YOGA AS STEADINESS TRAINING: EFFECTS ON MOTOR VARIABILITY IN YOUNG ADULTS

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ABSTRACT

Hart, CEF and Tracy, BL. Yoga as steadiness training: effects on motor variability in young adults. *J Strength Cond Res* 22(5): 1659–1669, 2008—Exercise training programs can increase strength and improve submaximal force control, but the effects of yoga as an alternative form of steadiness training are not well described. The purpose was to explore the effect of a popular type of yoga (Bikram) on strength, steadiness, and balance. Young adults performed yoga training ($n = 10$, 29 ± 6 years, 24 yoga sessions in 8 weeks) or served as controls ($n = 11$, 26 ± 7 years). Yoga sessions consisted of 1.5 hours of supervised, standardized postures. Measures before and after training included maximum voluntary contraction (MVC) force of the elbow flexors (EF) and knee extensors (KE), steadiness of isometric EF and KE contractions, steadiness of concentric (CON) and eccentric (ECC) KE contractions, and timed balance. The standard deviation (*SD*) and coefficient of variation (CV, *SD*/mean force) of isometric force and the *SD* of acceleration during CON and ECC contractions were measured. After yoga training, MVC force increased 14% for KE (479 ± 175 to 544 ± 187 N, $p < 0.05$) and was unchanged for the EF muscles (219 ± 85 to 230 ± 72 N, $p > 0.05$). The CV of force was unchanged for EF (1.68 to 1.73%, $p > 0.05$) but was reduced in the KE muscles similarly for yoga and control groups (2.04 to 1.55%, $p < 0.05$). The variability of CON and ECC contractions was unchanged. For the yoga group, improvement in KE steadiness was correlated with pretraining steadiness ($r = -0.62$ to -0.84, $p < 0.05$); subjects with the greatest KE force fluctuations before training experienced the greatest reductions with training. Percent change in balance time for individual yoga subjects averaged +228% (19.5 ± 14 to 34.3 ± 18 seconds, $p < 0.05$), with no change in controls. For young adults, a short-term yoga program of this type can improve balance substantially, produce modest improvements in leg strength, and improve leg muscle control for less-steady subjects.

KEY WORDS strength, physiological tremor, force fluctuations, force variability, balance, physical function

INTRODUCTION

The various inputs to a motor unit pool during a steady contraction produce a muscle force that fluctuates around an average value (9,40,42). Because these fluctuations in motor output are of interest from both a neurophysiological (42) and functional (4,26,36) perspective, a number of studies have characterized the fluctuations and have attempted to determine the underlying neural mechanisms.

Various features of neuromuscular output exhibit plasticity. For example, strength training produces adaptations that alter the output of the nervous system and the size of the muscle so that the ability to exert a maximal force or lift a load is increased (34,38). However, strength training also alters neural mechanisms that underlie the variability of motor output. For example, fluctuations during submaximal isometric, shortening, and lengthening contractions were reduced in a hand muscle after strength training (1,17,21). Such training can also reduce fluctuations for the knee extensor muscles, particularly in elderly adults (26,38,41), and can also alter the coordination of muscles and improve control of movement (2,3). Thus, a strength training protocol that alters neural mechanisms to increase maximal force can also improve the control of submaximal force. In addition, force-control training protocols that employed hand manipulation training (33) or steadiness training of the first dorsal interosseus (19,20), ankle dorsiflexors (32), or knee extensors (41) can also reduce the variability of motor output. Furthermore, whole-body steadiness training such as Tai Chi can increase leg strength, reduce fluctuations in postural sway, and reduce fluctuations during isolated, lab-based knee extensor contractions (6,16,22,48). It seems that this widely practiced exercise program can alter neuromuscular output, but there is little information about other alternative exercise interventions that may alter the control of motor output.

The practice of yoga requires control of force output in large muscles. Bikram yoga, performed in a heated, humidified studio, is an increasingly popular (31) but

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unstudied form of yoga. This strictly trademarked exercise program is amenable to systematic study because it consists of a standardized series of 26 postures performed similarly, in the same order, and held for a similar duration across sessions, instructors, and studios. Most of the postures require forceful, controlled isometric contractions of the lower- and upper-limb muscles. This contrasts with other popular and effective but less-standardized forms of yoga for which the intensity, duration, and postural details can vary substantially.

The rationale for the study is, thus, twofold: 1) such training should provide a stimulus that will alter strength and the control of neuromuscular output, and 2) to initiate study into this widely practiced type of yoga and provide an initial description of the effects. Indeed, despite the popularity of this form of exercise (18), there has been relatively little systematic, controlled examination of yoga and control of neuromuscular output in the Western literature, and, to our knowledge, there is no published research on Bikram yoga. For example, a small, uncontrolled study found increased arm and leg strength after yoga participation (44), and yoga has been shown to improve eye-hand coordination (37) and manual dexterity (7,27). Therefore, the purpose of this exploratory study was to provide the first controlled description of the effects of short-term Bikram yoga practice on the strength and steadiness of proximal muscles–albeit delimited to healthy young adults. Because of the evidence that other forms of functional steadiness training can improve strength and control of force, we hypothesized an increase in maximal force output and a decrease in the fluctuations in submaximal motor output. The data have been presented in abstract form (10).

Methods

Experimental Approach to the Problem

Subjects in the yoga group performed yoga training for 8 weeks, and control subjects were instructed to simply maintain their usual level of physical activity for the same time period. Subjects were tested before and after training (week 0 and week 9). Testing consisted of measurements of maximum voluntary contraction (MVC) force for the elbow flexor and knee extensor muscles, force fluctuations during isometric contractions of the elbow flexors and knee extensors, acceleration fluctuations during constant-velocity contractions with the knee extensor muscles, and a timed balance test. The rationale for these measures was based on the fact that the training requires control of substantial muscle forces and involves many balance postures. We therefore measured changes in strength and force control for large, functionally important muscles via well-accepted isolated experimental tasks, and we also assessed the impact on functional balance.

Subject assigned to the yoga group participated in a 90-minute class, three times a week, for 8 weeks (24 classes). Each session consisted of a series of 26 postures (Figure 1) performed in a heated (95–105° F) and humidified (60% relative humidity) studio. This form of yoga (Bikram) is a trademarked and strictly standardized program across instructors and locations; each class was, therefore, instructed in precisely the same manner. Each posture was performed twice, and the series was performed in the same order. The first 60 minutes consisted of standing and balance postures,

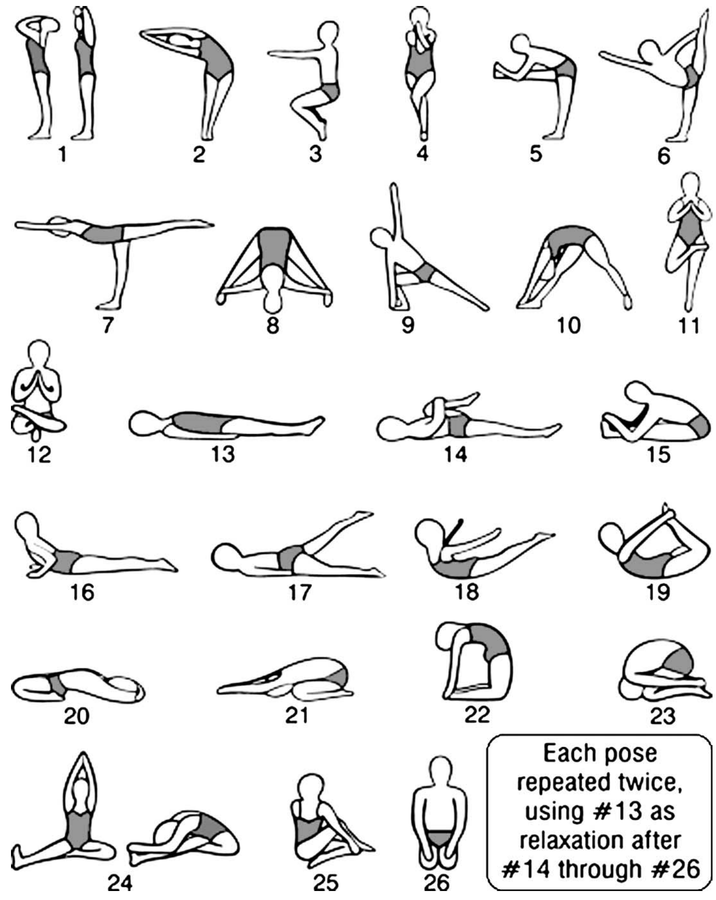

Figure 1. The standard series of postures performed during a Bikram yoga session.

and the last 30 minutes involved seated postures. An attendance log was maintained; the average attendance during the 8 weeks was 22.5 ± 2.3 classes. One subject attended 17 classes but did not exhibit attenuated responses to the training compared with the rest of the group. The others attended 22–25 classes during the 8-week period. The physical activity of subjects outside training was not monitored via questionnaire or device over time, but all subjects were asked to maintain their usual physical activity levels and diets for the duration of their participation.

The elbow flexors and knee extensors were the muscle groups tested during the force-control experiments; 19 of the postures required forceful, controlled, sustained isometric contractions of the knee extensors, and 10 of the postures involved the elbow flexor muscles. The resources were not available to measure the gross activation level (electromyogram) of the test muscles during actual yoga sessions, but the postures are depicted in Figure 1.

Subjects

Healthy young volunteers were recruited via campus and community advertisements, oriented to the study, and provided written informed consent. They were first asked whether they had been exercising regularly in the last 3 months; only two subjects answered yes. Subjects were queried more specifically on their physical activity using questions from the Stanford Usual Physical Activity Assessment. They were also asked whether they had participated in the following activities regularly in the last 3 months: 1) jog or run more than 10 miles per week, 2) strenuous sports more than 5 hours per week, 3) cycling more than 50 miles per week, or 4) swimming more than 2 miles per week. The same two subjects responded affirmatively–one subject cycled more than 50 miles per week, and the other subject performed weight training for about 2 hours per week at a moderate intensity and used an elliptical trainer 1 hour per week at a moderate intensity. One of these active subjects was in the yoga group, and one was in the control group. Thus, the majority of the subjects were no more than minimally active in purposeful, vigorous, physical exercise. Importantly, they reported no prior long-term yoga participation and no acute experience with yoga at least 4 months before the study. Subjects reported no medical conditions, previous injuries, surgeries, or medications that could influence the dependent measures or affect participation. Participants were assigned to the yoga or control groups by drawing slips of paper that represented the assignment. Those assigned to the control group received an equivalent number of free yoga classes after the control period. The human research committee at Colorado State University approved the procedures, which are in accordance with the human research guidelines of the American College of Sports Medicine.

A total of 21 subjects were assigned to either yoga training (29.0 ± 6.1 years, range: 21–39 years, four men, six women) or the control group (25.1 ± 5.0 years, range: 21–39 years, six men, five women). The yoga and control groups were of similar age, height, and body mass before training ($p = 0.37$, 0.40, 0.36, Table 1).

Procedures

Knee Extensor Muscles. Subjects were seated in a custom experimental chair (39,46) with the hip joint at about 100° and the knee joint at 90°. The torso, pelvis, and thighs were firmly stabilized with straps. Depending on the force to be exerted during a particular task, load cells with different sensitivities (1112-, 223-, 111-, or 22-N maximum) were used to maximize the signal-to-noise ratio for the task or trial. The load cells (model LCHD, Omegadyne, Inc.) were bolted onto a small metal plate that was adjustable along a rigid, adjustable steel bar in front of the lower leg. The knee extensor force was thus registered through the axis of the load cell perpendicular to the shank (39,46). The force signal was displayed on a 48-cm flat-panel computer monitor placed about 75 cm in front of the subject. This monitor displayed the force by displaying the VGA video output from an oscilloscope (TDS 3014B, Tektronix) in a similar fashion for the elbow flexors and knee extensors.

Elbow Flexor Muscles. Subjects were seated in the same position as above with the same restraints. The upper arm was slightly abducted (39) with the elbow at a right angle resting on a rigid, adjustable (three axes) platform and the forearm fixed in a rigid, form-fitting plastic orthosis (Orthomerica) in a neutral position (12,39). The orthosis was designed to hold the forearm snugly with the thumb pointing up and was attached to a load cell. The axis of force measurement for the load cell was perpendicular to the orthosis and forearm.

Elbow Flexor and Knee Extensor Experiment. After MVCs, the order of testing of the elbow flexor constant-force, knee extensor constant-force, and knee extensor constant-velocity tasks was randomized. Subjects were familiarized with the details of the experiment.

Table 1. Subject characteristics.

Group	Age (y)	Body mass (kg)	Height (cm)	Sex (M/F)
Yoga (*n* = 10)	29.0 ± 6.1	73.8 ± 5.6	170 ± 8.2	4/6
Control (*n* = 11)	25.1 ± 5.0	64.9 ± 5.1	167 ± 11	6/5

Subject characteristics before training. Values are means ± *SD*.

Maximum Voluntary Contraction Force.. The maximal force was determined during unilateral MVC tasks with the knee extensors and elbow flexors. Subjects increased the force for approximately 3 seconds and were strongly, verbally encouraged to exert maximally for 2–3 seconds. After a practice trial, at least three trials were performed, with 60 seconds of rest between trials. Additional trials were performed if two trials within 5% of each other were not obtained (38,40), to a maximum of five trials. Most subjects met this criterion within four trials. This standard protocol did not produce muscle fatigue that can be detected as a decline in maximal force. The maximal force measured during any trial was taken as the MVC force.

Isometric Steadiness. Isometric contractions of the elbow flexors and knee extensors were performed at target forces of 2.5, 30, and 65% of MVC force. The 65% MVC trials were performed first using the load cell from the MVC task (1113-N maximum). The 2.5% and 30% MVC trials were subsequently performed in random order using more sensitive load cells. One practice trial was performed at each target force, followed by two trials that were recorded for analysis.

For visual feedback, a bold horizontal target line was displayed on the 48-cm computer monitor. For each target force, the vertical sensitivity of the oscilloscope was adjusted so that the target line would remain 16 cm up the screen (39,40,46). The visual gain of the force feedback was, therefore, much greater for 2.5% MVC than for 65% MVC, but, importantly, it was similar for a subject across study time points. This strategy was chosen to facilitate comparison with our previous data (39,40,46) and because the focus was on changes in individuals across time.

The muscle force was represented by a bold horizontal line that moved up or down with changes in force. For a trial, the subject increased the force to the target line and was instructed to match the force with the target as steadily as possible for 5–8 seconds (Figure 2). Midway through the trial, the visual feedback was removed and the subject was instructed to exert the force as steadily as possible for another 5–8 seconds. The trials at 65% MVC were briefer, to prevent fatigue.

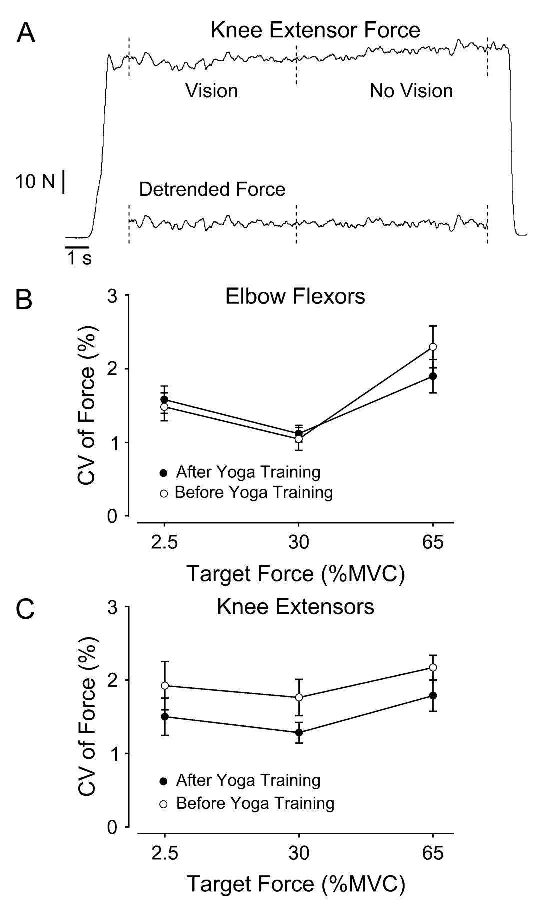

Figure 2. (A) Original data from a subject performing a submaximal, constant-force contraction with the knee extensor muscles, with and without visual feedback of the force. The vertical dashed lines define the vision and no-vision segments for analysis. Coefficient of variation (CV) of force for the elbow flexors (B) and knee extensors (C) for the 2.5, 30, and 65% MVC target forces before and after yoga training (vision data only). For the knee extensors, the change in CV of force with training was not different from controls.

Concentric/Eccentric Steadiness. The constant-velocity task was performed only with the knee extensors because of logistical and experimental time constraints. The range of motion was 60° (90–150°). The shank was unloaded. An electronic goniometer (model SG150, Biometrics) on the lateral aspect of the knee joint was used to monitor knee position. Acceleration of the lower leg was measured during the concentric and eccentric contractions using a sensitive uniaxial accelerometer (model 7265A-HS, Endevco) taped to the tibia at midshank. The visual feedback during this task consisted of a bold horizontal line that represented the target velocity and another horizontal line that represented the knee angle (goniometer signal). The vertical movement velocity of the target line was determined by a waveform generator that created a triangular waveform output at 0.083 Hz (1/12 cycles per second), which produced a 6-second concentric and 6-second eccentric phase. For the steadiness task, subjects were instructed to match the knee joint angle to the constant-velocity target line as closely and as steadily as possible (Figure 3). A trial consisted of three consecutive concentric/eccentric repetitions performed with visual feedback, followed by three repetitions during which the target velocity was visible but the knee angle feedback was removed. The goal for the trials without knee angle feedback was to use the target velocity line for pacing so that the contraction velocity would be similar for vision and no vision. Subjects completed one practice trial of six complete cycles (three vision, three no vision) before two trials that were recorded for analysis.

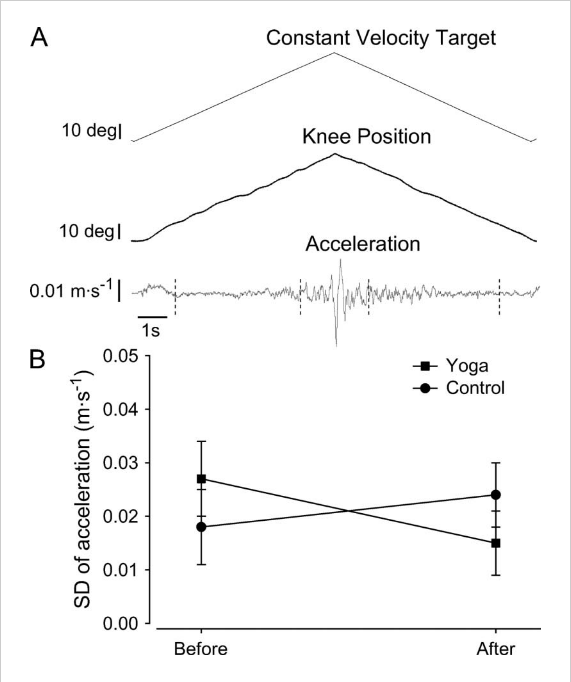

Figure 3. (A) Original data from one repetition of the concentric and eccentric constant-velocity contractions with the knee extensors. Data traces from top to bottom are the constant-velocity target, knee joint position, and shank acceleration. The target line provided a 6-second concentric and eccentric phase. The vertical dashed lines define the 4-second concentric and eccentric segments used for analysis of the acceleration fluctuations. (B) The *SD*s of acceleration ($m \cdot s^{-1}$) for the yoga and control groups before and after training. Values are pooled across repetition, trial, phase (concentric, eccentric), and visual feedback condition.

Data Acquisition/Analysis. The force data were acquired through a strain-gauge transducer coupler (model V72-25A, Coulbourn Instruments), and the goniometer signal was acquired through the Biometrics amplifier (Biometrics); both signals were digitized at 1 kHz to a computer for subsequent analysis (Power 1401 A/D device, Cambridge Electronic Design).

Without vision, the force drifted from the target slightly (Figure 2), as expected (13,45). To remove the drift, the low-frequency content (< 0.5 Hz) in the force signal was removed for the vision and no-vision segments with the DC remove function in the Spike 2 software (Cambridge Electronic Design). The function subtracted the mean of the signal during a 1-second period centered around each data point ($1\ k \cdot s^{-1}$), effectively acting as a high-pass filter with a 0.5-Hz cutoff. After extensive pilot testing, the 1-second time constant was chosen to remove only the drift and to preserve the force fluctuations (Figure 2). The drift was removed because it would produce exaggerated standard deviation (*SD*) of force values not representative of the fluctuations of interest (39,46). Importantly, the *SD* of force during the vision segments was not significantly affected by the detrending function (Figure 2). The longest possible segments of detrended vision or no-vision force data without artifact were chosen for steadiness analysis (Figure 2). Thus, one advantage of the detrending procedure was that it allowed lengthy segments of vision and no-vision data to be analyzed. Others have detrended the force signal before fluctuation analysis (13,45).

Because the *SD* of force scales with the mean force exerted can be different between subjects and visual conditions, the main steadiness outcome was a normalized measure–the coefficient of variation (CV) of force (CV = [*SD* of force/mean force] × 100). The detrending process resulted in a signal that fluctuated around a mean of zero. Therefore, the *SD* of force was measured from the detrended signal, and the mean force exerted was measured from the original, nondetrended signal (39,46). The CV of force was then calculated from these values for the appropriate data segment. The values from two trials were averaged.

For the constant-velocity tasks, the *SD* of acceleration ($m \cdot s^{-1}$) was measured for the middle 4 seconds of the 6-second concentric or eccentric portion (Figure 3). There was no difference in the *SD* of acceleration across repetitions, trials, or visual feedback conditions, thus the values were averaged across repetitions, concentric and eccentric phases, and visual feedback conditions. The movement velocity was also measured for the concentric and eccentric phases and averaged across the three repetitions.

Balance

There was no access to force plates for more sophisticated measures of postural stability, and therefore a timed, one-legged balance test was used. With hands on the hips, the subject lifted one foot off the ground and maintained his or her stance for as long as possible or until he or she reached 30s. Time was recorded from foot-off until the foot touched the ground or the stance leg, the hands were removed from the hips, or the foot of the stance leg was moved. Two trials with eyes open and eyes closed were performed with each foot. For trials with vision, most of the trials lasted longer than 30 seconds, thus only the trials without vision were used as the outcome measure. There was no difference across trials or between legs, thus the values were averaged across trials and summed across legs to produce a total balance time (seconds).

Statistical Analyses

Analysis of variance with repeated measures on the within-subjects variables was used. The between-subjects variable was group (yoga, control). The within-subjects variables included in the analysis were time point (before training, after training), target force (2.5, 30, and 65% MVC), visual feedback condition (vision, no vision), and contraction phase (concentric, eccentric). Planned a priori contrasts, both within and between subjects, were used for the comparisons; no adjustments for multiple comparisons were made. Statistically significant findings are denoted as $p < 0.05$, $p < 0.01$, or $p < 0.001$.

The dependent variables for the steadiness experiments were maximum force (N) during the MVC, mean force (N), *SD* of force (N), and CV of force (%) during the constant-force task, and *SD* of acceleration ($m \cdot s^{-1}$) during the constant-velocity task. The dependent variable for the balance test was total balance time (seconds) for the eyes-closed condition. The consistency of the strength and steadiness measures over time has been established in control subjects in a longitudinal context (38,41). Here, the intraclass correlation coefficient was $r = 0.93 - 0.95$ for strength measures and $r = 0.81$ for balance time. For the yoga group ($n = 10$), the observed statistical power for this exploratory study was 0.57, and it was 0.41 for the change in balance time and knee extensor MVC, respectively.

RESULTS

Maximum Voluntary Contraction Force

Before training, elbow flexor and knee extensor MVC force were similar between the yoga and control groups ($p > 0.05$, Table 1). The MVC force for the elbow flexor muscles was unchanged ($p > 0.05$) over the training period for the yoga and control groups (Table 2). The 14% increase in knee extensor MVC force for the yoga group was significantly different ($p < 0.01$) than the 10% decrease for the control group (Table 2). The change in MVC force for subjects in the yoga group was not correlated with the pretraining MVC force for either muscle group ($p > 0.05$). Changes in MVC force were not different between sexes ($p > 0.05$).

Isometric Elbow Flexor Fluctuations. For the elbow flexors, the CV of force was similar between the yoga and control groups before training ($p > 0.05$, Table 3). Pooled across yoga and control subjects, the CV of force was higher at 2.5% MVC, declined to a minimum at 30% MVC, and increased again at 65% MVC ($p < 0.05$, Table 3, Figure 2B), as expected (39,40,43). When pooled across target forces or examined for each target force, the CV of force for the elbow flexors was unchanged during the training period for the yoga and control groups ($p > 0.05$, Table 3, Figure 2B). Changes in elbow flexor fluctuations were not different between sexes ($p > 0.05$).

Isometric Knee Extensor Fluctuations. The CV of force for the knee extensors was not different ($p > 0.05$) between the control and yoga groups before training (Table 3). As with the elbow flexors, the CV of force was higher at 2.5% MVC, declined to a minimum at 30% MVC, and increased again at 65% MVC ($p < 0.05$, Table 3, Figure 2C). The CV of knee extensor force for all target forces and visual feedback conditions was reduced ($p < 0.05$) after the training period similarly ($p > 0.05$) for the yoga and control groups (Table 3, Figure 2C). For the CV of force values, however, there was a range of response to the training (Figure 4). For the yoga group, the change in the CV of force with training was negatively correlated with the pretraining CV of force values for five of the six target force/visual feedback conditions ($r = -0.62$ to -0.84, $p < 0.05$); the subjects with the greatest CV of force values before training experienced the largest reductions in the CV of force (Figure 4). Only three correlations were significant in the control group ($r = -0.64$ to -0.86, $p < 0.05$). Changes in knee extensor fluctuations were not different between sexes ($p > 0.05$).

Concentric and Eccentric Knee Extensor Contractions. The *SD* of acceleration was unchanged during the training period for the yoga and control groups ($p > 0.05$, Figure 3B). The change in the *SD* of acceleration was not different between concentric and eccentric contractions ($p > 0.05$). The changes were not different between sexes ($p > 0.05$).

Balance. Before training, balance time was not different between the control and yoga groups ($p > 0.05$). The individual changes in balance time averaged +228 ± 355% (range = −68 to +1,066%) for the yoga group ($p < 0.05$), with no change ($p > 0.05$) for the control group (29 ± 104%, range = −70 to +304%) (Figure 5). Ninety percent of the yoga subjects increased their balance time (range = −26 to +46 seconds). The change in balance time was not correlated with the pretraining balance time for either group ($p > 0.05$).

TABLE 2. Isometric strength changes with training.

	Elbow flexor MVC force (N)		Knee extensor MVC force (N)	
	Week 0	Week 8	Week 0	Week 8
Yoga ($n = 10$)	219 ± 85	230 ± 72	479 ± 175	544 ± 187*†
Control ($n = 11$)	243 ± 90	236 ± 90	445 ± 121	400 ± 133*

Strength values (mean ± *SD*) for the yoga and control subjects before and after training.

Elbow flexors MVC force = maximal voluntary contraction force for the elbow flexors; knee extensor MVC = maximal voluntary contraction force for the knee extensors.

*$p < 0.05$ compared with before training.

†$p < 0.01$ for change in MVC for yoga group compared with control (time × group interaction).

Changes in balance time were not different between sexes ($p > 0.05$).

DISCUSSION

This study set out to provide a basic description of the strength, steadiness, and balance effects of a particular yoga program compared with no exercise (control). The results are limited, therefore, to the extent that the yoga group was not compared with some other nonyoga exercise program. Nonetheless, maximal isometric force of the knee extensors increased after 8 weeks of yoga training. On average, isometric force fluctuations for the knee extensor muscles decreased slightly and similarly for the training and control groups. However, the reduction in knee extensor fluctuations over the training period was greater for the least steady subjects in the yoga group. There were no significant changes in knee extensor concentric and eccentric fluctuations or elbow flexor strength and steadiness. Yoga training improved timed balance substantially.

The adaptations were generally greater for the knee extensor than the elbow flexor muscles. For example, the increases in knee extensor MVC force, though modest (14%), were greater than the nonsignificant changes for the elbow flexors. This finding is likely explained by the greater focus of the training stimulus on the lower-limb muscles. Nineteen of the 26 postures in this highly standardized training program require forceful contractions of the knee extensors, but only 10 of the postures require forceful contractions of the elbow flexors. Therefore, the knee extensors probably received a greater training stimulus than the upper-limb muscles. The modest gains in maximal force were lower than those from Christou et al. (6), who found a 19% increase in knee extensor strength after Tai Chi training in elderly adults. The results are not directly comparable with those of the present study because of different training programs, training duration, and subject age. There has been little controlled research on the effects of yoga training on neuromuscular output. Although yoga programs can increase hand strength (8,25) and may (no control comparison) increase arm and leg strength (44), we are not aware of other controlled trials on yoga training and strength in upper- and lower-body muscles. These data, therefore, provide new information on muscle specificity and plasticity of maximal neuromuscular output after Bikram yoga. The knee extensor data should be interpreted conservatively in light of the unexpected 10% decrease in MVC force observed for the control subjects. This unexpected decrease was driven by two subjects who each exhibited a 29% in MVC force for the knee extensor muscles.

The adaptations in motor variability, though not robust on average, also suggest specificity for the knee extensor muscles. First, the finding that the change in CV of force with training was greatest in the least steady subjects–a relation that was more consistent for the yoga group–suggests that an adaptation occurred in those who began training with greater knee extensor force fluctuations (Figure 4). This relation was

TABLE 3. Force steadiness during constant-force isometric contractions.

	Target force		2.5%		30%		65%	
			Vision	No vision	Vision	No vision	Vision	No vision
Elbow flexors	Yoga (n = 10)	Week 0	1.48 ± 0.60	1.43 ± 0.82	1.05 ± 0.49	1.08 ± 0.51	2.30 ± 0.89	1.92 ± 0.71
		Week 8	1.58 ± 0.58	1.77 ± 1.07	1.12 ± 0.36	1.03 ± 0.28	1.90 ± 0.71	1.75 ± 0.91
	Control (n = 11)	Week 0	1.83 ± 0.86	1.63 ± 0.74	1.36 ± 0.41	1.31 ± 0.66	1.95 ± 0.78	1.88 ± 0.97
		Week 8	1.66 ± 0.57	1.57 ± 0.48	1.41 ± 0.34	1.24 ± 0.37	2.40 ± 0.64	2.56 ± 1.39
Knee extensors	Yoga (n = 10)	Week 0	1.92 ± 1.03	1.47 ± 0.65	1.76 ± 0.78	1.66 ± 0.61	2.17 ± 0.53	2.03 ± 0.85
		Week 8	1.50 ± 0.80*	1.17 ± 0.59*	1.28 ± 0.44*	1.05 ± 0.35*	1.79 ± 0.67*	1.56 ± 0.62*
	Control (n = 11)	Week 0	2.25 ± 0.81	1.76 ± 0.71	1.95 ± 0.49	1.65 ± 0.51	2.53 ± 1.08	2.02 ± 0.69
		Week 8	1.69 ± 0.46*	1.40 ± 0.54*	1.64 ± 0.59*	1.36 ± 0.54*	2.29 ± 0.93*	1.94 ± 0.83*

Coefficient of variation of force (%) for the yoga and control groups before and after training. Contractions were performed at 2.5%, 30%, or 65% of maximal voluntary contraction force. Values are means ± *SD*.

*Knee extensors: pooled across target forces and visual feedback conditions, the effect of time was significant ($p < 0.05$) for both yoga and control groups. Pooled across target force, training group, and time point, the effect of visual feedback was significant ($p < 0.001$).

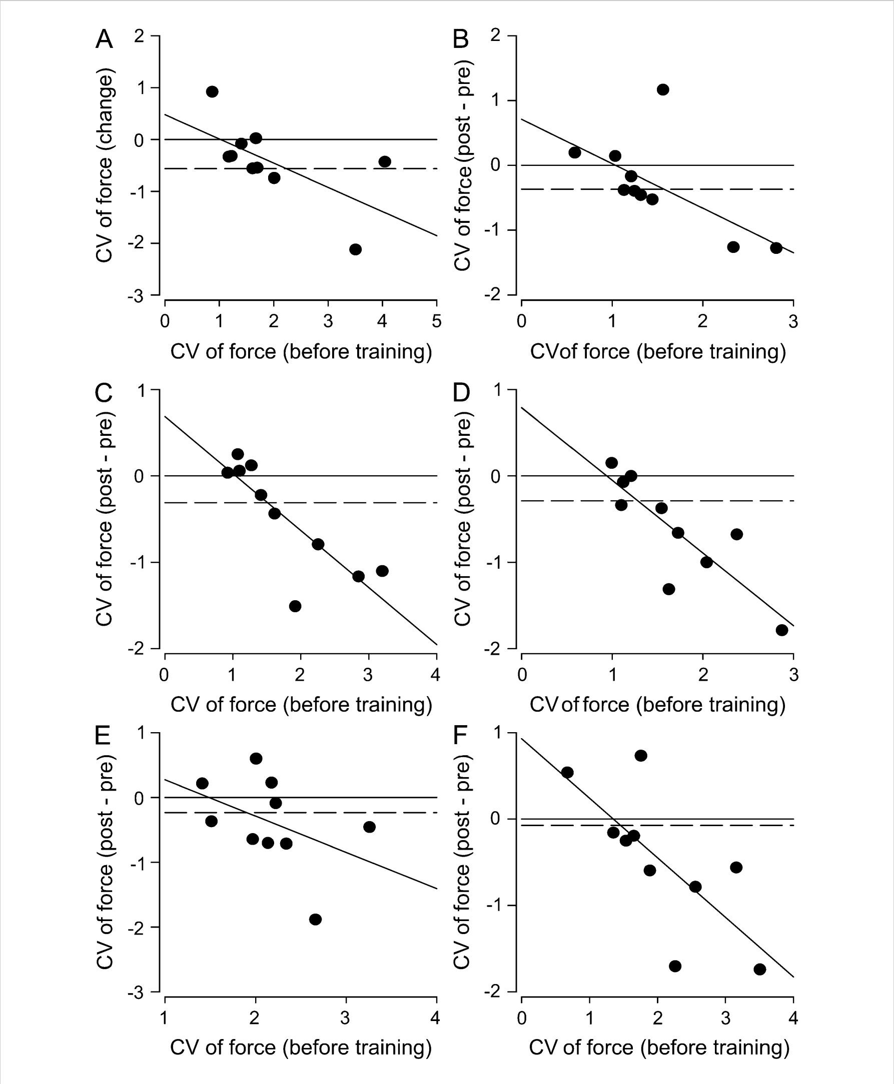

Figure 4. The relation between the change in the coefficient of variation (CV) of force with training and the CV of force before training in the yoga group for knee extensor constant-force tasks performed at 2.5% (A,B), 30% (C,D), and 65% MVC (E,F) target forces with vision (A,C,E) and without vision (B,D,F). (A) $r = 0.64$, $p < 0.05$. (B) $r = 0.62$, $p = 0.054$. (C) $r = 0.82$, $p < 0.01$. (D) $r = 0.84$, $p < 0.01$. (E) $r = 0.43$, $p > 0.05$. (F) $r = 0.73$, $p < 0.05$. The horizontal dashed line in each graph depicts the average change in CV of force for the control group.

significant for five of six target force/visual feedback conditions for the knee extensors and was exhibited by the elbow flexors only in more isolated instances (30% MVC no vision, 65% MVC with vision). Compared with the elbow flexor muscles, the knee extensors were involved in more training contractions that required force control, which presumably explains the specificity of the steadiness adaptations to the knee extensor muscles. Christou et al. (6) found significantly reduced force fluctuations in the knee extensors after a Tai Chi functional steadiness training program in elderly adults, which suggests that the improved force control during slow, steady, whole-body movements can be detected by laboratory-based steadiness tasks. There is ample evidence to support the notion of neural adaptations that improve coordination and stability of movement or muscle force after strength or force-control training (2,3,19,32, 38,41). The present findings should be interpreted in light of the small, similar average reduction in the CV of force for yoga and control subjects in the knee extensors, which suggests that at least part of the adaptation was attributable to motor learning that was specific to the experimental task.

Our finding of greater responses for the least steady subjects despite no average group effect has been observed elsewhere. For example, strength training of the first dorsal interosseus muscle produced greater reductions in fluctuations for those essential tremor patients with the largest fluctuations (1). Furthermore, elderly subjects with the most impaired knee extensor steadiness exhibited the largest steadiness improvements after heavy resistance training (38) or steadiness training with light loads (41). Thus, within the limited context of this relatively small exploratory dataset, there is a likelihood that the neural mechanisms that underlie knee extensor force variability underwent a greater degree of adaptation in participants who began with greater unsteadiness.

Isometric fluctuations were measured with and without visual feedback. Although this report is not focused on the visual feedback effect (39,46), the observed isometric steadiness adaptations were not different for vision and no-vision contractions, which suggests a neural mechanism independent from visuomotor control of force. The specific location of the adaptation in the nervous system cannot be determined from these data, but alterations in the inputs to the motor unit pool that affect the variability of individual motor unit discharge (19,20,32) or that influence the common behavior of multiple motor units (35) have recently emerged as likely mechanisms. There is ample evidence of changes in fluctuations after training in the elderly, but the effects in young subjects are minimally documented and are usually small (17).

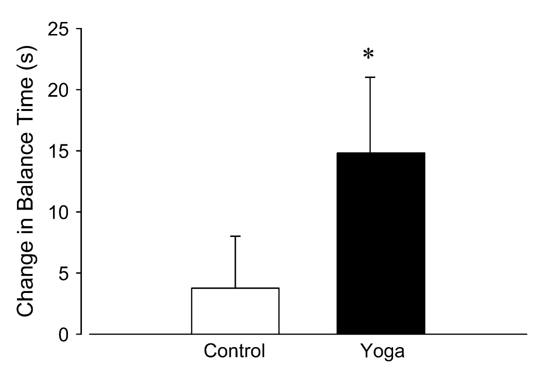

Figure 5. Change in total balance time (seconds) for yoga and control groups. *$p < 0.05$ compared with zero. The change for the control group was not significant ($p > 0.05$).

Yoga participation can reduce sympathetic nervous system activity, presumably through meditative and relaxation effects (15). Interestingly, sympathetic activity associated with heightened physiological arousal increases force fluctuations during isometric contractions (5,29,30). Although we did not measure sympathetic activity, it is possible that the subjects who improved their steadiness experienced reduced sympathetic activity that contributed to the reduced fluctuations after training.

In contrast to the isometric adaptations in unsteady subjects, concentric and eccentric fluctuations were unchanged. This at least suggests a specificity of adaptation for isometric compared with concentric and eccentric contractions and could be explained by the nature of the yoga postures. During training, each posture was held in a static fashion for 20–60 seconds, thus the muscle stimulus was primarily isometric. There seems, however, to be little transfer of the isometric adaptation (observed in the least steady subjects) to dynamic contractions with the knee extensors. In support of this notion, the change in concentric and eccentric knee extensor fluctuations, within individual subjects, was not correlated with the change in isometric knee extensor fluctuations. This agrees with the well-established principle that neuromuscular adaptations are usually greatest for the type of contraction performed during training (14).

Yoga training produced an improvement in timed balance performance for 90% of participants. The lack of change in the control group indicates that the improvement can be attributed with a high likelihood to yoga training. Thus, this training seems to alter postural control mechanisms, at least as measured with a simple timed balance test. Six of the 26 training postures required maintenance of a standing balance position for as long as 60 seconds, and therefore there was a significant training stimulus for the neural control of balance. Because the balance improvement was observed for eyes-closed balance trials, the contribution of improved use of visual feedback to the improvements in postural control was minimal. These findings indicate that this training, or a program of similar postures, would be appropriate to improve balance in young, healthy adults. Similar effects have been observed in elderly adults after popular movement training exercise such as Tai Chi (23,24,48). For example, Wu et al. (48) found that older Tai Chi participants exhibited 10% less variability during quiet stance on a force plate compared with age-matched control subjects. Furthermore, 70- to 92-year-olds who trained with Tai Chi improved their Berg balance scale score more than subjects who only performed stretching (23,24,48). In addition, elderly adults who participate in proprioceptive activities exhibit better postural control compared with those active only in aerobic activities (11). However, other than the study of Jacobson et al. (16) that showed improved lateral stability in 20- to 45-year-olds after Tai Chi, we are not aware of controlled reports of Tai Chi or yoga training and balance performance in young adults. Because regular Tai Chi improves balance in the elderly, and the present yoga training improved balance in young adults, the impaired postural control of elderly adults (28,47) would presumably respond to supervised yoga with balance postures.

PRACTICAL APPLICATIONS

Within the context of this exploratory dataset compared with nonexercising controls, a short-term Bikram yoga training protocol resulted in adaptations specific to the training stimulus. Strength increases were modest and were confined to the knee extensors; elbow flexor strength was unchanged. This finding is most likely attributable to the greater focus of the training stimulus on the lower limb. Improved force control was also limited to isometric knee extensor contractions and did not transfer to concentric and eccentric knee extensor contractions. However, the yoga participants showed varying steadiness adaptations; the least steady subjects exhibited the greatest improvements in knee extensor force control. This suggests that the neural mechanisms that underlie force control in these relatively unsteady subjects were altered by the training. The substantially improved balance suggests that neural mechanisms underlying sensorimotor control of posture were altered by the training. This type of training could have a significant impact on people with impaired leg steadiness and poor balance.

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