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Abstract

The purpose of this study was to determine the effects of different volumes of high-intensity resistance training on isometric torque and muscle thickness. Training was conducted three times per week using one set (low volume, EX-1, N = 18) or three sets (high volume, EX-3, N = 20) of dynamic variable resistance exercise. Ten subjects acted as nontraining controls (CONT). Bilateral knee extension (KEXT) and flexion (FLEX) exercise was performed to fatigue within 8-12 repetitions for 14 wk. Maximal isometric KEXT and KFLEX torque was tested at 6°, 24°, 42°, 60°, 78°, 96°, and 108° of KFLEX using a MedX (Ocala, FL) KEXT/KFLEX ergometer. The anterior (ANT), lateral (LAT), and posterior (POST) right thigh, the medialis muscle (MED), and the lateralis muscle (LATER) were assessed for thickness by B-mode ultrasound (ULTRA). Both training groups improved torque output at most angles, but there was no difference between EX-1 and EX-3 ($P \geq 0.05$). ULTRA detected increases in muscle thickness for EX-1 at 60% LAT and 40% and 60% POST. EX-3 increased muscle thickness at the MED, and 40% and 60% POST. In conclusion, one set of high-intensity resistance training was as effective as three sets for increasing KEXT and KFLEX isometric torque and muscle thickness in previously untrained adults.

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ABSTRACT

STARKEY, D. B., M. L. POLLOCK, Y. ISHIDA, M. A. WELSCH, W. F. BRECHUE, J. E. GRAVES, and M. S. FEIGENBAUM. Effect of resistance training volume on strength and muscle thickness. *Med. Sci. Sports Exerc.* Vol. 28, No. 10, pp. 1311–1320, 1996. The purpose of this study was to determine the effects of different volumes of high-intensity resistance training on isometric torque and muscle thickness. Training was conducted three times per week using one set (low volume, EX-1, $N = 18$) or three sets (high volume, EX-3, $N = 20$) of dynamic variable resistance exercise. Ten subjects acted as nontraining controls (CONT). Bilateral knee extension (KEXT) and flexion (KFLEX) exercise was performed to fatigue within 8–12 repetitions for 14 wk. Maximal isometric KEXT and KFLEX torque was tested at 6°, 24°, 42°, 60°, 78°, 96°, and 108° of KFLEX using a MedX (Ocala, FL) KEXT/KFLEX ergometer. The anterior (ANT), lateral (LAT), and posterior (POST) right thigh, the medialis muscle (MED), and the lateralis muscle (LATER) were assessed for thickness by B-mode ultrasound (ULTRA). Both training groups improved torque output at most angles, but there was no difference between EX-1 and EX-3 ($P \geq 0.05$). ULTRA detected increases in muscle thickness for EX-1 at 60% LAT and 40% and 60% POST. EX-3 increased muscle thickness at the MED, and 40% and 60% POST. In conclusion, one set of high-intensity resistance training was as effective as three sets for increasing KEXT and KFLEX isometric torque and muscle thickness in previously untrained adults.

RESISTANCE TRAINING, VARIABLE RESISTANCE EXERCISE TRAINING, VOLUME, KNEE EXTENSION, KNEE FLEXION, ISOMETRIC TORQUE, MUSCLE THICKNESS, ULTRASOUND

Resistance training has become a primary component of athletic conditioning, rehabilitation, and general fitness programs (2,11,26). The prescription of a resistance training program requires the consideration of several factors, including the intensity, frequency, and volume of exercise (11). For the adult interested in developing general fitness, a training regimen that requires the minimum of a single set of 8–12 repetitions performed to volitional fatigue is widely recommended (2,26,34). Because of the large time commitment required by multiple set regimens and the fact that these regimens have produced only 5–10% greater improvements in strength than a single set of exercises, the American College of Sports Medicine and the American Heart Association recognize single set training as a viable means to develop and maintain muscular strength and lean body mass in healthy adults (1,11). However, research in this area is limited, and many experts maintain that adults would derive greater benefits from multiple set programs (4,6,14,18). Therefore, the purpose of this study was to determine the effects of training volume (1 set vs 3 sets) on the development of full range of motion (ROM), knee extension (KEXT), and knee flexion (KFLEX) strength, and associated muscle thickness measures in healthy adults.

METHODS

Subjects. Fifty-nine subjects were initially tested; 48 subjects (21 males, 27 females) completed the study. All subjects were healthy untrained volunteers (age range 18–50 yr) who did not participate in any other form of training during the study. Descriptive characteristics of the subjects are presented by group and gender in Table 1.

The methods and procedures used in this study were approved by the Institutional Review Board of the University of Florida College of Medicine prior to data collection and are in accordance with the policies of the American College of Sports Medicine. Documented informed consent for testing and training was obtained from all subjects.

Strength testing. The initial test session was considered a practice and orientation session. Each subject was seated in a specially designed KEXT and KFLEX ergometer (MedX Corporation, Ocala, FL), and the joint axis of the knees was aligned with that of the machine by adjusting the position of the seat with a cranking mechanism attached to the back of the seat. This allowed the subject's hips and thighs to slide forward or backward on the seat, making it possible to align the subject's lateral epicondyle with that of the machine's axis of rotation. A

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TABLE 1. Subject characteristics by group and gender (values are mean ± SD).

Group	Variable	Total	Male	Female
Control	*N*	10	4	6
	Age (yr)	45.4	31.3 ± 9.0	39.3 ± 8.6
	Height (cm)	168.3 ± 9.2	177.8 ± 4.2	161.9 ± 4.5
	Weight (kg)	67.9 ± 8.5	75.2 ± 6.9	63.0 ± 5.6
One set 3×/wk	*N*	18	9	9
	Age (yr)	34.3 ± 10.3	32.3 ± 9.1	36.2 ± 11.5
	Height (cm)	170.1 ± 8.4	174.5 ± 7.7	165.7 ± 6.9
	Weight (kg)	71.1 ± 14.4	76.1 ± 12.1	66.0 ± 15.4
Three sets 3×/wk	*N*	20	8	12
	Age (yr)	34.9 ± 8.3	33.6 ± 9.8	35.8 ± 7.5
	Height (cm)	170.3 ± 8.9	178.9 ± 5.1	164.7 ± 5.8
	Weight (kg)	69.2 ± 11.7	75.7 ± 6.9	65.0 ± 12.6

second criterion for assessing proper seat positioning was the absence of any movement of the anterior edge of the tibia (shins) against the movement arm of the machine during dynamic exercise. Once this was accomplished, the subject's position was stabilized. A belt was placed across the upper thighs to hold the hips down and back. A resistance pad attached to the movement arm was then secured using adjustable straps attached to the subject's lower legs (approximately midway between the knee and ankle). The ROM was then assessed using an internal electronic goniometer as a reference guide. The subject fully extended and then flexed the knees. The angle of full extension and flexion was recorded.

The initial isometric test angle was set at the subject's fully flexed position. The subject was then instructed to gradually build up tension against the machine's movement arm over a 3- to 4-s period by slowly extending the legs. Once maximum tension was developed, the subject was encouraged to maintain this force for an additional 1–2 s, then gradually release this force by relaxing the quadriceps muscles. Each subject was initially tested at 108°, 78°, 42°, and 6° of KFLEX. (All angles referred to as the angle in which the joint is being tested are angles in degrees of KFLEX). Each isometric contraction was followed by a 10-s rest period while the next angle of measurement was set. Once isometric strength was obtained at all four test positions, the subject rested for 5 min. To measure hamstring muscle strength, the subject's maximal KFLEX strength was then assessed at the same angles and in the same order as those tested for KEXT.

During the second test session, maximum isometric KEXT and KFLEX torque was measured bilaterally using the same method that was used during the first (practice) session, except torque was measured at a total of seven positions throughout the subject's ROM (108°, 96°, 78°, 60°, 42°, 24°, and 6°) instead of the four angles previously mentioned. The order of testing, extension first and then flexion or flexion first and then extension, was randomized and balanced among subjects. Testing sessions (days) were separated by a 3- to 7-d rest period.

Muscle thickness testing. Muscle thickness was measured prior to and following 14 wk of training using

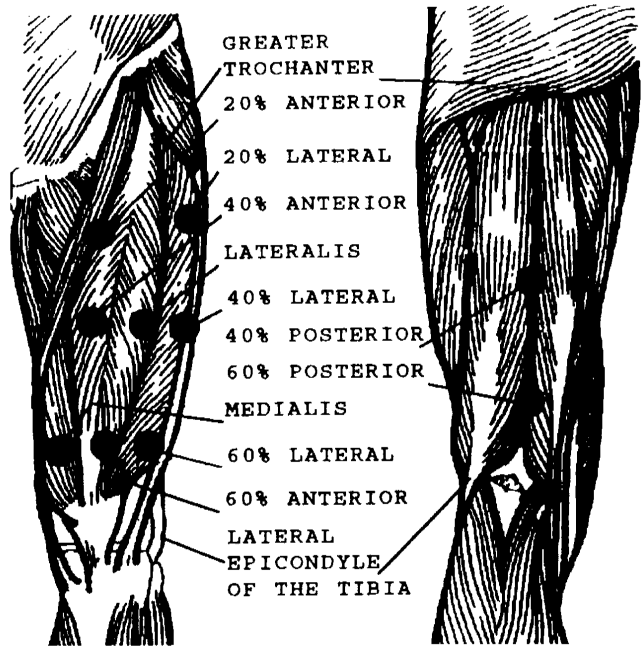

Figure 1—Approximate ultrasound locations showing the sites for ultrasound measures for the anterior and lateral sites on the quadriceps and the posterior sites on hamstring muscles.

B-mode ultrasound (19). The length of the right thigh was measured from the greater trochanter to the lateral epicondyle of the tibia, and 20%, 40%, and 60% of this distance was marked on the midline of the anterior, lateral, and posterior faces of the thigh. Also marked on the anterior face was the medialis muscle, located 3 cm to the right of the 60% anterior mark, and the lateralis muscle, located 3 cm to the left of the 60% anterior mark. All sites were measured except for the 20% posterior site. See Figure 1 for the approximate measurement locations. The same tester marked and measured all sites both pre- and post-training and was blinded as to group assignment. All ultrasound scans were made with each subject in the standing position and with body weight shifted to the left leg.

The subject's muscle thicknesses were measured with B-mode ultrasound apparatus (Aloka Echo Camera SSD-210 DXII, Tokyo, Japan), using a 5 MHz transducer. A water-based gel was applied to the transducer head to ensure sound wave transmission. The transducer was held perpendicular to the skin surface being careful to avoid compression of the skin and underlying tissues. Scanning at each site was continued until adequate resolution of the fat/muscle and muscle/bone interfaces was obtained. A cross-sectional image was frozen on the video display screen (Sony, Video Graphic Printer UP-701, Tokyo, Japan) before multiple photographic copies were produced for subsequent measurement. Measurements were made to the nearest 0.1 mm with a Vernier caliper (Mitutoyo, Japan). Muscle thickness was measured from the fat/muscle tissue interface to the muscle/bone interface.

Resistance training. After the initial evaluation subjects were randomly assigned to one of two training groups or to a nonexercising control group, with twice as many subjects in the training groups as in the control group. The training groups completed three bilateral training sessions per week for 14 wk using either one (EX-1, $N = 18$) or three (EX-3, $N = 20$) sets of exercise (i.e., one set, three times per week, or three sets, three times per week). The control group (CONT, $N = 10$) were instructed not to train their legs during the 14-wk control period. Each set of exercises required performing 8–12 repetitions of dynamic variable resistance exercise to volitional fatigue for both KEXT and KFLEX. Intial load for dynamic training was set at 60% for KEXT and 50% for KFLEX of the peak torque determined during initial testing. Strict form was required for the repetitions to be accepted. Subjects concentrically extended or flexed their legs for a count of two, pause, then eccentrically lowered the training weight for a count of four. EX-3 was allowed to rest 1–3 min between sets. Weight was increased approximately 5% when subjects were able to perform 12 repetitions or more. As long as the EX-3 group could maintain a minimum of eight repetitions on sets 2 and 3, the same weight was used for all three sets. Subjects alternated sets of KEXT and KFLEX exercise until the required number of sets were completed. The order of the exercises was alternated from one training session to the next. Exercise load, number of repetitions performed, and rating of perceived exertion (RPE) (7) were recorded after each set to document intensity, perceived effort, and progression of training.

After 14 wk of training, isometric KEXT and KFLEX strength was measured on all groups using the methods described above. Post-training ultrasound measurements of muscle thickness were conducted on a separate day from or prior to strength testing using the same methods used for the pre-testing ultrasound measures.

Treatment of the data. Descriptive statistics (mean ± SD) for age, height, and weight were calculated. Isometric torque was measured in ft-lb and converted to Newton meters (Nm). The second pre-training test was used to obtain criteria measures of pre-training isometric

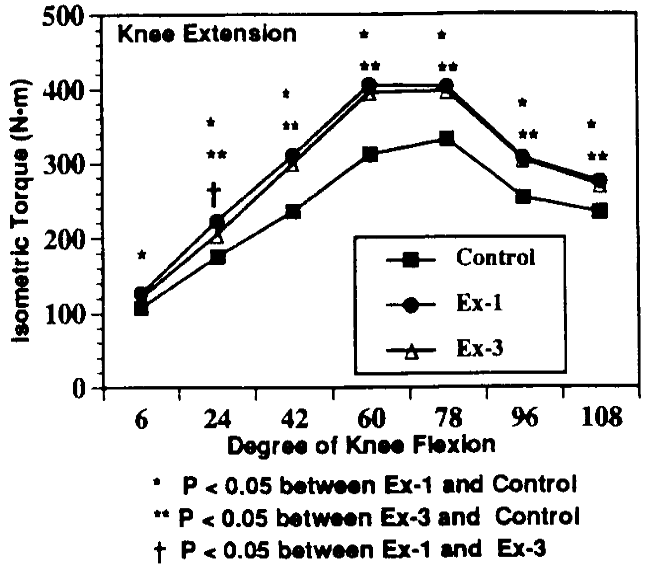

Figure 2—Bilateral knee extension increases in isometric torque of EX-1 (N = 18) and EX-3 (N = 20) over the control group (N = 10) (ANCOVA). Percent gains in isometric torque were 18.4% vs 13.2% at 6°, 26.7% vs 16.3% at 24°, 31.6% vs 27.1% at 42°, 30.1% vs 26.8% at 60°, 21.4% vs 19.5% at 78°, 20.9% vs 20.0% at 96°, and 17.5% vs 15.3% at 108° for the EX-1 and EX-3 groups, respectively.

torque. The same procedure was used to obtain the criteria measures for post-training isometric torque. Means, standard deviation, and standard error of the means were calculated for the pre- and post-training torques at each angle of measurement and for all ultrasound measures. An analysis of variance (ANOVA) determined any differences among the three groups' initial isometric torque and muscle thickness measures. No significant differences were found among the groups. Therefore, pre- and post-training torques and muscle thicknesses were compared among groups using a 3 by 2 repeated measures ANOVA. When significant differences were found, a *post-hoc* test was used to determine differences among groups or treatments. ANCOVA was also used to obtain adjusted post-training torque values to formulate figures to compare data among groups (Figs. 2 and 3). For this purpose, pre-training torques were used as the covariates. Pre- to post-training gender effects were also analyzed with ANOVA.

Training load, RPE, and the number of repetitions performed during each set of each exercise session were averaged for weeks 1 and 2, 7 and 8, and 13 and 14. An ANOVA was performed to determine any differences between training groups for training load, repetitions, RPE, and the time to complete each set of KEXT and KFLEX exercise. Also differences among sets were analyzed for the EX-3 group.

Statistical procedures were performed using the Statistical Analysis System (28) general linear models procedure. Statistical significance was accepted at $P \leq 0.05$.

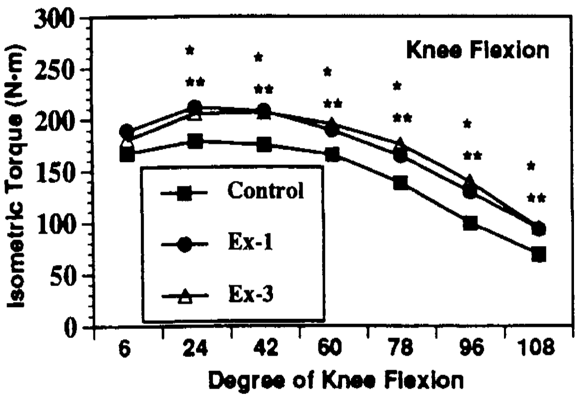

Figure 3—Bilateral knee flexion increases in isometic torque of EX-1 (N = 18) and EX-3 (N = 20) over the control group (N = 10) (ANCOVA). Percent gains in isometric torque were 13.0% vs 7.8% at 6°, 18.3% vs 14.9% at 24°. 18.7% vs 17.7% at 42°, 14.4% vs 17.8% at 60°, 19.0% vs 27.0% at 78°, 30.6% vs 40.7% at 96°, and 34.8% vs 37.0% at 108° for the EX-1 and EX-3 groups, respectively.

RESULTS

Subjects. Forty-eight subjects (N = 21 men, N = 27 women) of the original 59 completed the study. Of the 11 (five men and six women) who did not finish, seven were dropped by the investigators for not adhering to the training protocol or dropped out voluntarily for reasons of inconvenience. Of the other four, one subject moved out of the Gainesville area, one changed his job, one had knee discomfort, and one dropped out on doctor's advice. Characteristics of those who completed the study are listed by group and gender in Table 1. There were no statistically significant differences among groups for age, height, and weight ($P \geq 0.05$).

Dynamic training. Training data for KEXT and KFLEX for both training groups are presented in Tables 2 and 3. No differences in the initial training weights were noted between groups. Significant increases ($P \leq 0.01$) in the amount of weight used between weeks 1 and 2, 7 and 8, and 13 and 14 were noted for the one- and the three-set groups and were not different between groups ($P \geq 0.05$). Significant increases in RPE were found for both training groups between weeks 1 and 2 and weeks 7 and 8 but not between weeks 7 and 8 and weeks 13 and 14. By weeks 7 and 8 the subjects were exercising with what they felt was their maximum weight for 8–12 repetitions. These data indicate a similar progression and effort between training groups.

The data for KEXT for the EX-3 group are shown by set in Table 4 and for KFLEX in Table 5. No differences were noted for training loads among sets 1, 2, or 3 for weeks 1 and 2, 7 and 8, and 13 and 14. As the number of sets increased, the number of repetitions performed decreased, and the RPE increased for the entire training period except for set 3 for weeks 7 and 8 and weeks 13 and 14 for KEXT, and set 2 for weeks 13 and 14 for KFLEX. These data indicate that with no change in training weight a decrease in repetitions and an increase in RPE occurred as training sets increased from one to two sets and from two to three sets. Although significant, the RPE differences among sets was considered small, and thus it was felt that subjects worked equally as hard at all three sets.

Isometric strength. Tables 6 shows the pre- and post-test means (±SD) for isometric torque for KEXT and Table 7 for KFLEX. Both EX-1 and EX-3 improved bilateral isometric knee extension and flexion torque significantly ($P \leq 0.05$) from pre- to post-training at most angles (Tables 6 and 7). For KEXT the EX-1 showed no significant improvements at 96° and 108°and the EX-3 at 6°, 96°, and 108°. In contrast, the CONT showed no significant changes in isometric torque at five angles of KEXT and a significant decrease at 42° and 62°. For KFLEX both the EX-1 and the EX-3 groups showed no significant improvement at 6°. In contrast, the CONT showed no significant change for all angles of KFLEX. There were no significant differences ($P \geq 0.05$) in increased isometric torque values and dynamic strength gains between the EX-1 and EX-3 at any angle for both KEXT and KFLEX. When data from Tables 6 and 7 were analyzed by ANCOVA using the pre-training torques as the covariate, both the EX-1 and EX-3 groups improved significantly in KEXT at all angles of ROM except for the EX-3 at 6° (see Figure 2). For KFLEX both EX-1 and EX-3 improved at all angles except at 6° (see Figure 3). The ANCOVA analysis confirmed the ANOVA results (Tables 6 and 7) because there were no differences in increased isometric torque values between the EX-1 and EX-3 groups except for KEXT at 24°. This significant difference between groups at 24° favored the EX-1 but was considered physiologically small. The ANOVA analysis showed no gender effect, and males and females improved to the same extent.

Muscle thickness. The results of the muscle thickness data are shown for the anterior, medialis, and lateralis thigh muscles in Table 8 and for the lateral and posterior thigh muscles in Table 9. Because of scheduling difficulties during post-testing, a few subjects were not retested; thus, the sample size for muscle thickness results are smaller than those reported for strength. The same coinvestigator (Y.I.) took all the ultrasound measures for the pre-tests and for the post-tests. The sample size for muscle thickness was: CONT, N = 8 (4 males and 4 females); EX-1, N = 14 (7 males and 7 females); and for EX-3, N = 17 (8 males and 9 females).

Muscle thickness for the anterior and lateralis thigh muscles did not change for the CONT, EX-1, or EX-3 groups ($P \geq 0.05$). Although the magnitude of change in muscle thickness of the medialis was similar for the EX-1 and EX-3 groups ($P \geq 0.05$), it only reached significance

TABLE 2. Dynamic knee extension training data for groups that trained using one set and three sets (mean ± SD).

	N	Weight (kg)	Reps	RPE	Time (s)
One set					
Weeks 1 and 2	18	65.9 ± 21.8	12.9 ± 1.5	17.2 ± 1.9	98.9 ± 15.4
Weeks 7 and 8	18	90.9* ± 29.2	11.7* ± 1.4	19.0* ± 1.4	89.9* ± 14.8
Weeks 13 and 14	18	102.0*† ± 14.8	11.7† ± 1.5	19.5† ± 0.8	89.7† ± 15.1
Three sets					
Weeks 1 and 2	20	57.0 ± 15.0	11.8§ ± 1.2	18.3§ ± 1.1	89.8 ± 16.3
Weeks 7 and 8	20	79.8* ± 23.7	11.2 ± 1.5	19.5* ± 0.7	82.4 ± 11.4
Weeks 13 and 14	20	86.8*† ± 31.9	10.3†§ ± 1.0	19.2† ± 0.5	75.5*†§ ± 10.6

Training data were averaged for weeks 1 and 2, 7 and 8, and 13 and 14; $N = 18$, 9 males and 9 females who trained using one set and $N = 20$, 8 males and 12 females who trained using three sets. Reps = repetitions; RPE = Borg rating of perceived exertion.
*Significant ($P \leq 0.05$) difference from prior 2 wk.
†Significant ($P \leq 0.05$) difference from weeks 1 and 2.
§Significant ($P \leq 0.05$) difference from the group that trained using one set.

TABLE 3. Dynamic knee flexion training data for groups that trained using one set and three sets (mean ± SD).

	N	Weight (kg)	Reps	RPE	Time (s)
One set					
Weeks 1 and 2	18	53.5 ± 12.8	14.0 ± 1.1	15.7 ± 1.9	102.7 ± 17.5
Weeks 7 and 8	18	82.1* ± 20.9	11.7* ± 1.3	18.8* ± 1.5	86.4* ± 9.2
Weeks 13 and 14	18	92.0*† ± 23.4	11.4† ± 1.5	19.5*† ± 0.9	84.7† ± 15.5
Three sets					
Weeks 1 and 2	20	51.2 ± 13.5	12.7§ ± 1.3	17.1§ ± 1.2	93.2 ± 15.1
Weeks 7 and 8	20	75.8* ± 19.0	11.5* ± 1.5	19.2* ± 1.1	81.5* ± 9.0
Weeks 13 and 14	20	83.1*† ± 25.3	10.0*†§ ± 1.0	19.1† ± 1.4	70.9*†§ ± 10.4

Training data were averaged for weeks 1 and 2, 7 and 8, and 13 and 14; $N = 18$ subjects (9 males and 9 females) who trained using one set and $N = 20$ subjects (8 males and 12 females) who trained using three sets. Reps = repetitions; RPE = Borg rating of perceived exertion.
* = Significant ($P \leq 0.05$) difference from prior 2 weeks.
† = Significant ($P \leq 0.05$) difference from weeks 1 and 2.
§ = Significant ($P \leq 0.05$) difference from the group that trained using one set.

TABLE 4. Dynamic knee extension training data by set for the group that trained using three sets (mean ± SD).

	N	Weight (kg)	Reps	RPE	Time (s)
Weeks 1 and 2					
Set 1	20	57.0 ± 15.1	12.9 ± 1.5	17.4 ± 1.4	97.3 ± 18.9
Set 2	20	57.0* ± 15.1	11.8* ± 1.3	18.4* ± 1.2	90.3* ± 18.3
Set 3	20	57.1 ± 14.8	10.8*† ± 1.4	19.0*† ± 1.0	81.9*† ± 15.2
Weeks 7 and 8					
Set 1	20	79.8 ± 23.5	12.1 ± 1.7	19.1 ± 1.1	89.6 ± 13.8
Set 2	20	79.9 ± 23.7	11.2* ± 1.7	19.6* ± 0.7	81.5* ± 12.6
Set 3	20	79.8 ± 23.9	10.3*† ± 1.4	19.7† ± 0.5	76.2*† ± 10.6
Weeks 13 and 14					
Set 1	20	86.7 ± 31.9	11.0 ± 1.4	19.0 ± 1.5	79.5 ± 14.9
Set 2	20	86.7 ± 31.9	10.2* ± 1.2	19.2* ± 1.3	75.3 ± 12.8
Set 3	20	86.9 ± 31.9	9.8*† ± 1.4	19.3† ± 1.1	71.5*† ± 8.8

Data were averaged for weeks 1 and 2, 7 and 8, and 13 and 14; $N = 20$ (8 males and 12 females). Reps = repetitions; RPE = Borg rating of perceived exertion.
* = Significant ($P \leq 0.05$) difference from previous set.
† = Significant ($P \leq 0.05$) difference from set 1.

relative to the CONT group in the EX-3 (Table 8). Muscle thickness for the lateral muscle showed a small increase for the CONT group, but it was not significant when compared with the EX-1 or EX-3 groups ($P \geq 0.05$) (Table 9). In contrast, muscle thickness for the posterior 40% and 60% increased significantly and of similar magnitude ($P \leq 0.01$) for both the EX-1 and EX-3 groups compared with the CONT (Table 9).

DISCUSSION

This 14-wk study investigated the effects of two different training volumes of high-intensity resistance exercise on the development of strength and hypertrophy of the quadriceps and hamstring muscles. Training intensity was standardized to an 8–12 repetition maximum (RM) load, and volume was differentiated by EX-1 and EX-3 programs. Both training groups followed similar progressions in training (weights and repetitions) and exerted equivalent efforts based on RPE. We hypothesized that EX-3 of KEXT and KFLEX exercise three times per week would elicit greater strength development than EX-1 in healthy untrained adults. Furthermore, it was thought that EX-1 of exercise three times per week would evoke approximately 80–90% of the improvement produced by EX-3. Our data show that one set of KEXT and KFLEX exercise performed to volitional fatique three times per week was as effective as three sets three times per week for improving torque output and increasing muscle thickness.

TABLE 5. Dynamic knee flexion training data by set for the group that trained using three sets (mean ± SD).

	N	Weight (kg)	Reps	RPE	Time (s)
Weeks 1 and 2					
Set 1	20	51.0 ± 13.5	13.4 ± 1.2	15.9 ± 1.5	97.4 ± 15.8
Set 2	20	51.3 ± 13.5	12.9* ± 1.4	17.3* ± 1.2	94.7 ± 17.6
Set 3	20	51.3 ± 13.5	11.8*† ± 1.7	18.0*† ± 1.1	87.5*† ± 14.2
Weeks 7 and 8					
Set 1	20	75.8 ± 19.0	12.3 ± 1.5	18.8 ± 1.6	87.4 ± 10.9
Set 2	20	75.7 ± 19.0	11.4* ± 1.6	19.3* ± 1.1	80.5* ± 9.8
Set 3	20	75.7 ± 19.0	10.9*† ± 1.7	19.6*† ± 0.6	76.7*† ± 9.9
Weeks 13 and 14					
Set 1	20	83.1 ± 25.3	10.5 ± 1.3	18.9 ± 1.5	74.3 ± 13.7
Set 2	20	83.1 ± 25.3	9.9* ± 1.1	19.1 ± 1.4	70.3 ± 9.1
Set 3	20	83.1 ± 25.3	9.6† ± 1.0	19.3*† ± 1.1	68.2*† ± 10.1

Data were averaged for weeks 1 and 2, 7 and 8, and 13 and 14; $N = 20$ (8 males and 12 females); Reps = repetitions; RPE = Borg rating of perceived exertion.
* = Significant ($P \leq 0.05$) difference from previous set.
† = Significant ($P \leq 0.05$) difference from set one.

TABLE 6. Pre- and post-14 week isometric torque values (mean ± SD in Nm) for the control and exercise for one- and three-set groups for knee extension.

	Degrees of Knee Flexion						
	6°	24°	42°	60°	78°	96°	108°
Controls							
Pre-KEXT	101.7 ± 40.9	178.4 ± 72.4	273.5 ± 109.3	369.5 ± 132.9	375.2 ± 160.7	296.8 ± 136.9	266.0 ± 117.6
Post-KEXT	97.4 ± 47.1	167.5 ± 63.9	238.7* ± 80.9	326.6* ± 114.1	343.2 ± 128.4	263.1 ± 107.9	241.9 ± 97.1
One set							
Pre-KEXT	123.5 ± 40.6	197.8 ± 67.0	277.7 ± 95.4	357.2 ± 141.5	383.4 ± 173.6	309.8 ± 142.6	278.2 ± 120.2
Post-KEXT	136.3* ± 39.9	231.1** ± 64.0	316.9** ± 86.7	411.2** ± 116.6	421.0** ± 148.1	326.4 ± 121.1	292.3 ± 102.4
Three sets							
Pre-KEXT	110.0 ± 33.0	186.4 ± 48.9	263.5 ± 71.8	333.9 ± 104.0	335.7 ± 130.7	258.8 ± 108.6	237.2 ± 101.2
Post-KEXT	118.8 ± 30.5	202.9* ± 51.8	294.4** ± 79.8	383.5** ± 110.8	375.4** ± 128.1	283.7 ± 97.5	252.6 ± 81.9

*$P \leq 0.05$.
**$P \leq 0.01$.

TABLE 7. Pre- and post-14 week isometric torque values (mean ± SD in Nm) for the control and exercise for one- and three-set groups for knee flexion.

	Degrees of Knee Flexion						
	6°	24°	42°	60°	78°	96°	108°
Controls							
Pre-KFLEX	162.9 ± 84.2	183.9 ± 77.9	177.2 ± 67.4	159.6 ± 57.5	144.3 ± 63.3	114.2 ± 56.9	79.2 ± 39.4
Post-KFLEX	160.0 ± 84.0	174.7 ± 78.3	173.2 ± 71.7	161.1 ± 67.7	139.7 ± 65.6	104.8 ± 50.4	72.4 ± 34.7
One set							
Pre-KFLEX	178.8 ± 84.3	201.4 ± 85.8	191.7 ± 77.0	179.9 ± 70.5	152.7 ± 59.1	112.7 ± 42.7	78.6 ± 32.9
Post-KFLEX	195.0 ± 68.6	222.3* ± 70.2	218.4** ± 70.2	202.2** ± 65.3	173.5** ± 54.9	134.1** ± 44.9	96.2* ± 38.5
Three sets							
Pre-KFLEX	170.4 ± 56.3	181.2 ± 58.9	171.3 ± 57.4	155.5 ± 54.7	134.0 ± 44.7	101.3 ± 35.2	73.4 ± 30.1
Post-KFLEX	179.4 ± 62.0	199.2** ± 61.5	199.1** ± 54.0	187.2** ± 49.6	168.1** ± 48.0	134.3** ± 37.1	92.0** ± 38.1

*$P \leq 0.05$.
**$P \leq 0.01$.

Strength increase for knee extension and flexion exercise. A comparison of the magnitude of strength gain in subjects trained by KEXT and evaluated by isometric testing or with the same method in which they were trained, e.g., a 1-RM or number of repetitions completed, is shown in Table 10 (8,10,16,17,25,30). The peak strength improvements of 30.1% and 26.8% (Fig. 2) for our EX-1 and EX-3 groups were comparable to those reported by Braith et al. (8), Cureton et al. (10), and Hakkinen et al. (16) for the three times per week groups. The improvements were 5–15% greater than the groups who trained with less frequency (twice per week) (8) and for a shorter period of time (6–10 wk) (8,25,30). Hakkinen and Komi (17) showed a 21% increase in KEXT strength using three sets of exercise, but their subjects trained with fewer repetitions than in the other studies.

Subjects in only two other studies trained their knee flexor muscles and used a testing method consistent with exercises in this study (Table 10). The 18.6% improvement reported by Cureton et al. (10) is similar to our findings of 18.7% and 17.7% for EX-1 and EX-3 groups, respectively, but greater than the 14.5% found by Smith and Melton (30). The difference in the results is probably because of the duration of training. Messier and Dill (23) show a 5.0% increase in KFLEX strength using a variable resistance weight machine (1 set, 10–12 repetitions) and 6.1% increase with free weights (3 sets, 6 repetitions) ($P \geq 0.05$ between groups) over a 10-wk period. These groups were tested using a nonspecific testing device (Cybex II isokinetic dynamometer), making it impossible to adequately compare them with the 18% peak strength increases found in this study. The comparative data shown in Table 10 do not support the idea that groups

TABLE 8. Ultrasound values for anterior (ANT), medialis (MED), and lateralis (LATER) muscle thickness pre- and post-training. Data include mean ± SD (mm).

Group	20% ANT	40% ANT	60% ANT	MED	LATER
Control Pre-training	57.1 ± 7.4	49.3 ± 8.7	35.8 ± 5.7	37.9 ± 5.9	39.4 ± 6.8
Control Post-training	57.0 ± 6.7	48.5 ± 8.6	36.2 ± 6.3	36.6 ± 7.8	39.3 ± 6.8
One set Pre-training	57.1 ± 6.1	52.2 ± 6.3	40.1 ± 7.1	41.0 ± 7.3	42.5 ± 5.4
One set Post-training	57.4 ± 7.0	53.1 ± 6.6	41.1 ± 6.8	42.1 ± 7.3	42.1 ± 6.9
Three set Pre-training	55.0 ± 7.4	49.3 ± 8.0	38.0 ± 7.5	38.8 ± 7.2	41.1 ± 5.9
Three set Post-training	56.1 ± 7.6	50.3 ± 7.3	39.1 ± 7.3	39.8* ± 6.5	40.6 ± 6.0

* $P \leq 0.05$.
Control group, N = 8 (4 males and 4 females); One set group, N = 14 (7 males and 7 females); Three set group, N = 17, (8 males and 9 females).

TABLE 9. Ultrasound values for lateral (LAT) and posterior (POST) muscle thickness pre- and post-training. Data include mean ± SD (mm).

Group	20% LAT	40% LAT	60% LAT	40% POST	60% POST
Control Pre-training	25.6 ± 4.9	34.7 ± 5.2	33.3 ± 4.1	56.2 ± 5.7	59.6 ± 5.4
Control Post-training	25.6 ± 5.1	35.3* ± 4.8	33.6 ± 3.7	56.3 ± 4.9	59.3 ± 4.2
One set Pre-training	27.8 ± 6.2	35.7 ± 7.3	35.3 ± 5.5	60.9 ± 11.3	62.4 ± 9.2
One set Post-training	28.0 ± 6.9	36.4 ± 7.5	36.7* ± 5.9	64.3* ± 10.7	65.1** ± 9.1
Three set Pre-training	26.8 ± 4.1	35.6 ± 5.3	35.3 ± 4.6	56.1 ± 7.0	58.9 ± 7.0
Three set Post-training	28.3 ± 5.5	36.7 ± 5.8	36.3 ± 4.9	59.1* ± 7.8	61.3** ± 6.8

* $P \leq 0.05$.
** $P \leq 0.01$.
Control group, N = 8, (4 males and 4 females); one set group, N = 14, (7 males and 7 females); three set group, N = 17, (8 males and 9 females).

who trained with multiple sets show greater gains in strength than those who trained with a single set.

Comparison of strength increases in single versus multiple set regimens. The authors were surprised to discover the lack of well-controlled studies comparing single versus multiple set resistance training programs. The results from seven controlled investigations and the present study are shown in Table 11 (5,15,27,29, 31,33,35). The studies were conducted over a 4- to 14-wk period, using a variety of muscle groups and comparing programs using one, two, or three sets of resistance training exercise. No study showed a significant difference in strength gains when comparing one versus two sets of exercise (5,15,27,33,35). Only one (4) of five (28,30,34, and this study) studies showed a significantly greater increase in strength comparing 3- versus one-set regimens. It is interesting that even though the Berger (5) study, which used the bench press exercise, found a statistically significant difference when training with three sets compared with one or two sets, the magnitude of difference is small. Berger's ANCOVA data (5) show that all groups started with a weight of 124.5 lb and finished with 157.2 (27.1%), 154.5 (24.2%), and 153.9 (23.3%) lb, respectively, for the three-, two-, and one-set groups. (These data were the average of his 6 and 10 repetition groups). Although Anderson and Kearney (3) (not shown in Table 11) show significantly greater improvement in strength training three sets versus two or one set, the gross differences in the repetitions used (1 set, 100–150 repetitions; 2 sets, 30–40 repetitions; 3 sets, 6–8 repetitions) do not allow for meaningful comparisons among sets. Except for the Berger study (5), the literature supports the present findings for a wide variety of muscle groups.

Muscle thickness changes. B-mode ultrasound provides a two-dimensional image of fat and muscle thicknesses. Its more advanced technology (compared with A mode—uni-dimensional images) allows for better identification and differentiation of various reflections produced by the sound waves. Fukunaga et al. (13) show that the B-mode technique was valid for measuring muscle thicknesses by comparing ultrasound measurements with direct cadaver muscle thickness measures. Abe et al. (1) reported that muscle thickness of the quadriceps femoris was highly correlated ($r = 0.91$, $N = 52$) to the cross-sectional area determined by MRI. The B-mode method is highly reliable with little day-to-day variation when performed by one investigator (19,20) as is done in this study.

In general, the mid to lower regions (40–60%) of the quadriceps and of the hamstring muscles showed modest increases in muscle thickness. The magnitude of change was approximately 1–1.5 mm for the quadriceps and 3.0 mm for the hamstring muscles. Although some of the quadriceps changes were not significant, there was a consistent and favorable trend toward increases in both

TABLE 10. Comparison of strength gains found in studies using knee extension and knee flexion resistance training exercise.

Reference	Sex	Age X̄	N	Exercise	d·wk^{-1}	Duration (wk)	Sets-Reps	% Increase
O'Shea (1966)	M	C	30	Knee extension (IT)	3	6	3 × 2 − 3	23.2
							3 × 5 − 6	15.5
							3 × 9 − 10	21.1
Smith and Melton (1981)	M	17	12	Knee extension (VR)	3	6	3 × 10	14.6
Hakkinen and Komi (1983)	M	25	14	Knee extension (IT)	3	16	3 × 1 − 6	21.0
Hakkinen et al. (1985)	M	25	14	Knee extension (IT)	3	24	3 × 10	26.8
Cureton et al. (1988)	M/F	26	22	Knee extension (VR)	3	16	1 − 3 × NA	31.4
Braith et al. (1989)	M/F	27	44	Knee extension (VR)	2	10	1 × 7 − 10	13.5
					3		1 × 7 − 10	21.2
Braith et al. (1989)	M/F	25	47	Knee extension (VR)	2	18	1 × 7 − 10	20.9
					3		1 × 7 − 10	28.4
Starkey et al. (1995)	M/F	35	48	Knee extension (VR)	3	14	1 × 8 − 12	30.1
							3 × 8 − 12	26.8
Smith and Melton (1981)	M	17	12	Knee flexion (VR)	3	6	3 × 10	14.5
Cureton et al. (1988)	M/F	26	22	Knee flexion (VR)	3	16	1 − 3 × NA	18.6
Starkey et al. (1996) (this study)	M/F	35	48	Knee flexion (VR)	3	14	1 × 8 − 12	18.7
							3 × 8 − 12	17.7

M = male; F = female; C = college undergraduates; IT = isotonic; VR = variable resistance; NA = data not available.

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exercise groups compared with the controls. The extent of these changes in muscle thickness were similar for both the EX-1 and EX-3 groups. The reason that the magnitude of muscle thickness change was greater for the hamstrings muscle compared with the quadriceps muscle is difficult to explain. The hamstring muscles normally perform eccentrically, acting as a brake to slow the acceleration of the leg, whereas the quadriceps get more total daily stimulation concentrically (walking up stairs, standing up and walking, etc.); thus, the hamstring muscles may have greater potential to hypertrophy than the quadriceps.

Length of the training period. Most resistance training studies (11) are of 8–12 wk duration (Tables 10 and 11). Most of the strength increases found in resistance training programs occur during this time. Although studies have shown continued increases in strength with added weeks of training up to 2 yr (22), the magnitude of gain is less and tends to level off after 3–6 months (9,11,21). In addition, when multiple angle isometric testing is used, muscular strength may not increase uniformly throughout the full ROM (9). For example, Carpenter et al. (9) found that peak torque increased dramatically during the first 12 wk of training but made no further significant increase from weeks 12 to 20 during training of the lumbar extensor muscles. Although peak torque did not change from weeks 12 to 20, muscular torque at five of the seven angles continued to improve. These angles were at the midpoint and more fully extended weaker part of the ROM.

Moritani and DeVries (24) showed that a resistance exercise training program must be performed for a minimum of 4–6 wk to elicit significant muscle hypertrophy. This agrees with others (16,21,32) who have shown significant increases in muscle mass with high-intensity resistance training conducted for 10 wk to 10 months. Although the 14-wk duration of this study was sufficient to increase muscle thickness, a longer duration program would most likely show more dramatic increases. Whether longer duration high-intensity resistance training would elicit a greater increase in muscle thickness with participants using EX-3 compared with EX-1 is not known.

Thus, it is felt that the 14-wk training program described here is sufficient to compare multiple versus single set progressive resistance exercise training regimens. Based on recent long-term experiments (9,11,21,22) conducted on elderly persons, it would be reasonable to assume that further increases in strength could be attained in KEXT and KFLEX exercise conducted over a longer period than 14 wk. Whether longer

TABLE 11. Comparison of strength gains found using single or multiple sets of resistance training exercise.

Reference	Sex	Age	N	Exercise	d·wk⁻¹	Duration (wk)	Sets-Reps	% increase
Berger (1962)	M	C	177	Bench press	3	12	1 × 6/10	23.6
							2 × 6/10	24.0 NS
							3 × 6/10	26.3[a]
Silvester et al. (1982)	M	C	48	Biceps curl	3	8	1 × 10 − 12	24.6
							3 × 6	26.2 NS
Stowers et al. (1983)	M	C	28	Squat	2	7	1 × 10	16.1
							3 × 10	21.1 NS
				Bench press			1 × 10	8.0
							3 × 10	10.6 NS
Westcott (1986)	M/F	35	44	Nautilus circuit[b]	3	4	1 × 10	11.2[b]
							2 × 10	10.8[b]NS
Westcott et al. (1989)	M/F	40	77	Dips/chin-ups	3	10	1 × 5/10/15	4.8[c]
							2 × 5/10/15	4.1[c]NS
							3 × 5/10/15	5.2[c]NS
Pollock et al. (1993)	M/F	26	78	Cervical extension	2	12	1 × 8 − 12	40.9
							2 × 8 − 12	43.5 NS
Graves et al. (1995)	M/F	31	110	Lumbar extension	1	12	1 × 8 − 12	19.0
							2 × 8 − 12	16.0 NS
Starkey et al. (1996) (this study)	M/F	35	48	Knee extension	3	14	1 × 8 − 12	30.1
							3 × 8 − 12	26.8 NS
				Knee flexion	3	14	1 × 8 − 12	18.7
							3 × 8 − 12	17.7 NS

M = male; F = female; C = college undergraduates; NA = data not available; NS = no significant difference when compared to 1 set.
[a] $P < 0.05$; 3 sets > 1 set.
[b] Nautilus circuit—average strength increase of five exercises: leg extension, leg curl, torso pullover, arm extension, arm curl.
[c] Data indicates the average increase in the number of dips and chin-ups combined.
References: Berger, R. Effect of varied weight training programs on strength. *Res. Q.* 33:168–181, 1962. Silvester, L. J. et al. The effect of variable resistance and free weight training programs on strength and vertical jump. *Natl. Strength Condit. J.* 3:30–33, 1982. Stowers, T. et al. The short-term effects of three different strength-power training methods. *Natl. Strength Condit. J.* 5:24–27, 1983. Westcott, W. L. Four key factors in building a strength program. *Scholastic Coach* 55:104–105, 1986. Westcott, W. L. et al. Strength-training research: sets & repetitions. *Scholastic Coach* 58:98–100, 1989. Pollock, M. L. et al. Frequency and volume of resistance training: effect of cervical extension strength. *Arch. Phys. Med. Rehabil.* 74:1080–1086, 1993. Graves, J. E. et al. Single versus multiple set dynamic and isometric lumbar extension strength training. In: *Proceedings, Book III, World Confederation for Physical Therapy, 11th Int. Congress.* London, 1991, pp. 1340–1342.

training would show a better result with a multiple set exercise compared with a single set is not known.

In summary, this investigation studied the effects of two different volumes of high-intensity resistance training on the quadriceps and hamstring muscles and has revealed valuable information concerning two different set routines used in general fitness programs. Both training groups significantly increased in dynamic training weight, isometric torque outputs, and muscle thickness measures. There were no differences between training with one and three sets of high-intensity KEXT and KFLEX exercise performed to fatigue within 8–12 repetitions. Thus, these data support the conclusion that one set of KEXT and KFLEX exercise performed to maximal fatigue is as effective as three sets. These findings have important practical implications for adult fitness and rehabilitation programs in which performing one set of exercise instead of two or three is more cost effective and time efficient. This information is important for the clinician because overtraining could be injurious to patients and for the healthy adult who wishes to build strength and muscle mass but does not have time to perform multiple set workouts. Finally, these findings should be interpreted within the context of the adult fitness setting. The goal of this type of program is to develop and maintain a significant amount of muscle mass, endurance, and strength to contribute to overall fitness and health, not to optimize strength, power, and hypertrophy. Other programs may be more appropriate for improving athletic endeavors.

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