difference due to different intensities was seen in the percentage increase of muscular strength of knee extension. However, in these training conditions, repetitions per one set were more for low intensity groups, and it is possible that the

difference in training amount may have compensated for the lack of intensity. Seynnes³²⁾ compared the effect of training on muscular strength keeping all training conditions the same except for intensity. As a result, he demonstrated that high intensity clearly increased the rate of increment in muscular strength. Beneka et al.³³⁾ formed 3 groups of 50%, 70%, and 90% 1 RM and conducted a study. They reported that as intensity increased, the incremental rate in muscular strength also increased. Therefore, from the above data, we can draw the conclusion that “With regard to the effect of resistance training on the muscular strength of elderly persons, while a significant increase can be seen even at low intensity, the incremental rate also becomes higher depending on intensity”.

In the research work that studied the effect of resistance training on walking distance, which is an index of daily life function, the power for climbing a staircase and time required for standing up from a chair, while clear functional improvement could be seen even at low intensity (40% 1RM), it was reported that the effect was more notable at high intensity (80% 1 RM)³²⁾.

Skeletal muscle is the main organ for energy consumption from resting metabolism and activity metabolism. It is clear that because of the decrease in skeletal muscle mass due to aging, the resting metabolic rate also declines³⁴⁻³⁶⁾.

However, it is reported that relatively high intensity resistance training increases the lean tissue weight of elderly persons, and significantly increases both muscular strength and resting metabolic rate³⁷⁻³⁹⁾. Ades et al.⁴⁰⁾ have found significant positive correlation between the amount of change in muscular strength and the amount of change in total energy expenditure. Moreover, Hunter et al.³⁹⁾ have suggested that lipid oxidation rates becomes brisk after changes in the respiratory quotient.

Table 2. Low-Moderate versus high-intensity machine-based resistance training studies

Study	n	Age (years)	Exercise movement	Intensity (%1RM)	Frequency, Volume, Duration of Training	Knee Extension Strength Change
Taaffe et al. ³⁰⁾	7	65 – 79	Leg press Knee extension	40%1RM	3 times/week 3 sets of 14 rep 52 weeks	60%
	7	65 – 79	Knee flexion	80%1RM	3 times/week 2 sets of 7 rep 52 weeks	85%
Hortobagyi et al. ²⁵⁾	9	66 – 83	Supine Leg press	40%1RM	3 times/week 5 sets of 8-12 rep 10 weeks	30%
	9	66 – 83	Supine Leg press	80%1RM	3 times/week 5 sets of 4-6 rep 10 weeks	37%
Vincent et al. ³¹⁾	24	60 – 83	Leg press Knee extension	50%1RM	3 times/week 1 set of 13 rep 24 weeks	11%
	22	60 – 83	Leg curl Calf press	80%1RM	3 times/week 1 set of 8 rep 24 weeks	15%
Seynnes et al. ³²⁾	6	73 – 95	Knee extension	40%1RM	3 times/week 3 sets of 8 rep 10 weeks	37% *
	8	73 – 95	Knee extension	80%1RM	3 times/week 3 sets of 8 rep 10 weeks	57% *

1RM: one repetition of maximum weight that could be lifted. rep: repetitions * $p < 0.01$, significantly different between groups.

In addition, the intake of protein in food is another important factor for increasing muscular strength and skeletal muscle hypertrophy through resistance training.

Esmarck et al.⁴¹⁾ conducted resistance training for elderly persons in their 70s and 80s for 3 times in a week over 12 weeks. As a result of providing nutritional support such as protein within 5 minutes after each training (group 1) and after 2 hours of training (group 2), in group 2 no change was seen in the cross-sectional area of the quadriceps. However, a significant increase was seen in group 1. These results show the importance of timing of food intake after resistance training.

Effects of resistance training on metabolic syndrome in aged adults

Metabolic syndrome. Metabolic syndrome is a set of risk factors that includes abdominal obesity, insulin resistance, hypertension, and dyslipidemia⁴²⁾. This combination of medical disorders markedly increases the risk of arteriosclerotic vascular disease. The prevalence of metabolic syndrome is rapidly increasing worldwide, largely as a consequence of the ongoing obesity pandemic.

Effect of resistance training on abdominal obesity and insulin resistance. Abdominal obesity and insulin re-

sistance are the key features of metabolic syndrome. At rest, skeletal muscle consumes 54.4 kJ/kg (13.0 kcal/kg) per day which is larger than adipose tissue at 18.8 kJ/kg (4.5 kcal/kg)⁴³⁾. Since resistance training increases muscle mass, it does not result in weight loss without caloric restriction. However, resistance training, even without caloric restriction, has a favorable effect on body composition since it decreases fat mass including abdominal fat⁴⁴⁻⁴⁶⁾. Several studies have examined the effects of resistance training on body composition and resting metabolic rate and have found that resistance training does in fact promote increases in both fat-free mass and resting metabolic rate, as well as a decrease in total fat mass (Table 3)^{38,46-50)}. Treuth et al.⁴⁸⁾, in 1995, studied the effects of resistance training on body composition, and found in 14 older women who exercised 3 times per week for 16 weeks that, although there was no significant change in body weight because of increased muscle mass, visceral adipose tissue was significantly reduced.

Skeletal muscle is an important determinant of insulin sensitivity. In many studies, resistance training has enhanced insulin sensitivity and improved glucose tolerance (Table 4)^{46,51-58)}. Meta-analysis of nine randomized controlled trials evaluated 372 subjects with type 2 diabetes⁵⁹⁾. When compared to not exercising, progressive resistance training led to small, but statistically significant

Table 3. Summary of the effects of various resistance exercise training regimens on obesity

Study	Intervention	Frequency and duration of training	Outcome
Treuth et al. ⁴⁷⁾	1 set of 15 reps performed to exhaustion for 9 upper-body and 5 lower-body exercises, then each lower-body exercise repeated in a second set. Resistance started at 90% 3RM and was gradually decreased to achieve 15 reps	3 nonconsecutive d/wk for 16 wk	Significant increases in upper-body strength (39%±8%), lower-body strength (42%±14%), total FFM (62.0±7.1 to 64±7.2 kg), FFM in arms (6.045±0.860 to 6.418±0.803 kg), legs (19.416±2.228 to 20.131±2.303 kg), and trunk (29.229±4.108 to 30.134±4.184 kg), and mid thigh muscle cross-sectional area (161±19 to 172±18 cm ²). Statistically significant decreases in total FM (23.8±6.7 to 21.8±6.0 kg), FM in arms (2.383±0.830 to 2.128±0.714 kg), legs (7.583±1.675 to 6.945±1.551 kg), and trunk (12.216 ±4.143 to 11.281±3.653 kg), and mid thigh fat (65±19 to 59±17 cm ²)
Treuth et al. ⁴⁸⁾	2 sets of 12 reps performed at 50%-67% 1RM for 7 upper-body and 5 lower-body exercises	1 h, 3 d/wk for 16 wk	Significant increases in upper-body strength (51%), lower-body strength (65%), and mid thigh muscle (52.9±2.6 to 58.0±2.0 cm ²). Significant decreases in VAT (143.9±13.3 to 130.0±12.4 cm ²), the ratio of VAT/SAT (0.48±0.04 to 0.44±0.04), and mid thigh SAT (141.7±11.5 to 133.6±10.8 cm ²)
Ross and Rissanen ⁴⁹⁾	1 set of 8-12 reps performed to exhaustion for 6 upper-body and 2 lower-body exercises	3 d/wk for 16 wk	Significant reductions in body weight (−10.1±3.0 kg or 11.7%), total SAT (−8.5±2.5 L or 22.6%), VAT (−0.69±0.40 L or 30.0%), intraperitoneal VAT (−0.57±0.34 L or 31.6%), extraperitoneal VAT (−0.10±0.09 L or 20.8%), and the ratio of VAT/SAT (−0.01±0.01 or 16.6%)
Ross et al. ⁵⁰⁾	Diet+RET: 1 set of 8-12 reps performed to exhaustion for 7 upper-body and 2 lower-body exercises. Diet only	Diet+RET: 3 d/wk for 16 wk, Diet only: 16 wk	Significant reductions in body weight (−13.2±4.1 kg or 12.3%), SAT (−8.0±2.8 L or 25.7%), VAT (−1.4±0.7 L or 40.4%), and the ratio of VAT/SAT. Significant increases were observed in muscular strength in the RET group (~20%). For the RET group, loss in abdominal SAT (~20%). Total lean tissue and skeletal muscle decreased significantly in the diet only group

RET: resistance exercise training, reps: repetitions, RM: repetition maximum, FFM: fat-free mass, FM: fat mass, SAT: subcutaneous adipose tissue, VAT: visceral adipose tissue

absolute reductions of 0.3% in HbA1c, indicating that resistance training is a feasible option in the management of glycemic control in diabetic subjects. Bweir et al.⁶⁰⁾ demonstrated that resistance training lowered HbA1c up to 18% in subjects with type 2 diabetes. In this recent study, the resistance training group used 7 exercises that included knee and hip flexion/extension, shoulder flexion/extension, adduction/abduction, elbow flexion/extension, and a chest press. Three sets of 8-10 repetitions were performed for all exercises with a rest period of 2 minutes between sets for a 30-35 minute period, 3 times per week for 10 weeks.

Improved glucose uptake appears to not be a mere consequence of the increased muscle mass associated with resistance training, but seems to also be a result of qualitative changes in resistance-trained muscle. Holten et al.⁵³⁾ studied the effect of resistance training (30 minutes 3 times per week for 6 weeks) on one leg while the other leg remained untrained, and found that resistance training enhances insulin action in skeletal muscle in both type 2 diabetic and healthy subjects. This effect was likely independent of the increases in muscle mass. They concluded that the increases in muscle glucose transporter isoform 4

(GLUT4) content and in insulin signaling protein expression and/or activity are part of the mechanism behind the improvement in insulin action.

In addition, several of these studies in Table 4 suggest that resistance training can elicit these metabolic benefits with low-to-moderate intensity, low-volume protocols. This has the potential advantage of engaging sedentary individuals who might otherwise be reluctant to participate in more strenuous activities such as high intensity resistance training or endurance training. Moreover, the benefits induced by resistance training begin to manifest themselves within a short period of time. This observation may serve as another incentive for these individuals to initiate and maintain such programs. Finally, it seems reasonable that untrained, obese, and frail individuals would be less likely to sustain injuries while performing a low-to-moderate intensity, low-volume resistance training program than they would be performing high-intensity, high-volume resistance training or endurance training.

Effect of resistance training on the other risk factors of metabolic syndrome. Resistance training increases blood pressure values acutely and is not therefore recommended

Table 4. Summary of the effects of various resistance exercise training regimens on measures of insulin resistance and glucose tolerance

Study	Intervention	Frequency and duration of training	Outcome
Derave et al. ⁵¹⁾	Initially 3 sets of 12 reps of single-leg knee extensions (75%1RM), progressing to 5 sets of 12 reps (85%1RM)	2-wk immobilization, followed by RET every other day for 6 wk	GLUT-4 content increased significantly in groups supplemented with creatine (24%) and creatine + protein (33%). Glucose tolerance in group supplemented with creatine ± protein improved a significant 25% (area under glucose curve during OGTT decreased from 232±23 to 170±23 mmol/L/min)
Durak et al. ⁵²⁾	3-7 sets of 12 reps 10 upper-body and 5 lower-body exercises performed with a 12RM	3 d/wk for 10 wk	Significant decrease in percentage of glycated hemoglobin (6.9%±1.4% to 5.8%±0.9%) in training group
Holten et al. ⁵³⁾	During wk 1-2, 3 sets of 10 reps for each of 3 different leg exercises (50%1RM). During wk 3-6, 4 sets of 8-12 reps for each of 3 different leg exercises (70%-80% 1RM)	3 d/wk for 6 wk	Trained type II diabetics exhibited significant increase in protein content of GLUT-4 (40%), IR (21%±6%), PKB (12%±7%), and GS (13%±5%), as well as in the total activity of GS (21%±4%). Trained healthy controls exhibited significant increases in protein content of IR (19%±7%), PKB (22%±9%), and GS (12%±9%), as well as in the total activity of GS (9%±3%)
Ishii et al. ⁵⁴⁾	2 sets of 10-20 reps for 6 upper-body and 3 lower-body exercises (40%-50% 1RM)	5 d/wk for 4-6 wk	Significant 48% increase in glucose disposal rate in training group (6.85±1.8 to 10.12±3.15 mg/kg lean body mass/min)
Tabata et al. ⁵⁵⁾	30 isometric maximal voluntary contractions lasting 3 seconds each, utilizing extensor muscles of the ankle, knee, and hip	Daily for 19 d	Significant 30% increase in GLUT-4 content in training group (510±158 to 663±189 counts/min/μg membrane protein)
Andersen et al. ⁵⁶⁾	4-5 sets of 6-15 reps of 4 lower-body and several upper-body exercises using heavy resistance, followed by 90-d detraining	3 d/wk for 90 d, followed by 90d detraining	Significant decrease (11%±4%) in whole-body glucose uptake from the end of training period to the end of detraining
Miller et al. ⁵⁷⁾	1 set of 15 reps for 9 upper-body and 5 lower-body exercises (90%3RM) followed by second set of lower-body exercises	3 d/wk for 16 wk	After training, significant reductions were observed in fasting plasma insulin levels (85±25 to 55±10 pmol/L) and insulin levels during OGTT ($F=4.9$, $P<.05$). Glucose infusion rates during clamp testing also increase after training by 24% during low insulin infusion and 22% during high insulin infusion. Nonoxidative glucose metabolism also increased by 40% during high insulin infusion
Zachwieja et al. ⁵⁸⁾	4 sets of 4-10 reps for 6 upper-body and 3 lower-body exercises (75%-90%1RM)	4 d/wk for 16 wk, sessions alternated between upper- and lower-body exercises	Glucose disappearance rate improved significantly from 3.0±0.3 to 4.0±0.4 mg/100mL/min, and insulin sensitivity trended toward a significant improvement (6.79±1.14 to 8.42±0.89=10 ⁴ per min/[μU/mL], $P=.06$)

GLUT-4: glucose transporter isoform 4, GS: glycogen synthase, IR: insulin receptor, OGTT: oral glucose tolerance test, PKB: protein kinase B reps: repetitions, RET: resistance exercise training, RM: repetition maximum

for patients with labile hypertension. However, a meta-analysis of 9 randomized controlled trials demonstrated a net reduction of diastolic blood pressure of 3.5 mmHg ($P<0.01$) and a nonsignificant reduction of systolic blood pressure of 3.2 mmHg associated with resistance training⁶¹⁾. Finally, the effects of resistance training on blood lipids are inconsistent. Resistance training might have some effect on low-density lipoprotein cholesterol (LDL-C) levels since almost half of the trials showed significant reductions in LDL-C levels ranging from 5% to 23%⁶²⁾.

References

- 1) Rosenberg IH. 1997. Sarcopenia: origins and clinical relevance. *J Nutr* 127: 990S-991S.
- 2) Tzankoff SP and Norris AH. 1997. Effect of muscle mass decrease on age-related BMR changes. *J Appl Physiol* 43: 1001-1006.
- 3) Hurley B and Roth S. 2000. Strength training in the elderly: effects on risk factors for age-related diseases. *Sports Med* 30: 249-268.
- 4) Larsson L. 1982. Physical training effects on muscle morphology in sedentary males at different ages. *Med Sci Sports*

Exerc 14: 203-206.

- 5) Murray M, Gardner G and Mollinger L. 1980. Strength of isometric and isokinetic contractions: knee muscles of men aged 20-86. *Phys Ther* 60: 412-419.
- 6) Vandervoort AA and McComas AJ. 1986. Contractile changes in opposing muscles of the human ankle joint with aging. *J Appl Physiol* 61: 361-367.
- 7) Skelton DA, Greig CA, Davies JM and Young A. 1994. Strength, power and related functional ability of healthy people aged 65-89 years. *Age Ageing* 23: 371-377.
- 8) Anthony A and Vandervoort AA. 2002. Aging of the human neuromuscular system. *Muscle Nerve* 25: 17-25.
- 9) Lexell J, Taylor CC and Sjostrom M. 1988. What is the cause of the ageing atrophy? *J Neurol Sci* 84: 275-294.
- 10) Kuno S, Itai Y and Katsuta S. 1994. Influence of endurance training on muscle metabolism during exercise in elderly men. *Adv Exerc Sports Physiol* 1: 51-56.
- 11) Bassey EJ, Fiatarone MA, O'Neill EF, Kelly M, Evans WJ and Lipsitz LA. 1992. Leg extensor power and functional performance in very old men and women. *Clin Sci* 82: 321-327.
- 12) Hyatt RH, Whitelaw MN, Bhat A, Scott S and Maxwell JD. 1990. Association of muscle strength with functional status of elderly people. *Age Ageing* 19: 330-336.
- 13) Judge JO, Underwood M and Gennosa T. 1992. Exercise to improve gait velocity in older persons. *Arch Phys Med Rehabil* 74: 400-406.
- 14) Wolfson L, Judge J, Whipple R and King M. 1995. Strength is a major factor in balance, gait, and the occurrence of falls. *J Gerontol* 50: 64-67.
- 15) Frontera WR, Meredith CN, O'Reilly KP, Knuttgen HG and Evans WJ. 1988. Strength conditioning in older men: skeletal muscle hypertrophy and improved function. *J Appl Physiol* 64: 1038-1044.
- 16) Charette SL, McEvoy L, Pyka G, Snow-Harter C, Guido D, Wiswell RA and Marcus R. 1991. Muscle hypertrophy response to resistance training in older women. *J Appl Physiol* 70: 1912-1916.
- 17) Fiatarone MA, O'Neill EF, Ryan ND, Clements KM, Solares GR, Nelson ME, Roberts SB, Kehayias JJ, Lipsitz LA and Evans WJ. 1994. Exercise training and nutritional supplementation for physical frailty in very elderly people. *N Engl J Med* 330: 1769-1775.
- 18) Lexell J, Downham DY, Larsson Y, Bruhn E and Morsing B. 1995. Heavy-resistance training for Scandinavian men and women over seventy: short- and long-term effects on arm and leg muscles. *Scand J Med Sci Sports* 5: 329-341.
- 19) McCartney N, Hicks AL, Martin J and Webber CE. 1996. A longitudinal trial of weight training in the elderly: continued improvements in Year 2. *J Gerontol Biol Sci* 51: B425-B433.
- 20) Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mäkiä E, Kraemer WJ, Newton RU and Alen M. 1998. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol* 84: 1341-1349.
- 21) Hunter SK, Thompson MW, Ruell PA, Harmer AR, Thom JM, Gwinn TH and Adams RD. 1999. Human skeletal sarcoplasmic reticulum Ca^{2+} uptake and muscle function with aging and strength training. *J Appl Physiol* 86: 1858-1865.
- 22) Tracy BL, Ivey FM, Hurlbut D, Martel GF, Lemmer JT, Siegel EL, Metter EJ, Fozard JL, Fleg JL and Hurley B. 1999. Muscle quality. II. Effects of strength training in 65- to 75-year-old men and women. *J Appl Physiol* 86: 195-201.
- 23) Yarasheski KE, Pak-Loduca J, Hasten DL, Obert KA, Brown MB and Sinacore DR. 1999. Resistance exercise training increases mixed muscle protein synthesis rate in frail women and men >76 yr old. *Am J Physiol* 277: E118-E125.
- 24) Hagerman FC, Walsh SJ, Staron RS, Hikida RS, Gilders RM, Murray TF, Toma K and Ragg KE. 2000. Effects of high-intensity resistance training on untrained older men. I. Strength, cardiovascular, and metabolic responses. *J Gerontol Biol Sci* 55: B336-B346.
- 25) Hortobágyi T, Tunnel D, Moody J, Beam S and DeVita P. 2001. Low- or high-intensity strength training partially restores impaired quadriceps force accuracy and steadiness in aged adults. *J Gerontol Biol Sci* 56: B38-B47.
- 26) Kalapotharakos VI, Michalopoulou M, Godolias G, Tokmakidis SP, Malliou PV and Gourgoulis V. 2004. The effects of high- and moderate- resistance training on muscle function in the elderly. *J Aging Phys Act* 11: 131-143.
- 27) Binder EF, Yarasheski KE, Steger-May K, Sinacore DR, Brown M, Schechtman KB and Holloszy JO. 2005. Effects of progressive resistance training on body composition in frail older adults: Results of a randomized, controlled trial. *J Gerontol Med Sci* 60A: 1425-1431.
- 28) Häkkinen K, Newton RU, Gordon SE, McCormick M, Volek JS, Nindl BC, Gotshalk LA, Campbell WW, Evans WJ, Häkkinen A, Humphries BJ and Kraemer WJ. 1998. Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *J Gerontol Biol Sci* 53: B415-B423.
- 29) Hikida RS, Staron RS, Hagerman FC, Walsh S, Kaiser E, Shell S and Hervey S. 2000. Effects of high-intensity resistance training on untrained older men. II. Muscle fiber characteristics and nucleocytoplasmic relationships. *J Gerontol Biol Sci* 55: B347-B354.
- 30) Taaffe DR, Pruitt L, Pyka G, Guido D and Marcus R. 1996. Comparative effects of high- and low-intensity resistance training on thigh muscle strength, fiber area, and tissue composition in elderly women. *Clin Physiol* 16: 381-392.
- 31) Vincent KR, Braith RW, Feldman RA, Magyari PM, Cutler RB, Persin SA, Lennon SL, Gabr AH and Lowenthal DT. 2002. Resistance exercise and physical performance in adults aged 60 to 83. *J Am Geriatr Soc* 50: 1100-1107.
- 32) Seynnes O, Fiatarone Singh MA, Hue O, Pras P, Legros P and Bernard PL. 2004. Physiological and functional responses to low-moderate versus high-intensity progressive resistance training in frail elders. *J Gerontol Med Sci* 59: 503-509.
- 33) Beneka A, Malliou P, Fatouros I, Jamurtas A, Gioufsideou A, Godolias G and Taxildaris K. 2005. Resistance training effects on muscular strength of elderly are related to intensity and gender. *J Sci Med Sport* 8: 274-283.
- 34) Keys A, Taylor HL and Grande F. 1973. Basal metabolism and age of adult men. *Metabolism* 22: 579-587.
- 35) Tzankoff SP and Norris AH. 1978. Effect of muscle mass decrease on age-related BMR changes. *J Appl Physiol* 45: 536-539.
- 36) Klausen B, Toubro S and Astrup A. 1997. Age and sex effects on energy expenditure. *Am J Clin Nutr* 65: 895-907.
- 37) Campbell WW, Crim MC, Young VR and Evans WJ. 1994. Increased energy requirements and changes in body composition.

- tion with resistance training in older adults. *Am J Clin Nutr* 60: 167-175.
- 38) Pratley R, Nicklas B, Rubin M, Miller J, Smith A, Smith M, Hurley B and Goldberg A. 1994. Strength training increases resting metabolic rate and norepinephrine levels in healthy 50- to 65-yr-old men. *J Appl Physiol* 76: 133-137.
  - 39) Hunter GR, Wetzstein CJ, Fields DA, Brown A and Bamman MM. 2000. Resistance training increases total energy expenditure and free-living physical activity in older adults. *J Appl Physiol* 89: 977-984.
  - 40) Ades PA, Savage PD, Brochu M, Tischler MD, Lee NM and Poehlman ET. 2005. Resistance training increases total daily energy expenditure in disabled older women with coronary heart disease. *J Appl Physiol* 98: 1280-1285.
  - 41) Esmarck B, Andersen JL, Olsen S, Richter EA, Mizuno M and Kjaer M. 2001. Timing of postexercise protein intake is important for muscle hypertrophy with resistance training in elderly humans. *J Physiol* 535: 301-311.
  - 42) Grundy SM, Brewer HB, Cleeman JI, Smith SC and Lenfant C. 2004. Definition of metabolic syndrome: report of the National Heart, Lung, and Blood Institute/American Heart Association conference on scientific issues related to definition. *Circulation* 109: 433-438.
  - 43) Heymsfield SB, Gallagher D, Kotler DP, Wang Z, Allison DB and Heshka S. 2002. Body-size dependence of resting energy expenditure can be attributed to nonenergetic homogeneity of fat-free mass. *American Journal of Physiology* 282: E132-E138.
  - 44) Hunter GP, Bryan DR, Wetzstein CJ, Zuckerman PA and Bamman MM. 2002. Resistance training and intra-abdominal adipose tissue in older men and women. *Med Sci Sports Exerc* 34: 1023-1028.
  - 45) Cuff DJ, Meneilly GS, Martin A, Ignaszewski A, Tildesley HD and Frohlich JJ. 2003. Effective exercise modality to reduce insulin resistance in women with type 2 diabetes. *Diabetes Care* 26: 2977-2982.
  - 46) Treserras MA and Balady GJ. 2009. Resistance training in the treatment of diabetes and obesity: mechanisms and outcomes. *J Cardiopulm Rehabil Prev* 29: 67-75.
  - 47) Treuth MS, Ryan AS, Pratley RE, Rubin MA, Miller JP, Nicklas BJ, Sorkin J, Harman SM, Goldberg AP and Hurley BF. 1994. Effects of strength training on total and regional body composition in older men. *J Appl Physiol* 77: 614-620.
  - 48) Treuth MS, Hunter GR, Kekes-Szabo T, Weinsier RL, Goran MI and Berland L. 1995. Reduction in intra-abdominal adipose tissue after strength training in older women. *J Appl Physiol* 78: 1425-1431.
  - 49) Ross R and Rissanen J. 1994. Mobilization of visceral and subcutaneous adipose tissue in response to energy restriction and exercise. *Am J Clin Nutr* 60: 695-703.
  - 50) Ross R, Rissanen J, Pedwell H, Clifford J and Shragge P. 1996. Influence of diet and exercise on skeletal muscle and visceral adipose tissue in men. *J Appl Physiol* 81: 2445-2455.
  - 51) Derave W, Eijnde BO, Verbesssem P, Ramaekers M, Van Leemputte M, Richter EA and Hespel P. 2003. Combined creatine and protein supplementation in conjunction with resistance training promotes muscle GLUT4 content and glucose tolerance in humans. *J Appl Physiol* 94: 1910-1916.
  - 52) Durak EP, Jovanovic-Peterson L and Peterson CM. 1990. Randomized cross-over study of effect of resistance training on glycemic control, muscular strength, and cholesterol in type 1 diabetic men. *Diab Care* 13: 1039-1043.
  - 53) Holten MK, Zacho M, Gaster M, Juel C, Wojtaszewski JFP and Dela F. 2004. Strength training increases insulin-mediated glucose uptake, GLUT4 content, and insulin signaling in skeletal muscle in patients with type 2 diabetes. *Diabetes* 53: 294-305.
  - 54) Ishii T, Yamakita T, Sato T, Tanaka S and Fujii S. 1998. Resistance training improves insulin sensitivity in NIDDM subjects without altering maximal oxygen uptake. *Diab Care* 21: 1353-1355.
  - 55) Tabata I, Suzuki Y, Fukunaga T, Yokozeki T, Akima H and Funato K. 1999. Resistance training affects GLUT-4 content in skeletal muscle of humans after 19 days of head-down bed rest. *J Appl Physiol* 86: 909-914.
  - 56) Andersen JL, Schjerling P, Andersen LL and Dela F. 2003. Resistance training and insulin action in humans: effects of detraining. *J Physiol* 551: 1049-1058.
  - 57) Miller JP, Pratley RE, Goldberg AP, Gordon P, Rubin M, Treuth MS, Ryan AS and Hurley BF. 1994. Strength training increases insulin action in healthy 50- to 65-yr-old men. *J Appl Physiol* 77: 1122-1127.
  - 58) Zachwieja JJ, Toffolo G, Cobelli C, Bier DM and Yarasheski KE. 1996. Resistance exercise and growth hormone administration in older: effects on insulin sensitivity and secretion during a stable-label intravenous glucose tolerance test. *Metabolism* 45: 254-260.
  - 59) Irvine C and Taylor NF. 2009. Progressive resistance exercise improves glycemic control in people with type 2 diabetes mellitus: a systematic review. *Aust J Physiother* 55: 237-246.
  - 60) Bweir S, Al-Jarrah M, Almalty AM, Maayah M, Smirnova IV, Novikova L and Stehno-Bittel L. 2009. Resistance exercise training lowers HbA1c more than aerobic training in adults with type 2 diabetes. *Diabetol Metab Syndr* 1: 27.
  - 61) Fagard RH. 2006. Exercise is good for your blood pressure: effects of endurance training and resistance training. *Clin Exp Pharmacol Physiol* 33: 853-856.
  - 62) Tambalis K, Panagiotakos DB, Kavouras SA and Sidossis LS. 2009. Responses of blood lipids to aerobic, resistance, and combined aerobic with resistance exercise training: a systematic review of current evidence. *Angiology* 60: 614-632.