exercise test (GXT). However, the direct measurement of VO_{2max} is often limited to laboratory, clinical, and research settings, because it is costly and requires specialized equipment and trained personnel. The need to assess cardiorespiratory fitness in the general public has led to the development of various exercise and non-exercise prediction models. Previous investigators (Blair et al. 1989; Jackson et al. 1990; Heil et al. 1995; George et al. 1997; Malek et al. 2004a, b; Wier et al. 2006; Sanada et al. 2007) have reported valid estimates of aerobic fitness using non-exercise test variables including, age, gender, body composition (e.g., percent body fat, BMI, or skeletal muscle mass), and a self-assessed PA score. Such models are effective for use in large epidemiological cohorts in which exercise tests to predict or measure VO_{2max} would be impractical. One limitation of those previous works has been the selection of a subjective self-reported PA measure to assess cardiorespiratory fitness. Self-reported PA measures can suffer from social desirability and recall biases (Tudor-Locke et al. 2004a, b), but perhaps their greatest limitation is their inability to accurately assess unstructured and incidental ambulatory PA, which may account for a greater proportion of total PA in sedentary people.

Pedometers are simple and inexpensive body-worn motion sensors that are increasingly used for objective assessment of PA behaviors. More recently, they have gained credibility as an accurate measure of ambulatory PA because they can provide a direct measure of incidental and unstructured PA (Bassett et al. 2000; Welk et al. 2000; Tudor-Locke and Myers 2001; Crouter et al. 2003; Schneider et al. 2004), and have been used in some epidemiological studies in Japan (Ministry of Health and Welfare Japan 2002) and in the USA (Centers for Disease Control and Prevention, National Center for Health Statistics 2004). Using the pedometer as a measure of PA has many other advantages. Pedometers have been shown to provide a reliable measure of PA (Welk et al. 2000; Crouter et al. 2003; Schneider et al. 2004), are sensitive to change (Tudor-Locke 2001; Crouter et al. 2003), and, unlike self-reported measures, can detect subtle changes in an individual's incidental PA (Bassett et al. 2000; Tudor-Locke and Myers 2001; Crouter et al. 2003). However, to our knowledge, there is no information on the prediction of VO_{2max} using pedometer-determined step counts (SC) as an objective PA variable.

We hypothesized that pedometer-determined PA should have a good positive relationship with cardiorespiratory fitness in Japanese women. More specifically, the purpose of this study was to develop a new non-exercise VO_{2max} prediction model using SC as an objective PA variable in Japanese women.

Methods

The present investigation consists of two studies, a Prediction study and a Validation study. Outcome measurements in the Prediction study were performed in two independent institutions supervised by two coauthors NM and MH, while the validation study was done in another institution by CZ, KI, and IT (CZ).

Subjects

The study included 189 Japanese women aged from 20 to 69 years old. None of the subjects had any chronic diseases or were taking any medications that could affect the study variables. The Prediction group included 87 healthy women, and the Validation group included 102 healthy women. All subjects provided written informed consent according to local institute policy before the measurement of physical fitness. Informed consent was obtained before the measurement of physical fitness. The research project was approved by the Ethical Committee of the National Institute of Health and Nutrition. The subjects' characteristics are described in Table 1.

Anthropometrics

Body mass was measured using an electronic scale (Inner Scan BC-600, Tanita Co., Japan) and was determined to the nearest 0.1 kg. Height was measured to the nearest 0.1 cm using a stadiometer (YL-65, Yagami Inc., Japan). Body mass and height were measured with the subjects wearing light clothing and no shoes. Body mass index (BMI) was calculated by dividing the body mass in kilograms by the square of height in meters (kg m^{-2}).

Table 1 Physical characteristics of the study subjects

Variable	Prediction group $n = 87$	Validation group $n = 102$
Age (years)	45.7 ± 10.9	53.0 ± 14.2*
Height (cm)	157.2 ± 5.6	155.6 ± 5.7*
Body mass (kg)	52.5 ± 6.9	54.3 ± 7.1*
BMI (kg m^{-2})	21.3 ± 2.9	22.5 ± 2.9*
VO_{2max} (ml kg^{-1} min^{-1})	31.4 ± 7.4	29.8 ± 5.5
SC (steps day^{-1})	9,809 ± 3,156	10,143 ± 3,096

Values are mean ± SD

BMI body mass index, *SC* pedometer-determined step counts

* Significant group difference between Prediction group and Validation group, $P < 0.05$

Maximal aerobic power

$V\mathrm{O}_{2\max}$ was measured using a GXT with bicycle ergometers [Lode Excalibur (NM), Lode BV, Groningen, Netherlands; Monark Ergomedic 828E (MH, CZ), Varberg, Sweden]. The initial work load was 30–60 W, and the work rate was increased thereafter by 15 W min^{-1} until the subject could not maintain the required pedaling frequency (60 rpm) (Miyachi et al. 2001). Heart rate (WEP-7404, NIHON KOHDEN Corp. Japan) and a rating of perceived exertion were monitored throughout the exercise. During the progressive exercise test, the expired gas of subjects in the Prediction group was collected, and the rates of oxygen consumption ($V\mathrm{O}_2$) and carbon dioxide production (VCO_2) were measured over 30-s intervals using an automated breath-by-breath gas analyzing system [Aeromonitor AE-280S (MH), Minato Medical Science, Tokyo, Japan; Oxycon Alpha (NM), Mijnhardt b.v., The Netherlands]. The Aeromonitor AE-280S consists of a microcomputer, a hot-wire flow meter, and oxygen and carbon dioxide gas analyzers (a zirconium element-based oxygen analyzer and an infra-red carbon dioxide analyzer). Gas was sampled at the rate of 220 ml min^{-1} through a filter by a suction pump through the analyzers. The Oxycon Alpha consists of a microcomputer, a capillaryline, and oxygen and carbon dioxide gas analyzers (O_2: differential paramagnetic; CO_2: infra-red absorption). Expiratory volumes were determined using a Triple V turbine volume sensor which was calibrated before each test according to the manufacturer's instructions. The systems were calibrated prior to each test with gases of known concentration. The expired air of subjects in the Validation group was collected in Douglas bags (at least three times). An oxygen and carbon dioxide mass spectrometer (Arco-1000, Arco System, Japan) was used to analyze oxygen and carbon dioxide concentrations. The volume of expired air was determined using a dry gas volume meter (DC-5, Shinagawa Seisakusho, Japan) and converted to standard temperature, pressure and dry gas (STPD). During the latter stages of the test, each subject was verbally encouraged by the test operators to give a maximal effort. Achievement of $V\mathrm{O}_{2\max}$ was accepted if two of the following conditions were met: subject's maximal heart rate (HR) was >95% age-predicted maximal HR (220—age), and the $V\mathrm{O}_2$ curve showed a leveling off.

Physical activity

PA was measured by pedometer using an acceleration sensor. Subjects wore the Kenz Lifecorder (SUZUKEN Co Ltd., Japan) for seven consecutive days. Subjects were instructed how to use the instrument, and were told to wear it on their belt or waistband in the right midline of the thigh from the moment they got up until they went to bed except while bathing or swimming. The pedometer was firmly attached to their clothes at the waist with the aid of a clip.

Statistical analyses

Measured and calculated values are presented as means ± SD. Differences between the Prediction group and Validation group for variables were tested with Student's *t* test for unpaired samples. Pearson's product correlations were calculated between the independent variables (age, height, body mass, BMI, and SC) and $V\mathrm{O}_{2\max}$. Hierarchical linear regression analysis was used to generate prediction formulas for $V\mathrm{O}_{2\max}$. We entered the age and BMI into the first block, SC into the second block. The prediction formulas obtained from the Prediction group were then validated in the Validation group using the Bland and Altman approach (Bland and Altman 1986) and linear regression. Measured and predicted $V\mathrm{O}_{2\max}$ values were compared using paired Student's *t* test, standard errors, and Pearson's product correlation value (*r*) between the measured and predicted $V\mathrm{O}_{2\max}$ values. Error terms for the validation analysis were calculated as follows: the standard error of estimate $(\mathrm{SEE}_1) = \mathrm{SD}_y\sqrt{1-r^2}$, and total error (TE) $=\sqrt{\left(\sum(\text{measured } V\mathrm{O}_{2\max} - \text{predicted } V\mathrm{O}_{2\max})^2 \big/ n\right)}$. All analyses were done with SPSS 16.0 J for Windows (SPSS Japan Inc., Tokyo, Japan). The statistical significance level was set at $P < 0.05$.

Results

Results from cardiorespiratory fitness testing for $V\mathrm{O}_{2\max}$, anthropometric variables, and SC are presented in Table 1. There were significant group differences in age, height, body mass, and BMI between the Prediction group and the Validation group.

Table 2 presents Pearson correlations matrix of $V\mathrm{O}_{2\max}$ and all independent variables. These correlations between $V\mathrm{O}_{2\max}$ and all independent variables were statistically significant ($P < 0.01$) and ranged from a low of 0.21 for height to a high of −0.60 for age in the Prediction group, indicating that each independent variable was related to $V\mathrm{O}_{2\max}$. There was a statistically significant correlation between SC and $V\mathrm{O}_{2\max}$ (partial correlation coefficient $r = 0.40$, $P < 0.001$, data not shown) after adjusting for BMI and age. Table 3 shows multiple regression analysis. When estimating $V\mathrm{O}_{2\max}$ with age and BMI, the addition of SC, raised the R^2 from 0.40 to 0.50, a significant 10.0% increase in the explained variance of $V\mathrm{O}_{2\max}$. Multiple linear regression analysis yielded the following equation ($R = 0.71$, SEE $= 5.33$ ml kg^{-1} min^{-1}, $P < 0.001$) for

Table 2 Correlations matrix of VO_{2max} and independent variables (n = 87)

	VO_{2max} (ml kg^{-1} min^{-1})	Age (years)	Height (cm)	Body mass (kg)	BMI (kg m^{-2})	SC (steps day^{-1})
VO_{2max} (ml kg^{-1} min^{-1})	–					
Age (years)	−0.60**	–				
Height (cm)	0.21*	−0.37**	–			
Body mass (kg)	−0.26*	0.08	0.22*	–		
BMI (kg m^{-2})	−0.37**	0.27*	−0.31**	0.86**	–	
SC (steps day^{-1})	0.26*	0.05	−0.18	0.02	0.10	–

BMI body mass index, *SC* pedometer-determined step counts

* $P < 0.05$; ** $P < 0.01$

Table 3 Multiple regression analysis with VO_{2max} as the dependent variable and age, BMI, and SC as the independent variables

VO_{2max} (ml kg^{-1} min^{-1})	Coefficients	β	SE
Model 1			
Constant	55.318		4.682
Age (years)	−0.260	−0.54***	0.042
BMI (kg m^{-2})	−0.565	−0.22*	0.224
Model 2			
Constant	49.859		4.516
Age (years)	−0.263	−0.55***	0.039
BMI (kg m^{-2})	−0.641	−0.25**	0.207
SC (10^{-3} steps day^{-1})	0.734	0.31***	0.183

Data from Prediction group

Standard error of estimate (SEE) = 5.79 ml kg^{-1} min^{-1} for Model 1; SEE = 5.33 ml kg^{-1} min^{-1} for Model 2

BMI body mass index, *SC* pedometer-determined step counts, β standardized regression weights, *SE* standard error

R^2 = 0.40*** for Model 1; R^2 = 0.50*** for Model 2

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

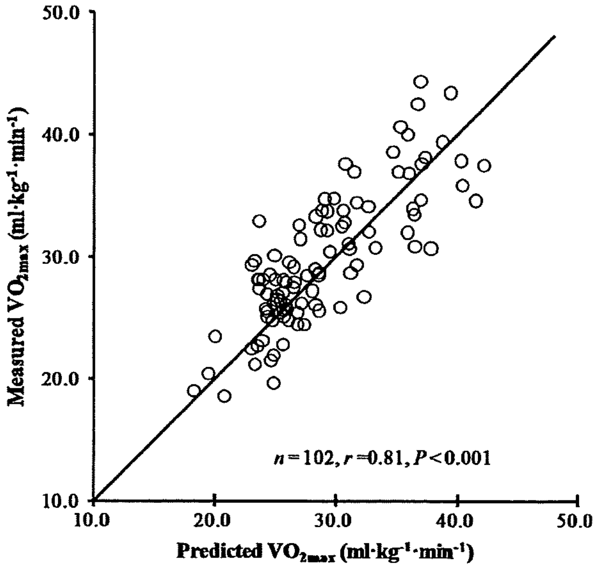

Fig. 1 Relationship between the measured and predicted VO_{2max} values in the Validation group. The *solid line* is the line of equality (measured VO_{2max} = predicted VO_{2max})

predicting VO_{2max}: $VO_{2max} = 49.859 - (0.263 \times \text{Age}) - (0.641 \times \text{BMI}) + (0.734 \times 10^{-3}\ \text{SC})$, where Age = age in years, BMI = body mass index in kg m^{-2}, and SC = pedometer-determined walk SC per day in steps day^{-1}.

Figure 1 shows the relationship between the measured and predicted VO_{2max} values in the Validation group. When the VO_{2max} prediction equation was applied to the Validation group, predicted VO_{2max} correlated well with measured VO_{2max} (r = 0.81, $P < 0.001$), and SEE_1 and TE were 3.25 and 3.43 ml kg^{-1} min^{-1}, or 10.9 and 11.5% of the average VO_{2max}, respectively. A slight difference was found between the measured (29.8 ± 5.5 ml kg^{-1} min^{-1}) and predicted (29.0 ± 5.3 ml kg^{-1} min^{-1}) VO_{2max}. The Bland–Altman plots display the individual subjects differences in the Validation group between the measured and predicted VO_{2max} against the mean measured and predicted VO_{2max} (Fig. 2). Each Bland–Altman plot displays the mean difference (dashed line) and the 95% confidence interval (±2SD; dotted lines). A strong agreement was found between the measured and predicted values of VO_{2max}. The mean difference (95% CI) between the measured and predicted VO_{2max} observed in the Validation group was 0.78 (−5.92, 7.49). Three cases were outside the limits of agreement. Bland–Altman plot and linear regression showed no significant relation (P = 0.47) between the mean measured and predicted VO_{2max} and the difference between them. The scatter on the Bland–Altman plot is distributed randomly, without signs of systematic bias.

Discussion

This study aimed to develop a non-exercise VO_{2max} prediction model using SC as a surrogate for the PA variable

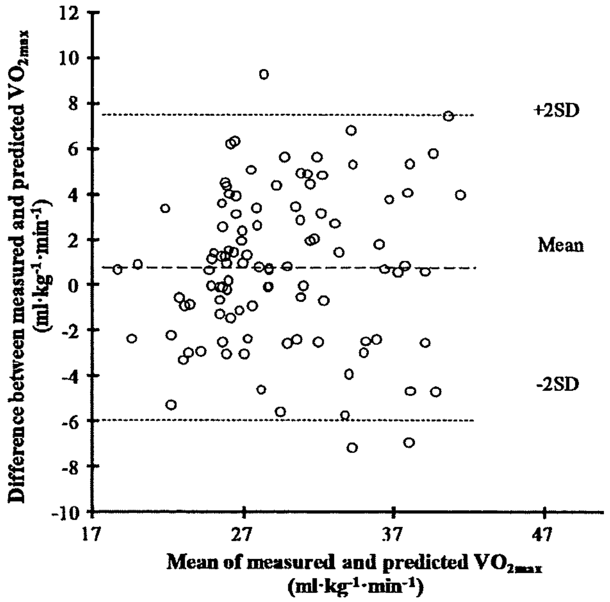

Fig. 2 Bland–Altman plot for the Validation group: mean $VO_{2\max}$ (measured and predicted) plotted against the difference (measured vs. predicted) in $VO_{2\max}$. Mean difference and 95% limits of agreement (mean ± 2SD) are indicated with *dashed and dotted lines*, respectively

in Japanese women. As we hypothesized, the PA variable of SC was significantly related to $VO_{2\max}$. Furthermore, the model is found to be able to predict $VO_{2\max}$ with satisfactory accuracy.

Cardiorespiratory fitness is considered a health-related fitness component that indicates the capability of the cardiovascular and respiratory systems to provide oxygen during PA. $VO_{2\max}$ is the most widely used measure of cardiorespiratory fitness, and has been shown to be strongly related to several health outcomes. Currently, direct measurement of $VO_{2\max}$ in a laboratory setting using maximal GXT is the most accurate assessment. However, the use of the direct measurement of $VO_{2\max}$ in epidemiological studies is limited by its high cost, by technical operational difficulties, and by the time required to measure it. Many attempts have been made to develop a non-exercise prediction model for $VO_{2\max}$ (Blair et al. 1989; Jackson et al. 1990; Heil et al. 1995; George et al. 1997; Malek et al. 2004a, b; Wier et al. 2006; Sanada et al. 2007). One limitation of those previous researches has been the selection of a self-reported PA measure to assess the cardiorespiratory fitness. Self-reported PA measures suffer from social desirability and recall biases (Tudor-Locke et al. 2004a, b). Further, their greatest limitation is their inability to accurately assess unstructured and incidental ambulatory PA, which may account for a greater proportion of total PA among sedentary people. To our knowledge, only one previous study has attempted to develop a non-exercise prediction model for $VO_{2\max}$ using the ratio heart rate and accelerometer-determined activity counts as an objective fitness index (Plasqui and Westerterp 2005). It was reported in this study that this fitness index contributed significantly to the explained variation in $VO_{2\max}$ (the additional explained variation from the fitness index beyond that of age, gender, and body mass was 9%, partial $r = -0.48$, $P = 0.02$). The total explained variation of their non-exercise prediction model was 71%, with an SEE of 409 ml min^{-1}, or 13.7% of the average $VO_{2\max}$. However, this prediction model may be less feasible for use in certain clinical applications because of the cost of and technical requirements for its use. Pedometers are simple and inexpensive body-worn motion sensors that are increasingly used for the objective assessment of PA behaviors. More recently, pedometers have been used in some epidemiological studies in Japan (Ministry of Health and Welfare Japan 2002) and in the USA (Centers for Disease Control and Prevention, National Center for Health Statistics 2004). Thus, there is a practical significance to the development of a non-exercise $VO_{2\max}$ prediction model using SC as a surrogate for the PA variable.

Multiple regression analysis demonstrated that each of the independent variables used in this study was independently related to $VO_{2\max}$. A number of studies have documented the relationship between pedometer-determined PA and $VO_{2\max}$ (Ichihara et al. 1996; Michaud et al. 2002; Bjørgaas et al. 2005). The correlation of 0.26 found in this study was similar to that found in healthy adolescents (Michaud et al. 2002), and was lower than the correlation ($r = 0.48$) in people with type 2 diabetes reported by Bjørgaas et al. (2005). Differences between the subjects in these two studies (healthy vs. diabetes) may explain the inconsistent finding. Those prior studies, in conjunction with the present study, document the value of using pedometer-determined PA when estimating $VO_{2\max}$.

Previously published non-exercise test prediction models reported varying success in predicting a measure cardiorespiratory fitness with SEE and R values ranging from 3.44 to 8.63 ml kg^{-1} min^{-1} and 0.46 to 0.88, respectively (Siconolfi et al. 1985; Kohl et al. 1988; Blair et al. 1989; Jackson et al. 1990; Heil et al. 1995; Whaley et al. 1995; Rankin et al. 1996; George et al. 1997; Malek et al. 2004a, b; Jurca et al. 2005; Plasqui and Westerterp 2005, 2006; Wier et al. 2006). The values determined by the regression model in the present study were well within this range. The wide range of R values reported in previous non-exercise test models may have been due in part to the differences among the studies in the type and number of predictor variables (Whaley et al. 1995). Moreover, differences in the ethnicity of the subjects between the present study (Japanese) and the previous studies (Caucasian) may explain the different correlation, because Wier et al. (2006)

reported that the addition of ethnicity to the non-exercise VO_{2max} prediction models significantly raised the correlation.

The purpose of the validation analysis was to estimate the prediction model's performance by measuring Pearson's product correlation value (r) between the measured and predicted VO_{2max} values and the error (SEE_1 and TE) in the Validation group. The low TE value, high r value, small difference (0.18 ml kg^{-1} min^{-1}) between TE and SEE_1 values for the Validation group, and slight differences between mean measured and predicted VO_{2max} values all provide evidence for model stability in the present study. The present validation analysis results achieved coefficients with higher validity compared with the cross-validation results of previous studies (George et al. 1997; Malek et al. 2004b). Malek et al. (2004b) reported that the SEE_1 values for the Validation groups in the former non-exercise VO_{2max} predictions present approximately 13.6–15.1% of the actual VO_{2max}, and that the TE values for the Validation groups in the former non-exercise VO_{2max} predictions present approximately 23–41% of the actual VO_{2max}. Therefore, the SEE_1 and TE values in the Validation group in the present study were lower than those associated with other non-exercise methods for estimating VO_{2max}.

The prediction accuracy of the model can be increased by enlarging the sample size. Therefore, the data from both the Prediction and Validation groups in the present study were pooled together (combined sample, $n = 189$) to develop the non-exercise VO_{2max} prediction $model_1$. Multiple regression analysis revealed that SC was a significant (partial correlation coefficient $r = 0.44$, $P < 0.001$, data not shown) contributor to the prediction of the measured VO_{2max}. The multiple regression $model_1$ obtained using the combined sample was the following: $VO_{2max} = 47.590 - (0.241 \times \text{Age}) - (0.540 \times \text{BMI}) + (0.672 \times 10^{-3}\ \text{SC})$, $R^2 = 0.56$, SEE = 4.33 ml kg^{-1} min^{-1}, $P < 0.001$. These results are consistent with a previous study (Wier et al. 2006) that showed an improvement in prediction accuracy, evidenced by larger R^2 and smaller SEE values, compared with a previous model with a smaller sample. Moreover, the PRESS (predicted residual sum of squares, Holiday et al. 1995) cross-validation statistic was similar to the regression statistic, supporting the validity of prediction $model_1$.

Many indirect methods of estimating VO_{2max} based on heart rate responses to submaximal exercise have been developed, resulting in good to very good prediction accuracy (Hermiston and Faulkner 1971; Fox 1973; Akalan et al. 2008). Akalan et al. (2008) reported an R value of 0.867, SEE of 4.23 ml kg^{-1} min^{-1}, and SEE% of 10% using their multiple regression equation with six independent variables during a submaximal cycle ergometer protocol, but did not present cross-validation results. They also reported that various submaximal tests based on heart rate responses to submaximal exercise have yielded correlations ranging from $R = 0.48$–0.97, and found that the mean difference between YMCA, ACSM, and Astrand-Ryhming Nomogram estimated VO_{2max} and observed VO_{2max} was significant. Zwiren et al. (1991) validated five methods of estimating VO_{2max} based on heart rate responses to submaximal exercise and reported $r = 0.55$–0.66, and $SEE_1\%$ of 13–13.5%. Therefore, the SEE_1 values in the Validation group in the present study were lower and the r values in the Validation group in the present study were higher than those reported for exercise-based prediction models. Plasqui and Westerterp (2005) developed a non-exercise model for estimating VO_{2max} using a fitness index based on accelerometer counts and heart rate, and they cross-validated this model in 2006. Compared with the Plasqui and Westerterp 2006 study, our study drew on a larger sample (87 vs. 26) and achieved good model stability, as evidenced by the absence of systematic bias and smaller $SEE_1\%$ values. Various tests should be evaluated not only for their accuracy and validity but also for their applicability in a varied study population, their cost, and the ease and convenience of the protocol. The large number of highly varied women who obtained measurements of VO_{2max} in our study helps support the generalizablity of the prediction model. In addition, because each of these predictor variables is easily obtained, it is believed that non-exercise VO_{2max} prediction model using SC as a surrogate for the PA variable can be a routine component of primary healthcare examination for women in large epidemiological cohorts.

Because the outcome measurements in the Prediction and the Validation groups were performed at different institutions, the effect of institution was assessed by adding a dummy-coded institution variable and then applying a multiple regression to determine whether the institution variable provided a significant increase in the explained variance of VO_{2max} over the independent variable. When the institution variable as an independent variable was added to the multiple regression, we found that the institution variable was not statistically significant ($P = 0.528$, data not shown) and did not improve the $model_1$ ($R = 0.75$, $P = 0.528$, data not shown).

This study has several limitations. First, the prediction model developed in this study may have limited generalizability because it was developed in a group of relatively healthy women 20 years of age and older. The stability of the predicted VO_{2max} values using the present model is unknown in groups of individuals whose characteristics vary substantially from the range of characteristics in our Validation group (e.g., men, children and adolescents, and individuals with metabolic syndrome). Our data showed that the correlation between pedometer-determined PA and VO_{2max} of 0.26 found in this study was slightly lower than the correlation ($r = 0.48$) in people with type 2 diabetes reported by Bjørgaas et al. (2005). Further research is needed to validate the prediction model in these groups. Second, SC alone does not discriminate the intensity of movement or reflect the amount of time spent in specific intensity categories of PA, which may weaken the accuracy of our prediction model. Aadahl et al. (2007) provided evidence that the amount of daily vigorous activity (>6 MET) showed a significantly positively better relationship with VO_{2max} ($P = 0.0001$, $r = 0.76$) compared with the total amount of PA done. If those indexes would encompass the prediction models, it is likely that the accuracy and validity of the prediction models would improve relative to the present prediction model. Therefore, further study is needed to investigate that possibility.

To our knowledge, this study marks the first attempt to develop a non-exercise VO_{2max} prediction model using SC as a surrogate PA variable that can be used in large epidemiological cohorts. This study demonstrated that SC was useful in predicting VO_{2max} variance and helped the present non-exercise VO_{2max} prediction model generate relatively accurate estimations of VO_{2max} in Japanese women.

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EFFECTS OF WHOLE-BODY LOW-INTENSITY RESISTANCE TRAINING WITH SLOW MOVEMENT AND TONIC FORCE GENERATION ON MUSCULAR SIZE AND STRENGTH IN YOUNG MEN

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ABSTRACT

Tanimoto, M, Sanada, K, Yamamoto, K, Kawano, H, Gando, Y, Tabata, I, Ishii, N, and Miyachi, M. Effects of whole-body low-intensity resistance training with slow movement and tonic force generation on muscular size and strength in young men. *J Strength Cond Res* 22(6): 1926–1938, 2008–Our previous study showed that relatively low-intensity (~50% one-repetition maximum [1RM]) resistance training (knee extension) with slow movement and tonic force generation (LST) caused as significant an increase in muscular size and strength as high-intensity (~80% 1RM) resistance training with normal speed (HN). However, that study examined only local effects of one type of exercise (knee extension) on knee extensor muscles. The present study was performed to examine whether a whole-body LST resistance training regimen is as effective on muscular hypertrophy and strength gain as HN resistance training. Thirty-six healthy young men without experience of regular resistance training were assigned into three groups (each $n = 12$) and performed whole-body resistance training regimens comprising five types of exercise (vertical squat, chest press, latissimus dorsi pull-down, abdominal bend, and back extension: three sets each) with LST (~55–60% 1RM, 3 seconds for eccentric and concentric actions, and no relaxing phase); HN (~80–90% 1RM, 1 second for concentric and eccentric actions, 1 second for relaxing); and a sedentary control group (CON). The mean repetition maximum was eight-repetition maximum in LST and HN. The training session was performed twice a week for 13 weeks. The LST training caused significant ($p < 0.05$) increases in whole-body muscle thickness (6.8 ± 3.4% in a sum of six sites) and 1RM strength (33.0 ± 8.8% in a sum of five exercises) comparable with those induced by HN training (9.1 ± 4.2%, 41.2 ± 7.6% in each measurement item). There were no such changes in the CON group. The results suggest that a whole-body LST resistance training regimen is as effective for muscular hypertrophy and strength gain as HN resistance training.

KEY WORDS resistance training regimens, muscular hypertrophy, continuous muscular activity, intramuscular hypoxic environment

INTRODUCTION

Resistance training at medium-to-high intensity (~80% one-repetition maximum [1RM]) is generally regarded as optimal for increasing muscular size and strength (21,23,32). It has been reported that resistance training at intensities lower than 65% 1RM is virtually ineffective for increasing muscular size and strength (6). Therefore, large mechanical stress has often been considered essential for increasing muscular size and strength. However, the concept of enhancing exercise movement variation was not explored in these studies. When exercise movement is devised to place muscles under continuous tension throughout the exercise movement, resistance training, even with low-intensity loads of less than 65% 1RM, may cause muscular hypertrophy and increase strength.

The results of our previous study indicated that a 12-week program of relatively low-intensity (~50% 1RM) resistance training with slow movement and tonic force generation (3 seconds for eccentric and concentric actions, 1-second pause and no relaxing phase; designated as LST) for knee extensor muscles caused significant increases in muscular size (~5% gain in cross-sectional area) and strength (~10% gain in

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maximum voluntary contraction [MVC], 30% gain in 1RM) in young men. The effects of muscular size and strength gains in LST were comparable with those seen in traditional high-intensity (~80% 1RM) resistance training with normal speed (1 second for concentric and eccentric actions, and 1 second for relaxing: HN) (37). The LST exercise movement was configured to achieve continuous force generation throughout the exercise movement. Continuous force generation at > 40% MVC has been shown to suppress both blood inflow to and outflow from the muscle because of an increase in intramuscular pressure (5,19). Therefore, LST training is expected to restrict muscular blood flow during exercise movement. Resistance training regimens with restricted muscular blood flow were considered to induce increases in muscular size and strength likely mediated by the following processes attributable to oxygen insufficiency in muscle: (a) stimulated secretion of growth hormone (GH) by intramuscular accumulation of metabolic byproducts, such as lactate (33); (b) moderate production of reactive oxygen species (ROS) promoting tissue growth (18,35); and (c) additional recruitment of fast-twitch fibers in a hypoxic condition (30,36).

However, our previous study examined only local effects (in knee extensor muscles) in one type of exercise (knee extension) training using LST. We had no information regarding the systemic effects of whole-body resistance training using LST. Single-joint exercises with exercise machines, such as knee extension and biceps curl, are considered more appropriate for LST to place specific muscles under continuous tension throughout the exercise movement than multijoint exercises, such as squat and chest press. Most single-joint exercise machines are designed to maintain almost-constant joint torque at any joint position. Therefore, we adopted knee extension exercise with a knee extension machine for the experimental exercise in our previous study (37). However, a whole-body resistance training program consisting of only single-joint exercises may not be realistic or appropriate. Multijoint exercises usually recruit one or more large muscle area as agonist muscles and some other muscles as coacting muscles, whereas single-joint exercises usually isolate a specific muscle or muscle group. Also, most sport and daily performance movements consist of multijoint movements. The more similar the training activity is to the actual sport and daily performance movements, the greater the likelihood that there will be a positive transfer to these movements (i.e., the specificity concept) (9,24). Therefore, multijoint exercises are considered more important for improving sport and daily performance than single-joint exercise.

In the present study, we investigated systemic effects, including changes in whole-body fat-free mass (FFTM) and percent body fat, of a long-term (13 weeks) whole-body LST training program consisting mainly of multijoint exercises on muscular size and strength. The results show that a whole-body LST training program caused increases in muscular size and strength as effectively as normal high-intensity training.

METHODS

Experimental Approach to the Problem

This study was designed to examine whether a whole-body resistance training regimen with the LST method (using a relatively low-intensity load with slow movement and tonic force generation–3 seconds for concentric and eccentric actions and no relaxing phase), as a training prescription program for the real field, is as effective on muscular hypertrophy and strength gain as resistance training with the HN method (a traditional method using a relatively high-intensity load with normal speed–1 second for concentric and eccentric actions and 1 second for relaxing). After providing informed consent, subjects were assigned to three experimental groups (LST training group, HN training group, and CON [no-training control group], $n = 12$ for each group) for this study. Subjects in the training groups (LST and HN) performed whole-body resistance training regimens consisting of five types of exercise by each resistance training method. Subjects performed each type of exercise with eight-repetition maximum (8RM) intensity. Exercise intensities on LST and HN were adjusted to the 8RM intensity. Mechanical load in LST training was much lower than that in HN training (~55–60% 1RM in LST vs. ~80–90% 1RM in HN).The difference of mechanical load between the two groups with the same 8RM intensities may be attributable to the difference in the type of movement. The training sessions were performed twice a week for 13 weeks.

We compared measurements of acute and chronic changes in LST and HN to investigate the physiological characteristics and evaluate the effects of muscular hypertrophy and strength gain of whole-body resistance training with the LST method. As acute changes in physiological parameters during exercise, we measured electromyographic (EMG) signals, peripheral muscle oxygenation level, blood lactate concentration, and blood pressure. As chronic changes after the training, we measured muscle thickness (MT) and subcutaneous fat thickness (SFT) using B-mode ultrasound, lean soft-tissue mass (LSTM: body mass minus bone mass minus fat mass), fat mass, and bone mineral density (BMD) using dual-energy X-ray absorptiometry (DXA), and 1RM strength in the five types of exercise used in the training regimen. These were measured before and after the training period.

Subjects

Thirty-six healthy young men who did not have experience of regular resistance training volunteered as subjects. The subjects were randomly assigned into three experimental groups (n = 12 for each group: LST, HN, and CON, described below), which were matched for physical parameters, such as height, weight, and age (Table 1). All subjects were advised to maintain their usual dietary habits and not to make any intentional changes such as protein

TABLE 1. Physical characteristics of the subjects.

	LST		HN		CON	
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
Age (y)	19.0 ± 0.6		19.5 ± 0.5		19.8 ± 0.7	
Height (cm)	174.1 ± 5.5		174.8 ± 4.3		174.3 ± 7.2	
Body mass (kg)	62.5 ± 4.8	64.1 ± 5.2	63.8 ± 4.0	65.3 ± 4.3	64.2 ± 4.0	64.7 ± 3.9

Values are mean ± *SD*; *n* = 12 for each group.

LST = low-intensity resistance training with slow movement and tonic force generation; HN = high-intensity resistance training with normal speed; CON = sedentary controls.

supplement intake or increasing the amount of intake or number of meals a day, to avoid nutritional influence. All subjects were fully informed about the experimental procedures to be used as well as the purpose of the study, and they gave their written informed consent before participating in the study. The study was approved by the ethics committee for human experiments at the National Institute of Health and Nutrition.

Resistance Training Regimens

The subjects in each training group performed whole-body resistance training regimens consisting of five types of exercise: vertical squat, chest press, latissimus dorsi pull-down, abdominal bend, and back extension. All of these exercises were performed using resistance exercise machines (Cybex Corp. USA for vertical squat; Nautilus Corp. USA for chest press, abdominal bend, and back extension; and Senoh Corp. Japan for latissimus dorsi pull-down); these machine exercises were considered easier to perform than free weight resistance exercises because of balance and coordination recruitment. The subjects performed their whole-body resistance training according to the following training regimens.

The LST group exercised at low intensity (~55–60% of 1RM), with slow movement and tonic force generation (3 seconds for concentric [lifting phase] and eccentric [lowering phase] actions, and no relaxing phase). In the vertical squat, chest press, and latissimus dorsi pull-down, the subjects did not extend their legs or arms fully, to maintain continuous tension in the muscles throughout the exercise movement.

The HN group exercised at high intensity (~80–90% 1RM), with normal speed (1 second for concentric and eccentric actions, and 1 second for relaxing).

The CON group served as the no-training control. The training session consisted of the five types of exercise described above, and each subject performed one warm-up set and three regular sets for each type of exercise, with an interset rest period of 60 seconds. A 3-minute rest period was taken between exercise events. The training session was performed twice a week for 13 weeks. The first 2 weeks were a preparation period, during which the subjects gradually increased the training volume and intensity, and in 2 weeks they reached regular volume and intensity. Subjects in both training groups (LST and HN) repeated the movement at approximately constant speed and frequency with the aid of a metronome. The subjects repeated the movement until exhaustion (repetition maximum [RM]) at each exercise set. The exercise intensity was determined at 8RM for each set but not at % 1RM, because the former method is more commonly used in actual exercise training. The intensity was adjusted in all training sessions based on the record of the previous training session. The intensities used in the LST and HN groups (8RM) in the first set corresponded to about 55–60% 1RM and about 85–90% 1RM, respectively (Table 2). In the HN group, the subjects performed the same RM (8RM) as in the LST group: that is, the same RM-based intensity. The difference in % 1RM intensities between the LST and HN groups may have been attributable to the difference in type of exercise movement. The exercise intensities actually used in both training groups are summarized in Table 2.

Procedures

Acute Changes in Physiological Parameters During Exercise. Electromyographic signals, peripheral muscle oxygenation level, blood lactate concentration, and blood pressure were measured during and after exercise to investigate the characteristics of these trainings. Electromyographic signals were measured to confirm muscle continuous activity in LST, because muscle continuous activity may lead to a decrease in peripheral muscle oxygenation level, and decreases in muscle oxygenation level during exercise movement may lead to increases in blood lactate concentration. Muscle oxygenation, which was the primary measurement element, could be measured only in limb muscles. Of the five types of exercise, only vertical squat limb muscles were mobilized as agonist muscles. Blood pressure was measured from the radial artery with the upper-body muscles kept relaxed. Of the five types of exercise, only vertical squat was performed with the upper-body muscles kept relaxed. Thus, EMG signal, muscle oxygenation, and blood pressure were measured during and after vertical squats, and the results were used as

Table 2. One-repetition maximum and exercise intensity during the experimental period.

		LST			HN			CON	
	Pretraining	7th week	13th week	Pretraining	7th week	13th week	Pretraining	7th week	13th week
Vertical squat									
1RM (kg)	106.5 ± 22.8	122.1 ± 22.9*	136.4 ± 20.5†‡	105.1 ± 16.1	125.2 ± 17.4*	136.5 ± 20.4†§	113.7 ± 16.3		112.9 ± 17.8
Intensity/first set (kg)		70.9 ± 22.8	82.4 ± 8.5		111.3 ± 17.4	121.9 ± 18.8			
% 1RM		59.0 ± 5.8	60.8 ± 5.8		88.7 ± 4.1	89.4 ± 4.2			
Chest press									
1RM (kg)	46.1 ± 10.4	56.1 ± 11.3*	62.0 ± 12.3†‡	41.3 ± 5.4	49.7 ± 8.5*	55.1 ± 9.1†§	46.1 ± 10.0		47.3 ± 11.1
Intensity/first set (kg)		30.8 ± 5.7	35.3 ± 6.3		40.5 ± 6.1	46.9 ± 7.3			
% 1RM		55.3 ± 5.6	57.3 ± 5.9		81.9 ± 5.4	85.2 ± 3.5			
Lat pull-down									
1RM (kg)	42.7 ± 6.7	56.3 ± 7.4*	62.0 ± 8.2†‡	39.6 ± 7.2	50.4 ± 6.9*	55.7 ± 9.0†§	47.7 ± 6.9		48.9 ± 7.3
Intensity/first set (kg)		32.9 ± 3.3	35.3 ± 6.3		41.7 ± 5.8	46.7 ± 7.3			
% 1RM		59.0 ± 5.9	57.3 ± 5.9		82.7 ± 3.9	83.9 ± 4.2			
Abdominal bend									
1RM (kg)	57.8 ± 8.1	74.5 ± 11.9*	82.0 ± 13.7†‡	59.3 ± 8.8	78.5 ± 10.6*	90.4 ± 13.4†§	66.4 ± 7.9		67.1 ± 8.5
Intensity/first set (kg)		40.1 ± 5.2	45.4 ± 5.2		69.8 ± 9.3	79.9 ± 9.8			
% 1RM		54.4 ± 5.6	56.0 ± 6.4		89.0 ± 3.4	88.8 ± 4.7			
Back extension									
1RM (kg)	63.8 ± 6.9	81.7 ± 11.1*	98.4 ± 14.1†‡	61.5 ± 10.0	94.7 ± 20.9*	113.0 ± 13.5†§‖	70.0 ± 16.4		72.4 ± 16.2
Intensity/first set (kg)		48.8 ± 7.9	58.9 ± 9.5		79.5 ± 18.9	96.6 ± 11.9			
% 1RM		59.7 ± 5.1	60.0 ± 6.8		83.7 ± 3.7	85.5 ± 1.7			

Values are mean ± *SD*; $n = 12$ for each group. One-repetition maximum in the 13th week was measured after completion of the 13-week training period (posttraining).

LST = low-intensity resistance training with slow movement and tonic force generation; HN = high-intensity resistance training with normal speed; CON = sedentary controls; 1RM = one-repetition maximum.

*Significant difference ($p < 0.05$) between pretraining and 7th week.

†Significant difference ($p < 0.05$) between 7th week and 13th week.

‡Significant increase from pretraining to 13th week in LST ($p < 0.05$) as compared with CON.

§Significant increase from pretraining to 13th week in HN ($p < 0.05$) as compared with CON.

‖Significant increase from pretraining to 13th week in HN ($p < 0.05$) as compared with LST.

representative for all five types of exercise. Each measurement was taken between weeks 7 and 9, when the participants had become sufficiently accustomed to the training routine.

Electromyographic Recording. Electromyographic signals during squat exercise were recorded from the left vastus lateralis (VL) muscle and long head of the biceps femoris (BF) muscle. Bipolar surface electrodes (Vitrode F; Nihon Kohden Corp., Japan) were placed over the belly of the muscle with a constant interelectrode distance of 30 mm. The EMG signals were amplified, fed into a full-wave rectifier through both low (30 Hz) and high (1 kHz) cut filters, and stored using a data-acquisition system (Power Lab/16SP; AD Instruments, Australia).

Measurement of Peripheral Muscle Oxygenation by a Near-Infrared Continuous-Wave Spectroscopic Monitor. A near-infrared continuous-wave spectroscopic (NIRcws) monitor (BOML1TR; Omegawave, Inc., Japan) was used to measure the peripheral muscle oxygenation in the left VL muscle during and after vertical squat exercise. The wavelengths of emission light were 780, 810, and 830 nm, and the relative concentrations of oxygenated hemoglobin/myoglobin (Oxy-Hb/Mb) in tissues were quantified according to the Beer-Lambert law (7). Because the NIRcws signals registered during exercise do not always reflect the absolute levels of oxygenation, the changes in oxygenation in working skeletal muscles are expressed as values relative to the overall changes in the signal monitored according to the arterial occlusion method (7,14). In the present study, the resting level of Oxy-Hb/Mb was defined as 100% (baseline), and the minimum plateau level of Oxy-Hb/Mb obtained by arterial occlusion was defined as 0%. A pressure cuff was placed around the proximal portion of the thigh and was inflated manually up to 300 mm Hg until the minimum plateau level of Oxy-Hb/Mb was attained (4). The distance between the incident point and the detector was 30 mm. The laser emitter and detector were fixed with tape after shielding with a rubber sheet. The NIRcws signals were stored on a personal computer.

Measurement of Blood Lactate Concentration. Blood samples were collected during the exercise sessions. Samples were collected before and immediately after each type of exercise. Blood samples of approximately 5 μl were taken from the fingertip using a needle and were analyzed immediately for blood lactate concentration using a lactate analyzer (Lactate Pro; Kyoto Primary Science, Japan).

Measurement of Blood Pressure. Blood pressure from the left radial artery was measured continuously during exercise with an arterial tonometry during the vertical squat exercise (JENTOW-7700; Colin, Japan). During measurements, the arm was supported with an adjustable board. To minimize the mechanical effects of the contraction of upper-body muscles and changes in posture, the upper body was kept relaxed and was immobilized on the machine during exercise. Blood pressure signals were stored on a personal computer.

Chronic Effects of Resistance Training. Muscle thickness and SFT using B-mode ultrasound, LSTM (body mass minus bone mass minus fat mass), fat mass, and BMD using DXA, and maximal muscular strength by 1RM test with the five types of exercise used in the training regimen were measured before and after the experimental period to evaluate the chronic effects of these training regimens.

Muscle and Subcutaneous Fat Thickness by B-Mode Ultrasound Imaging. The MT and SFT were measured by B-mode ultrasound (5-MHz scanning head) at six sites from the anterior and posterior surfaces of the body, in principle following the standard method described by Abe et al. (1). The sites were the chest, anterior and posterior upper arm, abdomen, subscapula, and anterior and posterior thigh. Six anatomic landmarks for the sites are noted below.

Chest: At a distance of 8 cm, directly above the mamilla.

Anterior and posterior upper arm: On the anterior and posterior surface, 60% distal between the lateral epicondyle of the humerus and the acromial process of the scapula.

Abdomen: At a distance 2–3 cm to the right of the umbilicus.

Subscapula: At a distance of 5 cm, directly below the inferior angle of the scapula.

Anterior and posterior thigh: On the anterior and posterior surface, midway between the lateral condyle of the femur and the greater trochanter.

Muscle thickness and SFT were scanned using a real-time linear electronic scanner with a 5-MHz scanning head (SSD-500; Aloka, Japan). The scanning head was prepared with water-soluble transmission gel that provided acoustic contact without depression of the skin surface. The scanner was placed perpendicular to the tissue interface at the marked sites.

Whole-Body Composition in Dual-Energy X-Ray Absorptiometry. Lean soft-tissue mass (body mass minus bone mass minus fat mass), fat mass, and BMD were determined for the whole body using DXA (Hologic QDR-4500A scanner; Hologic, USA). Subjects were positioned for whole-body scans according to the manufacturer's protocol. Participants lay in the supine position on the DXA table with the limbs close to the body. Fat-free body mass (FFM) was the sum of LSTM and bone mineral content (BMC). The bone densitometer delivers a very low dose of radiation (1.5 mR for the whole body) using quantitative digital radiography. To minimize interobserver variation, all scans and analyses were carried out by the same investigator, and the day-to-day coefficients of variation (CVs) of the observations were <0.8 whole-body BMD. The whole-body was divided into several regions: arms, legs, trunk, and head. The body compositions were analyzed using manual DXA analysis software (version 11.2.3). The arm region was defined as the region extending from the head of the humerus to the distal tip of the fingers. The reference point between the head of the humerus and the scapula was positioned at the glenoid fossa. The leg region was defined as the region extending from the inferior border of the ischial tuberosity to the distal tip of the toes. The whole body was defined as the region extending from the shoulders to the distal tip of the toes. We selected a reference point that could be visualized clearly on the DXA system terminal.

Measurements of Muscle Strength. Maximal muscular strength was tested with the five types of exercise used in the training regimen: vertical squat, chest press, latissimus dorsi pull-down, abdominal bend, and back extension. Values were obtained for 1RM according to the established guidelines (39). The 1RM strength test using resistance exercise machines was considered better suited to eliminate the influence of coordination recruitment skills than a test using free weights, such as barbells.

In this 1RM test, subjects lifted the load on a resistance exercise machine from a bottom position without preliminary (eccentric) muscle contractions, because preliminary muscle contraction enhances muscle force (41). In this study, 1RM has been underestimated compared with 1RM as tested with preliminary muscle contractions such as free weight bench press and squat lifting after eccentric movement. This means that the exercise loads (% 1RM) used in LST and HN might be overestimated.

Statistical Analyses

All values are expressed as mean ± *SD*. One-way analysis of variance (ANOVA) with a Fisher protected least significant difference test was used to determine the significance of any differences among the initial parameters of the three groups, such as body weight and muscle strength. One-way ANOVA with a Fisher protected least significant difference test was used to examine differences in peripheral muscle oxygenation and blood lactate concentration between groups. Two-way ANOVA with repeated measures (group × period) with the Newman-Keuls method was used to examine differences in changes in MT and SFT, body weight, LSTM, fat mass, percent body fat, BMD, and 1RM among groups. For all statistical tests, $p \leq 0.05$ was considered significant.

Power calculations (statistical power) were performed using G*power computer software. Statistical power of >80% was obtained in the main significant changes, such as MT, LSTM, and 1RM strength after the LST and HN training terms. Intraclass correlation coefficient and CV were calculated to examine the test-retest reliability for variables in MT and SFT measured by B-mode ultrasound and 1RM strength test, because these variables may be affected by manual handling technique. Intraclass correlation coefficient and the mean CV value for measurement values by B-mode ultrasound in our laboratory were 0.999 and 3.2%, respectively. Intraclass correlation coefficient and the mean CV value for measurement values of 1RM strength test were 0.995 and 2.8%, respectively.

RESULTS

Acute Effects of Exercises

Typical Examples of Muscle Electric Activity During Exercise. Figure 1 shows typical examples of changes in EMG signals from VL during vertical squat exercise. In LST, the EMG from VL showed almost continuous activity throughout the entire movement. In HN, EMG signals from VL exhibited intermittent activity. Data from two subjects, whose 1RM values were about the same, are shown. The measurements of EMG from VL were made for all subjects in the training groups ($n = 24$). All subjects showed essentially the same patterns.

Peripheral Muscle Oxygenation

Figure 2 shows minimum and maximum oxygenation levels in the left VL during and after vertical squat exercise in

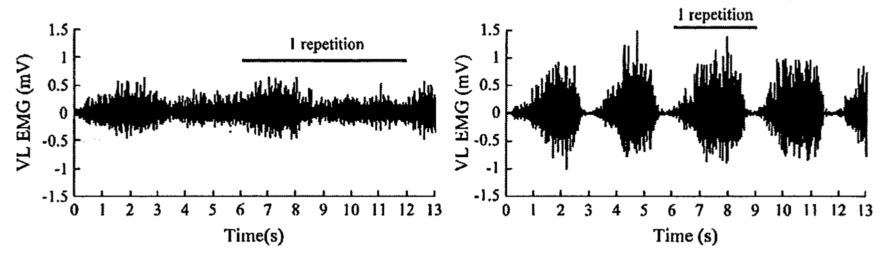

Figure 1. Typical electromyographic (EMG) signals from the vastus lateralis (VL) during vertical squat exercise. The signals were recorded during (A) low-intensity resistance training with slow movement and tonic force generation (LST) with a load of 75 kg (~57% one-repetition maximum [1RM]) and (B) high-intensity resistance training with normal speed (HN) with a load of 102 kg (~89% 1RM) in the vertical squat. Records were from the first to second lifting movements in the first set for LST and from the first to fourth lifting movements for HN. Data from two subjects, whose 1RM strengths were about the same, are shown.

LST and HN. In both LST and HN, the oxygenation level decreased immediately when the exercise repetitions started, and it recovered rapidly and was followed by a hypercompensation after the end of the exercise repetitions. The mean value of minimum oxygenation level during LST vertical squat exercise was significantly lower than that during HN exercise (Figure 2A). The large decrease in muscle oxygenation level during LST exercise was likely attributable to continuous activity of the knee extensor muscles (see Figure 1A). There were no significant differences in the mean values of maximum oxygenation level after LST and HN exercise (Figure 2B).

Blood Lactate Concentration

Figure 3 shows changes in blood lactate concentration measured at rest and immediately after each type of exercise in LST and HN. There were no significant differences in blood lactate concentration at rest between LST and HN groups. Both LST and HN exercise caused marked increases in blood lactate concentration after each type of exercise. No significant differences were observed between blood lactate concentrations after any of the exercise types in LST and HN. Changes in blood lactate concentration during exercise were similar in LST and HN, despite the much lower intensity and smaller amount of work in LST than in HN. The large increase in the concentration of blood lactate (which is an anaerobic energy metabolite) during LST exercise was likely attributable to the lower muscle oxygenation level in LST (see Figure 2A).

Blood Pressure During Exercise

Figure 4 shows peak blood diastolic pressure during LST and HN vertical squat exercise in the first set and at rest. In both LST and HN training groups, the diastolic pressure reached a peak at the last repetition or the second- or third-from-last repetition in the exercise set, and it exhibited significant increases from that at rest. The peak diastolic pressure during HN vertical squat exercise (183.4 ± 33.0 mm Hg) was significantly higher than that during LST exercise (124.4 ± 29.4 mm Hg). Peak blood systolic pressure during vertical exercise exceeded the measurement range of the equipment (300 mm Hg) in some subjects in the HN group. Therefore, we evaluated the elevation of blood pressure during vertical squat exercise with peak blood diastolic pressure during exercise.

Chronic Effects of Resistance Training

Changes in Muscle and Subcutaneous Fat Thickness. Figure 5 shows changes in total MT, defined as the sum of the values for all six measurement sites, in the three groups after the experimental period. There were no significant differences among groups in MT at each measurement site before the experimental period. In both LST and HN groups, MT increased significantly after the experimental period, whereas no such change was observed in the CON group. The percent changes in total MT after the experimental period were +6.8 ± 3.4% in LST, +9.1 ± 4.2% in HN, and +1.3 ± 2.2% in CON. These changes in LST and HN were significantly greater than those in CON, and there were no significant differences between the changes in LST and in HN (Figure 5). In LST and HN, the MT of all measurement sites except the anterior upper arm increased significantly after the experimental period. There were no changes at any of the sites in CON. Increases in MT at all measurement sites (except the anterior upper arm) in LST and in HN were significantly greater than those in CON, and there were no significant differences between the changes in LST and HN

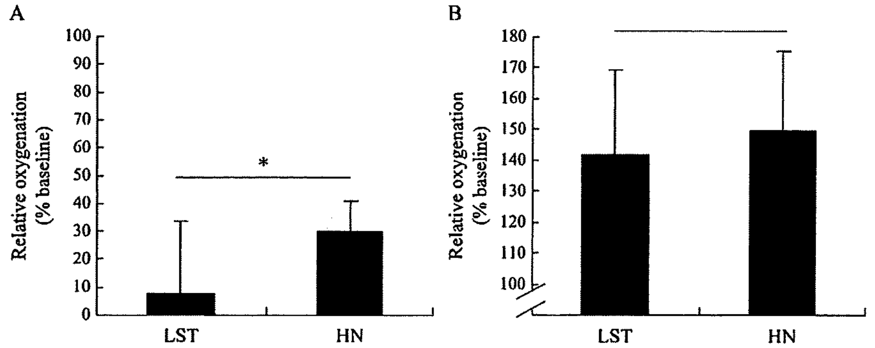

Figure 2. A) Mean values of minimum oxygenation level during low-intensity resistance training with slow movement and tonic force generation (LST) and high-intensity resistance training with normal speed (HN) in the vertical squat. Mean values ± *SD* (*n* = 12 for each group) are shown. *Significant differences ($p < 0.05$) between groups. B) Mean values of maximum oxygenation level after LST and HN exercises in the vertical squat. Mean values ± *SD* (*n* = 12 for each group) are shown.

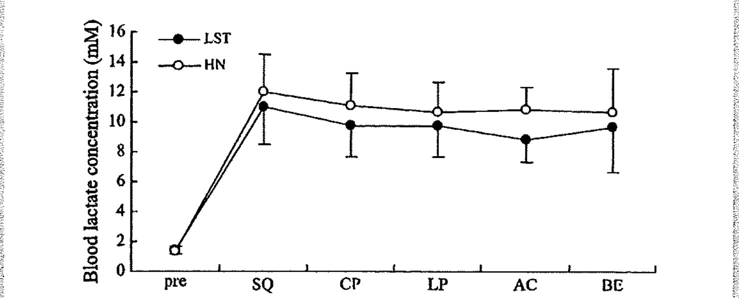

Figure 3. Changes in blood lactate concentrations before and immediately after low-intensity resistance training with slow movement and tonic force generation (LST; ●) and high-intensity resistance training with normal speed (HN; ○). Mean values ± *SD* ($n = 12$ for each group) are shown. SQ = vertical squat; CP = chest press; LP = latissimus dorsi pull-down; BE = back extension.

at any of the measurement sites. The values of MT at each measurement site before and after the experimental period are summarized in Table 3. Figure 6 shows changes in total SFT, defined as the sum of the values for all six measurement sites, in the three groups after the experimental period. No significant differences were observed among groups in SFT at each measurement site before the experimental period. In the HN group, total SFT decreased significantly after the experimental period, whereas there were no such changes in the LST or CON groups. The percent changes in total SFT after the experimental period were −2.1 ± 1.22% in LST, −10.2 ± 9.4% in HN, and +1.5 ± 10.2% in CON. This decrease in HN was significantly greater than those in the LST and CON groups (Figure 6). In HN, SFT in the posterior upper arm was significantly decreased after the experimental period. In LST and CON, the SFT in the subscapula increased significantly after the experimental period. The decrease in HN in the posterior upper arm was significantly greater than that in CON. The SFT decrease in the subscapula was significantly greater in HN than in LST and CON. All values of SFT at each measurement site before and after the experimental period are summarized in Table 3.

Changes in Lean Soft-Tissue Mass, Fat Mass, Percent Body Fat, and Bone Mineral Density in Dual-Energy X-Ray Absorptiometry

Table 4 shows all values measured by DXA, such as LSTM, fat mass, percent body fat, and BMD, before and after the experimental period. No significant differences were observed among groups before the experimental period. Whole-body LSTM in all groups, even in the CON group, increased significantly after the experimental period. The

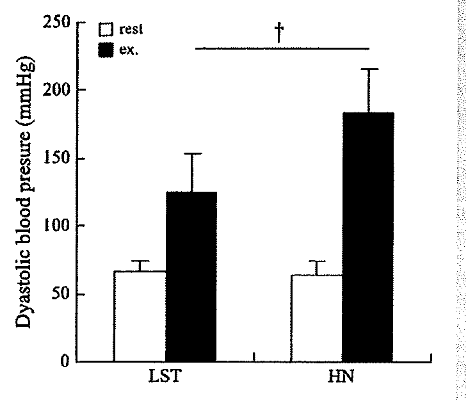

Figure 4. Peak blood diastolic pressure during low-intensity resistance training with slow movement and tonic force generation (LST) and high-intensity resistance training with normal speed (HN) vertical squat exercises (filled bars) and at rest (open bars). Mean values ± *SD* ($n = 12$ for each group) are shown. *Significant differences ($p < 0.05$) between groups. The values for both types of exercise showed significant changes as compared with the resting level ($p < 0.05$).

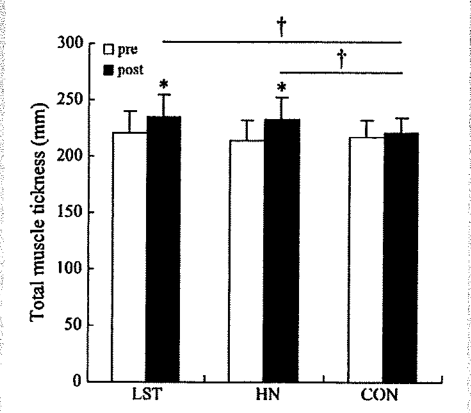

Figure 5. Sum of whole-body muscle thickness of six sites before (open bars) and after (filled bars) the experimental period. Mean values ± *SD* ($n = 12$ for each group) are shown. *Significant differences between pre- and posttraining values ($p < 0.05$). †Significant differences between groups ($p < 0.05$).

TABLE 3. Muscle and subcutaneous fat thickness before and after the experimental period.

	LST		HN		CON	
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
Muscle thickness, mm						
Chest	1.75 ± 0.34	2.03 ± 0.41*†	1.67 ± 0.44	2.02 ± 0.51*‡	1.62 ± 0.22	1.64 ± 0.23
Anterior upper arm	2.70 ± 0.21	2.76 ± 0.25	2.53 ± 0.21	2.66 ± 0.22	2.69 ± 0.24	2.70 ± 0.25
Posterior upper arm	2.87 ± 0.38	3.15 ± 0.41*†	2.84 ± 0.49	3.09 ± 0.38*‡	2.95 ± 0.55	2.96 ± 0.55
Abdomen	1.44 ± 0.19	1.56 ± 0.20*†	1.29 ± 0.13	1.45 ± 0.14*‡	1.30 ± 0.23	1.28 ± 0.23
Subscapula	2.42 ± 0.41	2.58 ± 0.47*†	2.31 ± 0.33	2.61 ± 0.44*‡	2.35 ± 0.35	2.23 ± 0.28
Anterior thigh	5.12 ± 0.59	5.45 ± 0.66*†	4.94 ± 0.36	5.49 ± 0.42*‡	5.16 ± 0.55	5.29 ± 0.50
Posterior thigh	5.72 ± 0.52	5.96 ± 0.37*†	5.82 ± 0.45	6.00 ± 0.49*‡	5.69 ± 0.35	5.76 ± 0.38
Subcutaneous fat thickness, mm						
Chest	0.52 ± 0.18	0.50 ± 0.18	0.82 ± 0.51	0.62 ± 0.31	0.67 ± 0.36	0.65 ± 0.34
Anterior upper arm	0.21 ± 0.06	0.22 ± 0.06	0.25 ± 0.07	0.26 ± 0.06	0.22 ± 0.06	0.25 ± 0.07
Posterior upper arm	0.54 ± 0.18	0.52 ± 0.22	0.69 ± 0.17	0.61 ± 0.14*§	0.59 ± 0.15	0.58 ± 0.13
Abdomen	0.85 ± 0.88	0.74 ± 0.70	1.03 ± 0.43	0.90 ± 0.36	1.07 ± 0.65	1.05 ± 0.56
Subscapula	0.57 ± 0.12	0.63 ± 0.15*	0.65 ± 0.16	0.63 ± 0.12‖	0.59 ± 0.13	0.68 ± 0.12*
Anterior thigh	0.50 ± 0.12	0.48 ± 0.19	0.62 ± 0.19	0.55 ± 0.17	0.56 ± 0.11	0.53 ± 0.13
Posterior thigh	0.63 ± 0.27	0.61 ± 0.27	0.71 ± 0.20	0.64 ± 0.15	0.71 ± 0.18	0.69 ± 0.18

Values are mean ± *SD*; $n = 12$ for each group.

LST = low-intensity resistance training with slow movement and tonic force generation; HN = high-intensity resistance training with normal speed; CON = sedentary controls.

*Significant difference ($p < 0.05$) between pretraining and posttraining.

†Significant increase in muscle thickness in LST ($p < 0.05$) as compared with CON.

‡Significant increase in muscle thickness in HN ($p < 0.05$) as compared with CON.

§Significant decrease in subcutaneous fat thickness in HN ($p < 0.05$) as compared with CON.

Significant decrease in subcutaneous fat thickness in HN ($p < 0.05$) as compared with LST and CON.

TABLE 4. Body composition in DXA before and after the experimental period.

	LST		HN		CON	
	Pretraining	Posttraining	Pretraining	Posttraining	Pretraining	Posttraining
Whole body						
LSTM (kg)	53.86 ± 3.86	55.23 ± 3.68*†	53.74 ± 3.04	55.57 ± 3.41*‡	54.56 ± 2.71	55.19 ± 2.57*
Fat mass (kg)	8.66 ± 2.75	58.86 ± 3.11	10.08 ± 2.35	9.75 ± 2.20	9.60 ± 2.70	9.55 ± 2.68
% Fat (%)	13.75 ± 3.63	11.68 ± 3.79	15.73 ± 3.21	14.85 ± 2.89*	14.83 ± 3.56	14.63 ± 3.54
BMD ($g \cdot cm^{-3}$)	1.19 ± 0.10	1.10 ± 0.10	1.17 ± 0.10	1.17 ± 0.10	1.21 ± 0.07	1.21 ± 0.07
Arms						
LSTM (kg)	5.35 ± 0.52	5.52 ± 0.59*†	5.10 ± 0.51	5.38 ± 0.51*‡	5.18 ± 0.46	5.24 ± 0.50
Fat mass (kg)	0.84 ± 0.30	0.86 ± 0.28	1.01 ± 0.29	0.99 ± 0.26	0.99 ± 0.34	0.94 ± 0.30
Legs						
LSTM (kg)	17.80 ± 1.45	18.26 ± 1.34*†	17.73 ± 1.43	18.55 ± 1.57*‡	17.91 ± 1.07	18.22 ± 1.35
Fat mass (kg)	3.30 ± 1.17	3.36 ± 1.24	3.96 ± 1.06	3.78 ± 0.86	3.55 ± 1.04	3.52 ± 1.04

Values are mean ± *SD*; $n = 12$ for each group.

DXA = dual-energy X-ray absorptiometry; LST = low-intensity resistance training with slow movement and tonic force generation; HN = high-intensity resistance training with normal speed; CON = sedentary controls; LSTM = lean soft-tissue mass; BMD = bone mass density; % fat = percent body fat.

*Significant difference ($p < 0.05$) between pretraining and posttraining.

†Significant increase in LST ($p < 0.05$) as compared with CON.

‡Significant increase in HN ($p < 0.05$) as compared with CON.

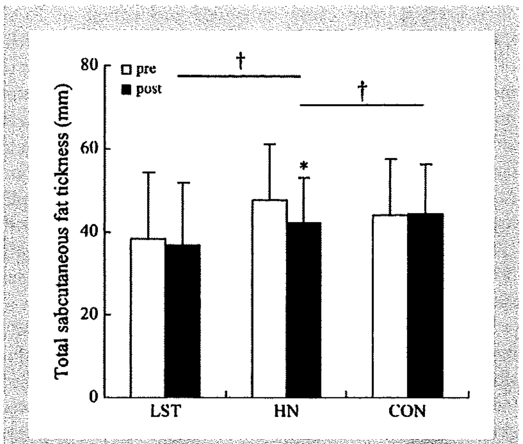

Figure 6. Sum of whole-body subcutaneous fat thickness of six sites before (open bars) and after (filled bars) the experimental period. Mean values ± *SD* ($n = 12$ for each group) are shown. *Significant differences between pre- and posttraining values ($p < 0.05$). †Significant differences between groups ($p < 0.05$).

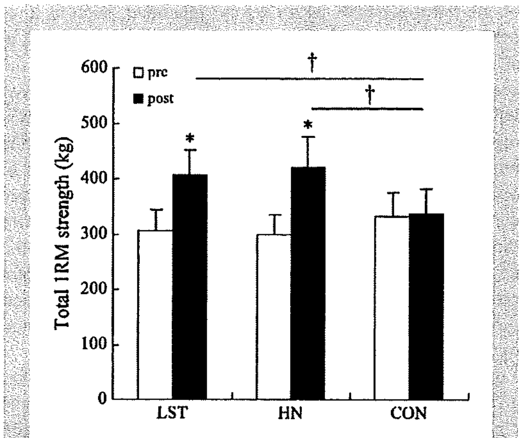

Figure 7. Sum of one-repetition maximum (1RM) strength of five exercises before (open bars) and after (filled bars) the experimental period. Mean values ± *SD* ($n = 12$ for each group) are shown. *Significant differences between pre- and posttraining values ($p < 0.05$). †Significant differences between groups ($p < 0.05$).

absolute changes in LSTM were 1.4 ± 1.4 kg in LST, 1.8 ± 1.3 kg in HN, and 0.6 ± 0.7 kg in CON. These changes in LST and in HN were significantly greater than those in CON, and there were no significant differences between the changes in LST and in HN. The LSTM increase observed in the CON group may have been attributable to weight gain associated with seasonal variations and growth. Whole-body percent body fat in the HN group decreased significantly after the experimental period. This decrease in HN was significantly greater than those in LST and CON, and there were no significant differences between the changes in LST and in CON. No significant changes occurred in body mass, fat mass, or BMD in any of the groups. All values measured by DXA before and after the experimental period are summarized in Table 4. Changes in FFM and fat mass in DXA were similar to those in MTH and SFT as determined by ultrasound imaging. Ultrasound imaging was used for direct assessment in regions involved in training, so ultrasound imaging may have higher detection sensitivity for detecting significant changes than DXA.

Changes in Muscular Strength

Figure 7 shows changes in total 1RM strength, defined as the sum of values for all five types of exercise used in the training regimen, in the three groups after the experimental period. No significant differences were observed among groups in 1RM strength in each type of training before the experimental period. In the LST group and the HN group, total 1RM strength increased significantly after the experimental period (Table 4), whereas there was no such change in the CON group (Figure 7). The percent changes in total 1RM strength were +33.0 ± 8.8% in LST, +41.2 ± 7.8% in HN, and +1.3 ± 2.4% in CON. These increases in LST and in HN after the experimental period were significantly greater than the value in CON, and there were no significant differences between the changes in LST and HN. In both LST and HN, 1RM strength in all five exercises increased significantly after the experimental period. There were no such changes in CON. The increases in LST and HN in 1RM strength in all five types of exercise were significantly larger than the values in CON, and there were no significant differences between the changes in LST and in HN except in back extension. The increase in 1RM strength on back extension in HN was significantly greater than that in LST. The values of 1RM strength in each type of exercise before and after the experimental period are summarized in Table 2.

DISCUSSION

The results of the present study indicate a significant increase in muscular size and concomitant increase in muscular strength after a 13-week whole-body LST training program consisting of the five following exercises: vertical squat, chest press, latissimus dorsi pull-down, abdominal bend, and back extension. The term *LST* refers to a low-intensity (~55–60% 1RM) resistance training program with slow movement and tonic force generation. The gains in muscular size and strength were similar to those after the same whole-body training program using a high-intensity load (~80–90% 1RM) with normal speed (HN). Previously, we reported that a 12-week LST training program with one type of exercise (knee extension) caused significant increases in muscular size and strength to the same degree as HN. This previous study investigated only local effects and provided no information about systemic effects of LST whole-body resistance training.

Single-joint exercises with exercise machines, such as knee extensions, are considered more appropriate for LST to achieve strict continuous force generation throughout the exercise movement than multijoint exercises. However, whole-body resistance training programs usually consist mainly of multijoint exercises. Multijoint exercises usually recruit more large muscle areas than single-joint exercises. In addition, the movements in most multijoint exercises are considered more similar to sport and daily performance movements. The significance of the present study lies in the demonstration that a whole-body LST training program consisting mainly of multijoint exercises, as a prescription program for actual training, was effective for muscular hypertrophy and strength gain as systemic effects.

In the previous study, the increase in muscular size after a 12-week knee extension LST training program tended to be higher than that after HN training. On the other hand, the increase in systemic muscular size after 13 weeks of whole-body LST training mainly consisting of multijoint exercises tended to be lower than that after HN in this study (no significant difference). The difference between the results in these two studies may be related to the fact that knee extension exercise, which is a single-joint exercise, is considered to be better suited for continuous muscle contraction in LST.

Multijoint LST exercise (vertical squat) has the following physiological characteristics: a) continuous muscle activity is kept constant throughout the entire exercise movement (Figure 1A); b) lowered peripheral muscle oxygenation level during exercise (Figure 2A); c) elevated peripheral muscle oxygenation level immediately after exercise (Figure 2B); and d) increased blood lactate concentration (Figure 3). These characteristics in multijoint LST exercise are similar to those of single-joint LST exercise with a knee extension exercise machine examined in the previous study (37). The lowered muscle oxygenation level and increased blood lactate concentration during LST exercise were likely attributable to the restriction of muscular blood flow by continuous muscle activity. It has been speculated that local accumulation of anaerobic energy metabolites, such as lactate, stimulates the hypophyseal secretion of GH (22,33) and the local secretion of growth factors, such as insulin-like growth factor 1 (28). It has also been shown that plasma GH stimulates synthesis and secretion of insulin-like growth factor 1 within muscle, which may then act on the muscle itself and promote growth (8,17). The production of ROS may play an important role in muscular hypertrophy. The activity of ROS within the muscle has been shown to be enhanced in hypoxic environments (20). A considerable amount of ROS could be produced when the muscle is kept hypoxic and subsequently exposed to reperfusion (31). Among the ROS, nitric oxide, which is the strongest vasodilator characterized to date, has also been shown to mediate the activation and proliferation of muscle satellite cells, which are muscle fiber stem cells (3). Therefore, both lowered and elevated muscle oxygenation levels during and after exercise may cause enhanced production of ROS, thereby stimulating muscle growth. Additional recruitment of fast-twitch fibers under a hypoxic condition is likely to mediate muscle hypertrophy (30,36). Almost all of the motor units were considered to be recruited at the final repetition in all sets in LST as well as in HN exercise, because subjects in both HN and LST repeated the movement until exhaustion (27). The physiological characteristics of LST differ significantly from those of HN using a high-intensity load. However, 13 weeks of whole-body resistance training using both LST and HN caused comparable increases in muscular size and strength.

Some recent studies have indicated that low-intensity resistance training combined with moderate vascular occlusion using artificial occlusive pressure causes marked increases in muscular size and strength (2,29,34,36). These studies suggest that large mechanical stress is not indispensable for muscular hypertrophy and strength gain. They also suggest that the muscle-trophic effect of resistance training involves not only large mechanical stress but also metabolic, hormonal, and neuronal factors. However, resistance training with vascular occlusion is so specialized that it should not be widely used without careful monitoring of occlusive pressure and blood flow. Its application is limited to upper-limb and lower-limb muscles, because it can be applied only to distal muscles from occlusive pressure belts. Usually, resistance training combined with moderate vascular occlusion is performed using occlusive pressure belts at the roots of the limbs. This is often associated with pain attributable to artificial occlusive pressure. The LST training, which sustains continuous force generation at >40% MVC to restrict muscle blood flow, would also be effective to make the intramuscular environment hypoxic even without artificial occlusive pressure. This can be applied not only to limb muscles but also to trunk muscles, and it is free from the pain associated with artificial occlusive pressure. Therefore, this represents a good alternative to resistance training with vascular occlusion.

The movement speed of LST in this study (3 seconds for concentric and eccentric actions) was configured so that all subjects could easily maintain continuous force generation throughout the exercise movement. In the exercise movement consisting of 2 seconds for concentric and eccentric actions, it seemed to be difficult for the subjects to maintain constant tension, whereas in the exercise movement consisting of 4 seconds for concentric and eccentric actions, the subjects could maintain constant tension easily, but it was almost impossible for them to perform several repetitions at sufficient intensity (>40% MVC) to restrict muscle blood flow. Thus, the movement speed of LST was determined based on the requirements described below.

1. Continuous force generation could be easily achieved even by beginners without previous experience of resistance training.

2. Continuous force generation throughout the exercise movement with more than 40% MVC load to restrict muscle blood flow.

The prime point of LST is slow movement to achieve tonic force generation, and not to slow movement itself. In this point, LST is different from SuperSlow (10-second lifting and 4-second lowering movement), a registered trademark of Ken Hutchins (42).

Fat mass measured by DXA decreased significantly, although not markedly, after HN training, whereas no significant decrease was observed after LST. Acute increase in plasma catecholamine concentration during exercise may be one of the reasons for fat loss in HN. We also have shown previously that LST and HN leg extension exercise immediately increased plasma norepinephrine concentration. The amount of increase in HN tended to be higher than that in LST (38). Acute increases in plasma catecholamine concentration during and immediately after exercise enhance fat oxidation for energy expenditure (12,25). In addition, the larger amount of mechanical work may cause fat loss in HN. The amount of work in HN was about 1.5 times that in LST.

Bone mass density (see Table 4) and bone mass component (BMC data not shown) were not increased after the experimental period in any groups. This result is perhaps related to the length of the experimental period. It is considered that the experimental period in this study was short, and therefore no changes were observed in BMD or BMC. Bone adapts to high mechanical stress by changing its size and density, and the heavier the magnitude of load, the greater the stimulus for bone growth (40). Thus, BMD and BMC increases from long-term resistance training would be more effective in HN than in LST.

High-intensity resistance training does not necessarily increase the risk of injury. High-intensity resistance training does not cause orthopedic or cardiovascular problems when performed or supervised appropriately (13). However, it has also been reported that approximately 20% of the elderly (aged 70–79 years) showed some symptoms of orthopedic injury after training at 1RM (26). In addition, a marked increase in systolic blood pressure (up to 250 mm Hg) has been reported to occur during high-intensity resistance training (~8RM) for large muscle groups (10). Some studies have reported large numbers of cases in which vascular events, such as aortic dissection, occurred during high-intensity resistance training (15,16). Thus, high-intensity resistance training can increase the risk of injury and vascular events during exercise. Therefore, the development of a resistance training regimen that can cause substantial gains in strength with much lower mechanical stress would be advantageous for the development of safer and effective methods of promoting muscle hypertrophy for a wider range of people, including older people and those with cardiovascular problems.

In conclusion, low-intensity whole-body resistance training with slow movement and tonic force generation consisting mainly of multijoint exercises was as effective for increasing muscular size and strength as high-intensity resistance training. This training method was not associated with the generation of large force or with any considerable elevation of blood pressure. Therefore, it would be useful for promoting muscular hypertrophy and strength increases in a larger population, including the elderly and those at higher risk of cardiovascular adverse events. In this regard, however, LST is anything but easy for subjects to carry out despite the use of a relatively low-intensity load. Subjects repeat movement until exhaustion in LST as in HN.

PRACTICAL APPLICATIONS

The guideline of "load and repetition assignments based on the training goal" based on Fleck and Kraemer's systematic review of resistance training (11) and other studies (39) has been widely used in the field of physical fitness. This guideline recommends resistance training with 6–12 repetitions using a 67–85% 1RM load for muscle hypertrophy. This guideline seems like an appropriate assignment in voluntary movement, but it does not include the concept of enhancing exercise movement variation. When exercise movement is devised to place muscles under continuous tension throughout the exercise movement as in the LST method, resistance training, even with low-intensity loads of less than 65% 1RM, can cause muscular hypertrophy and increase strength. The results of this study indicate that whole-body LST training is an effective method for gaining muscular size and strength in actual training. A regimen of LST training with a relatively low-intensity load can be chosen as a safe resistance training method with relatively low risk for orthopedic injury and cardiac event during exercise. The LST training should be performed with a speed that easily enables continuous force generation throughout the exercise movement. In actual training, LST does not have to be performed with the speed used in this study (3 seconds for concentric and eccentric actions). However, if the movement is too slow (e.g., more than 5 seconds for concentric and eccentric actions), it may be difficult to perform several repetitions at an intensity sufficient to restrict muscle blood (>40% MVC). Also, the mechanical work may not be sufficient to enhance local accumulation of metabolic byproducts such as lactate and proton. We recommend that the movement speed should be as fast as possible within the limits in which continuous force generation can be maintained. We regard tonic force generation rather than slow movement to be the primary point of LST training.

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