
EFFECTS OF FATIGUE FROM RESISTANCE TRAINING ON BARBELL BACK SQUAT BIOMECHANICS

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ABSTRACT

Hooper, DR, Szivak, TK, Comstock, BA, Dunn-Lewis, C, Apicella, JM, Kelly, NA, Creighton, BC, Flanagan, SD, Looney, DP, Volek, JS, Maresh, CM, and Kraemer, WJ. Effects of fatigue from resistance training on barbell back squat biomechanics. *J Strength Cond Res* 28(4): 1127–1134, 2014—Exhaustive resistance training programs that have been previously referred to as extreme conditioning protocols have increased in popularity in military and civilian populations in recent years. However, because of their highly fatiguing nature, proprioception is likely altered during such programs that would significantly affect the safety and efficacy of such programs. Therefore, the purpose of this study was to assess the alterations in movement patterns that result from extreme conditioning protocols and to evaluate if these protocols can be deemed safe and effective. Twelve men (age 24 ± 4.2 years, height 173.1 ± 3.6 cm, weight 76.9 ± 7.8 kg, body fat percentage $9.0 \pm 2.2\%$) and 13 women (age 24.5 ± 3.8 years, height 166.9 ± 8.5 cm, weight 66.1 ± 9.2 kg, body fat percentage $18.6 \pm 4.0\%$) with at least 6 months of resistance training experience involving barbell bench press, barbell deadlift, and barbell back squat performed a highly fatiguing resistance training workout. During the barbell back squat, a 2-dimensional analysis was performed where the knee and hip angles were recorded throughout the 55 repetitions of the workout. At the early stages of the protocol, knee angle was significantly lower in men and in women demonstrating less knee flexion. Also, hip angle was significantly lower early in the program in men and in women, demonstrating a greater forward lean. The technique changes that occur in high repetition sets do not favor optimal strength development and may increase the risk of injury, clearly questioning the safety and efficacy of such resistance training programming. This is likely

a display of self-preservation by individuals who are faced with high repetition programs.

KEY WORDS extreme conditioning protocols, resistance training, short rest, injury, squat, proprioception, exercise technique

INTRODUCTION

Performing resistance training has been shown to have a multitude of benefits ranging from increases in strength, hypertrophy, and muscular endurance (1,12). The specific adaptations that occur within this range are determined by manipulating the acute program variables, including exercise selection, exercise order, volume, rest period, and load. Although there is an almost infinite amount of resistance training possibilities, 1 particular manipulation of the acute program variables that has become increasingly popular is one that involves using exercises that target large muscle groups with moderate to high loads and short rest periods. These short rest protocols have been previously shown to produce a dramatic level of fatigue, as evidenced by high blood lactate concentrations and ratings of perceived exertion (11). A combination of these dramatic metabolic demands with relatively heavy loads creates a stress that is very different from that in conventional training. Because of the exhaustive nature of such a resistance training program, these types of workouts have previously been referred to as “extreme conditioning protocols” and have been increasing in popularity in military and civilian communities (2).

This particular type of resistance training program has been shown to lead to a significant testosterone and growth hormone response (1,12), and to a substantial metabolic response (16). Therefore, the adaptations that can result include increases in lean tissue and reductions in fat mass, which would certainly explain their popularity. Despite the enthusiasm for such workouts and the favorable hormonal and metabolic stimulus, there has been a growing concern that this type of resistance training programming may be leading to a disproportionate number of musculoskeletal injuries and an increased rhabdomyolysis risk (2,14). However, a dearth in peer-reviewed literature on this topic of extreme conditioning protocols has been identified, and as a result, it is difficult at present to validate or dismiss such claims (2).

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Although extreme conditioning protocols have not been well researched, drawing from the literature base regarding the deleterious effects of fatigue on proprioception from cardiovascular exercise (13) and light load resistance exercise (17) shows that these types of programs may possess an element that has cause for concern. Lattanzio et al. (13) demonstrated that 3 different cycle ergometer protocols (a ramp test, an interval test, and steady-state test), which terminated at exhaustion lead to significantly reduced proprioception as measured by the ability to reproduce knee angles. With a light load resistance training protocol, Trafimow et al. (17) discovered a similar reduction in the ability to reproduce movements during a box-lifting task, where subjects began to use a stoop lift rather than a squat lift. As a result of these reductions in proprioception, both authors suggested that their given method of fatigue could be putting individuals at an increased risk of sustaining an injury.

Not only do extreme conditioning protocols combine cardiovascular and local muscular fatigue but they also often use substantially higher loads than in previous research (such as 150% of body weight [4] vs. 30 kg [17]). In addition, these programs use lifts that involve the coordination of large muscle groups over multiple joints (Olympic lifts, squat, and deadlift, etc.), which require substantial technical precision that might be difficult to achieve under significant fatigue. This might be a concern as the National Strength and Conditioning Association (NSCA) Position Stand for the squat exercise states that although when performed correctly, the squat can may be a significant deterrent to knee injuries, fatigue-related problems do occur with squats (3).

Fatigue has been previously shown to abbreviate movement in the body weight squat (9). The reduced range of motion in a lift such as the barbell back squat could have a negative impact on strength development because previous research has shown that the muscle activity in the rectus femoris, vastus lateralis, vastus medialis, and gastrocnemius rises until a peak at approximately 90° of knee flexion in the barbell squat exercise (6). As a result, a reduced proprioception from the fatigue associated with extreme conditioning protocols could impede strength development. Another concern during the barbell back squat is the amount of forward lean, which could also be impacted by a reduction in proprioception. An increase in the range of motion at the hip has been associated with increases in trunk flexion, which increases shear forces in the spine (15). In an effort to reduce back injury during the squat, the NSCA Position Stand recommends that the torso be kept in as upright a position as possible (3).

If both cardiovascular and local muscular fatigue results in reduced proprioception, the combination of both stimuli in these extreme conditioning protocols could be a concern. Further, when these programs are performed with higher loads and with complex movements, the alterations in proprioception could be even more significant than has been previously shown. Based on previous literature, this

would result in erratic movements and in an overall decline in range of motion, significantly affecting the safety and efficacy of such programs. Therefore, the purpose of this study was to assess the alterations in movement patterns that result from extreme conditioning protocols and to evaluate if these protocols can be deemed safe and effective when using moderately heavy loads, short rest periods, and large, multijoint exercises.

METHODS

Experimental Approach to the Problem

To examine extreme conditioning protocols, a workout from a popular commercial program was adapted (4). The program was chosen as an extremely demanding resistance exercise program that combined substantial loads with short rest. Two adaptations were made; the clean was substituted for the squat, and the loads were assigned as percentages of 1-repetition maximum (1RM) rather than of body weight to provide the same relative intensity to all the subjects. To

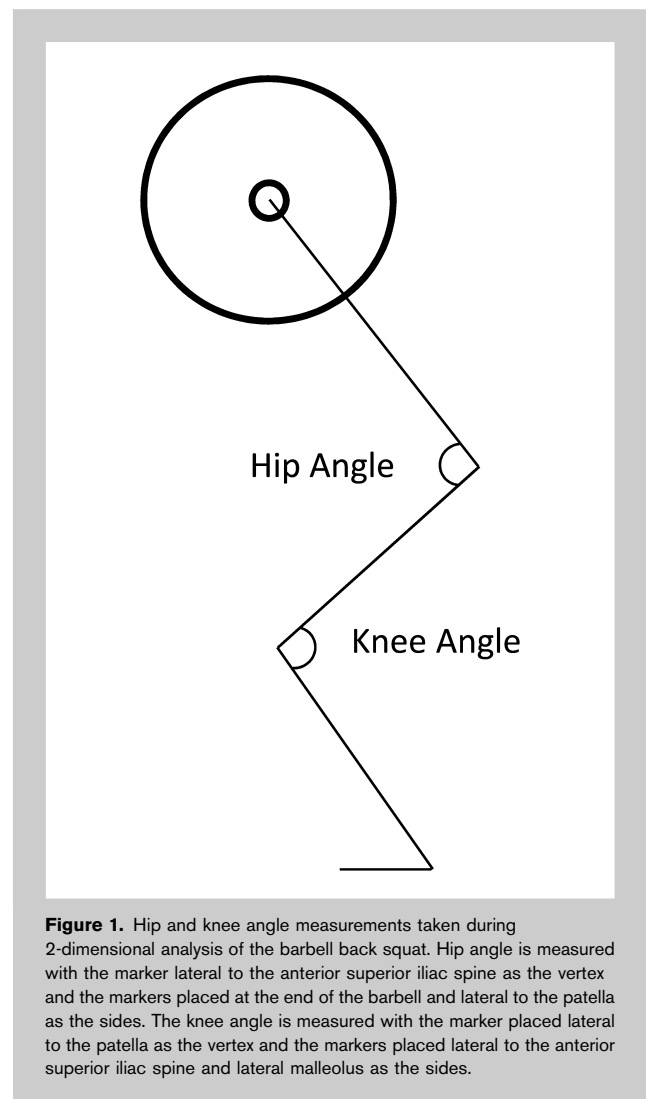
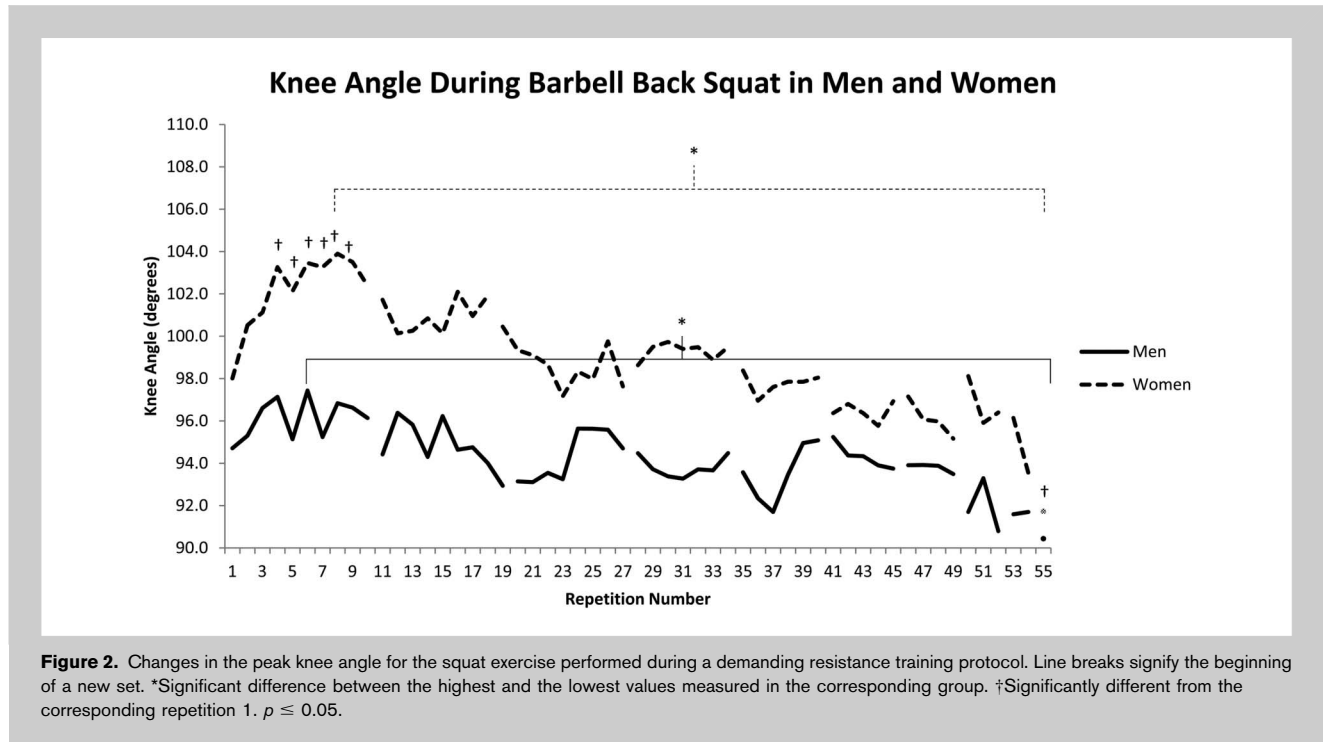
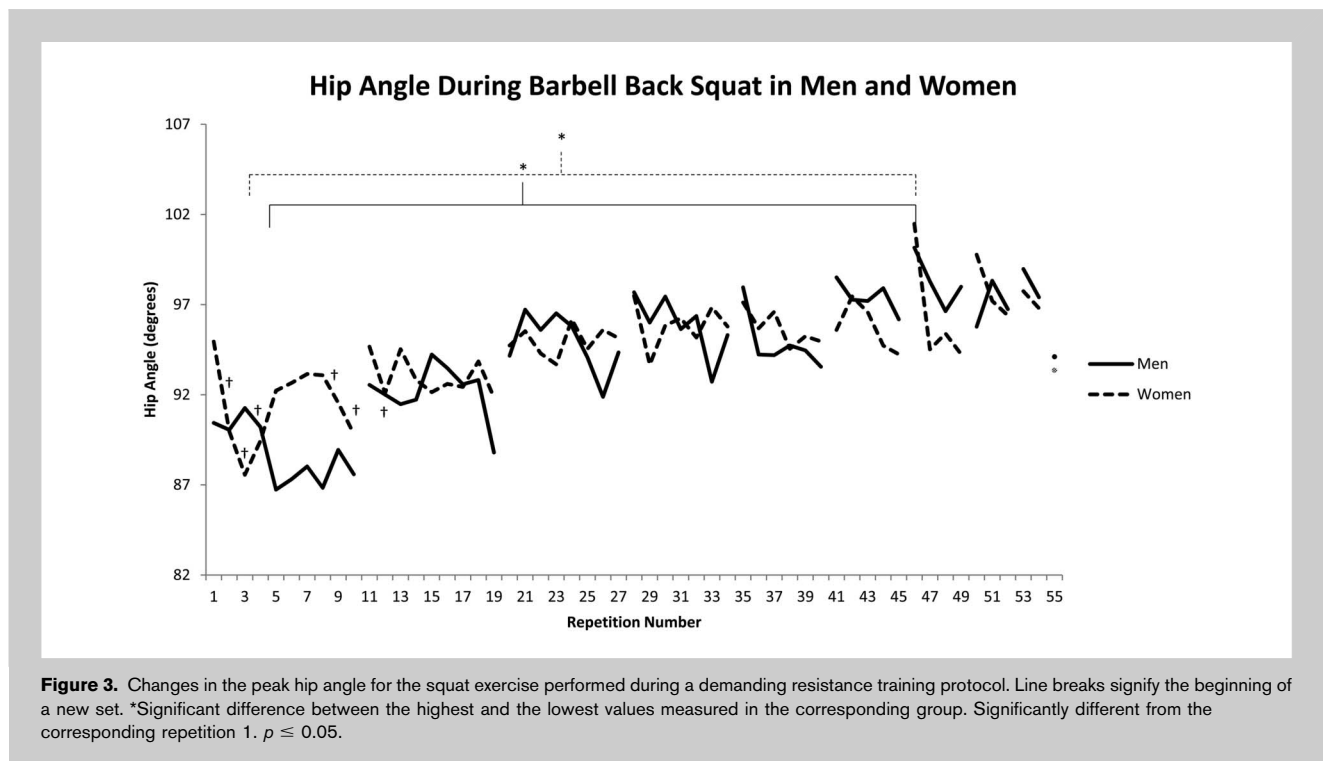


Figure 1. Hip and knee angle measurements taken during 2-dimensional analysis of the barbell back squat. Hip angle is measured with the marker lateral to the anterior superior iliac spine as the vertex and the markers placed at the end of the barbell and lateral to the patella as the sides. The knee angle is measured with the marker placed lateral to the patella as the vertex and the markers placed lateral to the anterior superior iliac spine and lateral malleolus as the sides.



analyze the impact that the fatigue from an extreme conditioning protocol has on movement patterns, a 2-dimensional analysis of the barbell back squat was performed, where the knee flexion and forward lean were analyzed. The protocol was preceded by a familiarization session and 1RM testing.

Before all experimental visits, the subjects were assessed for hydration level using a urine specific gravity (USG) refractometer (Reichert, Lincolnshire, IL, USA). The subjects were excluded from participating in that day of testing unless their USG was 1.025. If the USG exceeded 1.025, the



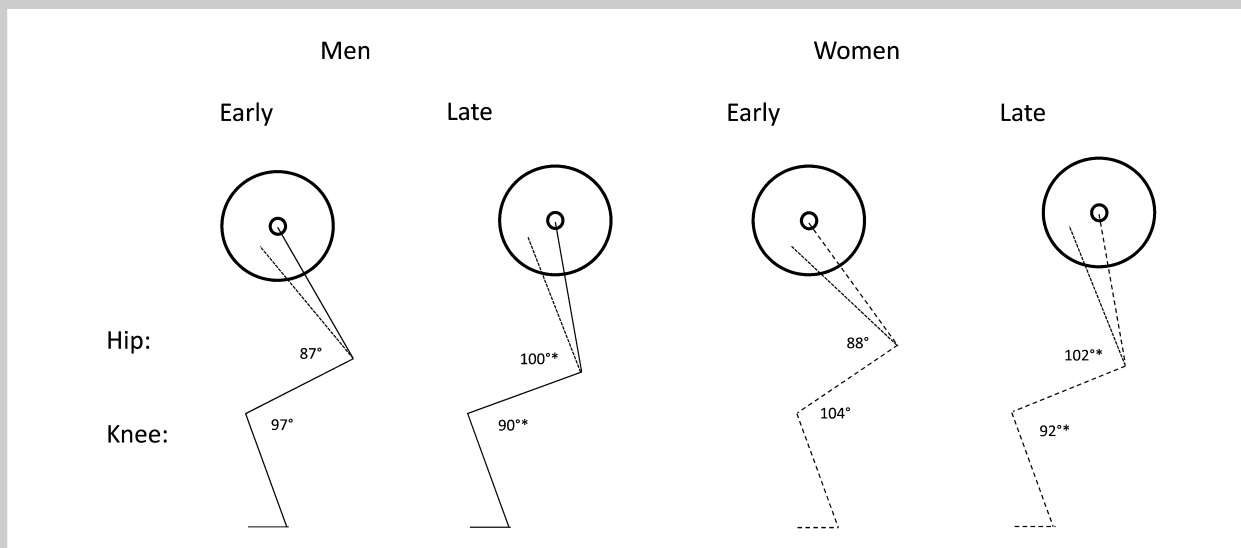


Figure 4. Visual representation of squat changes during an extreme conditioning protocol. Early hip angles are the lowest values measured, which occurred during the first 10 repetitions. Late hip angles are the highest values measured, which occurred during the last 10 repetitions. Early knee angles are the highest values measured, which occurred during the first 10 repetitions. Late knee angles are the lowest values measured, which occurred during the last 10 repetitions. *Significant difference between time points for the corresponding variable ($p \leq 0.05$). Note: The additional line represents where the torso would approximately be.

subjects were instructed to drink water, and the USG was measured repeatedly until the desired level was reached. Familiarization and strength testing were performed at any time of the day that was convenient for the subject, but every subject performed the resistance training protocol in the morning. All the subjects were fed breakfast approximately 2 hours before the protocol to standardize the diet before the workout.

Subjects

The subjects in this study were 12 men (age 24 ± 4.2 years, height 173.1 ± 3.6 cm, weight 76.9 ± 7.8 kg, body fat percentage $9.0 \pm 2.2\%$) and 13 women (age 24.5 ± 3.8 years, height 166.9 ± 8.5 cm, weight 66.1 ± 9.2 kg, body fat percentage $18.6 \pm 4.0\%$) with at least 6 months of resistance training experience in the barbell bench press, barbell deadlift, and barbell back squat exercises. All subjects had the experimental risks and benefits explained to them and subsequently signed an informed consent document approved

by the Institutional Review Board for use of human subjects at the University of Connecticut.

Familiarization

At the beginning of the familiarization, body composition was measured using the Jackson-Pollock method (10) with skinfold calipers (Body Care, Southam, United Kingdom), and the body mass was measured using calibrated electronic scales (Ohaus, Florham Park, NJ, USA). The subjects were then familiarized with the warm-up protocol to be used before all experimental visits, which included 5 minutes of using a cycle ergometer (Precor, Woodinville, WA, USA) at resistance level 5 with a speed of 60 rpm. This was followed by dynamic stretches, including body weight squats, forward and lateral lunges, knee hugs, quadriceps stretches, and a straight leg march. The 3 lifts used in the workout (barbell back squat, barbell bench press, and barbell deadlift) were demonstrated, and the subjects performed 2 sets of 8–10 repetitions with light loads and 2 minutes of rest between

TABLE 1. Fatigue indices after an extreme conditioning protocol.*

Sex	Lactate	Average RPE†	Peak RPE	Average HR	Peak HR
Men	14.21 ± 2.19	7.64 ± 1.75	9.5 ± 1.62	167.08 ± 10.14	179.08 ± 9.35
Women	10.07 ± 2.5	7.63 ± 1.51	9.19 ± 2.08	170.86 ± 9.95	179.46 ± 7.96

*All values are mean \pm SD.

†RPE average = mean rating of perceived exertion; RPE Pk. = highest rating of perceived exertion value given during the protocol; HR Avg. = mean heart rate; HR Peak = highest heart rate recorded during the protocol.

TABLE 2. Correlations between fatigue indices and the overall change in technique in men.*

Variable		Hip diff.	Knee diff.	Lactate	TtC	RPE avg.	RPE pk.	HR avg.	HR pk.
Hip diff.	<i>r</i>		0.676†	0.145	0.092	0.260	0.145	0.097	0.083
	<i>p</i>		0.016	0.654	0.777	0.414	0.652	0.764	0.797
Knee diff.	<i>r</i>	0.676†	1	0.290	0.031	0.194	0.054	-0.021	0.145
	<i>p</i>	0.016		0.360	0.923	0.546	0.868	0.948	0.652
Lactate	<i>r</i>	0.145	0.290	1	-0.134	0.290	0.279	0.588†	0.335
	<i>p</i>	0.654	0.360		0.677	0.361	0.381	0.044	0.287
TtC	<i>r</i>	0.092	0.031	-0.134	1	0.055	0.691†	-0.276	0.267
	<i>p</i>	0.777	0.923	0.677		0.866	0.013	0.385	0.401
RPE avg.	<i>r</i>	0.260	0.194	0.290	0.055	1	0.592†	0.189	0.243
	<i>p</i>	0.414	0.546	0.361	0.866		0.042	0.556	0.447
RPE pk.	<i>r</i>	0.145	0.054	0.279	0.691†	0.592†	1	-0.102	0.099
	<i>p</i>	0.652	0.868	0.381	0.013	0.042		0.751	0.760
HR avg.	<i>r</i>	0.097	-0.021	0.588†	-0.276	0.189	-0.102	1	0.634†
	<i>p</i>	0.764	0.948	0.044	0.385	0.556	0.751		0.027
HR pk.	<i>r</i>	0.083	0.145	0.335	0.267	0.243	0.099	0.634†	1
	<i>p</i>	0.797	0.652	0.287	0.401	0.447	0.760	.0027	

**r* = Pearson's correlation; *p* = significance level; Hip Diff. = highest hip value - lowest hip value; Knee Diff. = highest knee value - lowest knee value; TtC = time to completion; RPE Avg. = mean rating of perceived exertion; RPE Pk. = highest rating of perceived exertion value given during the protocol; HR Avg. = mean heart rate; HR Pk. = highest heart rate recorded during the protocol.

the sets. Further, the subjects chose a foot placement to use when performing the 1RM squat and during the resistance training protocol. The foot placement was traced on a mat that was used for all future performances of the squat, thus standardizing stance width and hip external rotation.

One-Repetition Maximum Testing

The subjects performed the back squat and bench press 1RM tests on the same day, with the 1RM deadlift test taking place 48 hours later, to ensure that the squat and deadlift exercises would not compromise each other. Each 1RM test followed the same protocol, which has been used in our laboratory previously (9). Before testing, the subjects performed the standardized warm-up. A warm-up weight of 50% of predicted 1RM was then performed with 8-10 repetitions. After 3 minutes of rest, a second warm-up set of 80% predicted 1RM was performed. After another 3 minutes of rest, a weight was selected that the subject believed they could lift once. After each successful lift, the weight was increased, and another lift was attempted. The 1RM was considered the maximum weight that the subject could lift 1 time with the appropriate technique. Appropriate technique was defined as that in which a full range of motion was completed for each lift; for the squat exercise, this was considered as the knee flexing until the upper leg was parallel to the ground, for the bench press, the barbell was required to make contact with the chest, and for the deadlift, the subjects were required to stand fully erect while maintaining their grip on the barbell. The 1RM was reached within 5 attempts for all the subjects.

Extreme Conditioning Protocol

Seventy-five percent 1RM was used on each of the 3 lifts: back squat, bench press, and deadlift. The subjects began with 10 repetitions of each lift, and then reduced the number consecutively by 1 until they reached only 1 repetition. The subjects were instructed to perform all the prescribed repetitions as quickly as possible, and their time to complete the workout was recorded. If the prescribed repetitions for a set were not able to be performed (i.e. rest was taken midset) that particular set was completed with the initially prescribed load. However, for the following set 5% 1RM was subtracted. These load reductions were used as many times as was required.

Two-Dimensional Analysis

The resistance training protocol was filmed using a video recorder (Panasonic 3CCD, Secaucus, NJ, USA) and later analyzed using video analysis software (Dartfish, Fribourg, Switzerland). Before the resistance training protocol, markers with contrasting colors that can be easily recognized by the software were placed at the end of the barbell, lateral malleolus, lateral to the patella, and lateral to the anterior superior iliac spine, which allowed us to measure the knee angle and hip angle (Figure 1). The knee angle and hip angle measurements were recorded at the bottom of each repetition of the barbell back squat. The bottom of the squat was considered the last frame of the video before the subject performed an upward movement.

Fatigue

Lactate. Blood lactate concentration was measured immediately before and after the workout. For the resistance

TABLE 3. Correlations between fatigue indices and the overall change in technique in women.*

Variable		Hip diff.	Knee diff.	Lactate	TtC	RPE avg.	RPE pk.	HR avg.	HR pk.
Hip diff.	<i>r</i>	1	0.320	0.108	-0.215	0.277	0.333	-0.342	-0.452
	<i>p</i>		0.286	0.724	0.480	0.359	0.267	0.252	0.121
Knee diff.	<i>r</i>	0.320	1	-0.313	0.320	-0.211	-0.045	-0.143	0.139
	<i>p</i>	0.286		0.298	0.286	0.489	0.885	0.642	0.651
Lactate	<i>r</i>	0.108	-0.313	1	-0.630†	-0.265	-0.273	0.047	-0.360
	<i>p</i>	0.724	0.298		0.021	0.382	0.366	0.880	0.227
TtC	<i>r</i>	-0.215	0.320	-0.630†	1	-0.071	-0.047	-0.065	0.336
	<i>p</i>	0.480	0.286	0.021		0.818	0.879	0.833	0.261
RPE avg.	<i>r</i>	0.277	-0.211	-0.265	-0.071	1	0.842†	0.042	0.032
	<i>p</i>	0.359	0.489	0.382	0.818		0.000	0.893	0.919
RPE pk.	<i>r</i>	0.333	-0.045	-0.273	-0.047	0.842†	1	-0.048	-0.028
	<i>p</i>	0.267	0.885	0.366	0.879	0.000		0.877	0.926
HR avg.	<i>r</i>	-0.342	-0.143	0.047	-0.065	0.042	-0.048	1	0.858†
	<i>p</i>	0.252	0.642	0.880	0.833	0.893	0.877		0.000
HR pk.	<i>r</i>	-0.452	0.139	-0.360	0.336	0.032	-0.028	0.858†	1
	<i>p</i>	0.121	0.651	0.227	0.261	0.919	0.926	0.000	

**r* = Pearson's correlation; *p* = significance level; Hip Diff. = highest hip value - lowest hip value; Knee Diff = highest knee value - lowest knee value; TtC = time to completion; RPE Avg. = mean rating of perceived exertion; RPE Pk. = highest rating of perceived exertion value given during the protocol; HR Avg. = mean heart rate; HR Pk. = highest heart rate recorded during the protocol.

exercise protocol session, an indwelling cannula (catheter) was inserted into the antecubital vein. The cannula was kept open with a saline solution. Before each blood draw, 3 ml of blood was extracted to avoid inadvertent saline dilution of the blood sample. Blood was collected, and serum was spun, aliquoted, and stored at -80° C until subsequent analyses. The liquid lactate assay (Point Scientific#L7596, Canton, MI, USA) was performed on human plasma samples as reported by Guttman and Wahlefeld (7).

Ratings of Perceived Exertion and Heart Rate. Ratings of perceived exertion were measured using the CR-10 scale (20). Heart rate was measured using a Polar (Lake Success, NY, USA) heart rate monitor chest strap and watch. Ratings of perceived exertion and heart rate data were obtained after each set of the squat exercise was completed.

Statistical Analyses

The mean values for the knee and hip angle in men and women were calculated for each repetition. If the subjects' values for the hip or knee angle were $>2SD$ from the mean of that particular repetition, their values were altered to represent the mean. The highest values recorded for men and women for the hip and knee angles were compared with the lowest values recorded using a dependent *t*-test to determine if significant differences were seen over the course of the entire protocol. To correlate technique change with fatigue indices and time to completion, the difference between the highest and the lowest value for the hip and knee angle was taken as an overall index of technique change. These hip and knee difference values were correlated with each fatigue vari-

able and time to completion using Pearson's correlation. All statistical tests were performed using SPSS software (SPSS Inc., Chicago, IL, USA). An a priori alpha level of 0.05 was used for all the analyses.

RESULTS

Joint Biomechanics

Over the course of the workout, the knee angle significantly changed for both men (early 97.4 ± 6.8 vs. late 90.4 ± 5.6) and women (early 103.9 ± 8.1 vs. late 91.7 ± 10.0). Also, the hip angle significantly changed for both men (early 86.7 ± 15.9 vs. late 116.8 ± 72.8) and women (early 87.6 ± 9.1 vs. late 101.5 ± 8.6). Furthermore, men displayed significantly greater knee angles during multiple repetitions, early in the workout. The hip and knee angle results for men and women are shown in Figures 2-4.

Fatigue

Fatigue indices are presented in Table 1.

Time to Completion

Men performed the workout in 35.9 ± 14.57 minutes (mean \pm SD). Women performed the workout in 30.72 ± 9.91 minutes (mean \pm SD).

Correlations

Correlations between the technique change and the indices of fatigue and time to completion are shown in Tables 2 and 3.

DISCUSSION

The primary finding from this study is that knee and hip flexion significantly changes during the course of an extreme

conditioning protocol in the barbell squat exercise (Figures 2–4), providing a valuable insight into what is happening during these workouts that have not been previously studied. This study demonstrated that the barbell squat movement is abbreviated early on in high repetition sets, which could significantly attenuate strength gains because of reduced muscle activity (5). Further, during high repetition sets, the subjects also displayed greater forward lean, which has been associated with greater shear force at the spine (15, #30) and is also contraindicated by the NSCA Position Stand (3 #65), which states that the torso should be as upright as possible during the back squat.

Not only is it a fact that movement patterns are erratic in these programs but the timing of the movement changes that occurred is also a crucial consideration with regard to the design of these extreme conditioning protocols. Although previous studies have consistently demonstrated evidence of altered proprioception in response to fatigue (13,17), it is typically viewed from a physiological perspective. It is important to note that often these extreme conditioning protocols are performed in an unsupervised environment and that individuals are therefore relying on their own proprioception to ensure that the lifts are performed safely and effectively. With the design of this study not prescribing a squat depth, this study was able to reveal changes in movement patterns that occur during an extreme conditioning protocol and demonstrated a behavior of self-preservation, where repetitions that were performed early in the workout were significantly abbreviated when compared with those later in the workout (Figure 2).

This study was also able to demonstrate that changes in proprioception are not solely dependent on the level of fatigue but that altered movement patterns are the result of multiple factors, and the negative effects of fatigue have the potential to be overcome. For example, the changes in movement that occurred at the hip and knee did not significantly correlate with any indicator of fatigue (Tables 2 and 3). Further, as the subjects moved toward the end of the protocol, both men and women increased knee flexion during the course of the workout. This is in contrast to findings seen during box lifting (8,17) and a body weight squat performed after an identical resistance training protocol (9). This favorable change in technique occurred despite an immediate postblood draw, demonstrating highly elevated blood lactate concentrations (Table 1) and the fact that this protocol was performed with much heavier loads in comparison with those used in box lifting (17–35 kg) and the lack of load used during the body weight squat. These data indicate that although extreme conditioning protocols might induce a behavior of self-preservation that results in a suboptimal squat technique early in the workout, the prescription of descending pyramid schemes might be able to mediate these negative effects.

Although a common programming tool, the use of descending pyramid schemes in this context must be viewed with caution. Although it can be argued that lowering the repetition prescription resulted in positive changes in the squat technique, it must be remembered that the load remained constant at 75% 1RM (or lower if the subjects were unable to continue at that load). As a result, the use of lower repetition sets with only a moderately heavy load would not favor optimal strength gains. Therefore, the coach must consider the delicate balance between the need for strength gains with the need to perform lifts safely and effectively.

This study also demonstrated important sex differences. It is apparent that when women performed this extreme conditioning protocol, there were significant negative changes in technique in the set of 10 that was performed at the beginning of the protocol. For example, when compared with repetition 1, women showed significantly less knee flexion (Figure 2) at the end of the set, along with a significantly lower hip angle (Figure 3), which demonstrates an increase in forward lean. When compared with men, it seems that women are more sensitive to changes in the squat technique when performing an extreme conditioning protocol, particularly at sets with higher repetition numbers.

PRACTICAL APPLICATIONS

Extreme conditioning protocols, which combine moderately heavy loads with short rest periods, significantly alter the technique in the barbell back squat. The technique changes that occur in high repetition sets do not favor optimal strength development and may increase the risk of sustaining an injury, clearly questioning the safety and efficacy of such resistance training programming. These technique changes are most likely a demonstration of self-preservation, where the squat movement is abbreviated when individuals are faced with high repetition programs. It also seems that women are more sensitive than are men to technique changes. Negative technique changes can be reversed with the prescription of lower repetitions, even in the face of extreme fatigue, but this prescription must be balanced with the need for strength gains. Ultimately, if movement patterns are erratic during a resistance exercise, particularly under heavy loads, it seems in the interest of athlete safety that this workout design is performed with less technical exercises (such as resistance machine exercises) to keep potential injury risk at a minimum while still seeing the positive adaptations associated with such program design.

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