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James L. Nuzzo
Edith Cowan University

Matheus D. Pinto
Edith Cowan University

Kazunori Nosaka
Edith Cowan University

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Muscle fatigue during maximal eccentric-only, concentric-only, and eccentric-concentric bicep curl exercise with automated drop setting

James L. Nuzzo | **Matheus D. Pinto** | **Kazunori Nosaka**

Centre for Human Performance, School of Medical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia

Correspondence
James L. Nuzzo, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA 6027, Australia.
Email: j.nuzzo@ecu.edu.au

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Abstract

Connected adaptive resistance exercise (CARE) machines are new technology purported to adjust resistance exercise loads in response to muscle fatigue. The present study examined muscle fatigue (strength loss, fatigue perceptions) during maximal eccentric-only (ECC_{max}-only), concentric-only (CON_{max}-only), and coupled ECC-CON (ECC_{max}-CON_{max}) bicep curl exercise on a CARE machine. Eleven men and nine women completed the three protocols in separate sessions and in random order. All protocols included 4 sets of 20 maximal effort muscle contractions. Strength loss was calculated as Set 4 set end load minus Set 1 highest load. The CARE machine's algorithm adjusted resistances automatically, permitting continued maximal effort repetitions without stopping. Consequently, all protocols caused substantial fatigue. Women were most susceptible to strength loss from exercise that included maximal efforts in the ECC phase, whereas men were most susceptible to strength loss from exercise that included maximal efforts in the CON phase. With ECC_{max}-only exercise, ECC strength loss (mean ± SD) was similar between men (55.9 ± 14.1%) and women (56.4 ± 10.8%). However, with CON_{max}-only exercise, men and women experienced 55.6 ± 6.2% and 35.3 ± 8.7% CON strength loss, respectively. With ECC_{max}-CON_{max} exercise, men experienced greater ECC (62.9 ± 7.7%) and CON (77.0 ± 5.3%) strength loss than women (ECC: 48.5 ± 15.7%, CON: 66.2 ± 12.1%). Heightened perceptions of fatigue and pain of the exercised limb were reported after all protocols. Women generally reported more biceps pain than men. The results illustrate CARE technology delivers ECC-only and accentuated ECC exercise feasibly. Acute responses to repeated maximal effort bicep curl exercise with such technology might differ between men and women depending on muscle contraction type.

KEYWORDS
bicep curl, concentric, eccentric, elbow flexor, muscle fatigue, resistance exercise, sex difference

1 | INTRODUCTION

A resistance exercise repetition typically consists of a muscle shortening (i.e., concentric: CON) and lengthening phase (i.e., eccentric: ECC). In recent years, researchers and practitioners have expressed considerable interest in resistance exercise that emphases the ECC phase.[1–13] Two methods used for ECC resistance exercise are *accentuated* ECC resistance exercise (i.e., "eccentric overload") and ECC-*only* resistance exercise. With accentuated ECC resistance exercise, resistance is placed upon the participant throughout the CON and ECC phases (coupled ECC-CON), but the resistance in the ECC phase is greater than the resistance in the CON phase. With ECC-only resistance exercise, resistance is placed upon the participant throughout the ECC phase but no resistance is placed upon the participant in the CON phase.

Connected adaptive resistance exercise (CARE) machines are new technology that might permit more feasible delivery of ECC-only and accentuated ECC resistance exercise in clinical and research settings.[14,15] CARE machines involve integration of software and hardware to provide a resistance that adjusts in real-time and in response to the participant's volitional force or movement velocity. Consequently, such machines can apparently change resistances within and between repetitions, overcoming the constant load characteristic of free weights and plate-loaded machines, which renders such equipment difficult to use for ECC resistance exercise. Nuzzo and Nosaka[14] have recently presented preliminary evidence in one participant of a CARE machine that delivered accentuated ECC resistances during maximal coupled ECC-CON repetitions (i.e., ECC_{max}-CON_{max}). The participant completed 25 *consecutive* ECC_{max}-CON_{max} repetitions of the bicep curl exercise without disengaging from the machine, illustrating that the machine automatically reduced resistances to accommodate muscle fatigue (i.e., drop setting).[14]

Given current interest in ECC resistance exercise among researchers and practitioners, and the potential for emerging technologies to make ECC resistance exercise prescriptions more feasible, knowledge of how individuals respond to ECC resistance exercise (with any machine) is increasingly important. However, whether an acute bout of ECC_{max}-only resistance exercise causes similar strength loss (fatigue) to an acute bout of CON_{max}-only resistance exercise remains unclear,[16–21] and whether the removal of the ECC or CON phase from an acute bout of resistance exercise (i.e., ECC_{max}-only or CON_{max}-only contractions) impacts strength loss and perceptions of fatigue compared to coupled ECC-CON exercise also remains unclear. Moreover, as CARE technology appears to automate drop setting,[14] and drop setting is recommended as a time-efficient way to increase resistance exercise participation among the general population,[22–24] examination of how muscles fatigue during different types of drop setting exercise might inform exercise prescription guidelines. Finally, the impact of participant sex on responses to resistance exercise also warrants consideration, as men tend to be more susceptible to muscle fatigue than women during isometric tasks,[25,26] but whether such sex differences occur during *non*-isometric (dynamic) resistance exercise remains unclear given the relative lack of information on the topic.[27]

Therefore, the aim of the current study was to investigate muscle fatigue during resistance exercise on a CARE machine. Specifically, we examined strength loss and perceptions of fatigue and pain before, during, and after four sets of ECC_{max}-only, CON_{max}-only, and ECC_{max}-CON_{max} unilateral bicep curl exercise. We also tested for potential sex differences in muscle fatigability given that roughly equal numbers of men and women volunteered for the experiment. Also, there is a relative lack of information on sex differences in muscle fatigability for non-isometric tasks,[27] and calls have been made for more sex-segregated data in exercise research.[28]

2 | METHODS

2.1 | Study design

Twenty participants performed unilateral bicep curl exercise with their right upper-limbs in three sessions. Sessions were usually separated by 7 days, but exercise that included ECC contractions sometimes caused delayed-onset muscle soreness (Supporting Information 1). Thus, sessions were sometimes separated by >7 days if additional recovery was necessary based on the participant's self-reported biceps pain. Sessions occurred at roughly the same time of day for each participant.

Each session tested a different protocol, either ECC_{max}-only, CON_{max}-only, or ECC_{max}-CON_{max} resistance exercise. The protocols were completed in a random order. The protocols were also matched for total contractions (i.e., 80 contractions), similar to the number of contractions completed by participants in other studies on muscle fatigue during ECC-only and CON-only resistance exercise.[16,18–21] Implementation of these different protocols allowed us to address questions such as: (a) do muscles fatigue similarly during ECC_{max}-only and CON_{max}-only resistance exercise? (b) do coupled ECC_{max}-CON_{max} repetitions cause equal strength loss in the ECC and CON phases? (c) does inclusion of CON_{max} contractions in repetitions increase ECC strength loss (i.e., ECC_{max}-CON_{max} vs. ECC_{max}-only)? (d) does inclusion of ECC_{max} contractions in repetitions increase CON strength loss (i.e., ECC_{max}-CON_{max} vs. CON_{max}-only)?

The primary outcome for the study was strength loss on the CARE machine. Secondary outcomes were perceptions of fatigue and pain. The investigator who conducted the sessions was a certified strength and conditioning specialist through the National Strength and Conditioning Association.

2.2 | Participants

Eleven men and nine women participated in the study (Table 1). To be eligible to participate, individuals could not have had a previous injury to their right upper-limb or have contraindications to exercise as determined by the physical activity readiness questionnaire (2020 PAR-Q+). All participants had participated in an earlier investigation which involved maximal and submaximal unilateral bicep curl exercise on the CARE machine and with dumbbells. Thus, participants were familiar with bicep curl exercise on the CARE machine, the scales used to assess perceptions of fatigue and pain, and they had completed a unilateral bicep curl CON 1RM with a dumbbell. Most participants were participating in resistance exercise or had participated in resistance exercise in the past. They were recruited through word-of-mouth and advertisements posted on social media and at a local fitness center. No sample size calculations were performed before the study. The sample size was based on the sample sizes used in previous studies[16–21] and time, resource, and staff constraints.[29] All participants provided their written informed consent to participate in the study protocol, which was approved by the Human Research Ethics Committee at Edith Cowan University (2021-02621-NUZZO). Participants were remunerated for their participation.

2.3 | CARE machine

The CARE machine used in the current study (Trainer$^+$, Vitruvian, Perth, Australia) consists of motorized winches that apply forces to two independent ropes that exit the top of the machine (Figure 1). The winches are controlled by a mobile phone application and software running in the machine. Handles are attached to the ropes. The participant stands on the machine and holds the handles. As the winches retract the rope, the participant exerts force against the handles to slow the retraction.

To exercise on the machine, the participant first completes three warm-up repetitions with little to no resistance on the rope. The warm-up repetitions allow the machine to learn the participant's range of motion and to identify the CON and ECC phases. Once exercise has commenced, the machine's algorithm adjusts resistances between 0 and 100 kg per rope in real-time at a rate of 50 Hz. The magnitude of adjustment depends primarily on movement velocity and repetition phase, with repetition phase based on rope displacement. The machine's algorithm adjusts the resistance based on whether the participant's movement velocity is above or below certain velocity thresholds (i.e., velocity band) in the ECC and CON phases. When the movement is within the velocity band, the resistance is constant. With the machine's default exercise mode of ECC-CON repetitions, slow movement velocities below the threshold in the CON phase inform the machine that the participant is struggling to overcome the resistance; thus, the machine's algorithm reduces the resistance in real-time to allow the participant to complete the CON phase. If the participant's movement velocity in the CON phase is above the velocity band, this informs the machine that the resistance is too light for the participant; thus, the algorithm increases the resistance in real-time to make the CON phase more difficult. During the ECC phase, slow movement velocities below the threshold cause the algorithm to *increase* the resistance, whereas fast movement velocities cause the algorithm to *decrease* the resistance. Because ECC muscle strength is greater than CON muscle strength,[30] the machine naturally delivers ECC overload so long as the participant gives an effort commensurate with their physiological potential. Of note, the CARE machine is not a traditional isokinetic dynamometer, as a traditional isokinetic dynamometer typically moves a participant's limb at a constant velocity irrespective of the participant's volitional force. In contrast, the CARE machine responds to the participant's force and velocity of movement and then adjusts the resistance accordingly in real-time.

In three sessions, participants completed three different resistance exercise protocols of the unilateral bicep curl exercise while standing on the machine. The protocols were completed in random order and consisted of either ECC_{max}-CON_{max} repetitions, ECC_{max}-only repetitions, or CON_{max}-only repetitions. All protocols were performed with the right upper-limb, and the forearm was supinated, though the rope permits movement in multiple planes, and slight changes in forearm posture can occur during bicep curl exercise on the machine. Maximal resistances were selected as the initial target resistances for all protocols. This maximal target resistance is the maximal resistance the participant will

TABLE 1 Summary of participant baseline characteristics and muscle force loss and perceptions of biceps fatigue and pain during acute bouts of maximal effort eccentric-only (ECC_{max}-only), concentric-only (CON_{max}-only), and eccentric and concentric (ECC_{max}-CON_{max}) unilateral bicep curl exercise on a connected adaptive resistance exercise (CARE) machine.

Outcome	Men ($n = 11$) Mean ± SD	Women ($n = 9$) Mean ± SD	Effect size of sex difference Hedges g [95% CI]
Age and anthropometrics			
Age (y)	30.0 ± 8.1	30.6 ± 8.4	−0.065 [−0.908, 0.780]
Body height (cm)	180.2 ± 8.0	167.8 ± 5.4	1.707 [0.682, 2.700]
Body mass (kg)	81.7 ± 13.5	62.1 ± 6.9	1.696 [0.672, 2.686]
Resistance exercise practices			
Current frequency (day/week)	3.0 ± 1.9	3.7 ± 1.3	−0.383 [−1.231, 0.475]
Years of experience (y)	8.2 ± 7.8	9.9 ± 8.9	−0.191 [−1.034, 0.658]
Maximal muscle strength			
Highest average ECC (kg)	23.7 ± 4.6	14.2 ± 1.8	2.516 [1.324, 3.671]
Highest average CON (kg)	17.0 ± 5.6	8.7 ± 1.5	1.856 [0.802, 2.875]
Muscle fatigue after four sets on CARE machine			
Strength loss (% decrease)			
ECC_{max}-only	55.9 ± 14.1	56.4 ± 10.8	−0.041 [−0.884, 0.803]
CON_{max}-only	55.6 ± 6.2	35.3 ± 8.7	2.609 [1.396, 3.785]
ECC_{max}-CON_{max}, ECC phase	62.9 ± 7.7	48.5 ± 15.7	1.156 [0.219, 2.066]
ECC_{max}-CON_{max}, CON phase	77.0 ± 5.3	66.2 ± 12.1	1.154 [0.218, 2.064]
Perceived arm strength capacity (0%–100% scale)			
ECC_{max}-only	17.0 ± 21.7	5.8 ± 6.6	0.670 [−0.246, 1.568]
CON_{max}-only	14.0 ± 16.6	14.4 ± 14.5	−0.027 [−0.870, 0.817]
ECC_{max}-CON_{max}	7.7 ± 7.0	14.7 ± 15.5	−0.575 [−1.431, 0.297]
Perceived biceps fatigue (0–10 scale)			
ECC_{max}-only	7.0 ± 2.3	8.4 ± 2.5	−0.579 [−1.436, 0.293]
CON_{max}-only	7.0 ± 1.9	7.9 ± 1.0	−0.592 [−1.449, 0.281]
ECC_{max}-CON_{max}	7.9 ± 1.5	7.6 ± 2.0	−0.504 [−1.356, 0.362]
Perceived biceps pain (0–10 scale)			
ECC_{max}-only	4.5 ± 3.2	7.3 ± 3.0	−0.886 [−1.766, 0.016]
CON_{max}-only	3.3 ± 3.2	5.6 ± 2.7	−0.733 [−1.600, 0.153]
ECC_{max}-CON_{max}	4.7 ± 3.2	6.6 ± 2.3	−0.637 [−1.498, 0.240]

Abbreviations: CI, confidence interval; SD, standard deviation.

ever experience during the set, not the resistance the participant will always experience during the set, as the machine's algorithm adjusts the resistance in real-time according to the participant's force-generating capacity and movement velocity. To aid participant learning and performance, the investigator provided continued verbal instruction and encouragement during all testing sessions. The participant's smartphone was positioned on a stand in front of them and provided real-time visual feedback of the machine's resistance. The investigator instructed the participant to keep the resistance number on the screen "as high as possible."

2.4 | ECC_{max}-CON_{max} exercise

The ECC_{max}-CON_{max} protocol consisted of 4 sets of 10 ECC_{max}-CON_{max} repetitions (i.e., 40 ECC contractions, 40 CON contractions). For this protocol, the participant attempted to generate maximal forces during both phases and for all repetitions. For the CARE machine to exert maximal resistances onto the participant during the CON phase, the participant must pull against the handle "as hard and fast as possible." During the ECC phase, the participant must resist the retraction of the cable as much as possible. The maximal target resistance that the

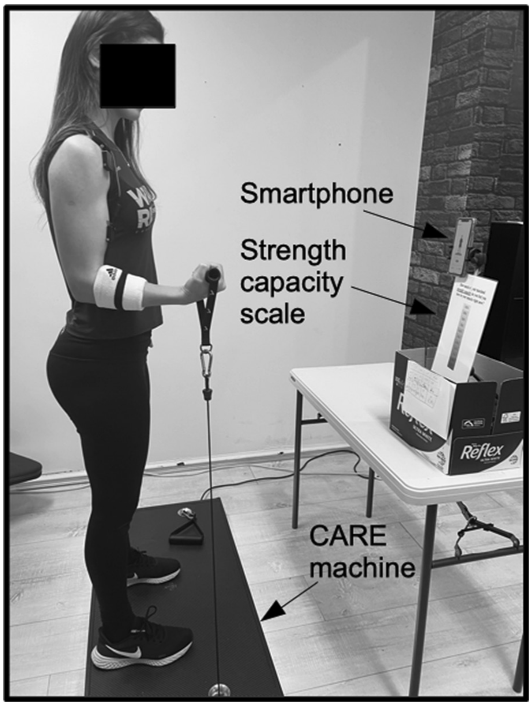

FIGURE 1 A participant performing unilateral bicep curl exercise while standing on the connected adaptive resistance exercise (CARE) machine. Located in front of the participant is their smartphone. The machine's smartphone application provided real-time visual feedback of the adjustable resistance. The arm strength capacity scale was also positioned in front of the participant and allowed them to quickly answer the question about arm strength capacity while performing exercise repetitions.

participant was trying to achieve was ~2 kg higher than their ECC maximum, which was known from familiarization sessions. A 1-min rest period was given between the four sets.

2.5 | ECC_{max}-only exercise

The ECC_{max}-only protocol consisted of 4 sets of 20 repetitions (i.e., 80 ECC contractions, 0 CON contractions). The smartphone application contains an ECC exercise mode. In this mode, the machine reduces resistance in the CON phase to zero or near zero to allow the participant to complete the CON phase with little effort. Then, by pausing at the end of the CON phase, the machine's algorithm recognizes the start of the ECC phase and begins to retract the rope in relation to the participant's ability to withstand or slow the retraction. The maximal target resistance that the participant was trying to achieve was ~2 kg higher than their ECC maximum. A 1-min rest period was given between the four sets.

2.6 | CON_{max}-only exercise

The CON_{max}-only protocol consisted of 4 sets of 20 repetitions (i.e., 0 ECC contractions, 80 CON contractions). The smartphone application did not have a CON_{max}-only mode. Thus, CON_{max}-only resistances were accomplished by using the default ECC-CON mode of the machine, but with the investigator taking the ECC load from the participant via a second handle attached to the rope. The investigator resisted the rope retraction to such a degree that when the participant started the CON phase, the initial resistance that the participant pulled against was equal to the target maximal resistance. For the CON_{max}-only protocol, the target maximal resistance was ~2 kg higher than the participant's CON maximum, which was known from familiarization. The participant was instructed to let the investigator "take the load" during the ECC phase, and the participant accomplished this by holding the handle loosely as the investigator lowered the rope back to the start of the CON phase. The participant might have experienced some minimal level of resistance in the ECC phase of this protocol, but any resistance they might have experienced would have been substantially different than the resistance experienced during the ECC_{max}-only and ECC_{max}-CON_{max} protocols. A 1-min rest period was given between the four sets.

2.7 | Perceptions of fatigue and pain

Before and after each exercise set, participants were asked about their perceptions of fatigue and pain (Supporting Information 2). One scale assessed biceps fatigue. It asked "How much fatigue do you feel in your biceps right now?" Its anchors were 0 (no fatigue) and 10 (maximal fatigue). Another scale assessed arm strength capacity. It asked "How much of your maximal strength capacity do you have in your right arm right now?" Its anchors were 0% and 100%, with 0% representing no arm strength capacity and 100% representing full arm strength capacity. This measure was acquired after every fifth muscle contraction. A third scale assessed biceps pain. It asked "How much discomfort/pain do you feel in your biceps right now?" Its anchors were 0 (none) and 10 (maximal). Participants were allowed to reflect upon the questions however they wanted. For perceptions assessed before and after the exercise sets, participants often flexed and extended their elbow before answering.

2.8 | Data processing

Files generated by the machine's smartphone application were downloaded and imported into Spike software for analysis (Cambridge Electronics Design, Cambridge, UK). Rope position data from the file were used to identify the ECC and CON phases. Average resistances or loads over the range of motions of the ECC and CON phases were measured for all repetitions. Because each muscle contraction was performed with maximal effort, and the CARE machine continually adjusted the resistance to accommodate the participant's force-generating capacity, the CARE machine's resistance or load reflected the maximal muscle strength or force-generating capacity of the participant. Thus, just as a barbell load (kg) might be used to express a participant's maximal muscle strength, in the current study, the continually-adjusting load that the participant exerted force against, also provided a measure of maximal muscle strength. Thus, a change in this load or resistance across repeated maximal effort contractions reflected strength loss. In the current paper, we use the phrases like "average strength" and "average load" interchangeably. They refer to the average of all resistances or loads sampled (50 Hz) over the entire movement ranges of the ECC and CON phase of a given repetition. Strength loss, an index of muscle fatigue, was calculated as the percent change in strength or load from the start of first set ("initial" strength) to the end of the fourth set ("final" strength). The initial strength for each exercise protocol was the highest average load among the first five repetitions in Set 1. For the ECC_{max}-only and CON_{max}-only protocols, "final" strength was the average of loads sampled across repetitions 17–20 of Set 4. For the ECC_{max}-CON_{max} protocol, the final strength was the average of loads sampled from repetitions 9 and 10 of Set 4 for each phase. Of note, Pearson's correlations (*r*) between participants' CON 1RM with the dumbbell and their initial CON phase strength values during the CON_{max}-only and ECC_{max}-CON_{max} protocols on the CARE machine were 0.974 and 0.946, respectively. This illustrates concurrent validity of the CARE machine loads.

2.9 | Statistical analyses

We used a mostly descriptive approach that emphasizes presentation of individual participant data supplemented by group means, standard deviations (SD), mean differences, effect sizes, and 95% confidence intervals (CI) of mean differences and effect sizes. This approach was taken based on a few considerations: some data violated assumptions of normality and homogeneity of variances; "ritual" null hypothesis testing and binary *p*-value criterion have been criticized; calls exist for increased reporting of individual participant data and effect sizes.[31–38] Hedges *g* effect sizes [95% CI] were used to correct for bias in small independent samples (men and women) and for unequal variances between groups.[39,40] Effect sizes are often considered small if they are equal to 0.2, moderate if they are equal to 0.5, and large if they are equal to 0.8, though such benchmarks are arbitrary and should not be interpreted rigidly.[39] In the figures, 95% CIs of mean differences between the groups or protocols being compared that do not include zero can be considered statistically significant (i.e., $p < 0.05$).[41] Version 28 of the Statistical Package for the Social Sciences (SPSS, Armonk, US) was used to complete the analyses.

3 | RESULTS

3.1 | Muscle strength loss

The machine reduced resistances automatically as participants fatigued (Figure 2A–F). This drop setting feature of the machine permitted all participants to complete all sets of exercise without stopping. It also caused marked reductions in muscle strength during all three resistance exercise protocols (Figures 2A–F and 3A–D). However, the magnitude of strength loss was impacted by contraction type and participant sex. By the end of set 4 of the ECC_{max}-only protocol, men and women lost, on average, 56% of their strength (Figure 3A). However, with the CON_{max}-only protocol, men experienced a level of strength loss equal to that which they experienced during the ECC_{max}-only protocol, whereas women lost less strength during the CON_{max}-only protocol than during the ECC_{max}-only protocol (Figure 3B). Men also exhibited greater strength loss than women during the ECC_{max}-CON_{max} protocol (Figure 3C,D). During this protocol, strength loss was more pronounced in the CON than ECC phase for both men and women.

Figure 4 displays answers to various questions of interest. Does ECC_{max}-only and CON_{max}-only resistance exercise cause equal strength loss (Figure 4A)? The answer depended on participant sex, as women were less susceptible to strength loss during CON_{max}-only than ECC_{max}-only exercise, whereas men experienced similar levels of strength loss in both protocols. Do coupled ECC_{max}-CON_{max} repetitions cause equal strength loss in the ECC and CON phases (Figure 4B)? The answer was no, as both men and women experienced greater strength loss during the CON than ECC phase of coupled ECC_{max}-CON_{max} repetitions. Does inclusion of CON_{max} contractions in coupled ECC_{max}-CON_{max} exercise repetitions increase ECC strength loss compared to ECC_{max}-only exercise (Figure 4C)? The answer was yes for men, whereas women tended to experience greater ECC strength loss from ECC_{max}-only than ECC_{max}-CON_{max} exercise. Finally, does inclusion of ECC_{max} contractions in coupled ECC_{max}-CON_{max} exercise

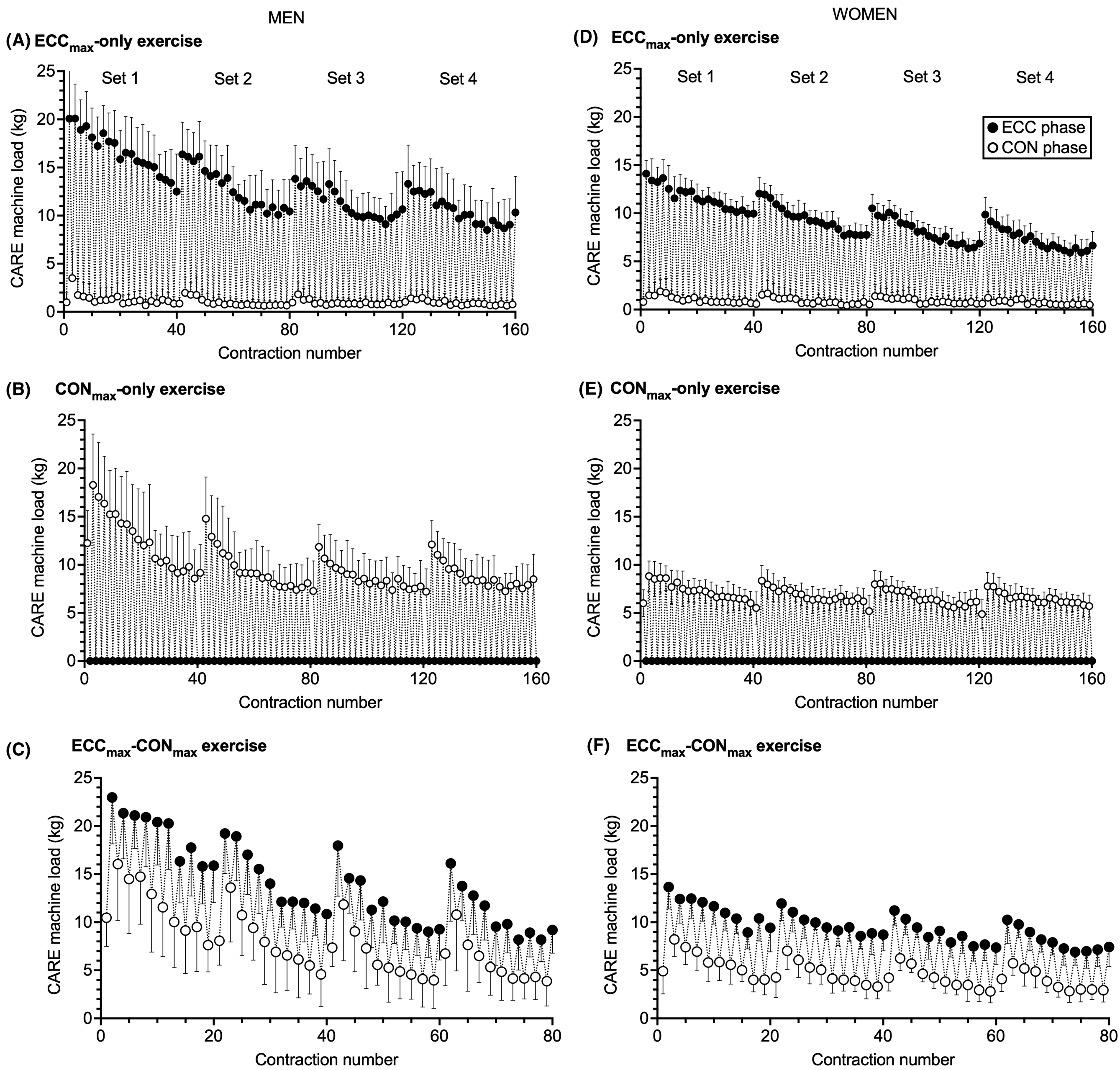

FIGURE 2 Eccentric (ECC, black circles) and concentric (CON, white circles) phase loads (kg) from the connected adaptive resistance exercise (CARE) machine across four sets of maximal effort eccentric-only (ECC_{max}-only) (A, D), concentric-only (CON_{max}-only) (B, E), and ECC_{max}-CON_{max} (C, F) bicep curl exercise. Data from men are presented in panels A–C. Data from women are presented in panels D–F. Because each muscle contraction was performed with maximal effort, the CARE machine load reflects the maximal strength or force-generating capacity of participants for each repetition. Data are presented as group mean ± SD. In panel A, the SD of the first contraction (±5.23) was truncated to improve visual clarity of the entire data set.

repetitions increase CON phase strength loss compared to CON_{max}-only exercise (Figure 4D)? The answer was yes for both men and women.

3.2 | Perceptions of fatigue and pain

The resistance exercise protocols on the CARE machine were also characterized by reduced perceived arm strength capacity (Figure 5A–F), heightened perceptions of biceps muscle fatigue (Figure 6A–F), and heightened perceptions of biceps muscle pain (Figure 7A–F). The 1-min rest allowed for partial alleviation of heightened perceptions of fatigue and pain. For arm strength capacity, reductions in perceived capacity after one set of exercise tended to be greatest after CON_{max}-only resistance exercise, but by the end of four sets of exercise, all three protocols reduced perceived arm strength capacity

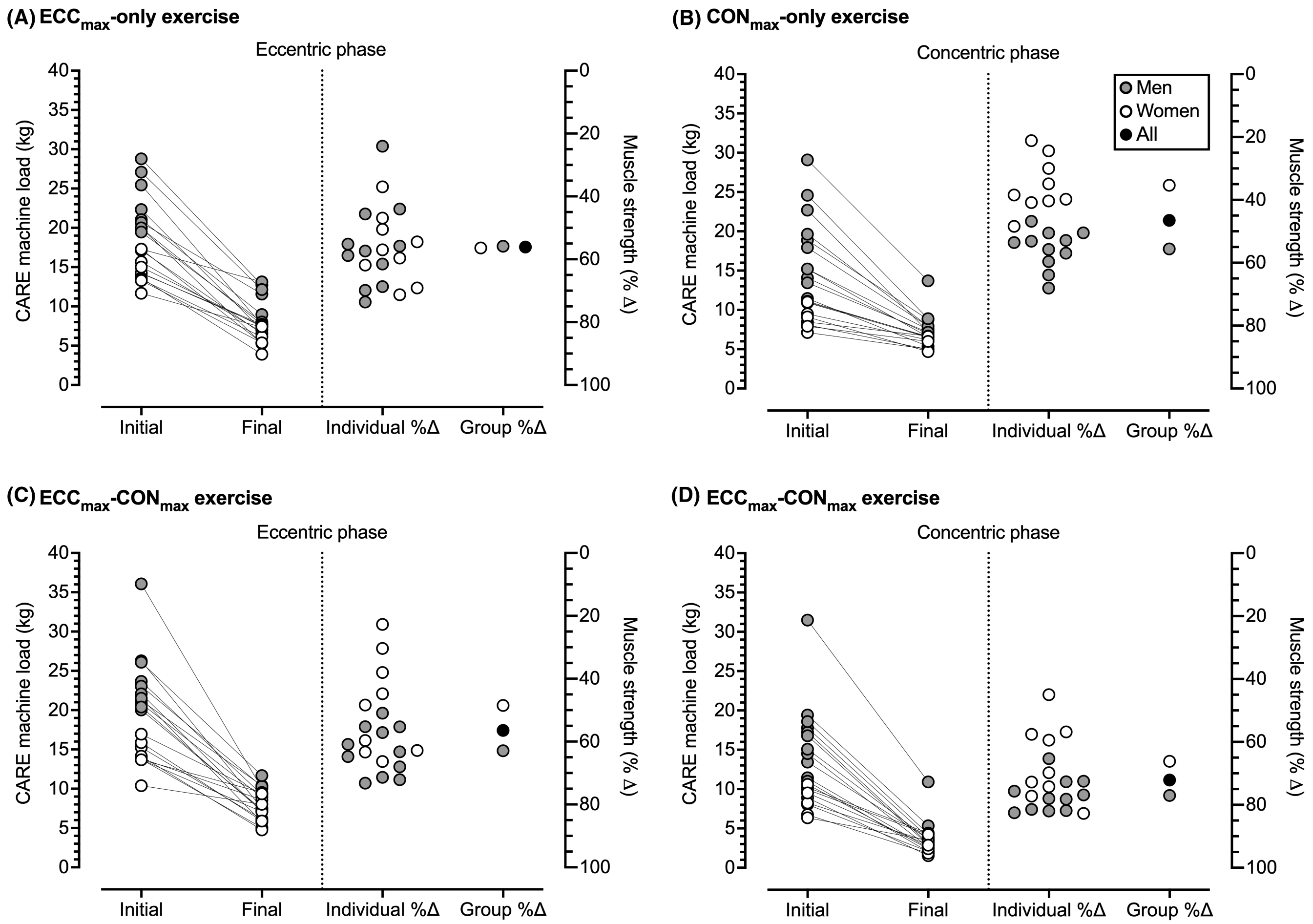

FIGURE 3 Initial and final loads (kg), and resultant percent changes in muscle strength, during the eccentric (ECC) phase of maximal effort eccentric-only (ECC_{max}-only) bicep curl exercise on the connected adaptive resistance exercise (CARE) machine (A), the concentric (CON) phase of maximal effort concentric-only exercise (CON_{max}-only) (B), and the ECC phase (C) and CON phase (D) of maximal effort ECC_{max}-CON_{max} exercise. Because each muscle contraction was performed with maximal effort, the CARE machine load reflects the maximal strength or force-generating capacity of participants at that time. Each male participant is represented by a gray circle. Each female participant is represented by a white circle. The black circle represents the male and female data combined.

to approximately the same level, with participants perceiving they had only 10%–15% of their arm strength remaining. For biceps fatigue, group means after set 1 were roughly 5–6 out of 10 ("moderate amount") irrespective of the type of exercise completed. Group means increased slightly with additional exercise, but by the end of all three protocols, participants perceived biceps fatigue to be about 7–8 out of 10 ("large amount"). Perceived biceps pain increased after one set of exercise and then generally increased with additional sets, particularly for ECC_{max}-only and ECC_{max}-CON_{max} exercise. Women tended to rate biceps pain higher than men throughout exercise, particularly for ECC_{max}-only exercise, where mean biceps pain after four sets of exercise was 4.5 out of 10 for men and 7.3 out of 10 for women. No other sex differences in perceptions existed.

4 | DISCUSSION

We examined muscle fatigue (strength loss, fatigue perceptions) during acute bouts of ECC_{max}-only, CON_{max}-only, and ECC_{max}-CON_{max} bicep curl exercise on a CARE machine. The machine's adjustable resistance algorithm reduced resistances as participants fatigued (i.e., automated drop setting) which allowed participants to complete all muscle contractions with maximal effort. Consequently, all three exercise protocols caused substantial strength loss and heightened perceptions of fatigue. The magnitude of strength loss was impacted by muscle contraction type and participant sex.

The results from the current study illustrate that when repeated maximal effort contractions are performed in sets of 20 contractions, the majority of strength loss occurs by

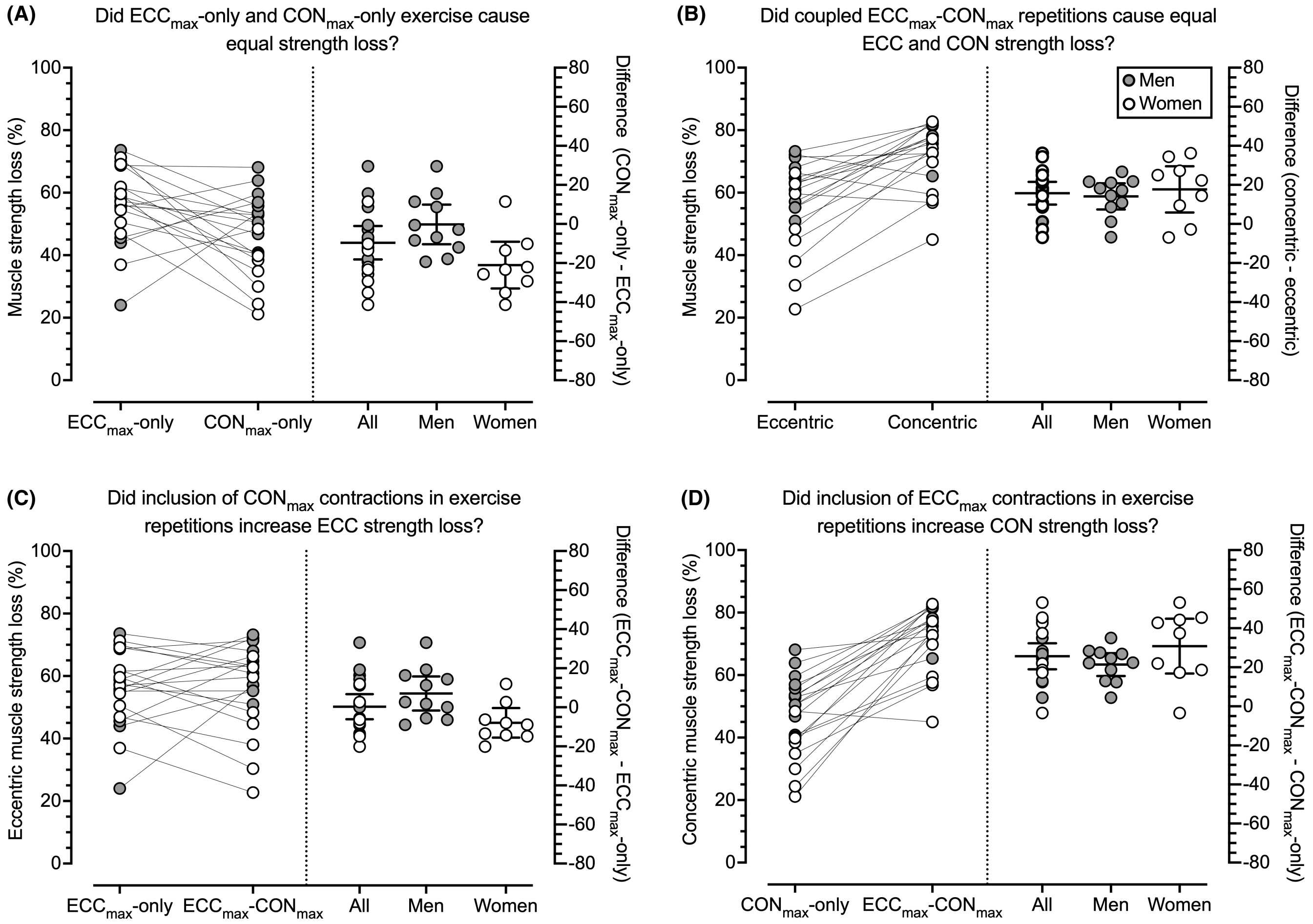

FIGURE 4 Comparison of muscle strength loss between maximal effort eccentric-only (ECC_{max}-only) and concentric-only (CON_{max}-only) bicep curl exercise on the connected adaptive resistance exercise (CARE) machine (A), between the ECC and CON phases of ECC_{max}-CON_{max} exercise (B), between the ECC phases of ECC_{max}-only and ECC_{max}-CON_{max} exercise (C), and between the CON phases of CON_{max}-only and ECC_{max}-CON_{max} exercise (D). Each male participant is represented by a gray circle. Each female participant is represented by a white circle. The difference scores on the right *y*-axes are raw differences between the two percent loss scores being compared. The two shorter horizontal lines about the mean difference represent the 95% CIs. Overall, the results show that men experienced similar losses in muscle strength during ECC_{max}-only and CON_{max}-only exercise, whereas women experienced greater strength loss from ECC_{max}-only than CON_{max}-only exercise (A); during coupled ECC_{max}-CON_{max} exercise, strength loss was greater in the CON than ECC phase of exercise in both men and women (B) inclusion of CON_{max} contractions in coupled ECC_{max}-CON_{max} exercise slightly increased ECC strength loss compared to exercise that did not include resistance in the CON phase (i.e., ECC_{max}-only exercise) for men, but not for women, inclusion of CON_{max} contractions in coupled ECC_{max}-CON_{max} exercise tended to decrease the magnitude of ECC strength loss compared to exercise that did not include resistance in the CON phase (C); inclusion of ECC_{max} contractions in coupled ECC_{max}-CON_{max} exercise increased CON strength loss compared to exercise that did not include resistance in the ECC phase (i.e., CON_{max}-only exercise) in both men and women (D).

the end of the first set, with partial strength recovery after 1-min rest. Further reductions in strength occur within and between subsequent sets, but the elbow flexors appear to exhibit a plateauing pattern in strength loss, wherein they continue to generate a minimal level of force with repeated maximal effort muscle contractions (i.e., strength preservation). Thus, the results suggest that for maximal effort bicep curl exercise, the majority of strength loss occurs in Set 1, strength is partially recovered with a 1-min rest, and a minimal level of strength (particularly in the ECC phase) is preserved to permit more muscle contractions.

Results from the current study also illustrate that muscle contraction type and participant sex influence strength loss from maximal effort bicep curl exercise on a CARE machine. Men and women experienced similar strength loss during ECC_{max}-only exercise (56%). However, women experienced greater strength loss during ECC_{max}-only exercise (56%) than during CON_{max}-only exercise (35%), whereas men experienced similar strength loss during ECC_{max}-only and CON_{max}-only exercise (56%), but greater strength loss during ECC_{max}-CON_{max} exercise (63%–77%). Thus, women appear to be more susceptible to strength

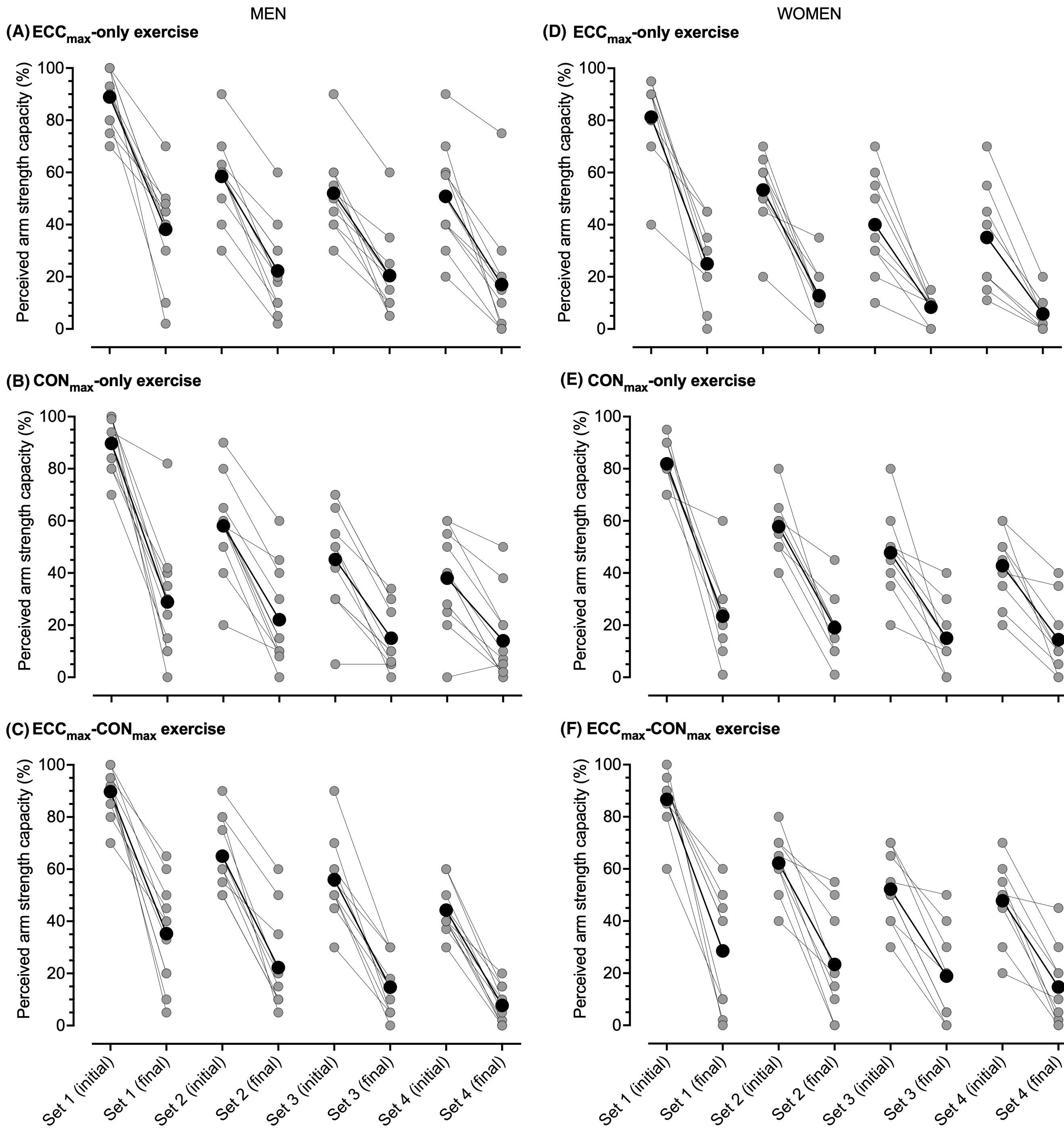

FIGURE 5 Perceived arm strength capacity among men (A–C) and women (D–F) across four sets of maximal effort eccentric-only (ECC_{max}-only) (A, D), concentric-only (CON_{max}-only) (B, E), and ECC_{max}-CON_{max} (C, F) bicep curl exercise on the connected adaptive resistance exercise (CARE) machine. Grey circles represent individual participants. Black circles represent group means. All exercise protocols reduced perceived arm strength capacity. The scale used to assess perceived arm strength capacity is provided in Supporting Information 2.

loss from bicep curl exercise that includes maximal resistances in the ECC phase, whereas men appear to be more susceptible to strength loss from exercise that includes maximal resistances in the CON phase. The finding in male participants of equal strength loss after ECC_{max}-only and CON_{max}-only exercise is consistent with the results from previous studies in which male participants performed fatiguing ECC_{max}-only and CON_{max}-only isokinetic exercise of the elbow flexors.[19,42–44] Few studies on this topic have included female participants, and those that have included females have not segregated data by sex, which makes comparisons with the current study's

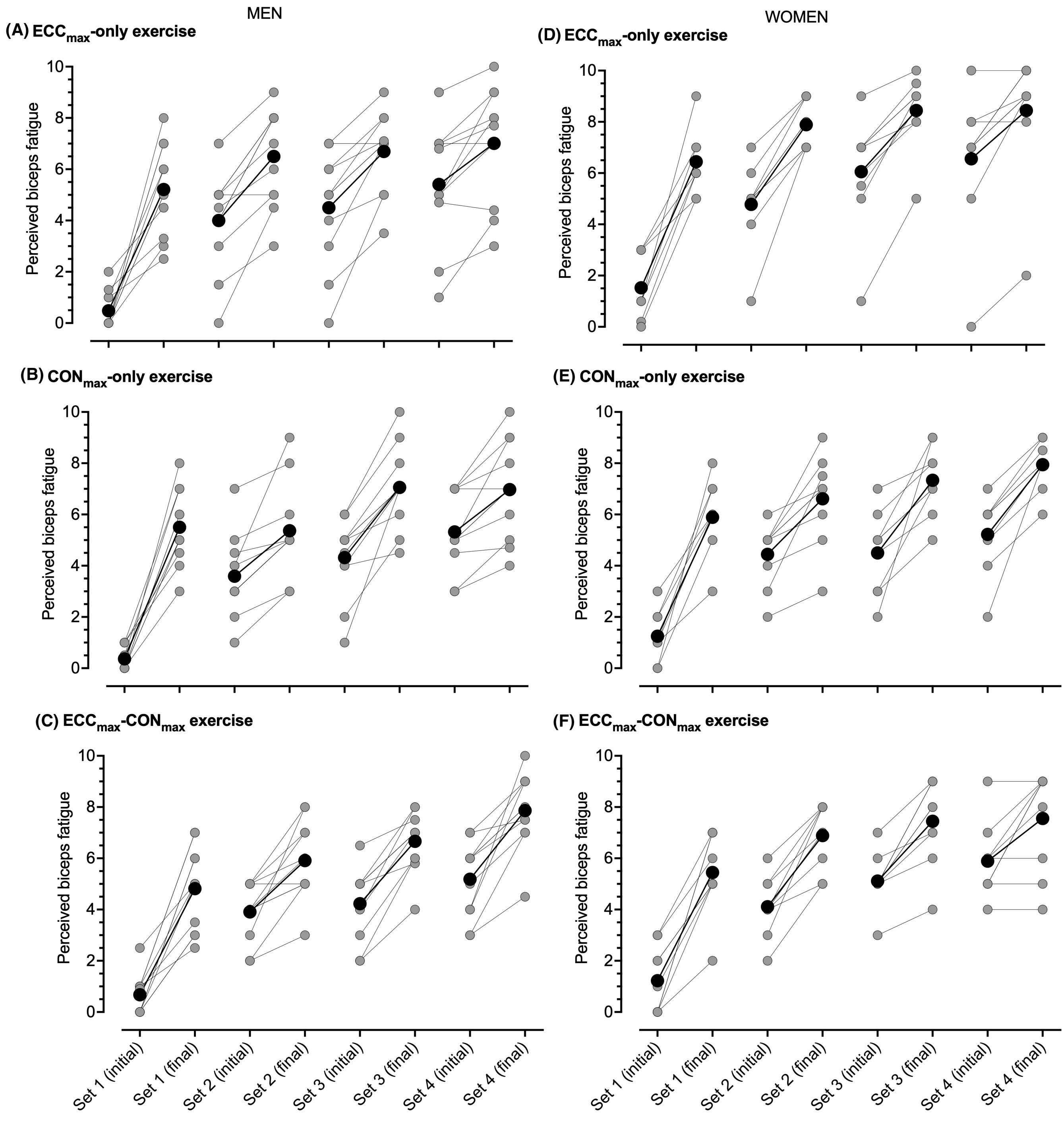

FIGURE 6 Perceived biceps fatigue among men (A–C) and women (D–F) across four sets of maximal effort eccentric-only (ECC_{max}-only) (A, D), concentric-only (CON_{max}-only) (B, E), and ECC_{max}-CON_{max} (C, F) bicep curl exercise on the connected adaptive resistance exercise (CARE) machine. Grey circles represent individual participants. Black circles represent group means. All exercise protocols increased perceived biceps fatigue. The scale used to assess perceived biceps fatigue is provided in Supporting Information 2.

findings difficult.[45,46] Interestingly, studies of the knee extensors and ankle plantarflexors have generally found greater strength loss immediately after CON_{max}-only than ECC_{max}-only resistance exercise, but with data not segregated by sex.[16,18,20,47] Finally, two studies have examined strength loss from ECC_{max}-CON_{max} resistance exercise on isokinetic dynamometers.[48,49] Both studies reported equal strength loss in the ECC and CON phases, whereas we found greater strength loss during the CON than ECC phase. The different findings might be attributed to the different volumes and machines used for resistance exercise in those studies.

The observed sex differences of greater susceptibly of men than women to muscle fatigue from CON_{max}-only

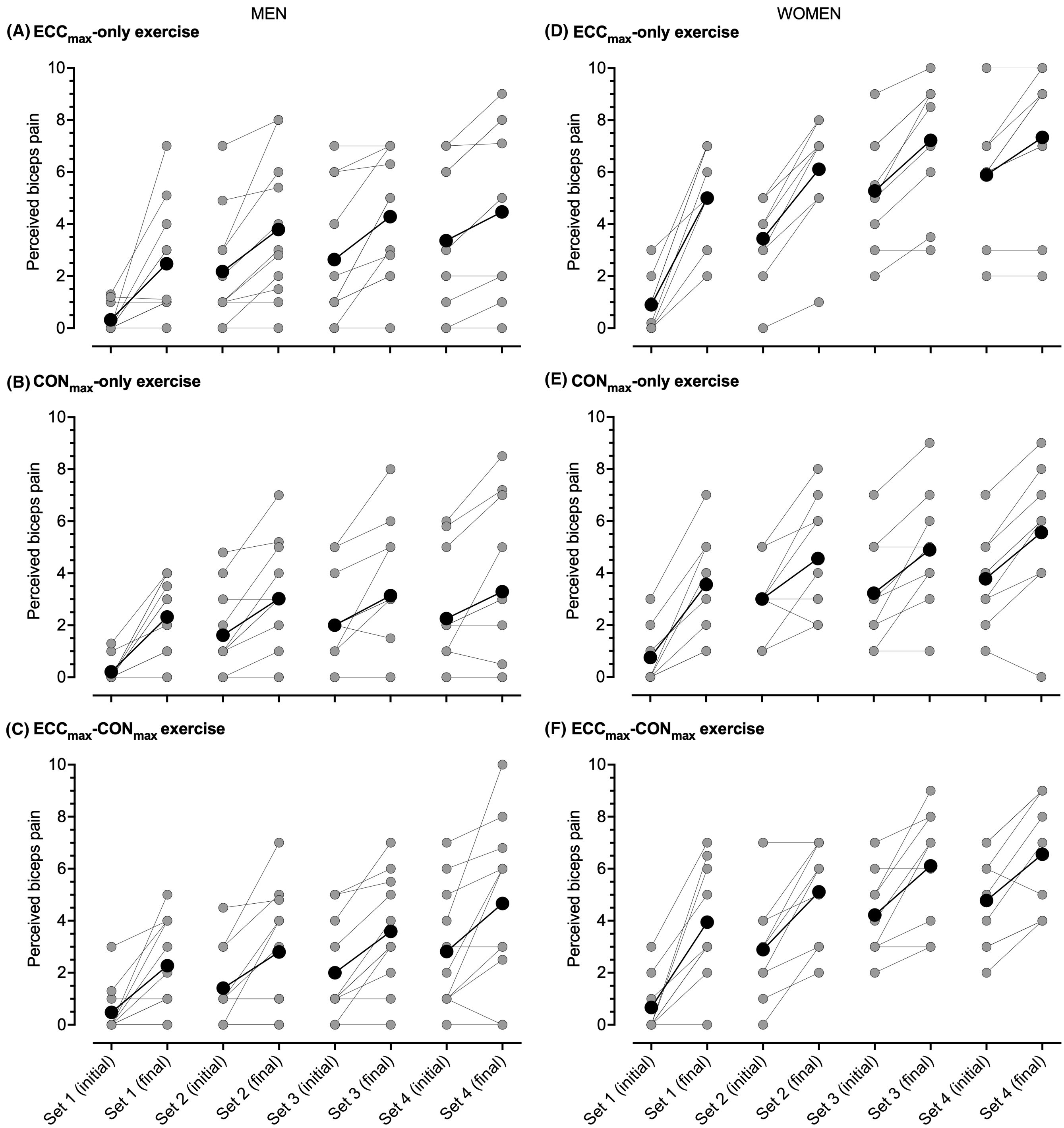

FIGURE 7 Perceived biceps pain among men (A–C) and women (D–F) across four sets of maximal effort eccentric-only (ECC_{max}-only) (A, D), concentric-only (CON_{max}-only) (B, E), and ECC_{max}-CON_{max} (C, F) bicep curl exercise on the connected adaptive resistance exercise (CARE) machine. Grey circles represent individual participants. Black circles represent group means. All exercise protocols increased perceived biceps pain. The scale used to assess perceived biceps pain is provided in Supporting Information 2.

and ECC_{max}-CON_{max} exercise are novel in that most studies that have observed sex differences in muscle fatigability have involved isometric rather than *non*-isometric tasks.[25–27] Potential causes of this sex differences include: greater muscle mass in men which causes greater intramuscular pressures on arteries that feed the exercising muscle and thus limits blood flow and oxygen supply to the muscle; greater proportional representation of type II muscle fiber areas in men than women; and larger exercise-induced reductions in voluntary activation in men than women.[25,26,50] Nevertheless, we acknowledge that the sample sizes in the current study were small and the observed sex differences in muscle fatigability should be interpreted with caution.

We also observed that all exercise protocols caused heightened perceptions of fatigue and pain in the exercised limb. Few differences existed between protocols and between men and women. After all protocols, participants generally perceived a "large amount" of fatigue in their biceps (~7.5 of 10), and they perceived they had only 10%–15% of their maximal strength capacity remaining in their arm. However, perceived biceps pain was greater after the protocols that included maximal resistances in the ECC phase (5–6 of 10, "moderate amount") than after the CON_{max}-only protocol (4 of 10, between "small" and "moderate"). Also, women generally reported greater biceps pain than men, particularly during ECC_{max}-only exercise. Thus, considering that men and women experienced similar strength loss after ECC_{max}-only exercise, but women reported higher ratings of biceps pain, this highlights the potential value of a holistic approach to clinical decision making that considers both objective and subjective measures of fatigue and pain. Further support for this comes from the finding in the current study that both the men and women reported similar levels of perceived biceps fatigue and reduced arm strength capacity after CON_{max}-only exercise, but men experienced greater relative strength loss.

The current study has several limitations. First, the male and female sample sizes were small. Consequently, estimates of effects were likely not as precise as they would have been with larger samples. Nevertheless, we believed that segregating the male and female data was important for the following reasons: (a) roughly equal numbers of men and women volunteered for the study, (b) sex differences in muscle fatigability are possible,[25,26] (c) combining the data would hide the observed sex differences, and (d) calls exist for more sex-segregated data in exercise research.[28] Future research with larger samples of men and women can help to establish more precise estimates of muscle fatigability during ECC_{max}-only, CON_{max}-only, and ECC_{max}-CON_{max} resistance exercise. Second, additional research is required to more firmly establish the reliability and validity of the forces delivered and reported by the CARE machine. Nevertheless, we observed concurrent validity of the CARE machine in two ways: (a) strong correlations ($r > 0.94$) existed between maximal CON phase strength on the CARE machine versus the bicep curl dumbbell 1RM; and (b) perceptions of fatigue were heightened with actual strength loss from exercise. Third, given their newness, scarce research exists on the effectiveness of CARE machines for increasing muscle size and strength.[51] Our results do not demonstrate such effectiveness, because only an acute bout of exercise was performed. Nevertheless, our results illustrate that a CARE machine can automate ECC overload and drop setting, which are training strategies known to increase muscle size and strength when other equipment is used.[1,2,8,24,52–54] Thus, CARE machines might be used in conjunction with, or independent of, other resistance exercise equipment, depending on one's goals, resources, and exercise preferences. Future research is necessary to examine the impact of regular use of CARE machines on muscle size and strength and other clinical outcomes. Such research can compare the effectiveness of CARE machines versus types of resistance exercise equipment whose use is known to increase muscle size and strength.

5 | PERSPECTIVES

Accentuated ECC and ECC-only resistance exercise can be difficult to prescribe to athletes and patients due to equipment limitations. Results from the current study illustrate that CARE technology can deliver accentuated ECC and ECC-only resistance exercise safely and feasibly, and the machine's adjustable resistance algorithm automatically reduces resistances (i.e., drop setting) in the ECC and CON phases as participants fatigue. Using these features of the machine, we explored characteristics of muscle fatigue during bicep curl exercise comprised of ECC_{max}-only, CON_{max}-only, and ECC_{max}-CON_{max} muscle contractions. We found that women were most susceptible to strength loss from exercise that included maximal resistances in the ECC phase, whereas men were most susceptible to strength loss from exercise that included maximal resistances in the CON phase. Thus, acute responses to maximal effort bicep curl exercise on such machines appear to differ between men and women depending on muscle contraction type, and such differences might warrant consideration when designing resistance exercise programs with drop sets for men and women.

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Research data are not shared.

ORCID

James L. Nuzzo https://orcid.org/0000-0001-9081-0522
Matheus D. Pinto https://orcid.org/0000-0002-2616-2492
Kazunori Nosaka https://orcid.org/0000-0001-7373-4994

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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