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ORIGINAL ARTICLE

Maximal strength training improves work economy, rate of force development and maximal strength more than conventional strength training

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Abstract This study compared maximal strength training (MST) with equal training volume (kg × sets × repetitions) of conventional strength training (CON) primarily with regard to work economy, and second one repetition maximum (1RM) and rate of force development (RFD) of single leg knee extension. In an intra-individual design, one leg was randomized to knee-extension MST (4 or 5RM) and the other leg to CON (3 × 10RM) three times per week for 8 weeks. MST was performed with maximal concentric mobilization of force while CON was performed with moderate velocity. Eight untrained or moderately trained men (26 ± 1 years) completed the study. The improvement in gross work economy was -0.10 ± 0.08 L min^{-1} larger after MST ($P = 0.011$, between groups). From pre- to post-test the MST and CON improved net work economy with 31 % ($P < 0.001$) and 18 % ($P = 0.01$), respectively. Compared with CON, the improvement in 1RM and dynamic RFD was 13.7 ± 8.4 kg ($P = 0.002$) and 587 ± 679 N s^{-1} ($P = 0.044$) larger after MST, whereas isometric RFD was of borderline significance 3,028 ± 3,674 N s^{-1} ($P = 0.053$). From pre- to post-test, MST improved 1RM and isometric RFD with 50 % ($P < 0.001$) and 155 % ($P < 0.001$), respectively whereas CON improved 1RM and isometric RFD with 35 % ($P < 0.001$) and 83 % ($P = 0.028$), respectively. Anthropometric measures of quadriceps femoris muscle mass and peak oxygen uptake did not change. In conclusion, 8 weeks of MST was more effective than CON for improving work economy,

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1RM and RFD in untrained and moderately trained men. The advantageous effect of MST to improve work economy could be due to larger improvements in 1RM and RFD.

Keywords Knee-extension · Quadriceps femoris · 1RM · Peak force · Power · Endurance performance

Introduction

During endurance performances it is generally thought that by spending as little energy (videlicet oxygen uptake) as possible at a given speed, an individual can either save energy or increase speed and thus improve the endurance performance (Pate and Kriska 1984). This distinct determinant of endurance performance, termed work economy, distinguishes individuals with similar peak oxygen uptakes (VO_{2peak}) (Helgerud et al. 1990). The poor work economy seen in many patients (Heggelund et al. 2012; Hoydal et al. 2007) is often a limiting factor for endurance performances necessary for daily living.

Resistance training improves work economy and endurance performance (Aagaard and Andersen 2010). Beneficial results are found in athletes (Hoff et al. 2002) and patients (Heggelund et al. 2012; Karlsen et al. 2009; Wang et al. 2010), after interventions ranging from explosive plyometric training with low loads (Paavolainen et al. 1999; Mikkola et al. 2007; Spurrs et al. 2003) to explosive maximal strength training with high load (MST) (Hoff et al. 1999, 2002; Karlsen et al. 2009; Kemi et al. 2011; Storen et al. 2008; Sunde et al. 2010; Wang et al. 2010; Barrett-O'Keefe et al. 2012). However, some studies fail to demonstrate improved work economy even though maximal strength improves (Jackson et al. 2007; Aagaard et al. 2011; Losnegard et al. 2011). High volume or multi-exercise protocols did not improve work economy (Ferrauti et al. 2010; Jackson et al. 2007; Losnegard et al. 2011) and combining strength, hypertrophic and power training methods in the same intervention did not improve endurance performance (Levin et al. 2009). Factors such as training status and/or program design variables might at least partly explain the divergent findings, but few attempts have been made to compare effects of different training programs on work economy.

The exact program variables that improve work economy are not evident, but it appears that improved maximal strength and rate of force development (RFD) coincide with improved work economy (Sunde et al. 2010). To improve maximal strength and RFD, it is beneficial to apply a program using heavy loads [>85 % of one repetition maximum (1RM)], few repetitions ($\leq$5), maximal mobilization of force in the concentric part of the movement and long resting periods (>3 min) (Bird et al. 2005; Campos et al. 2002; Cormie et al. 2011). MST utilizes these variables. On the other hand, conventional resistance training programs (CON) employ moderate loads corresponding to 60–70 % of 1RM for a repetition range of 8–12 performed with slow to moderate velocities (Ratamess et al. 2009). The conventional resistance training programs are considered safe for novice training and effective to improve strength and rapid force characteristics for untrained and moderately trained individuals (Ratamess et al. 2009). However, we are not aware of studies that aimed to clarify whether CON could attain the same profitable benefits (i.e. work economy, 1RM, RFD) as found after heavy, explosive strength training (i.e. MST). Comparisons of different strength training interventions are utmost important considering the lack of improvement in work economy in some studies.

The aim of this study was to compare MST with CON of equal training volume. Considering the large inter-individual responses to training, an intra-individual design was chosen. That is, one leg trained MST and the other trained CON. Our primary hypothesis was that MST would be superior to CON in improving work economy. Secondary hypothesis was that MST would be better in improving maximal strength and RFD.

Methods

Subjects

Ten healthy, non-smoking men volunteered for the study. Using an intra-individual design, one leg was randomized to MST and the other to equal volume of CON in a counterbalanced fashion. All but one of the subjects was right leg dominant. Leg dominancy was determined by asking the subjects with which leg they preferred to kick a ball. They were moderately trained or untrained students and were instructed to maintain their normal activity levels and asked not to commence a new training program and not to participate in concurrent strength training during the study period. Subjects did not use knee-extension in their regular training. One subject did not complete the study and one subject was excluded from the analysis because of concurrent strength training. The eight subjects that completed the study were aged 26 ± 1 years, of height 178 ± 7 cm and weighed 79 ± 7 kg. The study was approved by the regional committee for medical and health research ethics, middle Norway and conducted according to the principles of the Helsinki declaration. Written informed consent was obtained from all subjects.

Test procedures

Subjects were instructed to refrain from ingesting food and tobacco products within 3 h before entering the laboratory

(American College of Sports Medicine 2010) and to avoid vigorous exercise or ingest alcohol in the 24 h before testing.

Endurance testing

We built a single leg knee-extension apparatus according to the previously described model (Andersen et al. 1985; Andersen and Saltin 1985; Richardson et al. 1995). Subjects were sitting in the Felax HG-5114 knee extension machine. The padded lever arm used during strength training and strength testing was temporary removed to allow use of the endurance accessory. The leg was fastened to an aluminium-brace that via a bar was connected to the pedal arm of a Monark Ergomedic 839E cycle ergometer (Monark Exercise AB, Varberg, Sweden) behind the subject. The ergometer provides a constant workload independent of pedal speed. The extension was from 90° to 170°. Subjects were not strapped to the seat. We instructed the subject to hold his hands in his lap and to perform the exercise using the knee-extensors only. Subjects were corrected if unwanted movements occurred. Flexion was a passive movement. The bicycle ergometer was calibrated before each test and the friction made by the crank was subtracted to give a valid watt load. One week before pretesting, the subjects spent 20 min training with each leg to become familiarized with the test and improve reproducibility (Andersen et al. 1985; Richardson et al. 1995).

Knee-extension work economy (C_{ke}) and peak oxygen uptake ($VO_{2\mathrm{peak}}$) were measured in the single leg knee-extension apparatus using the Cortex Metamax 3x portable ergospirometry system (Cortex Biophysik GmbH, Leipzig, Germany). The test was performed in a quiet room and subjects were not auditorily or visually disturbed during the work economy test unless the contraction frequency or technique was inadequate. Subjects first performed 6 min at a 20-W workload with a cadence of 60 revolutions per minute (Hoelting et al. 2001). C_{ke} was determined as the average of three measures of 10 s of oxygen uptake between the 4.5th and 5th minutes. After 6 min, blood was sampled from the subject's fingertip and analysed for lactate concentration ($[\mathrm{La}^-]_{\mathrm{bl}}$) using a YSI Sport Lactate Analyzer (Yellow Springs Instruments Co, USA). Thereafter resistance was increase with 5 W every minute until the subject was not able to maintain a frequency higher than 50 revolutions per minute (Hoelting et al. 2001; Radegran et al. 1999). Time to exhaustion (TTE) was determined from the start at 25 W until discontinuance. $VO_{2\mathrm{peak}}$ was determined as the average of the three highest measures. Heart rate was measured (Polar Accurex Plus, Polar Electro, Finland) at 20 W and at $VO_{2\mathrm{peak}}$. Within 1 min after cessation, another blood sample was collected for lactate analysis. The subject then moved to a bicycle ergometer and cycled for at least 10 min at a heart rate corresponding to 70 % $\mathrm{HR}_{\mathrm{max}}$. A Blood sample was collected after 10 min of cycling to ensure removal of lactate. The mean ± SD blood lactate levels were 2.47 ± 0.68 and 2.17 ± 0.32 mmol L^{-1} at pre- and post-test, respectively. Thereafter we carried out the same procedure on the other leg. The leg order was randomized. The net oxygen uptake of the quadriceps femoris muscle (net VO_2) was calculated by subtracting the subjects' oxygen uptake at rest (3.5 ml kg^{-1} min^{-1}) from the gross VO_2. VO_2 was also evaluated using allometric scaling (ml $\mathrm{kg}_{\mathrm{m}}^{-0.67}$ min^{-1}).

Strength and RFD testing

We measured RFD and 1RM in the leg extension machine. A force transducer (Revere Transducers, California, USA) measured force parameters. All tests ensured a 90° flexion in the knee joint. Dynamic force parameters were attained using a 27.6-kg load on the knee-extension apparatus. Isometric force parameters were attained by 6-s maximal isometric contractions. All subjects held their buttocks on the seat, the hip angle steady and the back against the backrest. All procedures were repeated up to three times if the result improved on the second attempt. Subjects rested 3 min between each trial and alternated between the left and right leg. RFD was calculated as the force difference between 10 and 70 % of peak force (PF) at pre-test, divided by the time needed to achieve this difference (i.e. Δforce/Δtime) (Weiss 2000).

1RM was measured in 4–5 trials by successively increasing the load for each lift. Rest periods were 2–3 min between each trial (American College of Sports Medicine 2010). Approved lifts had to reach 160° in the knee joint.

Body fat (BF) was measured using the anthropometric techniques described by Norton et al. (2002) using a Holtain skinfold calipers (Holtain Ltd, Crosswell, Crymych, UK). The same exercise physiologist performed all measurements. Measurements were made on the right side of the upper body, at four sites (biceps, triceps, sub scapular and supra-iliac areas). Body density × 10^3 (kg/m^3) was estimated from Eq. 1 (Durnin and Womersley 1974):

$$\text{Density} = 1.1631 - 0.0632 \times \log S_{\mathrm{fold}}) \tag{1}$$

Body fat (BF) was calculated using Eq. 2 (Norton et al. 2002):

$$\%\text{BF} = (4.95 \times \text{density}^{-1} - 4.5) \times 100 \tag{2}$$

Quadriceps femoris muscle volume (V) in litres was calculated for both legs from Eq. 3 (Radegran et al. 1999):

$$V = L_{\mathrm{m}} \times (12\pi)^{-1} \times (\mathrm{O1}^2 + \mathrm{O2}^2 + \mathrm{O3}^2) - (S_{\mathrm{fold}} - 0.4) \times 2^{-1} \times L_{\mathrm{m}} \times (\mathrm{O1} + \mathrm{O2} + \mathrm{O3}) \times 3^{-1}/1{,}000 \tag{3}$$

L_m is the estimated muscle length measured as distance between the horizontal level through the pubic tubercle and the patellar basis (Radegran et al. 1999); O1, O2, O3 are the circumferences 10 cm above the middle, at the middle and 10 cm below the middle of the segment of the muscle length, respectively, and S_{fold} is the correction for subcutaneous fat measured by skinfold calipers at each circumference ($\Sigma\, S_{\text{fold}}/3$). Quadriceps femoris muscle mass (kg_m) was calculated from Eq. 4 (Andersen and Saltin 1985):

$$\text{kg}_m = 0.307 \times V + 0.353\,\text{kg}. \tag{4}$$

Training procedures

Training sessions started with a 5-min warm-up on a bicycle ergometer followed by three sets of 8–10 repetitions with a weight load approximately 40–50 % of 1RM in the knee-extension machine (Felax, Healthlife HG-5114, China).

All subjects started training on their dominant leg, that is, half of the subjects started with MST and half of the subjects with CON. After finishing the training in their dominant leg, subjects performed the other intervention using their non-dominant leg. The two training programs were equal with respect to training volume; hence the CON training was three sets of 10RM and the MST alternated each training session between four and five sets of 5RM (i.e. 85–95 % of 1RM). MST was carried out using maximal mobilization of force in the concentric muscle action. Resting was set to 3 min between each set. CON was performed according to the American College of Sports Medicine (ACSM) (Ratamess et al. 2009) guidelines with 10RM (i.e. 60–70 % of 1RM) which is considered a moderate intensity for 3 consecutive sets with moderate velocity and 1 min rest periods between each set. When a subject successfully executed the determined number of repetitions, the load was increased by approximately 1.25–2.5 kg in the next training session. An exercise physiologist supervised all training sessions.

Statistical analysis

Statistics were calculated using SPSS 17 for Windows. All values are expressed as mean ± standard deviation (SD) unless otherwise noted. The normality of the distribution of scores was assessed using the Kolmogorov–Smirnov test and by evaluating the skewness and kurtosis values. We then used the Paired samples *t* test to determine changes from pre- to post-test as well as to evaluate difference in pre to post changes between the MST leg and CON leg. Results were considered statistically significant at $P < 0.05$. We calculated Cohens' *d* effect size to evaluate the strength of the relationship of pre- to post-test changes between MST and CON. 0.2 is small, 0.5 is medium and >0.8 is considered a large effect size.

Results

Eight subjects completed the training period and carried out 93.3 % (±8.3 %) of the planned training sessions.

As demonstrated in Table 1, a significant difference in change was noted between training conditions in C_{ke} (ml kg_m^{-1} min^{-1}; $P < 0.024$). Cohens' *d* was >0.8 or higher for between groups differences, indicating a large effect in favour of the MST. Both MST ($P < 0.001$) and CON ($P < 0.01$) improved net C_{ke} from pre- to post-test (Fig. 1). The change in C_{ke} occurred without changes in

Table 1 Work economy during 20 W single leg knee-extension (C_{ke}) before and after 8 weeks training

	Maximal strength training ($n = 8$)			Conventional strength training ($n = 8$)			Pre–post between groups change		
	Pre-test	Post-test	*P*	Pre-test	Post-test	*P*	Mean ± SD	Cohens' *d*	*P*
Gross oxygen uptake (L min^{-1})	0.98 ± 0.10	0.77 ± 0.12	<0.001	0.95 ± 0.09	0.83 ± 0.13	0.009	−0.10 ± 0.08	0.94	0.011
Net oxygen uptake									
ml kg_m^{-1} min^{-1}	278.3 ± 35.3	191.9 ± 46.2	<0.001	266.9 ± 36.6	216.3 ± 46.7	0.01	−35.9 ± 35.3	0.79	0.024
ml $\text{kg}_m^{-0.67}$ min^{-1}	377.8 ± 41.9	262.2 ± 61.4	<0.001	361.3 ± 39.0	295.2 ± 60.3	0.01	−49.4 ± 45.9	0.84	0.019
HR (beats min^{-1})	103 ± 13	99 ± 14	0.048	102 ± 12	99 ± 13	0.192	0 ± 6	0.02	0.954
V_E (L min^{-1})	26.4 ± 3.5	20.1 ± 4.2	<0.001	25.2 ± 2.8	22.2 ± 4.9	0.023	−3.4 ± 3.8	1.02	0.041
RER	0.91 ± 0.06	0.93 ± 0.07	0.268	0.92 ± 0.05	0.95 ± 0.05	0.031	−0.01 ± 0.08	0.26	0.659
$[\text{La}^-]_{\text{bl}}$ (mmol L^{-1})	2.1 ± 0.7	2.0 ± 0.5	0.498	1.6 ± 0.6	1.7 ± 0.6	0.336	−0.2 ± 0.9	0.16	0.633

Values are mean ± SD

Net oxygen uptake, gross oxygen uptake minus 3.5 ml kg^{-1} min^{-1}; Kg_m, quadriceps femoris muscle mass; HR, heart rate; V_E, ventilation; RER, respiratory exchange ratio; $[\text{La}^-]_{\text{bl}}$, blood lactate concentration

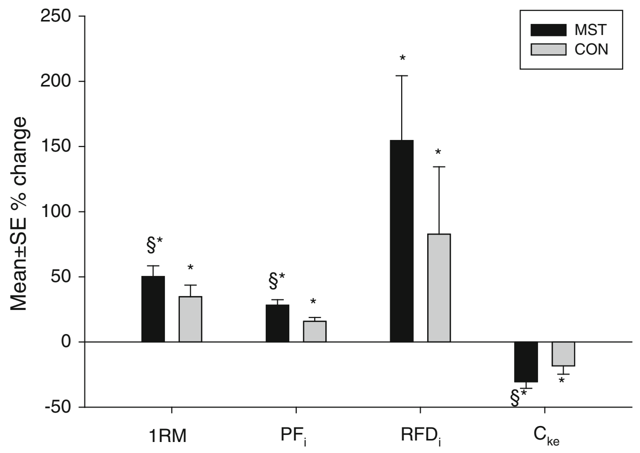

Fig. 1 Per cent changes from pre- to post-test in the maximal strength trained ($n = 8$) and the conventionally strength trained ($n = 8$) legs. *1RM* one repetition maximum, PF_i isometric peak force, RFD_i isometric rate of force development, C_{ke} knee-extension economy in ml kg_m^{-1} min^{-1}. *$P < 0.05$, changes from pre- to post-test. $^{\S}P < 0.05$, between group differences

VO_{2peak} (Table 2). TTE did not change within each group from pre- to post-test nor did the change differ between groups (Table 2).

As demonstrated in Table 3, significant differences in change were noted between training conditions on paired *t* tests for 1RM ($P = 0.002$), isometric PF (PF_i) ($P = 0.010$) and dynamic RFD (RFD_d) ($P = 0.044$). The between-groups change in isometric RFD (RFD_i) was of borderline significance ($P = 0.053$). Cohens' *d* was 1.1 or higher for between-groups differences in 1RM, PF and RFD tests, indicating a large effect in favour of the MST. 1RM, PF and RFD improved in both groups from pre- to post-test (Table 3; Fig. 1).

Quadriceps femoris muscle mass (kg_m) and volume are presented in Table 4. There was no significant change in kg_m from pre- to post-test in the MST group ($P = 0.12$) or in the CON group ($P = 0.20$). There were neither changes in total body mass (kg) nor total body fat after the training period ($P > 0.05$). Percentage body fat was 16.2 ± 1.6 % at pre-test and 15.5 ± 2.2 % at post-test.

Discussion

The main finding was that work economy improved more after heavy, explosive strength training (i.e. MST) than after conventional strength training (i.e. CON). Secondary findings were that MST also was more effective in improving maximal strength and dynamic RFD.

Work economy

Work economy was improved with 30 and 17 % after MST and CON, respectively. Studies indicate improvements from MST in the region of 5–28 % with the variation probably explained by different levels of training experience among subjects, muscle groups trained and methods of measuring work economy (Hoff et al. 1999, 2002; Osteras et al. 2002; Storen et al. 2008; Sunde et al. 2010; Wang et al. 2010). Hence, the 30 % improvement in the present study is in the upper range compared with the previous studies. This could be explained by the high similarity between the knee-extension strength training exercise and the knee-extension endurance exercise.

CON also improved work economy in this study, but the improvement was only ~half that of the MST. The CON intervention is not previously investigated but some studies have used similar training variables. These studies tend to combine different techniques in a periodised fashion or combine a number of resistance training exercises (Guglielmo et al. 2009; Hickson et al. 1988; Jackson et al. 2007; Johnson et al. 1997; Losnegard et al. 2011; Taipale et al. 2010; Aagaard et al. 2011), which makes it difficult to know what the important program variables are for improving work economy. These studies show ambiguous findings and some conclude that strength training does not improve work economy.

The foremost aim of improving work economy is to improve endurance performance. However, the measure of endurance performance did not improve in this study. This could be due to the test procedure. During the test, we successively increased load (5 W each minute) until exhaustion. This progressive protocol in a single-leg exercise probably curtailed improvements in TTE. Others have found improved endurance performance after resistance training in combination with/or without improved work economy (Aagaard et al. 2011; Losnegard et al. 2011; Storen et al. 2008; Sunde et al. 2010).

Maximal strength

1RM improved in MST and CON by 50 and 35 %, respectively. MST improved maximal strength substantially and statistically significantly more than CON. This is in agreement with the findings of Campos et al. (2002) that 3–5RM in four sets and 3-min rest periods was more effective than 9–11RM for three sets and 2-min rest periods. In contrast, Guglielmo et al. (2009) found that 12RM explosive training improved 1RM more than 6RM heavy weight training. However, emphasis on explosive performance in the 12RM group might underlie this favourable adaptation. Here the volume was equalized, whereas the differences between interventions were intensity, number of repetitions, length of rest period between sets and the maximal versus intended slow velocity. Thus, some or all of these factors must have contributed to the superior change after MST.

Table 2 Peak oxygen uptake during leg knee-extension before and after 8 weeks' training

	Maximal strength training ($n = 8$)			Conventional strength training ($n = 8$)			Between groups
	Pre-test	Post-test	P	Pre-test	Post-test	P	P
Gross oxygen uptake (L min^{-1})	1.73 ± 0.13	1.71 ± 0.34	0.898	1.81 ± 0.23	1.80 ± 0.37	0.877	0.950
Net oxygen uptake (ml kg_m^{-1} min^{-1})	574.8 ± 67.7	552.6 ± 86.0	0.583	607.5 ± 90.1	584.7 ± 98.0	0.324	0.979
HR (beats min^{-1})	143 ± 13	138 ± 23	0.683	150 ± 18	148 ± 25	0.694	0.757
V_E (L min^{-1})	58.1 ± 14.3	55.9 ± 19.8	0.706	61.8 ± 16.0	62.5 ± 18.1	0.794	0.511
RER	1.06 ± 0.06	1.07 ± 0.08	0.599	1.11 ± 0.16	1.12 ± 0.9	0.830	0.824
$[\text{La}^-]_\text{bl}$ (mmol L^{-1})	4.1 ± 0.7	3.9 ± 0.7	0.818	4.1 ± 1.2	4.5 ± 1.0	0.122	0.125
Maximal work load (W)	53 ± 8	57 ± 10	0.197	55 ± 13	59 ± 13	0.142	1.000
TTE (min)	6.38 ± 1.65	7.12 ± 2.06	0.162	6.84 ± 2.51	7.73 ± 2.57	0.123	0.714

Net oxygen uptake, gross oxygen uptake minus 3.5 ml kg^{-1} min^{-1}; Kg_m, quadriceps femoris muscle mass; HR, heart rate; V_E, ventilation; RER, respiratory exchange ratio; $[\text{La}^-]_\text{bl}$, blood lactate concentration; TTE, time to exhaustion

Table 3 Maximal and rapid force characteristics measures before and after 8 weeks' training

	Maximal strength training ($n = 8$)			Conventional strength training ($n = 8$)			Pre–post between groups change		
	Pre-test	Post-test	P	Pre-test	Post-test	P	Mean ± SD	Cohens' d	P
1RM (kg)	79.0 ± 18.9	116.2 ± 20.2	<0.001	78.8 ± 19.6	102.4 ± 14.2	<0.001	13.7 ± 8.4	1.07	0.002
RFD_d (N s^{-1})	2,093 ± 852	3,038 ± 837	<0.001	2,061 ± 808	2,419 ± 1,015	0.030	587 ± 679	1.46	0.044
RFD_i (N s^{-1})	5,473 ± 3,255	11,046 ± 3,554	<0.001	5,181 ± 3,252	7,727 ± 3,936	0.028	3,028 ± 3,674	1.11	0.053
PF_d (N)	412 ± 42	526 ± 46	<0.001	424 ± 33	491 ± 53	0.001	47 ± 45	1.16	0.021
PF_i (N)	1,027 ± 266	1,524 ± 247	<0.001	1,043 ± 235	1,293 ± 226	0.004	248 ± 199	1.35	0.010

Values are mean ± SD

1RM, one repetition maximum; RFD_d, dynamic rate of force development; RFD_i, isometric rate of force development; PF_d, dynamic peak force; PF_i, isometric peak force

Table 4 Anthropometric measurements of the thighs before and after the training period

	Maximal strength training ($n = 8$)			Conventional strength training ($n = 8$)			Between groups
	Pre-test	Post-test	P	Pre-test	Post-test	P	P
Quadriceps muscle volume (L)	7.17 ± 1.15	7.29 ± 1.01	0.197	7.13 ± 1.12	7.30 ± 1.16	0.118	0.675
Quadriceps muscle mass (kg)	2.55 ± 0.36	2.59 ± 0.31	0.198	2.54 ± 0.35	2.59 ± 0.36	0.116	0.673
Mid-thigh girth (cm)	53.9 ± 2.6	54.5 ± 1.8	0.273	53.7 ± 2.9	54.5 ± 2.4	0.099	0.540
Front thigh skinfold (cm)	1.2 ± 0.2	1.2 ± 0.3	0.844	1.3 ± 0.2	1.3 ± 0.3	0.871	1.000

Values are mean ± SD

Rate of force development

Both groups improved PF and RFD in both the dynamic and isometric muscle actions. The change was larger after MST for all variables apart from the RFD_i, which was of borderline significance, and the effect sizes suggest a strong effect in favour of MST. The RFD_i improved by 155 and 83 % in the MST and CON, respectively. Although MST was performed with heavy weights which cannot be moved at a high velocity, it was still very effective in improving explosive force measurements. This is in line with Behm and Sale (1993) who suggested that the intentional velocity is more important than the actual velocity. However, CON, with moderate repetition velocity also improved RFD, although to a lesser extent than MST.

Program variables that could improve work economy

This study indicates that a resistance training program that is most effective in improving maximal strength and RFD is superior for improving work economy. As all variables improved in both conditions, it seems reasonable that responsible mechanisms underlying improved work economy were similar for the two interventions although of a greater magnitude with MST.

To improve 1RM and RFD, program variables such as high intensity (>85 %) in few repetitions (≤5), maximal mobilization of force and long rest periods are recommended (3 min) (Bird et al. 2005; Campos et al. 2002; Cormie et al. 2011). Plyometric training using no/or low loads but explosive performance may also improve work economy (Mikkola et al. 2007; Paavolainen et al. 1999; Spurrs et al. 2003). Thus, repetition velocity, or rather intentional velocity, could be a likely candidate for the larger increase in work economy for MST than CON. Interestingly, Guglielmo et al. (2009) concluded that heavy weight training with moderate repetition velocity (6RM) improved work economy, whereas explosive strength training using a moderate load (12RM) did not. This is surprising considering that the 12RM group improved maximal strength more than the 6RM group did. Nevertheless, the collective studies suggest that both high intentional velocity and heavy loads are important factors for improving work economy. Combining these two factors may yield the most potent stimuli explaining why MST has consistently improved work economy in the past (Hoff et al. 1999, 2002; Karlsen et al. 2009; Kemi et al. 2011; Osteras et al. 2002; Storen et al. 2008; Sunde et al. 2010; Wang et al. 2010) and in this study appears to be better than CON. From these findings, we may suggest that the reason why work economy improves more with MST is linked to the greater improvement in both 1RM and/or RFD together.

Implications

Work economy is a major determinant of endurance performances. In real life, these performances may range from athletic competitions and all out performances to day-to-day activities in patients with reduced physical fitness. In some groups of patients such as chronic obstructive pulmonary disease and schizophrenia, the work economy is at a level that challenges the performance of physical activities and may lead to reduced quality of life. This study clearly advocates MST using heavy loads and explosive performance to improve work economy. By training MST the work economy improved by 31 %. In other words, an individual now has the ability to perform more work or to perform the same amount of work with reduced effort. This would likely have significant practical implications, particularly in individuals with reduced work economy.

Strengths and limitations

This study is the first to evaluate strength-training adaptations on work economy using the single leg kneeextension apparatus. The advantage of the model is that it enables investigation of variables under high internal validity. Training as well as measures of 1RM, RFD and C_{ke} is performed in the same apparatus. Furthermore, lack of familiarization to the resistance exercise might partly explain large improvements seen in this study. The anthropometric estimates used in this study did not reveal any changes although more sensitive measures of muscle morphology (i.e. MRI, DEXA or biopsies) may have detected changes. Employing an intra-individual design with unilateral training may obviously have caused cross-education. Cross-education is at least partly caused by enhanced neural drive to the contra lateral agonist muscle (Fimland et al. 2009). However, we consider this disadvantage to be outweighed by the fact that there is a considerable inter-individual variation to strength training adaptations. In addition, the magnitude of cross-education depends on the improvement in the trained leg. Hence, the improvements after CON might have been increased by the greater improvements of the MST leg.

Several hypotheses were tested in this study. The risk for a chance finding is therefore possible. However, adjusting the *P* values would greatly increase the risk of a type II error. This must be taken into consideration when interpreting the results.

Conclusion

Eight weeks of MST is more effective than CON for untrained and moderately trained men in improving work economy, maximal strength and RFD. Training with high loads, few repetitions and maximal mobilization of force in the concentric action is therefore recommended for vast improvements of these parameters, important for performance in athletic- and daily life activities.

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