Introduction

Force is produced through a combination of eccentric (ECC), concentric (CON), and joint-stabilizing isometric muscle actions (1). Together, these muscle actions form the basic components of the movements performed in daily living and resistance exercise. Eccentric muscle actions can produce the largest amount of force and are necessary for the development of maximal muscle hypertrophy (6,11). As Dudley et al. (5) demonstrated on a multijoint lower-body exercise, however, ECC muscle actions contribute only marginally to the metabolic cost of a full repetition (~15% increase from CON).

When an ECC muscle action directly precedes a CON muscle action, a characteristic increase in CON force is achieved through a neuromuscular phenomenon known as the stretch-shortening cycle. Different muscle actions contribute uniquely to the successful performance of a lift and fatigue. These contributions appear to differ in men and women.

Key Words resistance exercise, stretch-shortening cycle, fatigue
specific adaptations to resistance exercise (13,14). Since intensity is defined in terms of exercise loading, 1 repetition maximum (1RM) tests are regularly incorporated in exercise prescription and performance testing. Once a 1RM is obtained, loads at various percentages of the 1RM are used in exercise training. The volume of exercise then reflects multiple sets of a number of repetitions, which can be lifted until failure (known as a repetition maximum, or RM). However, RM zones (e.g., 3 repetition range) and 1RM percentages are more commonly used. Nevertheless, it is important to understand RM measurements provide important end point information about different loading schemes and muscle actions. This is important to avoid “undershooting” the neuromuscular recruitment thresholds that ultimately dictate training adaptations.

It is also important to note that at a given percent of a 1RM, RMs are not constant, but vary by exercise and more generally, the total amount muscle mass used (5,8,14,22). For a given exercise in men, this variability may be somewhat constant because training experience does not appear to influence the number of repetitions that can be performed (22). How different muscle actions contribute to RMs on upper- and lower-body lifts has yet only been partially elucidated. Moreover, sex-specific differences in fatigability during moderate- and high-intensity muscle actions may exist but have not been consistently observed (4,18,19).

The purpose of this investigation was to examine sex-specific differences in fatigue rates between ECC, CON, and combined (COMB) muscle actions. We hypothesized that at a given percent of a 1RM, the total number of repetitions that could be performed until failure would differ between muscle actions in the following order: ECC > COMB > CON. These differences might reflect the conservation of energy provided by the stretch reflex, and pronounced metabolic demands of CON muscle actions (5,15). In addition, because men may derive greater benefits from the stretch reflex, we hypothesized that loss of the ECC component would result in lower CON RMs in men when compared with women.

**Methods**

**Experimental Approach to the Problem**

To examine muscle action–specific differences in the number of repetitions that could be performed to failure on the squat and bench press, we used a mixed methods design, which allowed us to compare the number of repetitions performed for each muscle action on each lift, in addition to sex-specific differences for the same measures. After subjects were carefully familiarized, a baseline 1RM was obtained on the bench press and squat in order to determine the experimental load (85% 1RM). This load was chosen because it would require the recruitment of higher threshold motor units, while permitting a sufficient number of repetitions to detect muscle action–specific differences. This load corresponds with accepted estimates of a 6RM (1). After familiarization and 1RM tests, on 3 subsequent balanced and randomized visits, subjects performed RMs for a selected muscle action on each lift.

**Subjects**

Twenty (10 men and 10 women) healthy individuals volunteered to participate in the investigation. Subject characteristics are presented in Table 1. Subjects demonstrated a history of regular resistance training (minimum of 6 consecutive months up to study) in both the squat and bench press exercises. To ensure similarity of technique for the 2 exercises, each of the subjects was trained by the same strength and conditioning professional. After a detailed description of the testing procedures and associated benefits and risks, each participant signed a written informed consent form approved by the University’s Institutional Review Board for use of human subjects in research.

**Procedures**

Each subject completed 4 testing visits. The first visit provided familiarization for the testing procedures. Though subjects’ previous resistance exercise experience provided familiarity with the lifts and their corresponding muscle actions, the procedures were practiced extensively at this time. In addition, baseline measures of height (cm), body mass (kg), and body fat % (16) were obtained. Finally, subjects performed 1RM testing for each of the 2 exercises.

The protocol for 1RM testing was based on previously described methods (17). In summary, subjects warmed up for 5 minutes on a Lifetime cycle ergometer (Life Fitness Classic Series Recumbent; LifeFitness, Schiller Park, IL, USA) followed by a standardized series of dynamic stretches. A warm-up set of 5–10 repetitions was performed using 40–60% of the subject’s estimated 1RM. After a 1-minute rest period, a set of 2–3 repetitions was performed at 60–80% of the estimated 1RM. This and every progressively heavier subsequent set were followed by a 3-minute rest interval. A maximum of 3 trials were given to determine the 1RM. Complete range of motion in the squat was defined as the point in the movement where thighs were parallel to the floor, followed by return to a standing position where the knees were fully extended. For the bench press, complete range of motion was defined by the lowering of the bar until contact with the chest near the midpoint of the sternum, followed by return to the starting position, with the elbows fully extended.

<table>
<thead>
<tr>
<th>Table 1. Subject characteristics.*</th>
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<tr>
<td><strong>Women</strong></td>
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<tr>
<td>Age (y)</td>
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<tr>
<td>Height (cm)</td>
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<tr>
<td>Weight (kg)</td>
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<td>Body fat (%)</td>
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*Data are expressed as mean ± SD.
Once obtained, 1RMs were used to calculate the RM load (85% 1RM) for the 3 testing trials, which were separated by at least 24 hours. Each of the 3 visits were conducted at least 24 hours apart. After completion of the previously described warm-up, 1 set to failure was performed for each exercise. Experimental sessions were standardized: subjects performed the bench press exercise, were given 3 minutes of rest, and then performed the back squat exercise. On CON repetitions, 3 spotters lowered the bar to chest level, where the subject would assume control and perform the lift. At the top of the lift, the spotters would again assume control of the bar and lower it to chest level. Conversely, ECC repetitions involved the subject lowering the bar, with 3 spotters assuming control of the bar at the bottom of the lift, and returning it to the starting position. The time to perform each CON and ECC repetition was controlled to mimic that of the corresponding portion of a COMB repetition. Failure was reached when the subject could no longer perform a repetition with proper form (evaluated by the investigator) or voluntarily terminated the protocol.

Immediately after each of the 2 sets to failure, rating of perceived exertion (RPE) and heart rate (HR) (Polar Electro, Lake Success, NY, USA) were obtained. All subjects were verbally encouraged to produce maximum effort during testing.

**Statistical Analyses**

Data are reported as mean ± SD. To determine the presence of significant differences for each exercise, a (sex × muscle action) repeated-measures analysis of variance was performed. When significant differences were found, Tukey post hoc tests were used to determine pairwise differences. Significance in this investigation was set at $p \leq 0.05$.

**RESULTS**

**Squat Repetitions**

The mean number of repetitions differed significantly by muscle action (Figure 1), with ECC > COMB > CON ($p \leq 0.05$). However, men and women did not differ with respect to number of repetitions performed in any muscle action.

**Bench Press Repetitions**

Muscle action affected the number of repetitions performed on the bench press (Figure 2), with ECC > COMB > CON ($p \leq 0.05$). Women performed more CON and ECC repetitions, whereas men performed slightly more COMB repetitions. Overall, number of repetitions decreased from ECC to COMB to CON. "Significant difference in number of repetitions performed for muscle action when compared to other muscle actions. Overall, number of repetitions decreased from ECC to COMB to CON. #sex-specific difference in number of repetitions performed for a given muscle action."
Muscle Action and Sex-Specific Differences in Fatigue

(Table 2. Heart rate and rating of perceived exertion during different muscle actions in men and women on the squat and bench press.*

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<tr>
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<th>Bench press</th>
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<tr>
<td></td>
<td>ECC†</td>
<td>COMB</td>
<td>CON</td>
</tr>
<tr>
<td>RPE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>7.8 ± 1.4</td>
<td>7.7 ± 0.8</td>
<td>7.8 ± 1.6</td>
</tr>
<tr>
<td>Women</td>
<td>6.6 ± 1.4</td>
<td>7.7 ± 0.7</td>
<td>7.5 ± 1.6</td>
</tr>
<tr>
<td>All</td>
<td>7.2 ± 1.5</td>
<td>7.7 ± 0.7</td>
<td>7.7 ± 1.6</td>
</tr>
<tr>
<td>HR</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Men</td>
<td>138.3 ± 22.3</td>
<td>139.4 ± 23.0</td>
<td>127.0 ± 18.6</td>
</tr>
<tr>
<td>Women</td>
<td>126.2 ± 16.5</td>
<td>123.3 ± 18.3</td>
<td>117.3 ± 11.8</td>
</tr>
<tr>
<td>All</td>
<td>132.3 ± 20.1</td>
<td>131.4 ± 21.9</td>
<td>122.2 ± 15.9</td>
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</table>

*Data are expressed as mean ± SD. HR and RPE did not differ by sex or muscle action on the bench press, but muscle action significantly affected HR on the squat (ECC > COMB > CON).
†HR = heart rate; RPE = rating of perceived exertion; ECC = eccentric; COMB = combined; CON = concentric.
‡Significant difference at p ≤ 0.05.

Men performed more COMB repetitions than women (p ≤ 0.05).

Rate of Perceived Exertion and Heart Rate

Ratings of perceived exertion did not differ by sex or muscle action for either exercise. A significant difference in HR was found on the squat, where ECC > COMB > CON. However, HR did not differ by sex. On the bench press, HR values did not differ by sex or muscle action. Data for these variables are presented in Table 2.

Discussion

The primary findings of this investigation were (a) at 85% of 1RM on the squat and bench press, the number of repetitions an individual could perform varied by muscle action and (b) on the bench press, men and women differed in terms of the number of repetitions performed for each muscle action. These findings build on previous characterizations of RMs by demonstrating that muscle actions, in addition to sex, training status, intensity, and exercise choice, influence the number of repetitions that can be performed to volitional failure (7,8).

On the squat and bench press, both sexes performed the greatest number of repetitions on ECC muscle actions, followed by COMB muscle actions, and then CON muscle actions. These data provide an indication of muscle action fatigue rates. Our observation is consistent with previous studies, which have suggested that ECC muscle actions are more metabolically efficient (2,21,23). For example, previous work determined that the metabolic cost of a COMB repetition was only one-seventh greater than that of a CON repetition alone (6). In this investigation, the inability to perform 7 times more ECC repetitions illustrates that the cause of fatigue is multifaceted and not attributable solely to metabolic constraints. Further, differences between COMB and CON may be explained by greater metabolic efficiency as a result of the SSC (3,10). In this context, elastic energy stored in the muscle during the ECC phase was used to reduce the energetic cost of the CON phase, allowing for a greater number of CON repetitions. This conclusion is in line with previous research, where elastic energy was shown to contribute to increased metabolic efficiency of countermovement jumps, as compared to noncountermovement jumps (3).

Though there were significant sex-specific differences in bench press repetitions for different muscle actions, these differences were not uniform. Women performed more ECC and CON repetitions, whereas men performed more COMB repetitions. Moreover, men performed 6.60 ± 1.58 COMB repetitions, but only 3.30 ± 0.95 CON repetitions, an ~50% decrease. In contrast, women performed 6.20 ± 1.48 COMB repetitions and 4.10 ± 1.52 CON repetitions, an ~34% decrease. These results suggest that men rely more on the SCC in upper-body lifts, a contention supported by previous work (20). Moreover, while increased upper-body SSC responses were observed in men, this work was conducted using an elbow flexion apparatus specifically designed for the experiment. Our findings confirm these observations in 2 of the most common resistance exercise movements.

Sex-specific SSC differences do not solely reflect strength differences because men and women show similar strength when normalized to muscle cross sectional area (19). The finding that men only performed better on the COMB trial further weakens this argument. While beyond the scope of this study, subtle differences in bench press technique may also partially explain increased COMB in men. However, this explanation seems somewhat unlikely, as subjects were relatively advanced in terms of resistance exercise experience.

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(men and women typically squatted more than their body-weight), and repetition cadence was controlled.

Despite differences in the number of completed repetitions, RPE values did not differ by muscle action. This demonstrates a “disconnect” in resistance exercise to failure between muscle action and perception during resistance exercise to failure; a novel finding that supports a degree of caution in using RPE to monitor fatigue. This finding corresponds with previous work, where RPE was thought to primarily reflect load, as opposed to contraction type (9). Importantly, when performing RMs to failure at any load, preliminary data from our laboratory in the squat suggests another potential disconnect of such capability for perception to accurately monitor recruitment of motor units: perceived exertion does not necessarily correspond with the amount of motor unit recruitment (unpublished data, Looney DP and co-workers, 2013). Heart rate increased most during ECC and least during CON. Because repetition duration was kept constant, trial duration was primarily determined by number of repetitions performed. Thus, ECC trials were longest, and CON trials were shortest. This difference in “time under tension” explains the observed differences in HR under different muscle values.

In conclusion, the results of this investigation demonstrate that ECC, COMB, and CON muscle actions possess inherent fatigue rates, resulting in different RMs at a given load. These differences may be attributable to differences in the metabolic efficiency of muscle actions. Finally, men appear to produce a greater SSC response than women in upper-body movements, which contributes to greater COMB performance, despite lower ECC and CON performances.

**Practical Applications**

The findings of this investigation reinforce the need to consider muscle actions in resistance training prescription. If using COMB IRM or RM values, the volume of ECC or CON only movements should be modified accordingly. In addition, this study further underscores the importance of individualization. Sex, training history, exercise, load, and muscle action all affect the number of repetitions that can be performed, and do so interactively. Compared with resistance-training women, trained men may perform more repetitions when the stretch-shortening cycle is present, and fewer repetitions when performing ECC or CON only. Finally, this effect is not evident in all movements.

**Acknowledgments**

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**References**


