

Overview of neuromuscular adaptations of skeletal muscle to KAATSU Training

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Skeletal muscle adapts to a progressive overload, but the response can vary between different modes and intensities of exercise. Generally, a minimal threshold intensity of 65% of the one repetition maximum (1-RM) is needed to elicit muscle hypertrophy; however, recent studies have challenged this hypothesis and have provided evidence that low-intensity training (LIT) combined with vascular restriction (KAATSU) may also elicit increases in muscle size and strength. The physiological aspects of applying vascular restriction during exercise are not fully understood and may be explained by several factors. Examining the results of previous studies may help elucidate the factors responsible for the adaptations associated with vascular restriction in humans. Therefore, the objectives of this review are to summarize current knowledge regarding the physiological adaptations of skeletal muscle after low-intensity exercise combined with vascular restriction, the different training protocols used to elicit adaptations, and suggested areas for future research.

Key words: blood restriction, skeletal muscle, hypertrophy, KAATSU.

INTRODUCTION

Skeletal muscle can adapt positively when the appropriate training principles are followed. Central to the concept of physiological adaptation are the training principles dealing with overload, progression, and adaptation. It is well established that in order for physiological adaptation to occur, the exercise intensity must be sufficient to elicit the desired training response, i.e., muscle hypertrophy, muscle power, muscular endurance, etc. Intensity of the exercise and training volume can be manipulated in several ways, for example, increasing the load being lifted or by increasing the frequency of training (times per week) or the duration of a single bout of exercise. Often times, positive adaptations can take several weeks (as seen with skeletal muscle changes) or even several months (as seen with bone changes) before improvements can be noted.

The recent development of exercise training at greatly reduced intensities when combined with blood flow restriction (KAATSU) has challenged many of the widely accepted principles of exercise training (Sato, 2005). A number of studies have demonstrated that low-intensity resistance exercise (i.e., 20% 1-RM) combined with vascular restriction (KAATSU) can elicit increases in muscle size [Abe et al., 2006; Beekley et al., 2005; Takarada et al., 2002; Takarada et al., 2000a] and strength [Shinohara et al., 1998; Takarada et al., 2002] to a similar or even greater extent than traditional resistance training utilizing intensities greater than the recommended 65% 1-RM threshold [Goto et al., 2005; Goto et al.,

2004; McCall et al., 1999]. Although the precise mechanisms underlying these adaptations remain unclear, reducing the relative intensity of resistance training to 20% 1-RM and including vascular restriction would have obvious advantages for individuals who may exhibit limited strength or health-related risks with higher resistance training loads, such as older adults and diseased or injured patients. In addition to the relative low intensity (20% 1-RM) utilized with KAATSU (even though the absolute intensity may be as high or higher than traditional training loads), other important aspects such as shorter training periods (duration) and lower volumes of work (load x sets x reps) are needed to induce muscle hypertrophy and improve strength when compared to traditional resistance training principles. Generally, training volumes utilizing moderate to higher number of repetitions per set (6 to 12) at 67-85% 1-RM have been associated with muscle hypertrophy [Baechle and Earle, 2000]; however, KAATSU training requires much lower exercise volumes for similar or even a greater hypertrophic response of skeletal muscle. Since increases in skeletal muscle size in response to KAATSU training is relatively fast (even after one week of KAATSU training) and can be achieved with low training volumes, this may be useful from a clinical standpoint for decreasing rehabilitation time following injury.

A review of the available evidence on training in combination with vascular restriction may help elucidate the physiological mechanisms responsible

for skeletal muscle adaptation. The following paper is a brief summary of the recent history of skeletal muscle adaptation to lower intensity exercise when accompanied by vascular occlusion, which has its' modest beginning in the late 1990's [Shinohara et al., 1998; Yoshida and Watari, 1997] but has recently become an area of increased interest for many researchers. Detailed information about each of the studies examined in this review such as the exercises performed, if control groups were included, subject information (gender, training frequency, etc.), and the pressures used to induce blood flow restriction are provided in Tables 1 and 2. This paper will present both KAATSU training responses and acute findings related to vascular restriction on skeletal muscle physiology in humans.

TRAINING RESPONSES

1. Hypertrophy

Duration and intensity of training

Muscular hypertrophy is an adaptation to increasing work loads that exceeds the capacity of the muscle fiber, resulting in an increase in muscle mass and cross-sectional area [Russell et al., 2000]. Traditional resistance training programs use high intensity ($\geq 65\%$ 1-RM) exercises to elicit muscle hypertrophy. One study reported that the cross-sectional area (CSA) of the biceps brachii muscle increased by $\sim 11\%$ following a training protocol consisting of three sets of 10 repetition maximum ($\sim 75\%$ 1-RM) for 8 exercises during a 12 week period (33 sessions) [McCall et al., 1999]. Others have investigated the effects of combinations of different intensity resistance exercises on muscular adaptations [Goto et al., 2004]. Subjects performed nine sets of exercises at varied intensities (from 40 to 80% 1-RM), during a designed hypertrophy phase (6-week). Following this 6-week hypertrophy phase, subjects were then assigned to either a hypertrophy / combination (HC) or a hypertrophy / strength (HS) group and performed leg press and knee extension exercises for an additional four weeks (strength phase). The HS group performed 5 sets of leg exercises at 3-5 RM ($\sim 90\%$ 1-RM), whereas the HC group performed the same protocol as the HS group but included an additional set of low-intensity and high-repetition exercise at 25-35 RM ($\sim 50\%$ 1-RM) during the strength phase. Both groups experienced similar changes in muscle CSA ($\sim 4\%$) after completion of the hypertrophy phase; however, only the HC training program resulted in a further increase in CSA ($\sim 2\%$) compared to HS training protocol. These studies suggest that the intensity and volume of traditional training programs are important factors and should always be considered in order to induce hypertrophic responses.

On the other hand, recent KAATSU studies

(summarized in Table 1) indicate that the intensity and volume of training do not have to be high when compared to traditional resistance training programs in order to elicit skeletal muscle hypertrophy. Researchers have reported statistically significant increases in muscle size in mid-thigh muscles of 8.5% in a KAATSU group compared to a group performing the same protocol without blood flow restriction (no-KAATSU) [Abe et al., 2005b]. KAATSU and no-KAATSU groups also experienced changes in muscle volumes for the quadriceps (7.7% and 1.4%, respectively) biceps femoris (10.1% and 1.9%, respectively) and gluteus maximus (9.1% and -0.6%, respectively) after two-weeks of twice daily low intensity (20% 1-RM) resistance training; however, only the changes with the KAATSU protocol were statistically significant following training and changes in muscle size with KAATSU were similar to those utilizing traditional high-intensity resistance training programs for 3 months [Goto et al., 2005; McCall et al., 1999]. Additionally, one week of twice-daily KAATSU training consisting of knee extension exercises at 20% of 1-RM resulted in a 3% increase in the quadriceps muscle CSA [Abe et al., 2005a], whereas completion of an 8-week training program that included five sets of knee extension exercises at an intensity of 20% 1-RM with KAATSU resulted in a 10.3% increase in knee extension CSA, but no significant changes in muscle CSA were determined when exercising at the same intensity without blood flow restriction [Takarada et al., 2004]. Finally, Yasuda et al (2005) observed a 7.8% and a 1.8% increase in quadriceps muscle CSA in KAATSU and no-KAATSU groups, respectively, after a 2-week training (at 20% 1-RM) program. Type I and Type II muscle fiber CSA increased 5.9% and 27.6% following KAATSU training, whereas changes in Type I and Type II fiber CSA were -2.1% and 0.5% after no-KAATSU training, respectively. The findings suggest that skeletal muscle hypertrophic responses may not only be due to changes in water balance created by blood flow restriction, but due to increased protein synthesis.

It appears as though when KAATSU is used in combination with resistance training (20% 1-RM) that the adaptation period is greatly reduced (one to two weeks) compared to the time required to demonstrate significant changes from traditional resistance training programs (80% 1-RM and 8 to 16 weeks) and that the relative intensity of the training program is also lower (20% 1-RM versus 80% 1-RM).

Modes of training

Generally, the application of external pressures to produce vascular restriction, have been used in combination with resistance training, but the

Table 1.
Training Studies on the Effects of Vascular Restriction on Skeletal Muscle Physiology

Author	Group	Duration of Study (Week)	N	Gender	Freq (d/wk)	Set x Rep	Intensity	Change in CSA Increase (↑) Decrease (↓)	Change in Strength Increase (↑) Decrease (↓)	Change in EMG, MMG, motor unit activation, PAP Increase (↑) Decrease (↓)	Comments	
Abe et al. (2005a)	E	1 wk	1	M	7 d	30 reps + 3 x 15 reps of knee extension	20% 1-RM	3.5% (↑) in quadriceps	17% (↑) in MVC 14% (↑) in 1-RM	NA	The cuff pressure: day 1= 160 day4= 220 mmHg. 30 sec rest between sets.	
Abe et al. (2005b)	E	2 wk	9	M	6x/wk	3 x 15 reps of squad + leg press	20% 1-RM	8.5% (↑) in mid-thigh	16.8% (↑) in squad 22.6% (↑) in leg curl	NA	The cuff pressure= Day 1=160 Day 9= 240 mmHg 30 sec rest between sets.	
	C	2 wk	7	M	6x/wk	3 x 15 reps of squad + leg press	20% 1-RM	1.8% (↑) in mid-thigh	8.9% (↑) in squad 1.3% (↑) in leg curl	NA		
Abe et al. (2006)	E	3 wk	9	M	2x /d 6x/wk	5x 2min walking	50m/min	5.7% (↑) in Quads 7.6% (↑) in hamstrings	7.4% (↑) in leg press (1-RM) 8.3% (↑) in leg curl (1-RM) Hamstrings 10.4% (↑) in knee ex. (MVC) 9.4% (↑) in knee flex. (MVC) No sig. change	NA	The cuff pressure: 200 mmHg Walking study	
	C	3 wk		M	2x /d 6x/wk	5x 2min walking	50m/min	No sig. change		NA		
Burgomaster et al. (2003)	E	8 wk	8	M	2x/wk	2x /10 + 1x/failure (1 st 2 wk) # of sets increased by 1-set/wk 5x /10 + 1x / failure (from wk 5 to 8)	50% 1-RM	NA	10.5% (↑) in isokinetic strength 22% (↑) in isotonic strength	NA	The cuff pressure: 100 mmHg One min rest between sets and 5 min rest between blocks (3 sets= a block)	
	C	8 wk	8	M	2x/wk	# of repetitions were matched with the occluded arm	50% 1-RM	NA	9.6% (↑) in isokinetic strength 23% (↑) in isotonic strength	NA		The contralateral arms were trained without occlusion
Ishii et al. (2005)	E	8 wk	11	F	3x/wk	6 exercises (knee-up, bent-knee push up, leg raise, seated knee flexion, squad, and forward lunge).	NA	3% increase	NA	NA	The cuff pressure: 50-80 for upper limbs 80-120 mmHg for lower limbs. (KAATSU sportswear) Circuit training (No external loading)	
	C	8 wk	11	F	3x/wk	Number of repetitions varied.		No sig. change	NA	NA		
Moore et al. (2004)	E	8 wk	8	M	2x/wk	2x /10 + 1x/failure (1 st 2 wk) # of sets increased by 1-set/wk 5x /10 + 1x / failure (from wk 5 to 8)	50% 1-RM	NA	22% (↑) in dynamic strength 8% (↑) in MVC	51% (↑) in PAP No sig. change in EMG activity & motor unit activation. Greater relative (↑) in EMG activity from 1 st rep of set-1 to 1 st rep of set-3 21% (↓) in resting twitch peak torque	NA	The cuff pressure: 100 mmHg One min rest between sets and 5 min rest between blocks (3 sets= a block) The contralateral arms were trained without occlusion
	C	8 wk	8	M	2x/wk	# of repetitions were matched with the occluded arm	50% 1-RM	NA	23% (↑) in dynamic strength No sig. change in MVC	No sig. change in PAP, EMG activity, & motor unit activation		
Sata S. (2005)	E	3 wk	1	M	5-6x/wk	3 x 15 (8 exercises)	30% 1-RM	7 mm (↑) in right thigh and 2 mm (↑) in left thigh circum.	NA	NA	Subject was one patella tendinitis patient	

Table was organized according to alphabetical order of names. N= Number of subjects; Freq= Frequency; Rep= Repetitions; E = Exercise group; C= Control group; M= Male; F= Female; NA= Not applicable.

Table 1. (continued)

Author	Group	Duration of Study (Week)	N	Gender	Freq (d/wk)	Set x Rep	Intensity	Change in CSA Increase (↑) Decrease (↓)	Change in Strength Increase (↑) Decrease (↓)	Change in EMG, MMG, motor unit activation, PAP Increase (↑) Decrease (↓)	Comments
Shinohara et al. (1998)	E	4 wk	5	M	3x/wk	~ 36x isometric knee extension (2s on 3s off)	40% MVC	NA	9% & 26% (↑) in ischemic-leg after 2-wk & 4-wk, respectively No sig. change in non-ischemic-leg	NA	The cuff pressure: >250 mmHg Same subjects trained with one leg ischemic and the other non-ischemic
Takarada et al. (2000a)	E	2 wk	8	4M 4F	2x/d 12 days (between the 3 rd and 14 th days after operation)	5 x 5 min blood flow restriction	A cuff was inflated No exercise	9.4% (↓) in knee extensors 9.2% (↓) in knee flexors	NA	NA	Mean cuff pressure: 238 mmHg 3 min rest between occlusions
	C	2 wk	8	4M 4F	2x/d 12 days (between the 3 rd and 14 th days after operation)	5 x 5 min blood flow restriction	A cuff was on, but not inflated	20.7% (↓) in knee extensors 11.3% (↓) in knee flexors	NA	NA	Patients with an operation for the reconstruction of the anterior cruciate ligament
Takarada et al. (2002)	E	8 wk	6	M	2x/wk	Subjects repeated the lifting (knee extension) until failure 4x	50% 1-RM	12.3% (↑) in knee extensors	12.3% (↑) in isokinetic torque (averaged over all velocities)	NA	Mean cuff pressure: 200 mmHg 30 sec rest between sets.
	E	8 wk	6	M	2x/wk	# of repetitions were matched with vascular occlusion group	50% 1-RM	No sig. change	3.2% (↑) in isokinetic torque (averaged over all velocities)	NA	
	C	8 wk	5	M	2x/wk	untrained	untrained	No sig. change	No sig. change	NA	
Takarada et al. (2004)	E	8 wk	6	M	2x/wk	5x subjects repeated the lifting until failure	20% 1-RM	10.3% (↑) in knee extensors	9.2% (↑) in isokinetic strength	NA	Mean cuff pressure: 218 mmHg 1-minute rest between sets.
	E	8 wk	6	M	2x/wk	5x subjects repeated the lifting until failure	20% 1-RM	No sig. change	3.1% (↑) in isokinetic strength	NA	
	C	8 wk	6	M	2x/wk	10 min vascular occlusion	untrained	No sig. change	2.8% (↑) in isokinetic strength	NA	
Takarada et al. (2000b)	E	16 wk	11	W	2x/wk	Subjects performed 5 sets of single-arm dumbbell curl, each set until failure	~30-50% 1-RM ~50-80% 1-RM	20.3% (↑) in biceps brachii 17.8% (↑) in brachialis	18.4% (↑) in isokinetic strength 22.6% (↑) in isokinetic strength	Sig. (↑) in iEMG compared to exercise of same intensity without restriction	Mean cuff pressure: 110 mmHg 1-minute rest between sets. Repeated the lifting until failure.
	E	16 wk	8	W	2x/wk	# of repetitions were matched with vascular occlusion group	~50% 1-RM	6.9% (↑) in biceps brachii 3.8% (↑) in brachialis	1.04% (↑) in isokinetic strength	No sig. change	In the subjects of occlusion group, the contralateral arms were trained with a high intensity exercise (80% 1-RM).
	C	16 wk	5	W	2x/wk	5x of single-arm dumbbell curl	untrained	No sig. change	No sig. change	NA	
Yasuda et al. (2005)	E	2 wk	3	M	2x/d 6x/wk	3x 15 (leg curl and squat)	20% 1-RM	7.8% (↑) in quadriceps	14% (↑) in 1-RM (squat)	NA	The cuff pressure= Day 1=160 Day 9= 240 mmHg 30 sec rest between sets and exercises.
	C	2 wk	2	M	2x/d 6x/wk	3x 15 (leg curl and squat)	20% 1-RM	1.8% (↑) in quadriceps	9.1% (↑) in 1-RM (squat)	NA	

Table was organized according to alphabetical order of names. N= Number of subjects; Freq= Frequency; Rep= Repetitions; E = Exercise group; C= Control group; M= Male; F= Female; NA= Not applicable.

KAATSU technique has also been used with different modes of exercise to investigate skeletal muscle adaptation and response. Three weeks of twice-daily walk training combined with vascular restriction (LIWT+R) compared to walking alone (LIWT) resulted in an increase in quadriceps muscle CSA of 5.7% and 1.5%, respectively (Abe et al., 2006), 7.5% and -0.6%, respectively [Beekley et al., 2005], and hamstring muscle CSA of 7.6% and -1.7%, respectively [Abe et al., 2006].

Using a different approach, subjects wearing "KAATSU Sportswear" (PHENIX Co. Ltd., Tokyo Japan) performed a circuit-training protocol only using body weight as the external load. The protocol consisted of six exercises (Table 1) with blood flow restriction to both upper and lower limbs for 8 weeks. The proximal ends of upper and lower limbs were compressed by elastic belts to restrict blood flow. The blood flow restriction pressure was determined by the stretched distance of the elastic belts and the circumference of the limbs. Thigh muscle CSA increased by ~3% in KAATSU group but no change was observed after circuit training without blood flow restriction, although there was no statistical difference between the two groups (Ishii et al., 2005). These studies indicate that the combination of KAATSU technique with different modes of training programs may also be used to elicit hypertrophy but further research is needed to support these claims.

Age related adaptation and training status

Decreases in muscular strength with aging are attributed to declines in muscle fiber area [Grimby et al., 1982] and fiber number [Lexell et al., 1983]. Maintaining or improving muscular strength is very important for middle-aged and elderly populations so that quality of life can be maintained or improved. It is known that high intensity exercise is needed to induce muscle hypertrophy [Baechle and Earle, 2000], however, elderly people (70-79 years of age) may be prone to orthopedic injury or be unable to perform traditional high intensity strength testing and training [Pollock et al., 1991].

Middle-aged female subjects (47-67 yr) increased their biceps brachii and brachialis muscle size by 20.3% and 17.8%, respectively, following a training protocol of five sets of single dumbbell curls at 30-50% 1-RM with blood flow restriction for a 16-week training period [Takarada et al., 2000b]. However, the same training program without blood flow restriction resulted in an increase in CSA of the biceps brachii of only 6.9% and in the brachialis of 3.8%. This finding suggests that KAATSU may be more effective and safer for improving muscle size in older individuals.

The positive effects of KAATSU on muscle size and strength have been reported not only in sedentary and active individuals but also in athletes and

patients. The CSA of the knee extensors in athletes increased by 12.3% after an 8-week period of KAATSU resistance training at 50% of 1-RM indicating that low-intensity exercise with vascular restriction can increase muscle size and strength regardless of training status [Takarada et al., 2002].

Rehabilitation

It was reported that low intensity KAATSU resistance training has also been used as part of the rehabilitation process in Japan [Sata, 2005]. A patient with patellar tendinitis incorporated KAATSU training on the right injured limb along with exercises for both lower extremities at 30% 1-RM for 3 weeks. It was reported that the patient was able to begin jogging one week after beginning the KAATSU training and that thigh circumference increased by 7 mm for the injured right leg and 2 mm for the uninjured left leg after three weeks of KAATSU training. It should be noted that the patient received both anti-inflammatory drugs and a steroid injection; therefore the training results are somewhat confounded by the administration of the drugs. However, the quick recovery of this patient suggests that this training method may be safe and decrease recovery times in these types of patients. In addition, the application of vascular restriction without any exercise for a 2-week period resulted in disuse-induced decreases in muscle CSA of the knee extensors and flexors of -9.4 and -9.2%, respectively but were significantly less than those in a control group without KAATSU application (-20.7 and -11.3%, respectively) [Takarada et al., 2000a]. Based on these findings, it can be suggested that blood flow restriction alone may reduce atrophy associated with inactivity or when accompanied with low-intensity exercise may increase muscle size in a variety of patient populations.

2. Strength and Neural Changes

a. Strength

Duration and intensity of training

Generally, strength adaptations have been assessed by measuring isometric [maximal voluntary contraction (MVC)], isokinetic, or dynamic [one repetition maximum (1-RM)] muscle strength, which may be due to neural adaptations, muscle hypertrophy, or both. Measuring changes in muscle CSA or the total amount of muscle mass can explain strength changes due to hypertrophy, whereas measuring motor unit activation (MUA), post activation potentiation (PAP), recording electromyography (EMG) and mechanomyography (MMG) activities provides additional information regarding any neural changes.

Traditional resistance training programs often report significant increases in both muscle hypertrophy and

strength of 5 to 39% depending on the type of training (dynamic), the mode of testing (isokinetic, isometric, or dynamic), and duration of training [Goto et al., 2004]. However, there is convincing evidence in the literature to indicate that similar benefits in terms of strength improvements can be achieved using much lower training intensities and durations of training if combined with the KAATSU training technique (Table 1).

Following 8 weeks of unilateral elbow flexion training (one arm was trained with restriction and the other without restriction) at 50% 1-RM, isometric MVC increased by 8.3% with blood flow restriction, but no significant change was observed without restriction [Moore et al., 2004]. The same exercise protocol with blood flow restriction to only one limb also resulted in a 10.5% increase in isokinetic strength versus 9.6% without KAATSU and a 22% increase in isotonic strength in elbow flexors with KAATSU compared to a 23% increase without KAATSU, with the increases in both conditions being statistically similar [Burgomaster et al., 2003]. The authors could not offer any physiological reasons why both limbs would respond in a similar fashion, contrary to all other published KAATSU protocols [Burgomaster et al., 2003]. We hypothesize that the adaptation to training may be affected by the mode of testing, because the mechanisms responsible for the changes in strength may be similar for isokinetic and isotonic strength, but different for isometric strength.

A 4-week training program of repeated isometric knee extensions at 40% of MVC resulted in significant increases in MVC values by 9% after the first 2-weeks and of 26% after the entire 4-week training period [Shinohara et al., 1998]. When dynamic knee extension exercises at 20% 1-RM were performed for 7 days, the authors reported a 17% and a 14% increase in MVC and 1-RM strength, respectively [Abe et al., 2005a]. In a somewhat similar study, a low intensity resistance training protocol was used in combination with blood flow restriction for two weeks, which resulted in 16.8% and 22.6% increases in squat and leg curl 1-RM strength, respectively. However, the control group performing the same exercises without blood restriction experienced only 8.9% and 1.3% increases in squat and leg curl 1-RM strength, respectively [Abe et al., 2005b]. In another 2-week study of twice-daily training that included three sets of leg curls and squats at 20% 1-RM, the 1-RM squat strength increased by 14% [Yasuda et al., 2005]. Takarada et al. (2004) reported a 9.2% increase in isokinetic strength in the knee extensors after an 8-week training program consisting of five sets of knee extension exercises (20% 1-RM) with KAATSU, but the isokinetic strength change in knee extensors in the group performing the same exercises without

KAATSU was only 3.1%. Trained elite athletes also experienced a 14.3% strength gain after completion of an 8-week KAATSU training program of the knee extensor muscles at about 50% of 1-RM [Takarada et al., 2002].

Gender effects

Although the subject population for most of the KAATSU studies were young males, postmenopausal females also increased isokinetic strength in elbow flexors by 18.4% following a 16-week resistance training (30-50% 1-RM) combined with vascular restriction [Takarada et al., 2000b]. Subjects in the KAATSU group exercised the contralateral arm with a high-intensity (80% 1-RM) exercise without restriction and increased isokinetic strength of the elbow flexors by 22.6%, similar to the arm trained with blood flow restriction. However, when exercises were performed at the same low intensity (30-50% 1-RM) with no blood flow restriction, there was only a 1.0% increase in strength. Gender does not appear to influence the adaptive ability of skeletal muscle in response to KAATSU training, with similar adaptations being demonstrated by both males and females.

b. Neural response

Another noninvasive technique that has been used to determine motor unit activation and post activation potentiation (PAP) is twitch interpolation [Allen et al., 1995]. This technique involves electrical stimulations applied to the muscle or nerve during and after isometric MVC (Shield and Zhou, 2004). PAP, which can improve muscular performance, is the first twitch obtained after a MVC trial [Moore et al., 2004]. Eight weeks of low intensity (50% of 1-RM) unilateral elbow flexion training with restricted blood flow resulted in a significant increase in PAP (51%), but no change was observed after low intensity exercise without blood flow restriction. No significant difference in increased dynamic strength was reported between the two conditions (22% increase with restricted blood flow and 23% increase without restriction); however, isometric strength (MVC) improved significantly more (8.3%) for the KAATSU condition compared to the control (no change). Additionally, resting twitch torque was depressed by 21% with vascular occlusion but was not changed in the unrestricted blood flow condition which might be attributed to low frequency fatigue in response to the KAATSU training regiment [Moore et al., 2004].

ACUTE RESPONSES

Neural response

Surface electromyography (EMG) reflects the linear algebraic summation of muscle action potentials that

propagate within the electrode recording areas. The time and frequency domains of the EMG signal may reflect muscle activation (combination of motor unit recruitment and firing rate) and motor unit action potential conduction velocity via the global shape of the action potentials, respectively [Basmajian and De Luca, 1985]. EMG signals were recorded from the triceps brachii and the pectoralis major during bench press exercises with or without vascular restriction [Yasuda et al., 2006] (Table 2). Normalized integrated EMG (iEMG) increased gradually during four sets of the dynamic exercise at 30% 1-RM; however, the magnitude of the EMG response for both the triceps brachii and the pectoralis major were significantly higher when KAATSU was applied.

Normalized iEMG determined that the exercise

intensity for the first set was the same for both the control and KAATSU session, but the intensity of exercise was higher in the KAATSU session during the fourth set [Yasuda et al., 2006]. Takarada et al. (2000b) also reported that the relative iEMG was 40% lower during low-intensity exercise (~50% 1-RM) without restriction compared to iEMG values during high-intensity exercise (~80% 1-RM) with no restriction indicating that there is a positive relationship between the level of the force exerted and iEMG activity. Restriction pressure was increased gradually during low-intensity exercise resulting in gradual increases in iEMG. This may be due to increasing lactic acid production inhibiting contraction of muscle fibers leading to the recruitment of additional motor units. However,

Table 2.
The Acute Effects of Vascular Restriction on Skeletal Muscle Physiology

Author	Group	Duration of Study (Week)	N	Gender	Set x Rep	Intensity	Change in CSA Increase (↑) Decrease (↓)	Change in Strength Increase (↑) Decrease (↓)	Change in EMG, MMG, motor unit activation, PAP Increase (↑) Decrease (↓)	Comments	
Karabulut et al. (2006)	E	one session	12	M	5 x 20 isometric knee extension with Kaatsu (2s on 1s off)	20% 1-RM	NA	No sig. change in MVC,	No sig. change in EMG amplitude (amp.), EMG mean power frequency (MPF), MMG amp, MMG MPF There were sig. difference between repetitions & MMG amp. increased from set-1 to set-2	7% (↓) in isometric MVC in Kaatsu session (not sig.) vs. 2% (↓) in isometric MVC in no-Kaatsu session (not sig.) Same subject performed same exercises without Kaatsu The cuff pressure= (Arm SBP×1.2)× 1.2	
	C	one session	12	M	5 x 20 isometric knee extension without Kaatsu (2s on 1s off)	20% 1-RM	NA	No sig. change in MVC			
Takarada et al. (2000b)	E	one session	5	M	Subjects performed 5 sets of single-arm dumbbell curl, each set until failure	-50% 1-RM (with restriction)	NA	NA	Sig. (↑) in iEMG compared to exercise of same intensity without restriction	Mean cuff pressure: 0- 100 mmHg 1-minute rest between sets. Repeated the lifting until failure.	
	E	one session	5	M		-80% 1-RM (without restriction)	NA	NA	Sig. change 40% higher iEMG than that of control group with no-restriction		No sig. change between iEMG values @ 100 mmHg and during high intensity without restriction
	C	one session	5	M		~50% 1-RM (without restriction)	NA	NA	NA		
Yasuda et al. (2006)	E	One session	12	M & F	30 reps + 3x 15 (bench press)	30% 1-RM	NA	NA	During first 30 reps= iEMG ~ 40% of 1-RM 3 rd set= iEMG ~ 60-70% 1-RM	The cuff pressure= Equaled to individual's resting systolic blood pressure 30 sec rest between sets	
	C	One session	12	M & F	30 reps + 3x 15 (bench press)	30% 1-RM	NA	NA	During first 30 reps= iEMG ~ 40% of 1-RM 3 rd set= iEMG ~ 50% 1-RM		

Table was organized according to alphabetical order of names. N= Number of subjects; Freq= Frequency; Rep= Repetitions; E= Exercise group; C= Control group; M= Male; F= Female; NA= Not applicable.

there was not a significant difference in iEMG values during low-intensity exercise with blood flow restriction at 100 mmHg and high-intensity exercise without restriction. A possible explanation for this finding might be that the magnitude of blood pooling affected the surface EMG electrode recordings.

The mechanomyogram (MMG) records and quantifies the low-frequency lateral oscillations of active skeletal muscle fibers [Barry and Cole, 1990; Orizio, 1993]. During voluntary muscle actions, the MMG signal represents a summation of the mechanical activity from individual motor units. The time and frequency domains of the MMG signal have been suggested to reflect motor unit recruitment and firing rate, respectively [Beck et al., 2007; Orizio, 1993]. MMG signals were recorded from the vastus lateralis muscle during repetitive isometric contractions at 20% MVC [Karabulut et al., 2006] (Table 2). There were no significant interactions and no significant main effects for pre- versus post-exercise or with- versus without blood flow restriction for either MMG amplitude or MMG mean power frequency (MPF). MMG amplitude increased from set 1 to 2, but there was no difference between sets 2, 3, 4, and 5 for both the restricted and non-restricted sessions; however, the authors suggested that it was possible that the isometric exercise task was at too low of an intensity and did not result in any substantial changes in motor unit firing rates [Karabulut et al., 2006]. Table 2 summarizes the data for the acute responses of skeletal muscle to a single bout of KAATSU training. Since no previous studies have examined the MMG responses to KAATSU-related interventions, it was not possible to compare these findings to other studies.

CONCLUSION

There seems to be some agreement that blood flow restriction during low intensity exercise can potentiate physiological improvements in skeletal muscle, apparently independent of the commonly accepted training principles associated with overload and progression. These changes in skeletal muscle size and strength may possibly be through neuromuscular adaptations such as improved muscle and/or nerve coordination and/or muscle hypertrophy and appear to be independent of gender, training status, and age. It should also be noted that there are probably numerous factors involved in muscle hypertrophy and strength changes such as metabolite accumulation (lactic acid, ADP, etc.), induced hypoxia, reperfusion of the muscle, and localized or systemic endocrine responses (Growth Hormone, Insulin-like Growth Factor-1, Testosterone, etc.).

One possible explanation for the relatively faster hypertrophic response (even after one week of KAATSU training) compared to traditional resistance

training programs may be the recruitment of more fast-twitch fibers and their higher threshold motor units. It is difficult to determine which factors are more important since there are close relationships between these various factors.

Since low-intensity exercises combined with vascular restriction requires less mechanical stress (20% versus 80% 1-RM), it may be an effective alternative method to increase strength and muscle size and used for strength training in the elderly or for people with orthopedic injuries. In addition, KAATSU training programs may also provide an opportunity to use different exercise modes such as walking for the purpose of muscle hypertrophy and strength gains. In summary, additional studies are required to clarify the physiology of the underlying factors associated with KAATSU training; however, it seems to be a potentially useful training method for improving the quality of life in the elderly, enhancing performance in athletes, and shortening rehabilitation time in patients.

SUGGESTIONS FOR FUTURE RESEARCH

One physiological system that needs further research is the area of bone physiology and the use of KAATSU training. Various situations like rehabilitation from injury (limb immobilizations, casting, etc), bed rest (hip or knee replacement, etc), and the loss of gravity (space flight) each have specific needs for being able to prevent bone and muscle loss which might be best accomplished with the aid of blood flow restriction and low intensity exercise.

Additionally, the longest published KAATSU training study lasted 16 weeks; therefore, more research is needed to understand the long-term effects of KAATSU training, especially since bone is typically much slower in responding to a training stimulus. Finally, other interesting areas of research could include the examination of the time course of the adaptive changes following the termination of KAATSU training or the implications of switching from KAATSU training to a traditional resistance training program (or vice versa) compared to similar length, single mode training programs (KAATSU or traditional resistance training).

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