High-Intensity Training versus Traditional Exercise Interventions for Promoting Health

LARS NYBO[1], EMIL SUNDSTRUP[1,2], MARKUS D. JAKOBSEN[1,2], MAGNI MOHR[1], THERESE HORNSTRUP[1], LENE SIMONSEN[2], JENS BÜLOW[2], MORTEN B. RANDERS[1], JENS J. NIELSEN[1], PER AAGAARD[2,3], and PETER KRUSTRUP[1]

[1]Section of Human Physiology, Department of Exercise and Sport Sciences, University of Copenhagen, Copenhagen, DENMARK; [2]Bispebjerg University Hospital, Copenhagen, DENMARK; and [3]Institute of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, DENMARK

ABSTRACT

NYBO, L., E. SUNDSTRUP, M. D. JAKOBSEN, M. MOHR, T. HORNSTRUP, L. SIMONSEN, J. BÜLOW, M. B. RANDERS, J. J. NIELSEN, P. AAGAARD, and P. KRUSTRUP. High-Intensity Training versus Traditional Exercise Interventions for Promoting Health. *Med. Sci. Sports Exerc.*, Vol. 42, No. 10, pp. 1951–1958, 2010. **Purpose**: The purpose of this study was to determine the effectiveness of brief intense interval training as exercise intervention for promoting health and to evaluate potential benefits about common interventions, that is, prolonged exercise and strength training. **Methods**: Thirty-six untrained men were divided into groups that completed 12 wk of intense interval running (INT; total training time 40 $\mathrm{min \cdot wk^{-1}}$), prolonged running (~150 $\mathrm{min \cdot wk^{-1}}$), and strength training (~150 $\mathrm{min \cdot wk^{-1}}$) or continued their habitual lifestyle without participation in physical training. **Results**: The improvement in cardiorespiratory fitness was superior in the INT (14% ± 2% increase in $\dot{V}O_{2max}$) compared with the other two exercise interventions (7% ± 2% and 3% ± 2% increases). The blood glucose concentration 2 h after oral ingestion of 75 g of glucose was lowered to a similar extent after training in the INT (from 6.1 ± 0.6 to 5.1 ± 0.4 mM, $P < 0.05$) and the prolonged running group (from 5.6 ± 1.5 to 4.9 ± 1.1 mM, $P < 0.05$). In contrast, INT was less efficient than prolonged running for lowering the subjects' resting HR, fat percentage, and reducing the ratio between total and HDL plasma cholesterol. Furthermore, total bone mass and lean body mass remained unchanged in the INT group, whereas both these parameters were increased by the strength-training intervention. **Conclusions**: INT for 12 wk is an effective training stimulus for improvement of cardiorespiratory fitness and glucose tolerance, but in relation to the treatment of hyperlipidemia and obesity, it is less effective than prolonged training. Furthermore and in contrast to strength training, 12 wk of INT had no impact on muscle mass or indices of skeletal health. **Key Words:** BONE MASS, BLOOD PRESSURE, CHOLESTEROL, GLUCOSE TOLERANCE, LEAN BODY MASS, $\dot{V}O_{2max}$

It is well established that factors such as poor cardiorespiratory fitness, adiposity, impaired glucose tolerance, hypertension, and arteriosclerosis are independent threats to health and that physical inactivity increases the risk for premature death and elevates the incidence of the abovementioned unhealthy conditions, which independently or in combination may be considered risk factors for chronic diseases (21). Epidemiologic cross-sectional investigations and longitudinal intervention studies have provided experimental evidence for the effectiveness of prolonged aerobic exercise training such as continuous running, brisk walking, or bicycling as interventions that may lower the relative risk for developing several metabolic diseases (3,5,14,25,26). In accordance, a recent pronouncement from the American College of Sports Medicine concludes that between 150 and 250 min of moderate physical activity per week is sufficient and effective to prevent weight gain (8), and the Centers for Disease Control and Prevention published national guidelines on physical activity and public health as well as the Committee on Exercise and Cardiac Rehabilitation of the American Heart Association have previously endorsed and supported these recommendations for healthy adults to improve and to maintain health (13).

However, lack of time is a common reason why many people fail to accomplish the "traditional training programs," and metabolic-related disorders arising secondary to a sedentary lifestyle have become a large and expanding health problem in the modern society (4). In this relation, it is interesting that short but very intense exercise training may induce similar improvements in cardiorespiratory fitness and skeletal muscle oxidative capacity as prolonged training (6,11), and a recent study (1) reported that very short duration high-intensity interval training substantially improves insulin action. Accordingly, it has been speculated that short-term high-intensity interval training could be a

---

Address for correspondence: Lars Nybo, Department of Exercise and Sport Sciences, Copenhagen Muscle Research Centre, University of Copenhagen, The August Krogh Building, Universitetsparken 13, Copenhagen 2100-Ø, Denmark; E-mail: lnnielsen@ifi.ku.dk.

Submitted for publication November 2009.
Accepted for publication February 2010.

0195-9131/10/4210-1951/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181d99203

time-efficient strategy for health promotion (10). Furthermore, in relation to reducing cardiovascular risk factors, studies by Schjerve et al. (28) and Tjonna et al. (30,31) elegantly demonstrate that high-intensity training has a major advantage compared with "isocaloric" moderate intense training. However, because the total energy turnover during training was matched across the different groups in the studies by Schjerve et al. (28) and Tjonna et al. (30,31), the overall exercise time was not markedly reduced in the intense compared with the moderate training group. Although the abovementioned studies indicate that intense training has the potential to improve various health parameters, it remains unknown if very intense but short-lasting exercise training can completely substitute for the higher training volume and consequently larger energy expenditure associated with prolonged moderate physical activity.

Many health-promoting exercise programs also include strength training, aiming with the intension to develop strength and to induce muscle hypertrophy (18). The increased lean body mass may increase the basal energy expenditure and favor the loss of body fat (29); in addition, it could benefit health by other means. Thus, heavy strength training is not only a stimulus for muscle hypertrophy, this type of training also appears to be a potent stimulus for osteogenesis and increased bone mass, and bone mineral density may increase bone strength, which is of major importance for the prevention of osteoporosis later in life. As an alternative to strength training, exercise with a high-impact load may also provide a significant osteogenic stimulus. High-intensity interval running may be considered as high-impact exercise and could therefore be speculated to have an effect on bone mineral density (12,27). Furthermore, strength training for 30 min three times per week increased insulin action in skeletal muscle in both normal subjects and patients with type 2 diabetes (15). This effect may in part relate to increased muscle mass and reduced body fat, but it also involves up-regulation of several key proteins in the insulin signaling cascade. In contrast, strength training has limited impact on cardiorespiratory fitness, and the influences on the metabolic capacity of the skeletal muscles and on the plasma lipoprotein profile seem to be minor importance (23).

The present study was undertaken to clarify how an intervention with brief but very intense aerobic training conducted as high-intensity interval running would influence specific parameters such as plasma lipid profile, glucose tolerance, fat mass, and blood pressure and compare changes in these physiological variables of with adaptations achieved through traditional training interventions. With the ambition to evaluate the efficiency of different training modes for the prevention or treatment of different types of metabolic and musculoskeletal disorders, 36 untrained subject were therefore divided into a control group (CON), a strength-training group (STR), a high-intensity interval running group (INT), and a group that performed "traditional" moderate-intensity running (MOD).

METHODS

Thirty-six untrained men that had not participated in any type of regular physical training for at least 2 yr were recruited for the study. The participants had a mean age of 31 yr (range = 20–43 yr; for anthropometric details, see Table 1), and they were all nonsmokers, without diagnosed metabolic or cardiovascular diseases. The study was carried out in accordance with the guidelines contained in the Declaration of Helsinki and approved by the local ethical committee of Copenhagen (14606; H-C-2007-0012), and informed written consent was obtained from all subjects.

Design. The subjects were divided into four groups: 1) a group that performed intense interval running (INT; *n* = 8); 2) a strength-training group (STR; *n* = 8); 3) a group that performed prolonged moderate intense continuous running (MOD; *n* = 9); and 4) a control group performing no physical training (CON; *n* = 11). The participant in the three training groups completed three different 12-wk training programs as described below, whereas the participants in CON continued their daily life activities during the period. Before and after the 12-wk intervention period, the subjects completed a series of tests that consisted of an exercise test, an oral glucose tolerance test (OGTT), measurements of resting blood pressure, a plasma lipoprotein profile, and obtainment of a muscle biopsy for determination of capillarization and metabolic enzyme levels.

TABLE 1. Subject characteristics, fat percentage, lean body mass, and bone mass before and after the 12-wk intervention period for the three training groups and controls.

	Intense Interval Running		Prolonged Running		Strength Training		Control	
	Before	After	Before	After	Before	After	Before	After
Age (yr)	37 ± 3		31 ± 2		36 ± 2		30 ± 2	
Body mass (kg)	96.3 ± 3.8	94.9 ± 4.2	85.8 ± 5.5	84.8 ± 5.3*	95.0 ± 8.4	96.7 ± 8.5†	86.5 ± 3.8	86.4 ± 3.7
Fat percentage	24.7 ± 1.5	24.2 ± 1.7	24.3 ± 1.6	22.6 ± 1.7*	24.9 ± 2.3	25.3 ± 2.4	22.3 ± 2.7	22.1 ± 2.8
Lean body mass (kg)								
Total	66.6 ± 1.8	66.8 ± 2.1	61.3 ± 2.8	61.9 ± 2.7	61.0 ± 2.3	62.8 ± 2.7†	63.3 ± 1.7	63.4 ± 1.5
Legs	23.1 ± 0.6	23.2 ± 0.8	21.0 ± 1.0	21.6 ± 1.1	21.4 ± 1.2	22.8 ± 1.3†	20.3 ± 0.7	20.0 ± 0.6
Bone mass (kg)								
Total	3.52 ± 0.12	3.59 ± 0.14	3.36 ± 0.11	3.40 ± 0.11	3.31 ± 0.07	3.37 ± 0.08†	3.24 ± 0.05	3.26 ± 0.06
Legs	1.38 ± 0.05	1.39 ± 0.07	1.36 ± 0.06	1.38 ± 0.06	1.29 ± 0.04	1.32 ± 0.05†	1.30 ± 0.04	1.30 ± 0.04

Age, body mass, fat percentage, total and leg lean body mass, and total and leg bone mass before and after training. Values are presented as mean ± SE for the four groups.
* Significantly lower than pretraining value ($P < 0.05$).
† Significantly higher than pretraining value ($P < 0.05$).

Except for the training regimens and for the days before the testing days, the subjects were instructed to continue their habitual lifestyle and to maintain their normal dietary practices throughout the 12-wk period. However, before the experimental days, the subjects were required to refrain from alcohol and exercise for 48 h before the resting measurement and the experimental exercise trials.

Measurements and test procedures. Subjects were familiarized with the exercise test and with the blood pressure measurements at least one time before the experiment. Fasting blood glucose, lipoproteins, resting HR, and blood pressure were determined in the morning under standardized conditions and after an overnight fast. Blood pressure was measured at least six times, with the subjects in a supine position, by an automatic upper arm blood pressure monitor (M-7 or HEM-709; OMRON, Schaumburg, IL), and an average of the six values for diastolic and systolic blood pressure was recorded. Mean arterial pressure (MAP) was calculated as $1/3 \times$ systolic pressure + $2/3 \times$ diastolic pressure. With this procedure, the coefficient of variation (CV) for repeated measures on the same day was less than 2%, and the day-to-day variation (CV for the control group) was 2.6%.

Exercise test. Pulmonary gas exchange (CPX MedGraphics, St. Paul, MN), HR (Polar Team System; Polar Electro Oy, Kempele, Finland), and venous blood sampling were performed during a standardized treadmill test consisting of 6 min of walking at 6.5 $\text{km}\cdot\text{h}^{-1}$ and 6 min of submaximal running at 9.5 $\text{km}\cdot\text{h}^{-1}$, followed by a 15-min rest period and thereafter an incremental test to exhaustion. Pulmonary oxygen uptake ($\dot{V}O_2$) and RER were measured during the last 3 min of walking at 6.5 $\text{km}\cdot\text{h}^{-1}$ and similarly during the last 3 min of running at 9.5 $\text{km}\cdot\text{h}^{-1}$. $\dot{V}O_{2\max}$ and $HR_{\max}$ were determined as the peak value reached in a 30-s period during the incremental test. Fat oxidation during walking was calculated from the RER and the steady state $\dot{V}O_2$ measured at 6.5 $\text{km}\cdot\text{h}^{-1}$ and similarly for submaximal running at 9.5 $\text{km}\cdot\text{h}^{-1}$.

Oral glucose tolerance test. Subjects refrained from performing any strenuous physical activity for 2 d before the OGTT and attended the laboratory having fasted overnight. Venous blood samples were collected from an antecubital venous catheter before and 15, 30, 60, 90, and 120 min after ingestion of 75 g of glucose.

Furthermore, before the OGTT, while the subject was still fasting, 2 mL of blood was drawn into heparinized syringes for determination of fasting insulin and glucose levels (ABL 615; Radiometer Medical, Copenhagen, Denmark). Furthermore, 10 mL was drawn into dry syringes for determination of plasma fatty acid, HDL cholesterol, and plasma triacylglycerol concentrations measured by commercial kits (Wako Chemicals, Neuss, Germany) on a Hitachi autoanalyzer (Roche Diagnostic, Basel, Switzerland). The analytical variations (CV) for these measures are reported to be less than 1.5%. LDL cholesterol was calculated in accordance with the Friedewald–Levy–Fredrickson equation (27b) as total cholesterol minus HDL cholesterol and one-fifth of total plasma triacylglycerol. Plasma concentrations of insulin were determined using a RIA kit (Pharmacia Insulin Radioimmunoassay 100; Pharmacia & Upjohn Diagnostics, Uppsala, Sweden; intra-assay CV 3%).

Body weight was measured in the morning after an overnight fast on a platform scale (Ohaus, Germany). Body composition was determined by dual-energy x-ray absorptiometry (DEXA scan, DPX-IQ version 4.6.6; Lunar Corp., Madison, WI).

Muscle biopsies were obtained at rest from musculus vastus lateralis under local anesthesia using the Bergstrom technique. The posttraining biopsy was obtained between 48 and 72 h after the final training session, and the pretraining biopsies were also obtained with no physical activity for 48 h before the biopsy. All biopsies were frozen in liquid nitrogen within 15 s and stored at −80°C for subsequent analysis. Muscle tissue was subsequently freeze dried and dissected free of all visible exogenous adipose tissue, connective tissue, and blood under a stereo microscope (Stemi 2000-C; Zeiss, Oberkochen, Germany).

Approximately 30 mg of wet weight muscle tissue was mounted in an embedding medium (OCT Tissue-Tek; Sakura Finetek, Zoeterwoude, The Netherlands), frozen in precooled isopentane, and analyzed histochemically for capillaries. Maximal citrate synthase (CS) and beta-hydroxyacyl-CoA-dehydrogenase (HAD) activities were determined fluorimetrically on a separate piece of muscle from the biopsy. The muscle fibers were mixed, and pooled fibers were used for the determination of maximal enzyme activity as expressed in micromole per gram (dry weight muscle) per minute (22).

Training. The high-intensity training consisted of a brief 5-min warm-up with light jogging followed by five intervals of 2 min of near-maximal running (HR above 95% of their $HR_{\max}$ at the end of the 2-min period; total exercise time per session = 20 min, including warm-up). For all training groups, there were three scheduled training sessions per week. However, because of injuries or absence for other reasons, the participants in the INT group completed 2.0 ± 0.1 sessions per week corresponding to a total training time during the 12 wk of approximately 480 min, including warm-up. Three of the subjects in INT missed between one and four training sessions because of overuse injuries (shin splints—periostitis tibialis medialis and/or lateralis); however, no acute injuries were registered. Furthermore, one of the subjects suffered from inflammation of the hollow foot tendon (fasciitis plantaris), and another had bilateral unspecific knee pain. The prolonged running sessions consisted of 1 h of continuous running at 80% of individual $HR_{\max}$ approximately 65% of $\dot{V}O_{2\max}$ (as evaluated from the correlation between $\dot{V}O_2$ and HR during the treadmill test). The average number of completed training sessions was 2.5 ± 0.2 per week for the participants in MOD corresponding to a total training time of approximately 1800 min. In the MOD group, two subjects missed training sessions because of overuse injuries similar to those reported for the INT group. The strength-training program consisted of 12 wk of

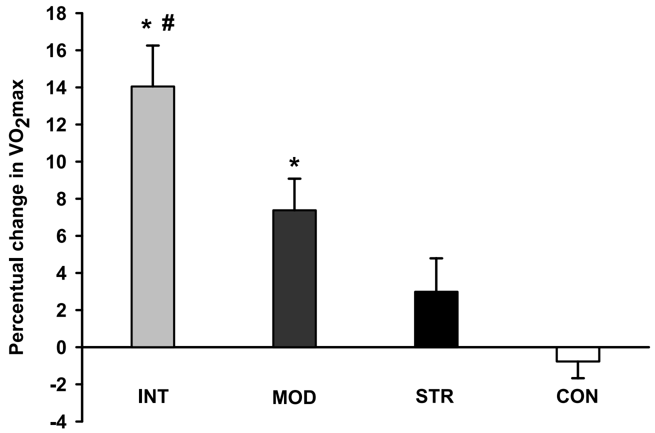

FIGURE 1—Percentage changes in maximal oxygen consumption for the intense interval running (INT), prolonged moderate intense running (MOD), strength training (STR), and control (CON) groups during the 12-wk intervention period. *Significant increase from pre- to posttraining ($P < 0.05$); #Significant larger response compared with the MOD group ($P < 0.05$).

progressive heavy-resistance strength training (2.0 ± 0.1 times a week; total time, ~1500 min). The training consisted of three to four sets of the following exercises: squat, hack squat, incline leg pres, isolated knee extension, hamstring curls, and calf raises. The loads corresponded to 12–16 repetition maximum (RM) during the first 4 wk and 6–10 RM during the remaining 8 wk of the training period, with the absolute loads gradually adjusted to match the individual progressions in muscle strength. The total exercise time was 60 min per session, and the subjects completed training with 1-min breaks between sets (average HR during training, ~50% of HR_{max}).

Statistics. Between- and within-group data were evaluated both by two-factor mixed ANOVA design and with one-way ANOVA on repeated measurement. When a significant interaction was detected, data were subsequently analyzed using a Newman–Keuls *post hoc* test. The significance level was set at $P < 0.05$. Data are presented as means ± SE unless otherwise indicated.

RESULTS

Aerobic fitness and cardiovascular adaptations. Although the total training time in the INT group was less than one-third of the time completed by the two other training groups, the intense interval training induced an increase in maximal oxygen uptake, which was superior to the other two training interventions (Fig. 1). Thus, the improvement in $\dot{V}O_{2max}$ was almost twofold higher in INT as compared with MOD, whereas there were no significant changes in the STR and CON groups. Systolic blood pressure was reduced by 8 mm Hg in all three training groups. In contrast, resting HR and diastolic blood pressure were reduced to a lesser extend in INT compared with MOD (Table 2). The prolonged running group also had a significant increase in capillaries per fiber, whereas capillarization remained unchanged in the INT group. HR during walking and during submaximal running was reduced to a similar degree in the INT and MOD groups (Table 2).

Metabolic fitness. Although aerobic fitness was enhanced in the INT group and the relative exercise intensity at a given submaximal load accordingly became reduced, there were no changes in fat oxidation during walking at 6.5 km·h^{-1} or submaximal running at 9.5 km·h^{-1} (Table 3). Fat oxidation during walking also remained unchanged in the other groups, but energy turnover from fat oxidation was enhanced during submaximal running in the MOD group (Table 3). The enhanced capacity for fat oxidation was not related to changes in HAD activity, and neither HAD nor CS measured in the biopsy from musculus vastus lateralis was significantly changed in any of the three training groups (Table 3).

HDL, LDL, and total cholesterol and accordingly the ratio between total and HDL cholesterol remained unchanged during the 12-wk period in the INT group (Table 3). In contrast, the ratio between total and HDL cholesterol decreased significantly in the MOD group and tended to be lower in STR after the 12 wk of training (see Fig. 2 and Table 3).

Both fasting blood glucose and blood glucose concentration 2 h after oral ingestion of 75 g of glucose were reduced to a similar extent in INT and MOD, whereas fasting glucose

TABLE 2. Aerobic fitness and cardiovascular factors before and after the 12-wk intervention period for the three training groups and controls.

	Intense Interval Running		Prolonged Running		Strength Training		Control	
	Before	After	Before	After	Before	After	Before	After
Resting HR (bpm)	55 ± 2	52 ± 2	59 ± 2	53 ± 2*	57 ± 2	56 ± 2	60 ± 3	61 ± 3
Systolic blood pressure (mm Hg)	127 ± 4	119 ± 4*	131 ± 4	123 ± 3*	129 ± 6	121 ± 4	129 ± 2	127 ± 3
Diastolic blood pressure (mm Hg)	75 ± 4	73 ± 3	81 ± 3	76 ± 2*	82 ± 4	75 ± 3	74 ± 3	76 ± 3
MAP (mm Hg)	92 ± 3	89 ± 3*	98 ± 3	92 ± 3*	97 ± 5	90 ± 3	92 ± 3	92 ± 3
Maximal oxygen uptake (mL·min^{-1}·kg^{-1})	36.3 ± 1.7	41.4 ± 2.2†	39.3 ± 2.5	42.2 ± 1.8†	36.8 ± 3.2	37.9 ± 3.3	39.2 ± 2.7	38.9 ± 2.4
HR (bpm)								
6.5 km·h^{-1}	121 ± 4	112 ± 3*	121 ± 6	107 ± 5*	125 ± 7	121 ± 6	115 ± 3	109 ± 4
9.5 km·h^{-1}	177 ± 3	160 ± 5*	167 ± 5	146 ± 6*	169 ± 6	163 ± 5*	162 ± 6	157 ± 6
Capillaries per fiber	2.2 ± 0.2	2.0 ± 0.2	1.8 ± 0.1	2.1 ± 0.1†	2.0 ± 0.1	2.1 ± 0.1	2.2 ± 0.1	2.3 ± 0.1

Resting values for HR, systolic and diastolic blood pressure, and MAP. Capillarization expressed as capillaries per muscle fiber, exercise values for maximal oxygen uptake, and HR during walking at 6.5 km·h^{-1} and submaximal running at 9.5 km·h^{-1}.

Values are presented as mean ± SE for the four groups.

* Significantly lower than the pretraining value ($P < 0.05$).

† Significantly higher than the pretraining value ($P < 0.05$).

TABLE 3. Indices of metabolic fitness before and after the 12-wk intervention period for the three training groups and controls.

	Intense Interval Running		Prolonged Running		Strength Training		Control	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Fat oxidation during walking ($kJ \cdot min^{-1}$)	10.2 ± 2.7	12.3 ± 2.8	11.5 ± 1.1	11.3 ± 1.5	11.9 ± 1.3	8.8 ± 1.5	13.9 ± 1.6	9.7 ± 2.6
Fat oxidation during running ($kJ \cdot min^{-1}$)	2.8 ± 2.3	4.1 ± 3.0	5.0 ± 3.1	11.1 ± 2.5†	3.0 ± 2.7	2.0 ± 1.5	6.3 ± 2.6	9.9 ± 2.2
Fasting total cholesterol (mM)	5.1 ± 0.2	5.0 ± 0.2	4.1 ± 0.3	3.8 ± 0.4	4.8 ± 0.3	5.3 ± 0.3†	4.1 ± 0.2	4.1 ± 0.3
Fasting HDL cholesterol (mM)	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	1.4 ± 0.1
Fasting LDL cholesterol (mM)	3.4 ± 0.2	3.3 ± 0.3	2.5 ± 0.2	2.4 ± 0.3	3.1 ± 0.3	3.5 ± 0.3	2.7 ± 0.2	2.7 ± 0.2
CS ($\mu mol \cdot g^{-1} \cdot min^{-1}$)	35.5 ± 3.4	37.7 ± 3.2	33.0 ± 2.8	35.4 ± 2.3	41.4 ± 3.4	39.2 ± 2.7	42.1 ± 3.2	37.5 ± 4.4
HAD ($\mu mol \cdot g^{-1} \cdot min^{-1}$)	23.6 ± 1.9	25.9 ± 2.6	28.1 ± 1.9	29.6 ± 2.4	29.3 ± 2.3	26.2 ± 2.6	31.0 ± 1.5	27.6 ± 2.3
Fasting glucose (mM)	5.7 ± 0.2	5.2 ± 0.1*	5.6 ± 0.7	5.1 ± 0.4*	5.3 ± 0.4	5.3 ± 0.3	4.7 ± 0.5	4.9 ± 0.4
OGTT end glucose (mM)	6.1 ± 0.6	5.1 ± 0.4*	5.6 ± 1.5	4.9 ± 1.1*	5.5 ± 0.5	5.7 ± 0.5	5.3 ± 1.7	5.5 ± 1.0
Fasting insulin ($\mu U \cdot mL^{-1}$)	7.1 ± 1.1	7.8 ± 2.2	5.0 ± 1.7	4.1 ± 0.9	7.3 ± 2.5	5.7 ± 1.2	—	—

Fasting values for total, HDL and LDL cholesterol, blood glucose, and insulin concentrations. The oral glucose tolerance test (OGTT) end glucose value represents the blood glucose concentration 2 h after oral ingestion of 75 g of glucose. Citrate synthase (CS; per gram of dry weight muscle) and beta-hydroxyacyl-CoA-dehydrogenase (HAD) activity measured from vastus lateralis muscle biopsy obtained at rest. Fat oxidation during walking and running are the values for energy turnover from fat oxidation during walking at 6.5 $km \cdot h^{-1}$ and running at 9.5 $km \cdot h^{-1}$. Values are presented as mean ± SE for the four groups.

* Significantly lower than the pretraining value ($P < 0.05$).

† Significantly higher than the pretraining value ($P < 0.05$).

and blood glucose response to the OGTT remained unaltered in STR and CON (Table 3). Fasting insulin levels were not changed in any of the three training groups.

Lean body, bone mass, and fat percentage. There were no significant changes in total body weight, total and leg lean body mass, fat percentage, total bone mass, or leg bone mass in the INT group (Table 1). In contrast, MOD training induced a significant reduction in the subject body weight and fat percentage, and the group that performed strength training increased their body weight and had significant increases in total and leg lean body mass (Table 1). Furthermore, the DEXA scans revealed that the STR group had significant increases in total and leg bone mass (Table 1).

DISCUSSION

The present investigation reveals that INT is an effective training stimulus for improvement of cardiorespiratory fitness and glucose tolerance, and in untrained subjects it may induce a significant reduction in systolic blood pressure. However, in relation to the treatment of hyperlipidemia and obesity, it is less effective than prolonged training, and in contrast to strength training, 12 wk of INT had no impact on muscle mass or indices of skeletal health.

Blood pressure, aerobic fitness, and CV risk factors. The present results reveal that brief but intense training has the potential to reduce arterial blood pressure and counteract the development of hypertension. Thus, the group that completed the high-intensity training intervention had a significant reduction in systolic blood pressure and consequently a lowering of the MAP. The 8-mm Hg reduction in systolic pressure was similar to the changes in the MOD and STR groups, whereas diastolic pressure appeared to be less affected in the INT group compared with the MOD group. However, from a statistical perspective, the study included relatively few subjects, and therefore we cannot conclude whether brief intense training is less or equally efficient compared with prolonged moderate-intensity exercise interventions. In contrast, it seems clear that reduction in systolic or MAP after aerobic training is not directly related to the concomitant improvements in cardiorespiratory fitness. Accordingly, the study by Cornelissen et al. (7) supports the findings that reductions in systolic blood pressure are not correlated to changes in $\dot{V}O_{2max}$ because they reported similar reductions in systolic blood pressure after moderate-intensity exercise training and training with a very low intensity, although the low-intensity training had a lower impact on $\dot{V}O_{2max}$ as compared with the moderate-intensity training (7).

The improvement of maximal oxygen consumption and performance during incremental treadmill running test was superior in the INT group compared with the MOD and STR groups, supporting the notion that the training intensity is more important than the training volume for the development of cardiorespiratory fitness (33). However, the larger improvement of cardiorespiratory fitness was not accompanied by superior adaptations in relation to metabolic fitness.

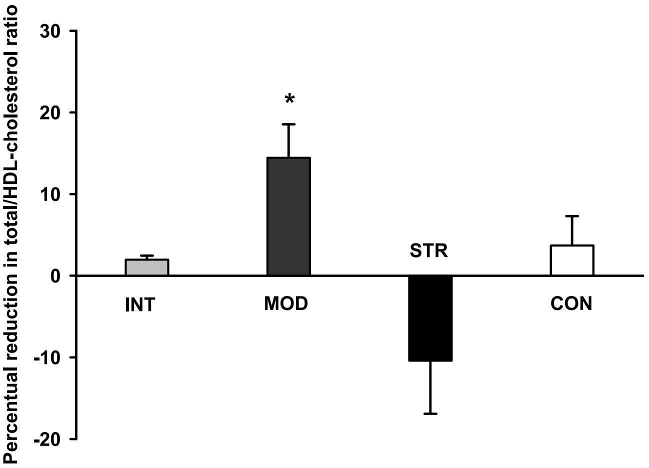

FIGURE 2—Reductions in the ratio between total cholesterol and HDL cholesterol for the intense interval running (INT), prolonged moderate intense running (MOD), strength training (STR), and control (CON) groups during the 12-wk period. *Significant change from pre- to posttraining ($P < 0.05$).

Thus, CS and HAD activity as well as fat oxidation during walking was not significantly altered in any of the three training groups, and only the MOD group appeared to have an improved capacity for fat oxidation during submaximal running. The lack of significant change in CS and HAD activity is in opposition to previous observations in our laboratory after bicycle (24) and soccer training (19) in subjects with a similar starting level. Considering the relatively low number of subjects, there is a risk of a type II error. However, the divergence may also relate to the different exercise modes because soccer and especially bicycling training may provide a strong stimulus for metabolic changes in vastus lateralis, whereas the training modes investigated in the present study do not appear to be as effective for vastus lateralis oxidative enzyme adaptations.

In contrast to the prolonged training program, the intense intermittent training intervention failed to lower the ratio between total and HDL cholesterol. Intense but short-lasting training therefore seems to be less efficient than prolonged training for improving the plasma lipoprotein–lipid profiles in untrained subjects, and in contrast to the stimuli for cardiorespiratory fitness, it seems that training volume rather than intensity is of importance for the improvement of the plasma lipoprotein–lipid profile (9). The observed lipoprotein responses may relate to the concomitant changes in the subjects fat percentage, which was lowered in the MOD group but remained unaltered in the INT group. Accordingly, previous training studies have observed correlations between changes in lipoprotein–lipid profile and loss of body fat (17), and the higher training volume and the larger total energy turnover in MOD compared with INT may explain both the significant loss of body fat and the improved lipoprotein–lipid profile in the MOD group, whereas total energy expenditure may have been insufficient in the INT group. The American College of Sports Medicine concludes that between 150 and 250 min of moderate physical activity per week is needed to counteract weight gain (8), and although the INT intervention induced a significant increase in the subjects aerobic metabolic capacity, it included only 40 min of training per week, with 20 min of high-intensity running and 20 min of low-intensity warm-up activities. It has been speculated that short-term high-intensity interval training could be a time-efficient strategy for health promotion (10), and the present results support that such training may influence some health parameters. However, it also demonstrates that in relation to treatment of hyperlipidemia and obesity, a certain training volume is needed, and the present study therefore supports the previously mentioned recommendations from the American College of Sports Medicine (8,13). Nevertheless, for individuals with the metabolic syndrome and overweight subjects, it appears that an exercise program that includes high-intensity training is more effective than a program that only includes moderate-intensity exercise (28,30,31). Consequently, the total weekly training time may be reduced to some extent when high-intensity bouts are included, but it appears that a certain volume is needed and that the total energy utilization is also of importance.

Glucose tolerance. The present results indicate that INT with a relatively low volume was equally efficient to moderate training with a substantially larger total training volume. Previously, Houmard et al. (16) suggested that the total exercise duration should be considered when designing training programs with the intent of improving insulin action. Thus, they observed that exercise prescription that incorporated approximately 170 min of exercise per week improved insulin sensitivity more substantially than a program using only 115 min of exercise per week—both exercise interventions with intensities comparable with the MOD group in the present study. However, recently the same group (2) concluded that although the weekly exercise duration may be of importance for insulin action measured less than 24 h after the last exercise bout, it appears that moderate-intensity exercise and vigorous-intensity exercise appear to result in similar beneficial long-term effects. The present study supports the later conclusion and indicates that when the intensity is close to maximal, as little as 40 min of training per week may result in similar improvements in glucose tolerance as 150 min of moderate intense exercise per week.

Muscle and bone mass. Both bone and muscle mass were significantly increased after the strength-training intervention, whereas both these parameters remained unchanged in the INT group as well as in the MOD running group. The observation of increased bone mass after 12 wk of strength training indicates that such training besides being an effective stimulus for muscle growth also provides a significant osteogenic stimulus. Similar effects have been demonstrated by intervention studies, which have included strength training for a prolonged period (in general, 1 yr or more (20)). Longitudinal studies also signify that exercise with a so-called high-impact load may provide an effective osteogenic stimulus. For example, it has been observed that short-term participation in intermittent sports such as soccer training increases bone mineral content (19), and cross-sectional studies have demonstrated that participants in sports that are characterized by multiple turns, jumps, and short sprints with accelerations and decelerations have higher bone mass and mineral density compared with sedentary subjects or athletes participating in non-weight-bearing or so-called low-impact sports (12,27). A high strain rate and a large magnitude of ground reaction and muscle forces seem to be important factors for providing the anabolic effect, and the loading pattern in sports that include running at different speeds and in multiple directions appears to be at least as effective as specific strength training (32). However, the present investigation indicates that a training program with "normal" straight forward running, although performed in interval with a high intensity, does not provide the adequate stimulus for enhancing bone mass or strength. In opposition, a recent cross-sectional study by Rector et al. (27) concluded that that long-term running and resistance training increase BMD compared with cycling, and running may have a greater positive effect on BMD than resistance training. The contradicting observation from the cross-sectional study and the present longitudinal investigation may illustrate the pitfall from drawing conclusions from cross-sectional studies because these may be influenced by other factors than the actual training that the subjects have conducted.

In conclusion, the present study investigated various health effects of brief but very intense exercise training, and the marked improvements in cardiovascular fitness, glucose tolerance, and exercise endurance as well as the lowering of systolic blood pressure put emphasis on the potential benefits of high-intensity training and its ability to improve certain physiological health parameters. However, the intense low-volume training regimen had limitations, and for the short-term intervention period, it was less effective than prolonged training in relation to the treatment of hyperlipidemia and obesity. Furthermore, 12 wk of INT had no impact on muscle mass or leg bone mass, whereas strength training besides increasing the subjects muscle mass also provided a significant osteogenic stimulus that may have both acute and prolonged effects for musculoskeletal health.

This study was supported by the Danish Ministry of Culture (Kulturministeriets Udvalg for Idrætsforskning).

The authors acknowledge the great effort by the subjects in the present study. They also thank Jens Bangsbo, Jesper Frank Christensen, Henrik Pedersen, Birgitte Rejkjær Krustrup, Edward Petersen, Mads Bendiksen, and Rikke Leihof for excellent technical support.

REFERENCES

1. Babraj JA, Vollaard NB, Keast C, Guppy FM, Cottrell G, Timmons JA. Extremely short duration high intensity interval training substantially improves insulin action in young healthy males. *BMC Endocr Disord*. 2009;9:3–11.
2. Bajpeyi S, Tanner CJ, Slentz CA, et al. Effect of exercise intensity and volume on persistence of insulin sensitivity during training cessation. *J Appl Physiol*. 2009;106(4):1079–85.
3. Blair S, Connelly J. How much physical activity should we do? The case for moderate amounts and intensities of physical activity. *Res Q Exerc Sport*. 1996;67(2):193–205.
4. Booth FW, Gordon SE, Carlson CJ, Hamilton MT. Waging war on modern chronic diseases: primary prevention through exercise biology. *J Appl Physiol*. 2000;88(2):774–87.
5. Booth FW, Winder WW. Highlighted topic: Role of exercise in reducing the risk of diabetes and obesity. *J Appl Physiol*. 2005; 99(1):3–4.
6. Burgomaster KA, Howarth KR, Phillips SM, et al. Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *J Physiol*. 2008; 586(1):151–60.
7. Cornelissen VA, Verheyden B, Aubert AE, Fagard RH. Effects of aerobic training intensity on resting, exercise and post-exercise blood pressure, heart rate and heart-rate variability. *J Hum Hypertens*. 2010;24(3):175–82.
8. Donnelly JE, Blair SN, Jakicic JM, Manore MM, Rankin JW, Smith BK. American College of Sports Medicine Position Stand. Appropriate physical activity intervention strategies for weight loss and prevention of weight regain for adults. *Med Sci Sports Exerc*. 2009;41(2):459–71.
9. Durstine JL, Grandjean PW, Cox CA, Thompson PD. Lipids, lipoproteins, and exercise. *J Cardiopulm Rehabil*. 2002;22(6):385–98.
10. Gibala MJ. High-intensity interval training: a time-efficient strategy for health promotion? *Curr Sports Med Rep*. 2007;6(4):211–3.
11. Gibala MJ, Little JP, van EM, et al. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J Physiol*. 2006; 575(Pt 3):901–11.
12. Guadalupe-Grau A, Fuentes T, Guerra B, Calbet JA. Exercise and bone mass in adults. *Sports Med*. 2009;39(6):439–68.
13. Haskell WL, Lee IM, Pate RR, et al. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Circulation*. 2007;116(9):1081–93.
14. Hawley JA. Exercise as a therapeutic intervention for the prevention and treatment of insulin resistance. *Diabetes Metab Res Rev*. 2004;20:383–93.
15. Holten MK, Zacho M, Gaster M, Juel C, Wojtaszewski JF, Dela F. Strength training increases insulin-mediated glucose uptake, GLUT4 content, and insulin signaling in skeletal muscle in patients with type 2 diabetes. *Diabetes*. 2004;53(2): 294–305.
16. Houmard JA, Tanner CJ, Slentz CA, Duscha BD, McCartney JS, Kraus WE. Effect of the volume and intensity of exercise training on insulin sensitivity. *J Appl Physiol*. 2004;96(1):101–6.
17. Katzmarzyk PT, Gagnon J, Leon AS, et al. Fitness, fatness, and estimated coronary heart disease risk: the HERITAGE Family Study. *Med Sci Sports Exerc*. 2001;33(4):585–90.
18. Knuttgen HG. Strength training and aerobic exercise: comparison and contrast. *J Strength Cond Res*. 2007;21(3):973–8.
19. Krustrup P, Nielsen JJ, Krustrup B, et al. Recreational soccer is an effective health promoting activity for untrained men. *Br J Sports Med*. 2009;43(11):825–31.
20. Layne JE, Nelson ME. The effects of progressive resistance training on bone density: a review. *Med Sci Sports Exerc*. 1999;31(1): 25–30.
21. Lee CD, Blair SN, Jackson AS. Cardiorespiratory fitness, body composition, and all-cause and cardiovascular disease mortality in men. *Am J Clin Nutr*. 1999;69(3):373–80.
22. Lowry OH, Passonneau JV. Some recent refinements of quantitative histochemical analysis. *Curr Probl Clin Biochem*. 1971;3:63–84.
23. Meka N, Katragadda S, Cherian B, Arora RR. Endurance exercise and resistance training in cardiovascular disease. *Ther Adv Cardiovasc Dis*. 2008;2(2):115–21.
24. Nybo L, Pedersen K, Christensen B, Aagaard P, Brandt N, Kiens B. Impact of carbohydrate supplementation during endurance training on glycogen storage and performance. *Acta Physiol*. 2009;197:117–27.
25. Paffenbarger RJ, Hyde R, Wing A, Lee I, Jung D, Kampert J. The association of changes in physical-activity level and other lifestyle characteristics with mortality among men. *N Engl J Med*. 1993;328(8):538–45.
26. Pedersen BK, Saltin B. Evidence for prescribing exercise as therapy in chronic disease. *Scand J Med Sci Sports*. 2006;16(suppl 1): 3–63.
27. Rector RS, Rogers R, Ruebel M, Widzer MO, Hinton PS. Lean body mass and weight-bearing activity in the prediction of bone

mineral density in physically active men. *J Strength Cond Res*. 2009;23(2):427–35.

27b. Roberts WC. The Friedewald-Levy-Fredrickson formula for calculating low-density lipoprotein cholesterol, the basis for lipid-lowering therapy. *Am J Cardiol*. 1998;62:345–6.

28. Schjerve IE, Tyldum GA, Tjonna AE, et al. Both aerobic endurance and strength training programmes improve cardiovascular health in obese adults. *Clin Sci*. 2008;115:283–93.

29. Stiegler P, Cunliffe A. The role of diet and exercise for the maintenance of fat-free mass and resting metabolic rate during weight loss. *Sports Med*. 2006;36(3):239–62.

30. Tjonna AE, Lee SJ, Rognmo O, et al. Aerobic interval training versus continuous moderate exercise as a treatment for the metabolic syndrome: a pilot study. *Circulation*. 2008;118:346–54.

31. Tjonna AE, Stolen TO, Bye A, et al. Aerobic interval training reduces cardiovascular risk factors more than a multitreatment approach in overweight adolescents. *Clin Sci*. 2009;116:317–26.

32. Von Stengel S, Kemmler W, Kalender WA, Engelke K, Lauber D. Differential effects of strength versus power training on bone mineral density in postmenopausal women: a 2-year longitudinal study. *Br J Sports Med*. 2007;41(10):649–55.

33. Wenger HA, Bell GJ. The interactions of intensity, frequency and duration of exercise training in altering cardiorespiratory fitness. *Sports Med*. 1986;3(5):346–56.