Journal of Strength and Conditioning Research, 2006, 20(2), 372–377

Effects of Vascular Occlusion on Muscular Endurance in Dynamic Knee Extension Exercise at Different Submaximal Loads

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Abstract. Wernbom, M., J. Augustsson, and R. Thomeé. Effects of vascular occlusion on muscular endurance in dynamic knee extension exercise at different submaximal loads. *J. Strength Cond. Res. 20(2):372–377. 2006.*—Strength training with low load under conditions of vascular occlusion has been proposed as an alternative to heavy-resistance exercise in the rehabilitation setting, when large forces acting upon the musculoskeletal system are unwanted. Little is known, however, about the relative intensity at which occlusion of blood flow significantly reduces dynamic muscular endurance and, hence, when it may increase the training effect. The purpose of this study was to investigate endurance during dynamic knee extension at different loads with and without cuff occlusion. Sixteen subjects (20–45 years of age) with strength-training experience were recruited. At 4 test sessions, the subjects performed unilateral knee extensions to failure with and without a pressure cuff around the thigh at 20, 30, 40, and 50% of their 1 repetition maximum (1RM). The pressure cuff was inflated to 200 mm Hg during exercise with occlusion. Significant differences in the number of repetitions performed were found between occluded and nonoccluded conditions for loads of 20, 30, and 40% of 1RM ($p < 0.01$) but not for the 50% load ($p = 0.465$). Thus, the application of a pressure cuff around the thigh appears to reduce dynamic knee extension endurance more at a low load than at a moderate load. These results may have implications regarding when it could be useful to apply a tourniquet in order to increase the rate of fatigue and perhaps also the resulting training effect. However, the short- and long-term safety of training under ischemic conditions needs to be addressed in both healthy and less healthy populations. Furthermore, the high acute pain ratings and the delayed-onset muscle soreness associated with this type of training may limit its potential use to highly motivated individuals.

Key Words. ischemia, quadriceps, low-intensity strength training, cuff occlusion, delayed-onset muscle soreness

Introduction

Strength training is an important tool in the prevention and rehabilitation of injuries (17). Intensity or load is generally regarded as the most important variable in the prescription of strength training (18). It is commonly agreed among researchers and authors (4, 6, 10, 17, 18, 22) that the intensity has to reach levels of at least 60% of the maximum in order to stimulate increases in strength and that the largest strength gains occur when the training load is between 80 and 100% of the maximum weight that can be lifted only once (1 repetition maximum [1RM]). Training programs aiming to stimulate muscle hypertrophy generally prescribe a load of 6–12RM, corresponding to about 70–85% of 1RM (4, 10, 17, 18, 22).

In the therapeutic setting, however, it is often difficult and sometimes even contraindicated to use such heavy loads as 70–85% of 1RM or more (e.g., early rehabilitation after a sports injury). This is a problem because of the atrophy that often takes place in the muscles in the injured area. For example, differences in quadriceps strength and volume on the order of ~10% between the injured and the uninjured sides may persist for several years after reconstruction of the anterior cruciate ligament (ACL) (5); thus, there is a need for effective therapeutic alternatives to heavy-resistance exercise to counteract the atrophy and the impairment in muscle function that occurs during the early postoperative phase after ACL reconstruction.

Two groups of scientists from Japan (37, 46) tested the hypothesis that training with a relatively low resistance under conditions of reduced blood flow (i.e., ischemia) would stimulate increases in strength. They used tourniquet cuffs to partially restrict the blood flow to the working muscles and thus to increase the rate of fatigue. Their studies (1, 2, 37, 45–47) have shown that low- to moderate-intensity (20–50% of 1RM) resistance training under conditions of vascular occlusion can lead to considerable increases in strength and muscle volume, similar to conventional resistance training with heavy loads.

In light of these findings, ischemic strength training appears well worth further investigation in rehabilitation and other contexts. Indeed, Ohta and colleagues (31) demonstrated superior results for low-intensity training with pressure cuffs compared with performing the same exercises without occlusion in patients who had undergone reconstruction of the ACL.

Studies (12, 24) investigating the static endurance of various muscle groups have shown that the difference in endurance between conditions of cuff occlusion and nonocclusion disappears when the force level reaches ~40–60% of maximal voluntary isometric action (MVIA). This can be explained by the intramuscular occlusion of the blood flow that occurs because of the high pressure in the muscle (35, 36, 38). To our knowledge, no study has investigated the effects of cuff occlusion on endurance during conventional dynamic resistance training with coupled concentric-eccentric actions. Hence, it is difficult to say anything about the load below which it may be an advantage to use a pressure cuff in order to increase the rate of fatigue and possibly also the training effect. Therefore, the purpose of the present study was to investigate dynamic endurance of the quadriceps muscle during external occlusion of the blood flow by a tourniquet cuff and to compare it with the endurance without a cuff at different submaximal loads. During pilot studies, we observed that training performed to exhaustion with multiple sets

TABLE 1. Subject characteristics.

	n	Mean	*SD*
Women	3		
Men	13		
Age (y)		27.9	6.1
Height (cm)		181.3	7.9
Weight (kg)		86.5	11.8

of low to moderate loads gave rise to acute ischemic muscle pain as well as delayed-onset muscle soreness (DOMS) regardless of whether a cuff was used. Thus, a secondary purpose was to collect data regarding acute pain and DOMS ratings and to compare pain and soreness ratings between occluded and nonoccluded conditions.

The null hypothesis was that there would be no significant difference in endurance, pain ratings, and DOMS between conditions of cuff occlusion and nonocclusion.

METHODS

Experimental Approach to the Problem

To examine the effects of vascular occlusion on dynamic knee extension endurance, a within-subjects study design was used in which one leg was tested with cuff occlusion and the other leg was tested without occlusion in a randomized fashion. The order of the conditions was also randomized and then remained the same throughout the study.

Subjects

Sixteen healthy persons (13 men and 3 women, 20–45 years of age) who exercised on a regular basis in a local fitness center volunteered for the study (Table 1). The participants had several years of experience in strength training, but none competed in bodybuilding, weightlifting, or power lifting. They were considered to be in a relatively steady state in their strength development, and no dramatic changes in their strength could be expected during the time course of the study. The subjects were permitted to train their quadriceps as usual except for 4 days before each test and for 3 days afterward, for ratings of DOMS were part of the study. They were informed about the procedures and potential risks of the tests before their informed consent was obtained. The Human Ethics Committee at the Faculty of Medicine, Göteborg University, Göteborg, Sweden, approved the study.

Strength-Testing Procedures

The subjects were tested for their unilateral 1RM strength for each leg in a variable resistance knee extension machine (Leg Extension FL130, Competition Line, Borås, Sweden). Because they were all familiar with the dynamic knee extension exercise, only 1 session was devoted to strength testing. The 1RM was established according to the procedures of Staron et al. (40).

Endurance-Testing Procedures

At 4 subsequent sessions after the 1RM testing, with at least 10 days between each session, the subjects were tested for their endurance in the knee extension exercise. The loads were 50, 40, 20, and 30% of 1RM for the first, second, third, and fourth sessions. This test order was chosen to allow for gradual familiarization to the pain level. A pressure cuff of 135 mm in width, with a 100-mm wide pneumatic bag inside, was connected to a surgical tourniquet system (Zimmer A.T.S. 2000, Zimmer Patient Care, Dover, OH) with automatic regulation of the pressure. The cuff was wrapped around the proximal part of the thigh and inflated to a pressure of 200 mm Hg just before exercise with external occlusion and deflated to 0 during the rest periods in between. After a warm-up, the subjects performed as many repetitions as possible for a total of 4 sets for each leg. The rest period between each set was 45 seconds for both the nonoccluded and the occluded conditions. The range of motion was between 105 and 5° of knee flexion (0° = full extension) and the tempo was set at 30 repetitions per minute (1 second each for the concentric and the eccentric action) with a metronome. This rate was based on the subjects' self-selected cadence during pilot trials. No rest was permitted between the repetitions, and the weight stack was allowed to touch down only very lightly to avoid relaxation of the quadriceps. The number of repetitions performed in the first set was noted as a measure of endurance. Hoeger et al. (25) showed a test-retest reliability of $r = 0.86–0.96$ for knee extension endurance tests at loads of between 40 and 60% of 1RM when performed in a similar continual cadence as in our study and $r = 0.98$ for the 1RM test.

Ratings of Pain, Perceived Exertion, and DOMS

At the end of both the occluded and the nonoccluded endurance protocols, the subjects were asked to use the Borg CR-10 scale (13) to rate the pain in their quadriceps at its worst. The value of 10 was anchored as "the worst lactic acid pain you have ever experienced in your quadriceps," and the subjects were allowed to mark even higher values if they felt that they had exceeded this. The maximum possible value was denoted as 12. The subjects were also asked to use a Borg RPE scale (13) to rate their maximum local perceived exertion. For the 40 and 20% of 1RM tests, the subjects were given a visual analog scale (VAS) to rate their soreness at baseline (before the tests) and every 24 hours thereafter until any eventual DOMS had subsided. The 0 value for the VAS was designated as "no soreness at all," and the maximum value of 10 was "extreme muscle soreness." The VAS has been used in several studies on DOMS (7, 39, 48, 49).

Statistical Analyses

Power analysis on data from pilot studies revealed that in order to detect a 3% difference in endurance, at least 13 participants were required to achieve a power of 0.90.

Differences in the number of repetitions between the occluded and the nonoccluded test conditions were computed by using a paired-samples t-test. The Friedman test and the Wilcoxon signed rank test were used to determine differences in Borg RPE, Borg CR-10, and DOMS ratings. Means and *SD*s were calculated for the number of repetitions, whereas median and interquartile ranges were computed for the Borg RPE, Borg CR-10, and DOMS ratings (ordinal). Significance was accepted at the alpha level of $p \leq 0.05$.

RESULTS

Significant differences in the number of repetitions performed were found between the occluded and the nonoccluded conditions for loads of 20, 30, and 40% of 1RM ($p < 0.01$) but not for the 50% load ($p = 0.465$) (Figure 1). Pain ratings were significantly higher for the occluded

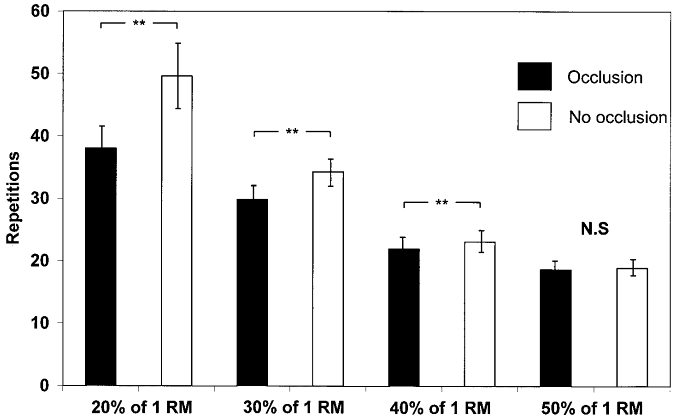

Figure 1. Maximal number of repetitions performed under occluded and nonoccluded conditions for loads of 20, 30, 40, and 50% of 1 repetition maximum. Values are expressed as mean ± *SD*. ** Difference ($p < 0.01$) from occluded condition.

condition compared with the nonoccluded condition for all loads ($p < 0.05$) except for the 20% load ($p = 0.112$) (Table 2). There were no significant differences between loads for either the occluded or the nonoccluded condition. Borg RPE values were not different between occluded and nonoccluded conditions for any load. For the DOMS ratings, no significant differences were noted between occluded and nonoccluded conditions for any load (Table 2).

Discussion

The major finding of the current study was that severe restriction of blood flow with a thigh tourniquet cuff had no influence on the endurance in the dynamic knee extension exercise at an intensity of 50% of 1RM. In contrast, the external compression had a markedly negative impact on the endurance at the 20% load. The most simplistic explanation for these results is that the intramuscular pressure, which rises in proportion to the force developed by the muscle (35), may reach levels high enough to cause serious impediment of the blood flow during dynamic resistance exercise with moderate loads (23).

Isokinetic data from Dudley et al. (16) suggest that the maximum torque capability of the quadriceps during slow concentric actions ($40–90°\cdot s^{-1}$) is on the order of ~70–90% of the isometric maximum. A 1RM may thus represent up to 70–90% of the MVIA in terms of the force developed by the muscle. Because the ratio of force to intramuscular pressure is the same for concentric and isometric actions (42), the force level at which a state of occlusion is reached may also be similar for these types of actions. The results from the current study therefore seem to agree with previous studies that have shown that the blood flow to the quadriceps is insufficient from force levels of ~15–25% of MVIA and upwards, approaching 0 at ~50% of MVIA (19, 28, 38). The results are also in line with a recent study by Hisaeda et al. (24), who showed no significant differences in endurance for static knee extension between conditions of external occlusion and without occlusion at 50% of MVIA.

During exercise, blood flow occurs mainly in the relaxation period between muscle actions (41, 50). In the current study, the rest periods between the repetitions were eliminated and each set was thus performed in a nonstop manner until failure. If rest periods even as short as 1–2 seconds had been included, the results would probably have been different, because the muscle blood flow becomes maximal almost instantly after relaxation of the working muscle (8).

A certain degree of caution should be taken when interpreting the results from the current study. First, the subjects were trained. This may have important implications for the degree of intramuscular pressure, which depends on the absolute force and the architectural features of the muscle (35, 36). Thick, bulging muscles generate higher levels of pressure than do long, slender ones with parallel fibers, and the more curved the muscle fiber is, the greater is the force component directed toward the center of the muscle (36, 42). Because hypertrophied muscles have a larger degree of pennation as well as greater thickness and volume (27), it is likely that a muscle of a strong person occludes its own blood flow at a lower relative force level than that of a weaker person (9, 26). Second, the results could vary with different knee extension machines because of the unique torque characteristics of each machine.

As expected, low- to moderate-load strength training with restricted blood flow was associated with considerable pain because of the ischemia and accumulation of metabolites in the quadriceps. The pain ratings were generally higher for the occluded condition. When questioned, however, most subjects reported that they experienced the most severe pain immediately after the end of each set in the occluded condition, just before the cuff was deflated. During the exercise itself, there appeared to be little or no difference between exercising with and without a tourniquet cuff. The Borg RPE values were generally high, as expected considering that the subjects performed all-out sets.

To our knowledge, no studies have reported DOMS after resistance exercise at such low intensities as 20% of 1RM. The soreness ratings for the 20% load are comparable with values reported by Sorichter et al. (39), whose subjects performed 7 sets of 10 pure eccentric actions in

Table 2. Median and interquartile ranges for delayed-onset muscle soreness (DOMS), pain, and exertion ratings for the occluded and the nonoccluded test conditions.

	Occluded				Nonoccluded			
Variables	20%	30%	40%	50%	20%	30%	40%	50%
DOMS	5.5 (2.6)		5.5 (6.0)		7.0 (3.8)		6.0 (4.8)	
Pain	9.5 (3.5)	10.0 (1.5)*	10.0 (3.0)†	9.0 (3.0)‡	8.5 (3.5)	8.0 (3.0)	8.0 (4.0)	7.0 (2.0)
Exertion	19.0 (2.0)	18.0 (2.2)	19.0 (3.0)	17.0 (2.0)	18.0 (2.0)	17.5 (2.2)	19.0 (1.0)	18.0 (2.2)

* Difference ($p = 0.043$) from the 30% nonoccluded condition.
† Difference ($p = 0.001$) from the 40% nonoccluded condition.
‡ Difference ($p = 0.037$) from the 50% nonoccluded condition.

the knee extension exercise at 150% of MVIA, and by Vincent and Vincent (48), whose subjects performed a total of 15 sets of 12RM for the quadriceps. The fact that the subjects in our study were adapted to heavy-resistance exercise, which includes a considerable eccentric component, makes the observation of DOMS even more intriguing. Vincent and Vincent (48), however, showed that strength-trained subjects experienced even greater DOMS compared with untrained subjects after a protocol of the same relative intensity and volume.

We speculate that in our model, fast muscle fibers were recruited toward the end of each set because of the anaerobic conditions. Greenhaff et al. (21) showed a greatly increased rate of glycogenolysis in type I fibers and a marked decline in force and near total depletion of phosphocreatine in both fiber types during intermittent electrical stimulation of the quadriceps with the blood flow occluded. In contrast, the decline in force during the same protocol of stimulation but with intact circulation was ascribed almost solely to fatigue in type II fibers. Although Greenhaff et al. (21) used electrical stimulation instead of voluntary activation, their findings are of relevance for the development of fatigue and soreness in the present study. With a decline in force in type I fibers, more type II fibers would have to be recruited for the work to continue (3). Near the end of the sets, the remaining force-producing fibers could be exposed to relatively high tensions. It is also possible that some fast fibers are preferentially recruited and slow fibers are derecruited during eccentric actions and that this may occur already at loads as low as 25% of MVIA (30). Fast muscle fibers are generally regarded as more susceptible to perturbations in their function after eccentric actions than are slow fibers (29). Because of the intense metabolic demands during ischemic exercise, reactive oxygen species may also have played a part in the etiology of DOMS (49).

It is important to note that although there are no published reports on any incidents or serious adverse effects as a result of training with cuff occlusion, there are very little data available regarding the short- and long-term effects of this type of exercise on the soft tissues beneath and distal to the tourniquet. As discussed by Takarada et al. (46), training with cuff occlusion may have the potential to create muscle damage and even more serious adverse effects such as thrombosis and damage to blood vessels. In another study (44), the same research group reported no evidence of muscle damage or oxidative stress as judged by the low levels of creatine phosphokinase and lipid peroxide after their protocol. To our knowledge, the authors have not reported any direct morphological data regarding effects of occlusion training on soft tissues. Because low-intensity resistance exercise with partial occlusion has been suggested as a possible countermeasure against sarcopenia (46), it is important that safety issues of this type of training in healthy as well as in less healthy populations be clarified. For example, diabetes is associated with increased risk for venous thromboembolism (33) and neuropathy (34), which is of relevance for the use of pressure cuffs.

In the context of limb surgery, studies with animal models have shown that the deleterious effects of long-duration cuff occlusion on soft tissues can at least in part be ascribed to the effects of compression of the underlying tissue, which compounds the effects of ischemia (32). However, the compounding effects of compression appear to be dependent on the degree of pressure. Pedowitz et al. (32) showed no necrosis in muscle samples after 2 hours of tourniquet application at 125 mm Hg but showed several necrotic samples after the same duration of application at 350 mm Hg. Absence of arterial pulsations was confirmed in both cases during the occlusion period. Thus, the necrosis was likely a result of the additional effects of the high degree of compression. The authors recommended the use of wide tourniquets during limb surgery, for wide cuffs have been shown to achieve occlusion at considerably lower pressures than have narrower cuffs (15, 20). Therefore, it could be argued that if pressure cuffs should be used during training, they should be wide so that the pressure necessary to achieve a partial occlusion will be low.

It is also worth noting that the studies published to date comparing strength training with and without cuff occlusion (1, 2, 14, 45–47) have controlled only for load and volume, not for effort. In these studies, narrow cuffs or cuffs with low pressures causing partial occlusion were applied throughout the entire workout, including rest periods. The occlusion groups generally trained to failure, whereas the groups training without cuff occlusion were instructed to perform the same number of repetitions as the groups training with cuffs. Because partial occlusion prolongs recovery, it could be argued that the occlusion groups performed multiple all-out sets, whereas the controls (no cuff) performed few, if any, all-out sets.

The results of the present study show that for strength-trained subjects performing the knee extension exercise at low to moderate loads (~40–50% of 1RM), there is little or no difference between training with and without a thigh tourniquet in terms of endurance if the repetitions are performed in a nonstop manner with no relaxation of the quadriceps muscle. Hence, it may be hypothesized that by performing all-out sets and using short rest periods (e.g., 15–45 seconds) between sets during low- to moderate-intensity training, thus creating a relatively ischemic state, similar training effects could be induced as when training with cuff occlusion. Although no studies testing this hypothesis have been published yet, several studies (3, 11, 43) have shown muscle hypertrophy as a result of conventional training with a high work:rest ratio at intensities of ~30–50% of maximum. Intuitively, a training model that is based on a muscle's own internal occlusion would have advantages from both a safety point of view and a practical point of view. On the other hand, at very low loads, such as 20% of 1RM and below, external occlusion will have a marked effect on the rate of fatigue and possibly also on the resulting adaptations.

PRACTICAL APPLICATIONS

Occlusion of the blood flow of the quadriceps muscle by means of a thigh tourniquet appears to reduce the dynamic knee extension endurance more at very low loads than at moderate loads. These results may have applications regarding when it could be advantageous to use a pressure cuff in order to increase the rate of fatigue and perhaps also the resulting training effect. However, the results regarding the pain and the soreness associated with all-out strength training during ischemia suggest that this type of exercise is mainly for highly motivated individuals and should be introduced carefully and with a low volume initially (e.g., 1–2 sets). It is recommended that future studies focus on the issue of whether cuff occlusion has any additive effects on adaptations in strength and muscle volume after low- to moderate-load strength training when the training is performed to muscular failure. Also, the minimum intensity that still results in strength gains and muscle hypertrophy or, equally important, preserves the existing muscle mass from atrophy deserves further investigation. Finally, the short- and long-term safety of training during ischemic conditions, especially concerning the use of pressure cuffs and their potential effects on soft tissues (i.e., nerves, blood vessels, and muscles), needs to be addressed regarding both healthy and less healthy populations.

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Acknowledgments

This study was supported by a grant from the Swedish National Centre for Research in Sports. The authors wish to thank the subjects for their time and effort and Zimmer Sweden for providing the automatic tourniquet system. The authors have no conflicts of interest that are directly relevant to the content of this study.

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